Effect of Convective Entrainment/Detrainment on the Simulation of the Tropical Precipitation Diurnal Cycle*

**Yuqing Wang, Li Zhou, and Kevin Hamilton**

*International Pacific Research Center, and Department of Meteorology, School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, Honolulu, Hawaii*

(Manuscript received 10 January 2006, in final form 28 May 2006)

**ABSTRACT**

A regional atmospheric model (RegCM) developed at the International Pacific Research Center (IPRC) is used to investigate the effect of assumed fractional convective entrainment/detrainment rates in the Tiedtke mass flux convective parameterization scheme on the simulated diurnal cycle of precipitation over the Maritime Continent region. Results are compared with observations based on 7 yr of the Tropical Rainfall Measuring Mission (TRMM) satellite measurements. In a control experiment with the default fractional convective entrainment/detrainment rates, the model produces results typical of most other current regional and global atmospheric models, namely a diurnal cycle with precipitation rates over land that peak too early in the day and with an unrealistically large diurnal range. Two sensitivity experiments were conducted in which the fractional entrainment/detrainment rates were increased in the deep and shallow convection parameterizations, respectively. Both of these modifications slightly delay the time of the rainfall-rate peak during the day and reduce the diurnal amplitude of precipitation, thus improving the simulation of precipitation diurnal cycle to some degree, but better results are obtained when the assumed entrainment/detrainment rates for shallow convection are increased to the value consistent with the published results from a large eddy simulation (LES) study. It is shown that increasing the entrainment/detrainment rates would prolong the development and reduce the strength of deep convection, thus delaying the mature phase and reducing the amplitude of the convective precipitation diurnal cycle over the land. In addition to the improvement in the simulation of the precipitation diurnal cycle, convective entrainment/detrainment rates also affect the simulation of temporal variability of daily mean precipitation and the partitioning of stratiform and convective rainfall in the model. The simulation of the observed offshore migration of the diurnal signal is realistic in some regions but is poor in some other regions. This discrepancy seems not to be related to the convective lateral entrainment/detrainment rate but could be due to the insufficient model resolution used in this study that is too coarse to resolve the complex land–sea contrast.

1. **Introduction**

Convection actively interacts with its environment through entrainment of environmental dry air into cumulus clouds and detrainment of moist air from convective plumes into the environment. Such an interaction is quite complex and is usually treated crudely as prescribed fractional convective entrainment/detrainment rates in most convective parameterization schemes (e.g., Arakawa and Schubert 1974; Tiedtke 1989; Kain and Fritsch 1990). There have been some previous studies of the effects of varying the entrainment rate in sophisticated atmospheric model simulations. For example, Yao and Del Genio (1989) found a general improvement of the January climate simulation in an atmospheric general circulation model when the effect of entrainment from deep convection was included, and Tokioka et al. (1988) reported an improved simulation of the equatorial 30–60-day oscillation when they introduced a minimum value for convective entrainment rate in the Arakawa–Schubert penetrative cumulus parameterization.

The diurnal cycle of rainfall provides one test of the performance of convective parameterizations in models. Most current atmospheric models have significant
biases in their simulations in this respect. Typically, model simulated rainfall rates over land peak too early in the day and display an unrealistically large diurnal range (e.g., Yang and Slingo 2001; Betts and Jakob 2002a; Neale and Slingo 2003; Dai and Trenberth 2004). In a recent study, Bechtold et al. (2004) showed that the simulated diurnal cycle of tropical precipitation in a global atmospheric model was very sensitive to the cumulus parameterization. A close examination of the results of Bechtold et al. (2004) suggests that better simulations in their model result from the use of slightly larger entrainment/detrainment rates for deep convection. Although this point was not explicitly emphasized, Bechtold et al. (2004) did suggest that possible candidates for future improvement in the simulation of the precipitation diurnal cycle could be an increase in the midtropospheric entrainment rate, and an improved shallow convective closure that could strongly ventilate the morning boundary layer. Both effects are expected to delay the development of deep convection over the land.

Despite their importance to realistic simulation of not only mean climate but also variability at various time scales, the fractional lateral convective entrainment/detrainment rates in most convective parameterization schemes have not been constrained by observations. Rather, they are empirically determined based on limited numerical or laboratory experiments (e.g., Arakawa and Schubert 1974; Tiedtke 1989) and considerable uncertainties remain. For example, Siebesma and Holtslag (1996) showed that the fractional entrainment/detrainment rates for shallow convection used in Tiedtke (1989) were about one order smaller in magnitude than that estimated from their large eddy simulations (LESs).

Although they are generally nonprecipitating, shallow cumulus clouds play an important role in regulating the morning development of a growing planetary boundary layer (PBL) over the land, destabilizing the lower troposphere, and moistening the midtroposphere, thus bridging the convective boundary layer and deep convection (Betts and Jakob 2002b). It is thus expected that an adequate representation of shallow convection must be important to the simulation of the diurnal cycle of convective precipitation. The development and strength of shallow convection is largely determined by the lateral fractional entrainment/detrainment rates. The possible effect of the entrainment/detrainment rates of shallow convection on the simulation of the tropical precipitation diurnal cycle, however, appears not to have been evaluated previously.

The objective of the present study is to provide an initial evaluation of the potential effect of lateral fractional convective entrainment/detrainment rates on the simulation of the precipitation diurnal cycle over the Maritime Continent and surrounding oceans (Fig. 1). This region was chosen because it is a unique environment with complex land–sea contrasts and strong convective activity on a broad range of time scales. Most atmospheric models have considerable biases in simulating the convective activity in this region (e.g., Neale and Slingo 2003).

A regional atmospheric model is utilized in this study. The model uses the mass flux cumulus parameterization scheme originally developed by Tiedtke (1989) and later modified by Nordeng (1995) with the convective available potential energy (CAPE) closure. The scheme treats shallow convection, deep convection, and midlevel convection, separately, based on their cloud top and base. Because the midlevel convection is mainly associated with midlatitude frontal systems and thus might not be important in the deep Tropics, we will focus on the effects of lateral fractional entrainment/detrainment rates of both parameterized deep and shallow convection on the simulated tropical precipitation diurnal cycle. We will show that the use of appropriate lateral fractional entrainment/detrainment rates for shallow convection cannot only reduce common discrepancies in the simulation of the precipitation diurnal cycle in the Tropics but can also lead to the improved simulation of tropical precipitation in general.

2. Model, experimental design, and data used for comparison

The model used in this study is the regional climate model (RegCM) developed at the International Pacific Research Center (IPRC) at the University of Hawaii. A detailed description of the model and its performance...
in simulating regional climate over East Asia and over the eastern Pacific can be found in Wang et al. (2003) and Wang et al. (2004a,b). The model uses hydrostatic primitive equations in spherical coordinates with \( \sigma \) (pressure normalized by surface pressure) as the vertical coordinate. The model equations are solved with a fourth-order conservative horizontal finite-difference scheme on a longitude–latitude grid system and a leapfrog scheme with intermittent use of an Euler backward scheme for the time integration.

The model physics include a cloud microphysics scheme for grid-scale moist processes (Wang 2001); a nonlocal \( E-\varepsilon \) turbulence closure scheme for subgrid-scale vertical mixing (Langland and Liou 1996); a Monin–Obukhov similarity scheme for surface flux calculation over the ocean (Fairall et al. 2003); the Biosphere–Atmosphere Transfer Scheme (BATS) of Dickinson et al. (1993) for land surface processes; the radiation package originally developed by Edwards and Slingo (1996) and further improved by Sun and Rikus (1999); and the mass flux convective parameterization scheme for subgrid-scale shallow, midlevel, and penetrative convection originally developed by Tiedtke (1989) and later modified by Nordeng (1995). The modified convective parameterization scheme uses a CAPE closure instead of the original moisture convergence closure for deep convection. Cloud amount is diagnosed using the Xu and Randall (1996) semiaempirical parameterization scheme. A summary of the model physics is given in Table 1.

### Table 1. List of physics parameterization schemes used in the IPRC-RegCM. Also included are references and comments where necessary.

<table>
<thead>
<tr>
<th>Physical process</th>
<th>Scheme</th>
<th>References</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>processes</td>
<td></td>
<td></td>
<td>With CAPE closure and organized entrainment and detrainment.</td>
</tr>
<tr>
<td>Mixing</td>
<td>Vertical: 1.5-level nonlocal turbulence closure</td>
<td>Langland and Liou (1996)</td>
<td>Modified to include cloud buoyancy production of turbulence (Wang 1999)</td>
</tr>
<tr>
<td></td>
<td>Horizontal: Fourth-order</td>
<td>Wang et al. (2003)</td>
<td>Deformation and terrain-slope dependent diffusion coefficient</td>
</tr>
<tr>
<td>Surface layer over ocean</td>
<td>Bulk scheme</td>
<td>Fairall et al. (2003)</td>
<td>TOGA COARE v3.0</td>
</tr>
<tr>
<td>Cloud optical properties</td>
<td>Longwave radiation</td>
<td>Sun and Shine (1994)</td>
<td>With specified cloud droplet number concentration (CDNC) of 100 cm(^{-3}) over ocean and 300 cm(^{-3}) over land</td>
</tr>
<tr>
<td></td>
<td>Shortwave radiation</td>
<td>Slingo and Schrecker (1982)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chou et al. (1998)</td>
<td></td>
</tr>
<tr>
<td>Cloud amount</td>
<td>Semi-empirical scheme</td>
<td>Xu and Randall (1996)</td>
<td>Dependent on relative humidity and cloud liquid/ice water extent</td>
</tr>
<tr>
<td>Land surface processes</td>
<td>BATS</td>
<td>Dickinson et al. (1993)</td>
<td>Modified algorithm for solving leaf temperature to ensure a convergent iteration of numerical solution (Wang et al. 2003)</td>
</tr>
</tbody>
</table>

in simulating regional climate over East Asia and over the eastern Pacific can be found in Wang et al. (2003) and Wang et al. (2004a,b). The model uses hydrostatic primitive equations in spherical coordinates with \( \sigma \) (pressure normalized by surface pressure) as the vertical coordinate. The model equations are solved with a fourth-order conservative horizontal finite-difference scheme on a longitude–latitude grid system and a leapfrog scheme with intermittent use of an Euler backward scheme for the time integration.

The model physics include a cloud microphysics scheme for grid-scale moist processes (Wang 2001); a nonlocal \( E-\varepsilon \) turbulence closure scheme for subgrid-scale vertical mixing (Langland and Liou 1996); a Monin–Obukhov similarity scheme for surface flux calculation over the ocean (Fairall et al. 2003); the Biosphere–Atmosphere Transfer Scheme (BATS) of Dickinson et al. (1993) for land surface processes; the radiation package originally developed by Edwards and Slingo (1996) and further improved by Sun and Rikus (1999); and the mass flux convective parameterization scheme for subgrid-scale shallow, midlevel, and penetrative convection originally developed by Tiedtke (1989) and later modified by Nordeng (1995). The modified convective parameterization scheme uses a CAPE closure instead of the original moisture convergence closure for deep convection. Cloud amount is diagnosed using the Xu and Randall (1996) semiaempirical parameterization scheme. A summary of the model physics is given in Table 1.

In the Tiedtke scheme, the updraft of the cloud ensemble is assumed to be in a steady state and its mass flux \( M_\alpha(z) \) is determined by the mass entrainment of the environmental air into convective plumes \( E_\alpha(z) \), and the mass detrained from convective plumes \( D_\alpha(z) \). The mass budget for the clouds thus is given by

\[
\frac{\partial M_\alpha(z)}{\partial z} = E_\alpha(z) - D_\alpha(z),
\]

where \( E_\alpha \) and \( D_\alpha \) are the rates of mass entrainment and detrainment per unit length, respectively. Two processes are considered, namely, turbulence exchange of mass through cloud edges (lateral entrainment/detrainment) and organized entrainment/detrainment due to organized inflow/outflow near the cloud base/top. The organized entrainment/detrainment was described in Nordeng (1995) for the modified Tiedtke scheme. Tur-
The turbulent entrainment and detrainment are parameterized following Turner (1963) as

$$E'_u = e_u M_a, \quad D'_u = \delta_u M_a,$$

(2)

where the superscript $T$ indicates the turbulent entrainment/detrainment. The fractional entrainment/detrainment rates $e_u/\delta_u$, depend inversely on cloud radii (Simpson 1971),

$$e_u = \delta_u = \frac{0.2}{R_u}$$

(3)

where $R_u$ is the radius of the cloud base. Tiedtke (1989) assumed the entrainment/detrainment rates to be $1 \times 10^{-4}$ m$^{-1}$ for penetrative deep convection and $3 \times 10^{-4}$ m$^{-1}$ for shallow convection implying an average cloud-base radius of 2 km for deep convection and 0.67 km for shallow convection. Because the sizes of individual cumulus clouds vary from less than several hundreds meters to several kilometers, the entrainment/detrainment rates may thus vary by an order of magnitude. Furthermore, the relationship in (3) was obtained under many assumptions and thus it contains uncertainties as well. In this study, we will focus on the effect of assumed fractional entrainment/detrainment rates for deep and shallow convection on the model simulated diurnal cycle of precipitation.

The experimental design follows Wang et al. (2003). The model domain was taken to be 30°S–30°N, 40°E–180° with a horizontal grid spacing of 0.5° (Fig. 1). The model has 28 $\sigma$ levels in the vertical (see Table 2). The United States Geological Survey (USGS) high-resolution topographic dataset ($0.0833^\circ \times 0.0833^\circ$) was used to obtain the model envelope orography. The high-resolution vegetation-type data from the USGS was reanalyzed for the model based on dominant vegetation type in each grid box. The 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40), available at 6-h intervals with a resolution of $2.5^\circ \times 2.5^\circ$ in the horizontal and 17 pressure levels up to 10 hPa, was used to define both the initial and lateral boundary conditions for the regional model. Sea surface temperatures (SSTs) over the ocean were obtained from the Reynolds weekly SST data with a horizontal resolution of $1^\circ \times 1^\circ$ (Reynolds and Smith 1994), which were interpolated into the model grids by cubic spline interpolation in space and linearly interpolated in time. These SST values have no diurnal variation, of course, a limitation that we will refer to later in our discussion of our results. Over the land, the initial surface soil and canopy temperatures were obtained from the lowest model level with a standard lapse rate of 6°C km$^{-1}$. Soil moisture fields were initialized depending on the vegetation and soil types following Giorgi and Bates (1989). The model was initialized from 0000 UTC 1 January 1998 and integrated continuously through 31 March 1998.

Three experiments were performed (see Table 3). In the control experiment (CTRL), all the parameters used in the mass flux cumulus parameterization scheme are the default ones as in Tiedtke (1989). In one of the sensitivity experiments (PEN_EN), the lateral fractional entrainment/detrainment rates for penetrative deep convection was doubled from $1 \times 10^{-4}$ m$^{-1}$ in CTRL to $2 \times 10^{-4}$ m$^{-1}$. Tiedtke (1989) showed in a single-column model that the enhanced entrainment/detrainment rates for deep convection would reduce subgrid convective precipitation. It is not clear, however, what the effect is, of such an enhanced entrainment/detrainment rate, on the fraction of grid-resolved precipitation and the precipitation diurnal cycle. The other sensitivity experiment (SH_EN) is the same as the CTRL but the lateral fractional entrainment/detrainment rate for shallow convection was increased from $3 \times 10^{-4}$ m$^{-1}$ in CTRL to $2 \times 10^{-3}$ m$^{-1}$. This enhanced entrainment/detrainment rate for shallow convection is in the range that is inferred from the LES results of Siebesma and Holtslag (1996) but is about 6.7 times of that used in Tiedtke (1989).

The observed rainfall rates that we will use for com-

Table 2. The vertical $\sigma$ levels used in the IPRC-RegCM.

<table>
<thead>
<tr>
<th>Level index</th>
<th>$\sigma$</th>
<th>Level index</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.011</td>
<td>15</td>
<td>0.580</td>
</tr>
<tr>
<td>2</td>
<td>0.029</td>
<td>16</td>
<td>0.640</td>
</tr>
<tr>
<td>3</td>
<td>0.044</td>
<td>17</td>
<td>0.700</td>
</tr>
<tr>
<td>4</td>
<td>0.061</td>
<td>18</td>
<td>0.755</td>
</tr>
<tr>
<td>5</td>
<td>0.080</td>
<td>19</td>
<td>0.803</td>
</tr>
<tr>
<td>6</td>
<td>0.105</td>
<td>20</td>
<td>0.844</td>
</tr>
<tr>
<td>7</td>
<td>0.140</td>
<td>21</td>
<td>0.876</td>
</tr>
<tr>
<td>8</td>
<td>0.180</td>
<td>22</td>
<td>0.901</td>
</tr>
<tr>
<td>9</td>
<td>0.225</td>
<td>23</td>
<td>0.922</td>
</tr>
<tr>
<td>10</td>
<td>0.280</td>
<td>24</td>
<td>0.942</td>
</tr>
<tr>
<td>11</td>
<td>0.340</td>
<td>25</td>
<td>0.961</td>
</tr>
<tr>
<td>12</td>
<td>0.400</td>
<td>26</td>
<td>0.977</td>
</tr>
<tr>
<td>13</td>
<td>0.460</td>
<td>27</td>
<td>0.989</td>
</tr>
<tr>
<td>14</td>
<td>0.520</td>
<td>28</td>
<td>0.997</td>
</tr>
</tbody>
</table>

Table 3. Fractional convective entrainment/detrainment rates for penetrative and shallow convection in three experiments discussed in this study.

<table>
<thead>
<tr>
<th>Expts</th>
<th>Penetrative convection</th>
<th>Shallow convection</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTRL</td>
<td>$1.0 \times 10^{-4}$</td>
<td>$3.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>PEN_EN</td>
<td>$2.0 \times 10^{-4}$</td>
<td>$3.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>SH_EN</td>
<td>$1.0 \times 10^{-4}$</td>
<td>$2.0 \times 10^{-3}$</td>
</tr>
</tbody>
</table>
parison with the modeled diurnal cycle were taken from the 3G68 precipitation radar dataset for the Tropical Rainfall Measurement Mission (TRMM) satellite (more detail is available online at ftp://trmmopen.gsfc.nasa.gov/pub/). These data represent instantaneous values of the rain rate (also provided is the fraction of the rain estimated to be of convective origin) on $0.5^\circ \times 0.5^\circ$ latitude–longitude grids. Given the limited sampling provided by the TRMM satellite, these data are composited for each grid box and each hour of the day from the January–March period in 7 consecutive years (1998–2004). Because our model simulation was performed only for 1998, this somewhat limits the direct comparability of the data and model results. Although it suffers from both a narrow swath and coarse sampling time intervals, the TRMM 3G68 is still a very useful dataset to represent the precipitation diurnal cycle (e.g., Negri et al. 2002). As suggested by Negri et al., a 4-h running mean was applied to the composite diurnal cycle to reduce the noise level.

We are also interested in evaluating the simulated mean rainfall rate. For the long-term mean validation we employ the TRMM 3B43 monthly-mean gridded dataset based on a combination of TRMM data, outgoing longwave radiation satellite observations, and rain gauge data (Huffman et al. 1997).

3. Results

a. Diurnal cycle of precipitation

The model results were composited for the full three months of integration to produce mean rainfall rates for each hour of the day [local time (LT)]. This composite daily cycle was then used to derive the amplitude and phase (local time of maximum) of the diurnal (i.e., 24 h) harmonic of the rainfall rates at each grid point. The composite diurnal cycle obtained from the TRMM 3G68 gridded hourly dataset is shown as the observational comparison.

The spatial distributions of the time of maximum rainfall rates in the diurnal cycle from observation and simulations are shown in Fig. 2. Consistent with previous studies, the rainfall rates from TRMM data peak between the late afternoon and midnight over most of the land areas (Fig. 2a). Note that Hamilton (1981) and Forbes et al. (1997) report the phase of the diurnal harmonic of rainfall computed from 38 yr of hourly rain gauge data at Kuala Lumpur, Malaysia ($3.1^\circ N, 101.7^\circ E$) is 1600 LT, in good agreement with the TRMM results in Fig. 2a. There is a clear signal of coherent offshore diurnal migration from the main islands, indicating the reversal of sea breeze and/or the activity of gravity waves forced by deep convection over the land areas.
during the daytime (Yang and Slingo 2001; Mapes et al. 2003; Mori et al. 2004). Earlier studies indicated the evening/early morning maximum of rainfall over the open oceans (e.g., Gray and Jacobson 1977). This seems not to be the case over the western Pacific warm pool region where TRMM observation also shows morning and afternoon maxima (Fig. 2a). This is consistent with recent studies by Liberti et al. (2001) and Mori et al. (2004), who found the remote effect of deep convection over the Maritime Continent on the surrounding oceans.

The peak of the simulated diurnal rainfall rates in CTRL is in the early–late afternoon over most of the land areas, about 2–4 h earlier than the observed, and occurs predominantly in the early morning over most of the ocean areas (Fig. 2b). These discrepancies are typical of most current atmospheric models (e.g., Yang and Slingo 2001; Neale and Slingo 2003). In the coastal regions around the Maritime Continent islands, the time of the simulated diurnal maximum rainfall rates is also too early compared with observations, indicating a close connection to the unrealistically early development of deep convection over the continents.

With the enhanced fractional entrainment/detrainment rates for deep convection in PEN_EN, the time of the simulated diurnal peak in rainfall rates is delayed by about 1–2 h over most of the land areas and in some of the coastal regions, but there is little change over the open-ocean areas (Fig. 2c). Such a marginal improvement in the diurnal phase is consistent with the results of Bechtold et al. (2004), who showed the sensitivity of the simulated precipitation diurnal cycle to different convective parameterization schemes used in different versions of the ECMWF global model.

With the enhanced fractional entrainment/detrainment rates for shallow convection in SH_EN, the peak of the simulated diurnal rainfall rates occurs at a time much closer to that observed both over the Maritime Continents and over the oceans but with a phase that is still about 1–2 h too early over most of the land areas in general (Fig. 2d). The migration of the diurnal signal is clearer than that in the control experiment. In the coastal regions, the direction of diurnal migration is generally offshore, consistent with observations (Fig. 2a), but considerable discrepancy exists in some regions (see further discussion below). Further offshore over the western Pacific warm pool region, the diurnal migration in the simulation is predominantly westward, but no coherent migration is apparent in TRMM observations (Fig. 2a). The dominant westward migration in the model, however, is consistent with the predominant westward propagation of the organized mesoscale convective systems in the western Pacific warm pool region (Chen and Houze 1997; Hall and Haar 1999). This migration feature could be affected by transient motions and it may be difficult to be properly represented in the TRMM observations because of their narrow swath and infrequent sampling.

The observed diurnal cycle of precipitation shows large amplitudes over land areas and very small amplitudes over the oceans (Fig. 3a). Also there are along-coastline maxima in the diurnal amplitude. The model simulated amplitude of diurnal precipitation was too large in CTRL (Fig. 3b) and too small in PEN_EN (Fig. 3c). Overall, the diurnal amplitude of precipitation in SH_EN is comparable to the TRMM observations in spatial distribution over land areas and coastal regions offshore (Fig. 3d). However, the model underestimated the diurnal amplitude over the open oceans in all three experiments, although a marginal improvement is visible in SH_EN south of the equator. This discrepancy is common to most atmospheric models that are driven by observed SST with no diurnal signal included.

To provide an overall contrast of the precipitation diurnal cycle between land and ocean, we show in Fig. 4 the composite diurnal evolutions of total, convective, and large-scale precipitation rates over all land points and over all ocean points, respectively, in the Maritime Continent region (10°S–10°N, 90°–160°E) from TRMM observations and model simulations. Note that the results shown hereafter are composited hourly without doing the harmonic decomposition. Also note that the definitions of convective and large-scale rainfall may differ somewhat in the model (where the partitioning is just determined by the parameterization responsible for the rain) and the observations. The TRMM observations over land show a peak in total precipitation in the late afternoon around 1600–1700 LT and a minimum in the morning around 0900–1000 LT (Fig. 4a). A similar pattern is true for the convective rainfall rate (Fig. 4b). The stratiform precipitation from TRMM observations shows a similar evolution to the convective rainfall but with its phase delayed by several hours and with much smaller amplitude (Fig. 4c). As already seen from Fig. 3, the diurnal amplitude of the rainfall rate over the land is too large in CTRL and too small in PEN_EN (Fig. 4a). The former results from the too strong convective rainfall during the day (Fig. 4b), while the latter is mainly due to the too small convective rainfall and an out-of-phase of stratiform rainfall (Fig. 4c). The stratiform rainfall rate is larger in both PEN_EN and SH_EN than in CTRL, partially as a result of the reduced convective rainfall.

Although the peak in total and convective rainfall in the simulations is only about 1–2 h too early during the
day compared with the observations over land, the development of deep convection is in the morning instead of in the afternoon (local time) in the observations (Fig. 4b). A similar discrepancy is also found in other atmospheric models (e.g., Betts and Jakob 2002a,b). Note that the development of convective rainfall is delayed in both PEN_EN and SH_EN compared with that in CTRL, indicating that bias is partially reduced by enhancing the fractional convective entrainment/detrainment rates.

Over the oceans, the simulated precipitation diurnal cycle is comparable to TRMM observations (Fig. 4e) except for an overestimation of convective rainfall in CTRL and SH_EN (Fig. 4e) and an underestimation of stratiform rainfall in all three experiments (Fig. 4f). The minimum in total precipitation occurs at 2200 LT in TRMM observations, while in all simulations it occurs around 1600 LT, about 6 h too early. The amplitude of diurnal variation of stratiform precipitation is too small or even negligible in the simulations compared with TRMM observations, contributing to an overall underestimation of the diurnal amplitude over the ocean in Fig. 3.

The overall offshore migration of the diurnal signal of precipitation in both observations and simulations is shown in Fig. 2. A close-up look at the westward offshore migration from Sumatra is shown in Fig. 5 as the time evolution of hourly rainfall rates averaged between the two segments in Fig. 1. The rainfall rate peaks at around 1600–1800 LT over Sumatra and migrates offshore with a strong peak at 0600 LT about 150–200 km away from the coast in the TRMM observations (Fig. 5a). This offshore migration is reasonably simulated in all three experiments except for too early peaks over the land (to the right of the vertical line). As discussed above, the rainfall rate is too large in CTRL both over the land and near the coast (Fig. 5b), but too small in PEN_EN over the land (Fig. 5c). SH_EN simulated too large rainfall rates along the coastline, much the same as CTRL, and too weak rainfall rates offshore (Fig. 5d). Overall, the offshore migration simulated in the model is clearer than that in TRMM observations.

Note that the offshore migration of the diurnal signal of precipitation is affected by many key factors, such as the prevailing mean winds, the size of the islands, the extent and height of orography, and the orientation of the coastlines. The model with a 0.5° resolution cannot capture all these effects accurately. The offshore migration over the western Pacific warm pool region to the north of New Guinea is poorly simulated in all experiments (Fig. 6) and the amplitude of the simulated diurnal cycle is too small over the coastal and remote ocean areas, especially to the north of the equator (Fig. 3). These systematic biases seem not to be related sig-
significantly with the convective entrainment/detrainment rates.

b. Heat and moisture budgets

To understand the difference in the simulated precipitation diurnal cycle over the land areas in the three experiments discussed above, we have performed heat and moisture budgets. Specifically we examined the heating and moistening rates due to subgrid-scale vertical mixing, shallow convection, deep convection, and grid-scale condensation. In addition, we also examined the heat balance at the surface. All the budgets are averaged over the land areas in the Maritime Continent region (10°S–10°N, 90°–160°E).

Consistent with recent cloud-resolving simulations (Cuichard et al. 2004), the processes involved in the simulated diurnal precipitation over land occur as surface warming after sunrise, vertical turbulent mixing in the PBL, development of shallow convection as a preconditioning for, and followed by, deep convection. As we can see from Figs. 7a,e, vertical turbulent mixing transports the heat and moisture upward in the PBL after sunrise as the surface turbulent sensible and latent heat fluxes increase as a result of the surface warming. Both warming and moistening peak in the afternoon and quickly weaken after sunset. Shallow convection deepens the PBL by vertical transport of heat and moisture across the boundary layer top, and destabilizes the lower troposphere by cooling the upper cloud layer and nocturnal inversion layer through evaporation of clouds and turbulent heat fluxes (Fig. 7b; see also Tiedtke 1989). This moistens the mid to lower free troposphere.
but dries the PBL (Fig. 7f). As a result, shallow convection plays dual roles in both moistening the mid to lower free troposphere and destabilizing the lower troposphere, providing preconditioning for the development of deep convection (Derbyshire et al. 2004). Deep convection generally warms and dries the large-scale environment by subsidence (Figs. 7c,g), but cools the subcloud surface layer by convective downdrafts (Fig. 7c). The large-scale condensation removes the water vapor in the mid- to upper troposphere and increases the moisture in the lower troposphere due to the evaporation of the falling rain (Fig. 7h). It therefore produces latent heating in the mid- to upper troposphere and evaporative cooling in the lower troposphere (Fig. 7d).

Enhancing the fractional lateral entrainment/detrainment rates of deep convection in PEN_EN generally dilutes the convective plumes and reduces the convective precipitation (Figs. 8c,d) while increasing the strati-
form precipitation (Figs. 8d,h). This seems to have little effect on either the subgrid vertical mixing (Figs. 8a,e) or shallow convection (Figs. 8b,f). Note that the decrease in convection occurs mainly in the afternoon, while the increase in stratiform precipitation occurs during the nighttime. As a result, the diurnal amplitude of precipitation is greatly reduced in PEN_EN, as seen in Figs. 3c and 4a.

Enhancing the fractional lateral entrainment/detrainment rates of shallow convection in SH_EN warms and destabilizes the lower troposphere during the daytime (Fig. 9b). This also reduces the drying effect of shallow convection in the lower troposphere in the morning, increases the cloud fraction of low clouds, and cools the land surface (see below), suppressing the vertical turbulent mixing in the lower part of the boundary layer (Fig. 9a). These changes act to prolong the preconditioning stage of deep convection and thus delay and weaken the convective precipitation (Figs. 9c,g) while increasing the stratiform precipitation (Figs. 9d,h). Therefore, the treatment of shallow convection can directly affect both the phase and amplitude of diurnal

---

**Fig. 6.** Same as in Fig. 5, but across New Guinea (Fig. 1), showing the discrepancy in the simulated migration of diurnal signal. The vertical line shows the northern coastal line of New Guinea with land to the left and ocean to the right (the horizontal axis shows the distance in km).
cycle of tropical precipitation over land areas. In the absence of shallow convection, although the time of maximum rainfall can be delayed as seen in SH\_EN, the convective precipitation would be largely suppressed. Thus, the amplitude of diurnal cycle will be reduced considerably, leading to unrealistic vertical thermal and moisture profiles (results not shown).

The fractional convective entrainment/detrainment rates have a considerable effect on the diurnal cycle of clouds as well. Figure 10 shows the time–vertical cross
section of cloud fraction averaged over the land areas in the Maritime Continent region from CTRL and the differences between PEN_EN and CTRL and between SH_EN and CTRL. The CTRL simulated the peak in high cloud fraction in the upper troposphere in the late afternoon and early evening, several hours after the peak in rainfall rate (Fig. 10a). This is followed by a peak in mid- to low clouds between $\sigma = 0.6$ and 0.8 at around 0800 LT. During early morning between 0400–0600 LT, there is high cloud fraction in the boundary
layer with cloud base only about 100–200 m from the surface due to the cold land surface and the quite stable surface layer.

Enhancing the fractional entrainment/detrainment rates for deep convection in PEN_EN causes a dramatic decrease in high clouds due to the weakening of deep convection and thus a reduced drying effect of deep convection in the upper troposphere (Fig. 10b). This results in a small increase in cloud fraction of mid-to low clouds. In contrast, enhancing the fractional entrainment/detrainment rates for shallow convection in SH_EN significantly increases the cloud fraction in low
clouds and slightly increases the very high cloud fraction as well (Fig. 10c). The increase in low-level cloud fraction is much more pronounced during the daytime after sunrise, consistent with the less drying effect in the lower troposphere by shallow convection (Fig. 9f).

Clouds affect the radiative flux and thus the surface heat budget. Enhancing the fractional entrainment/detrainment rates for deep convection has little effect on the downward shortwave radiative flux at the surface and the upward shortwave flux at the top of the atmosphere (Figs. 11a,b). Therefore, there is not much difference in the land surface temperature (Fig. 11d) and surface latent and sensible heat fluxes (Figs. 11e,f). However, the outgoing longwave radiation (OLR) is increased in PEN_EN compared with CTRL (Fig. 11c), due to a considerable decrease in cloud fraction of high clouds. Enhancing the fractional entrainment/detrainment rate for shallow convection in SH_EN reduces the downward shortwave radiative flux at the surface (Fig. 11a) and increases the upward shortwave radiative flux at the top of the atmosphere (Fig. 11b), consistent with the increased cloud fraction (Fig. 10c). As a result, the land surface temperature decreased by 0.5–1.0 K between 1100 and 1600 LT (Fig. 11d). The reduced surface temperature results in smaller latent (Fig. 11e) and sensible (Fig. 11f) heat fluxes at the surface. Because of the increased cloud fraction, the OLR is slightly decreased in SH_EN (Fig. 11c). The results shown here thus indicate that the fractional entrainment/detrainment rates for shallow convection have a considerable effect on the diurnal cycle of both clouds and precipitation, affecting the surface heat balance and the hydrological cycle.

c. Mean and variability

In addition to the effect on the precipitation diurnal cycle, the convective entrainment/detrainment rates may affect the mean and variability of the simulated precipitation as well, as mentioned by Bechtold et al. (2004). Here we examine the difference in the mean and variability of the simulated precipitation in the three experiments.

The spatial distribution of the simulated three-month mean precipitation is shown in Fig. 12. Compared with the TRMM 3B43 precipitation (Fig. 12a), all three experiments (Figs. 12b,c,d) reproduced the spatial pattern of the mean precipitation reasonably well, but all over-estimated the precipitation in most of the Maritime Continent and Indian Ocean south of the equator. Note that overall PEN_EN simulated smaller mean precipitation over most of the Maritime Continent and Indian Ocean than CTRL, while SH_EN simulated larger mean precipitation.

A realistic simulation of the fraction of large-scale stratiform precipitation is important for simulating aspects of non-diurnal variability in the Tropics, such as the intraseasonal oscillation (Lin et al. 2004). The fraction of stratiform precipitation in CTRL in the deep Tropics (between 15°S and 15°N) is generally less than...
20% on average (Fig. 13a). Enhancing the entrainment/detrainment rate of deep convection can redistribute the moist static energy by enhancing the transport of moisture into the upper troposphere but suppress deep convection. These effects moisten the upper-tropospheric environment and increase the fraction of large-scale precipitation, as seen in Fig. 13b. A similar effect is seen for the enhanced entrainment/detrainment rates for shallow convection in SH_EN (Fig. 13c). Note that the fraction of stratiform precipitation averaged in the deep Tropics is 30%–40% in PEN_EN and SH_EN, very close to recent TRMM observations (Schumacher and Houze 2003). Although, as noted earlier in section 2, the definitions of the stratiform precipitation in TRMM observations and model simulations could be quite different, this comparison at least provides a rough reference from a different perspective.

We also computed a measure of the variability of rainfall on periods longer than about 3 days. Specifically, Fig. 14 shows the temporal standard deviation of the 3-day running mean of daily rainfall rates simulated in each of the three model experiments. The temporal variability of precipitation has a similar spatial pattern to the three-month mean precipitation (Fig. 12). Generally, the variability of the simulated precipitation increases as the entrainment/detrainment rates increase (Figs. 14b,c). Therefore our results concur with the results of Bechtold et al. (2004), who also found that convective entrainment/detrainment rates could change the partitioning of precipitation between convective and stratiform and the temporal variability as well. Because most GCMs underestimate the variability in the tropical precipitation, it will be interesting to see if our present results apply as well to global GCM simulations.

4. Summary

The lateral convective entrainment/detrainment rates are a measure of the interaction between convection and its large-scale environment. Their effect on the simulation of tropical precipitation thus could be very important. Unfortunately, the appropriate values for the entrainment/detrainment rates are not well constrained by direct observations. Previous studies have shown the sensitivity of simulated precipitation to the entrainment/detrainment rates but little attention has been given to the effect of these rates on the simulated diurnal cycle of precipitation. In this study, a regional
climate model is used to investigate the effect of lateral convective entrainment/detrainment rates on the simulated precipitation diurnal cycle over the Maritime Continent and the surrounding oceans.

With the default convective entrainment/detrainment rates, the model simulates mature convective precipitation that occurs too early in the day and has an unrealistically large amplitude over land. In two sensitivity experiments with the entrainment/detrainment rates increased for deep and shallow convection, respectively, the diurnal phase of precipitation is delayed by 1 h with reduced diurnal amplitude over the land areas. The simulated diurnal cycle over both land and ocean is more realistic with enhanced entrainment/detrainment rates for shallow convection.

Although there are many physical processes affecting both the amplitude and phase of diurnal cycle of precipitation, the lateral entrainment/detrainment rate of shallow convection is found to be very effective in modifying the diurnal cycle of precipitation through changing the timing of cloud regime transition. In general, increasing the entrainment/detrainment rate for either deep or shallow convection prolongs the development and reduces the strength of deep convection, and thus delays the mature phase and reduces the magnitude of convective precipitation over the land in our simulation. This also causes an increase in low-level clouds, a colder land surface, and reduced surface latent and sensible heat fluxes, thus potentially modifying the energy and water cycle of the climate system. In addition to the improved diurnal characteristics, the model with the increased entrainment/detrainment rates also simulated a larger fraction of stratiform precipitation and the increased temporal variability of daily mean precipitation.

Note that although the model simulated the overall features of diurnal cycle in the Maritime Continent, the simulation of the observed offshore migration of the diurnal signal forced by deep convection over the land is realistic in some regions but is poor in some other regions. This discrepancy seems to be unrelated to the convective lateral entrainment/detrainment rates but could be due to the insufficient model resolution used in this study that is too coarse to resolve the complex land–sea contrast in the region.

The diurnal variation is one of the most fundamental modes of variability of the global climate system, which is associated with well-defined large variation in solar radiation. Realistic representation of the diurnal cycle of clouds and precipitation in climate models is important because the diurnal cloud–sun correlation rectifies into mean radiation balance, affecting climate simulation and weather prediction (Randall et al. 1991; Yang and Slingo 2001; Neale and Slingo 2003). The diurnal
variation of latent heat release may also act as a very significant excitation for large-scale atmospheric tides that play a very important role in the upper atmosphere (Hamilton 1981; Forbes et al. 1997). The simulation of the amplitude and phase of the diurnal cycle provides an excellent test bed for model physical parameterizations and for the representation of realistic interactions among the surface, PBL, and the free atmosphere (Lin et al. 2000; Yang and Slingo 2001; Betts and Jakob 2002b).

Although we have shown the importance of convective fractional entrainment/detrainment rates to both phase and amplitude of the simulated diurnal precipitation, it is not clear whether the finding would be altered by changes in the PBL parameterization, the closure assumptions in the cumulus parameterization, and other model physical processes. These need to be addressed in future studies. In addition, our primary objective in this study is to investigate how the convective entrainment/detrainment rates prescribed in a mass flux cumulus parameterization scheme affect the simulated tropical precipitation diurnal cycle over the Maritime Continent. We have not attempted to provide any optimal values for them. Future efforts should be made to realistically determine the fractional lateral entrainment/detrainment rates in convective parameterizations in order to optimize the simulation of tropical precipitation in general.

Acknowledgments. This study has been supported in part by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) through its sponsorship to the International Pacific Research Center (IPRC) in the School of Ocean and Earth Science and Technology (SOEST) at the University of Hawaii at Manoa, and in
part by the CAS Partnership Project. The authors express their gratitude to two anonymous reviewers for their helpful comments.

REFERENCES


Liberti, G. L., F. Cheruy, and M. Desbois, 2001: Land effect on the diurnal cycle of clouds over the TOGA COARE area, as observed from GMS IR data. Mon. Wea. Rev., 129, 1500–1517.


Siebesma, A. P., and A. A. M. Holtslag, 1996: Model impacts of


