Regional Model Simulations of Marine Boundary Layer Clouds over the Southeast Pacific off South America. Part II: Sensitivity Experiments*

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ABSTRACT

The sensitivity of a regional climate model to physical parameterizations and model resolution is investigated in terms of its simulation of boundary layer stratocumulus (SCu) clouds over the southeast Pacific. Specifically, the physical schemes being tested include shallow cumulus convection, subgrid vertical mixing, cloud droplet number concentration (CDNC), and drizzle.

As described in Part I, the model with standard settings captures the major features of the boundary layer in the region, including a well-mixed marine boundary layer, a capping temperature inversion, SCu clouds, and the boundary layer regime transition from the well-mixed layer near the coast of South America to a decoupled cloud layer over warmer water to the west. Turning off the shallow cumulus parameterization results in a dramatic increase in the simulated SCu clouds while the boundary layer structure becomes unrealistic, losing the decoupled regime over warm water. With reduced penetrative mixing at the top of shallow cumuli, the simulated SCu clouds are somewhat increased while the boundary layer structure remained largely unchanged. Reducing the CDNC increases the size of cloud droplets and reduces the cloud albedo but has little effect on the vertical structure of the boundary layer and clouds. Allowing more drizzle decreases boundary layer clouds considerably.

It is also shown that the simulated depth of the boundary layer and its decoupling is highly sensitive to the model horizontal and vertical resolutions. Insufficient horizontal or vertical resolutions produce a temperature inversion and cloud layer too close to the sea surface, a typical problem for global general circulation models.

Implications of these results for global and regional modeling of boundary layer clouds and the areas that need more attention in future model development are discussed.

1. Introduction

Tropical eastern Pacific climate is characterized by strong equatorial asymmetry, with warm sea surface temperatures (SSTs) and deep convective clouds north of, and cold SSTs and extensive low clouds south of, the equator (see Xie 2004 for a recent review). Despite their climatic importance in maintaining this north-south asymmetry and regulating the seasonal cycle over the tropical eastern Pacific (Nigam 1997; Yu and Mechoso 1999), the marine boundary layer (MBL) stratocumulus (SCu) clouds over the southeast Pacific off South America are poorly represented in most global atmospheric general circulation models (GCMs) because of insufficient model resolution and/or inadequate physical parameterizations (Delecluse et al. 1998; Bretherton et al. 2004). This deficiency in simulating these clouds appears to be responsible for the failure of many coupled GCMs to keep the intertropical convergence zone (ITCZ) north of the equator and maintain an equatorial cold tongue of a realistic strength over the eastern Pacific (Mechoso et al. 1995; Philander et al. 1996; Ma et al. 1996; Frey et al. 1997; Delecluse et al. 1998).

Although there are recent efforts to improve the simulation of SCu clouds in GCMs by developing and/or improving physical parameterizations (Bachiochi and Krishnamurti 2000; Teixeira and Hogan 2002), most GCMs are still low in their skill in simulating these clouds (Bretherton et al. 2004). The difficulty appears to lie in the fact that MBL SCu clouds are only a few hundred meters thick and capped by a sharp temperature inversion and that they are maintained by a complex array of physical processes and feedbacks that have just begun to be investigated in models.

Several recent studies using regional atmospheric models show significant improvements in simulating MBL SCu clouds over the eastern Pacific (McCaa and
Bretherton 2004a,b; Wang et al. 2004a, manuscript submitted to *J. Climate*, hereafter WXWX; Wang et al. 2004b, hereafter Part I). With the use of elaborate parameterizations for planetary boundary layer (PBL) turbulence and shallow convection, McCaa and Bretherton (2004b, hereafter MB04b) show that the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (Penn State–NCAR) Mesoscale Model (MM5; Grell et al. 1994) is able to simulate quite realistically the MBL structure and SCu clouds over both the northeast and southeast Pacific Ocean. They also show that the simulated MBL SCu clouds are sensitive to the PBL parameterization, shallow convection scheme, the cloud droplet number concentration (CDNC), and the model horizontal resolution. They found that all four PBL schemes currently in use in the standard MM5 produce too shallow a boundary layer with excessive clouds. Using the new PBL parameterization scheme of Grenier and Bretherton (2001) improves the simulation to some degree, but the inclusion of a shallow cumulus parameterization is critical to the realistic simulation of subtropical MBL clouds and to the cloud regime transition from SCu to trade cumulus clouds in particular.

Part I and WXWX show that the regional climate model developed at the International Pacific Research Center (IPRC–RegCM), University of Hawaii, reproduces reasonably well the large-scale circulation over the eastern Pacific, precipitation in the ITCZ north of the equator, and MBL SCu clouds over the southeast Pacific. Consistent with previous large-eddy simulations (LESs; e.g., Moeng and Lenschow 1995), WXWX show that the cloud radiative feedback is critical to the maintenance of MBL SCu clouds and the boundary layer structure. Compared to MB04b, Part I and WXWX use a much larger model domain to cover both the northern and southern tropical eastern Pacific Oceans, allowing the interaction between the ITCZ north of the equator and the SCu cloud deck south of the equator. WXWX show that this cross-equatorial interaction provides an additional feedback, amplifying the equatorial asymmetry of the eastern Pacific climate (Philander et al. 1996; Ma et al. 1996; Xie 1996).

The results from the above regional atmospheric model studies are encouraging. Further studies that critically test model physical parameterizations in terms of the simulation of the persistent and radiatively active subtropical SCu clouds are necessary to identify the areas where GCMs need to be improved. In this regard, regional atmospheric models can serve as a useful bridge between global GCMs and LES models or single-column models (SCMs). The latter models must specify large-scale forcing and ignore the feedback of the simulated clouds to the large-scale circulation (e.g., Wang and Wang 1994; Moeng and Lenschow 1995; Stevens et al. 1998). With a limited domain, regional models can afford higher resolution than global GCMs while still allowing interaction of MBL clouds with the resolved large-scale circulation.

The present study reports the results from experiments that test the sensitivity to the model resolution and model physical parameterizations. In particular, we address the following questions: (i) Is the sensitivity of the MBL cloud simulation reported in MB04b model dependent? (ii) Given the well-known difficulty in modeling MBL SCu clouds, what are the critical areas where the GCMs and regional climate models (RCMs) need to be improved in order to achieve a realistic simulation of these clouds? Since it was independently developed with its own model dynamics and physics and has been shown to be able to simulate the MBL SCu clouds, the IPRC–RegCM is particularly suitable to address the first question. We show that the general findings by MB04b are not strongly model dependent except for the sensitivity to the model horizontal resolution. Regarding the second question, we suggest that in addition to the PBL and shallow convective parameterizations, adequate vertical resolution in the lower troposphere, realistic parameterizations for precipitation/drizzle, and subgrid cloud condensation in cloud microphysics are also important.

The rest of the paper is organized as follows: Section 2 briefly describes the regional climate model used and its experimental design. Section 3 presents the results from the sensitivity experiments. Conclusions are drawn in section 4 together with a discussion of implications of our results for global and regional atmospheric modeling and areas to which more attention needs to be paid in future model development.

2. Model and experimental design

a. The IPRC–RegCM (version 1.2)

The numerical model used in this study is version 1.2 of IPRC–RegCM. A detailed description of the IPRC–RegCM (version 1.1) and its performance in simulating regional climate over east Asia can be found in Wang et al. (2003). The model has also been used in modeling the regional climate over the eastern Pacific, including the response of the atmosphere to Pacific tropical instability ocean waves (Small et al. 2003), simulation of boundary layer clouds over the southeast Pacific (Part I), and the effect of the Andean mountains on eastern Pacific climate (Xu et al. 2004). The latest version 1.2 includes several modifications and improvements in order to realistically simulate subtropical MBL clouds (WXWX). Here only some key model features are summarized (see Table 1 for a summary of the model physical parameterizations).

The model uses hydrostatic primitive equations in spherical coordinates in the horizontal and in the \( \sigma \) (pressure normalized by surface pressure) coordinate in the vertical. It is solved numerically with a fourth-order conservative finite-difference scheme on an unstaggered
Table 1. List of physical parameterization schemes used in the IPRC–RegCM (version 1.2). Also included are references and comments where necessary.

<table>
<thead>
<tr>
<th>Physical process</th>
<th>Scheme</th>
<th>Reference</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<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></td>
<td></td>
<td></td>
<td>TOGA COARE version 3.0*</td>
</tr>
<tr>
<td>Surface layer over ocean Radiation</td>
<td>Bulk scheme</td>
<td>Fairall et al. (2003)</td>
<td>TOGA COARE version 3.0*</td>
</tr>
<tr>
<td></td>
<td>Multiband</td>
<td>Edwards and Slingo (1996), updated by Sun and Rikus (1999)</td>
<td>Seven bands for longwave, four bands for shortwave and full coupling between cloud microphysics and cloud liquid/ice water path</td>
</tr>
<tr>
<td>Cloud optical properties</td>
<td>Longwave radiation</td>
<td>Sun and Shine (1994)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shortwave radiation</td>
<td>Slingo and Schrecker (1982), Chou et al. (1998)</td>
<td>With specified CDNC of 100 cm$^{-3}$ over ocean and 300 cm$^{-3}$ over land</td>
</tr>
<tr>
<td>Cloud amount</td>
<td>Semiempirical 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>Dickenson 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>

* TOGA COARE = Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment.

The model physics include the cloud microphysics scheme of Wang (1999, 2001); a mass flux parameterization scheme for subgrid shallow convection, midlevel convection, and deep convection developed by Tiedtke (1989) and modified by Nordeng (1995) and Gregory et al. (2000); the radiation package developed by Edwards and Slingo (1996) and further improved by Sun and Rikus (1999); the Biosphere–Atmosphere Transfer Scheme (BATS) developed by Dickinson et al. (1993) for land surface processes; a modified Monin–Obukhov similarity scheme (Wang 2002; Fairall et al. 2003) for surface flux calculations over the ocean; and a nonlocal $E−\varepsilon$ turbulence closure scheme for subgrid vertical mixing (Langland and Liou 1996), which was modified to include the effect of cloud buoyancy production (Wang 1999).

Compared to the previous version 1.1 used in Part I, the new version 1.2 allows an environmental relative-humidity-dependent detrainment of cloud condensates from convection into grid-resolved cloud water/ice so that immediate and complete evaporation of detrained cloud water/ice takes place only for relatively dry conditions (WXWX). The version 1.2 also uses the nonlocal $E−\varepsilon$, turbulence closure scheme documented in Langland and Liou (1996) for subgrid vertical mixing instead of the original local $E−\varepsilon$ turbulence closure scheme. The threshold cloud water mixing ratio above which the cloud water converts effectively into rainwater/drizzle in the Kessler (1969)–type precipitation/drizzle parameterization is increased from 0.4 to 0.5 g kg$^{-1}$ to reduce drizzle from SCu clouds. In addition, the fraction of the cloud ensemble that penetrates into the inversion layer and detrains there into the environment is set to be 0.3 [β in Eq. (21) of Tiedtke 1989] instead of 0.23 used in Part I for shallow convection. These adjustments in parameters improve the simulation of boundary layer clouds significantly, especially near the coastal region.
off South America (see WXWX). For other model details, see Wang et al. (2003), Part I, and WXWX.

b. Experimental design

The IPRC–RegCM version 1.2 described above is used to study the sensitivity of the simulated Scu clouds to model resolution and physical parameterizations. The model configuration is the same as that in Part I and WXWX. The model domain covers an area of 35°S–35°N, 150°–30°W, including a large portion of the eastern Pacific and the South American continent. In the model domain, there are persistent marine Scu clouds off the west coast of South America and the trade cumuli to the west. The model uses a horizontal grid spacing of 0.5°, thus including 241 by 141 grid points. The U.S. Geological Survey (USGS) high-resolution topographic dataset (0.0833° × 0.0833°) was used to obtain the model envelope topography (Fig. 1a). The high-resolution vegetation-type data from USGS is reanalyzed for the model based on dominant vegetation type in each grid box.

The National Centers for Environmental Prediction (NCEP)–NCAR reanalysis data at every 6-h interval with a resolution of 2.5° × 2.5° in the horizontal and 17 pressure levels up to 10 hPa (Kalnay et al. 1996) are used to define the driving fields, which provide both initial and lateral boundary conditions to the regional climate model (Wang et al. 2003). The SST distribution is obtained from the Reynolds and Smith (1994) weekly SST data with horizontal resolution of 1° × 1°, which are interpolated into the model grids by cubic spline interpolation in space and linearly interpolated in time. Over the land, the initial surface soil and canopy temperatures are obtained from the lowest model level with a standard lapse rate of 6.5°C km⁻¹. Initial soil moisture fields are initialized such that the initial soil moisture depends on the vegetation and soil types defined for each grid cell (Giorgi and Bates 1989).

The model is initialized at 0000 UTC 29 July and integrated continuously through 30 September 1999. The first 3-day integration is used to spin up the model physics and is excluded from our analysis below.

Eight experiments (see Table 2 for a summary) are performed. The control experiment (CTL) is the same as the control experiment in WXWX with significant improvements in the coastal region over the control simulation in Part I. The experiment NoSC is the same as the CTL, but with the effect of parameterized shallow convection turned off. The experiment SCDh is the same as the CTL, but with the fraction of the detrained cloud water penetrated into the nonbuoyancy inversion layer being reduced by half to 0.15 from the default value 0.30 in CTL. In experiment CNh, the CDNC is reduced by half to 50 from 100 cm⁻³ over the ocean (a typical value for marine stratiform clouds; Twyoh et al. 1995) in CTL. In QCh, the threshold cloud water mixing ratio for autoconversion of cloud water to rainwater/drizzle in the Kessler (1969) scheme is reduced by half to 0.25 from 0.5 g kg⁻¹ used in CTL. In L2C, the $E$–$e$ subgrid vertical mixing scheme used in CTL is replaced with a level 2 closure scheme with an asymptotic mixing length of 100 m (Wang 2001), which is a typical value used in many applications (e.g., Mellor and Yamada 1982). Finally, the sensitivity to the model resolution is tested in ResH and ResV. ResH has a resolution of 2.0° latitude/longitude, typical of or slightly better than that of current state-of-the-art GCMs, instead of 0.5° latitude/longitude used in CTL, while ResV has only 7 levels below 800 hPa, typical of or slightly better than that of many current GCMs, instead of 11 levels in the CTL.

### Table 2. Summary of the numerical experiments.

<table>
<thead>
<tr>
<th>Expt</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTL</td>
<td>The standard model settings given in Table 1</td>
</tr>
<tr>
<td>NoSC</td>
<td>As in CTL, but with the shallow convective parameterization turned off</td>
</tr>
<tr>
<td>SCDh</td>
<td>As in CTL, but with the fraction of the detrained cloud water penetrated into the nonbuoyancy inversion layer being reduced by 50%</td>
</tr>
<tr>
<td>CNh</td>
<td>As in CTL, but the cloud droplet number concentration is reduced by 50%</td>
</tr>
<tr>
<td>QCh</td>
<td>As in CTL, but with the threshold mixing ratio above which the autoconversion of cloud water into drizzle/rainwater becomes effective reduced by 50%</td>
</tr>
<tr>
<td>L2C</td>
<td>As in CTL, but a simplified level-2 turbulence closure scheme is used instead of the comprehensive $E$–$e$ scheme</td>
</tr>
<tr>
<td>ResV</td>
<td>As in CTL, but the vertical resolution in the lower troposphere is reduced*</td>
</tr>
<tr>
<td>ResH</td>
<td>As in CTL but 2° lon/lat grid spacing is used instead of 0.5° lon/lat used in CTL</td>
</tr>
</tbody>
</table>

* In CTL, the model atmosphere is divided into 30 vertical layers with the interfaces $\sigma = 0.0, 0.03, 0.04, 0.054, 0.072, 0.097, 0.13, 0.165, 0.205, 0.255, 0.31, 0.37, 0.43, 0.49, 0.55, 0.61, 0.67, 0.72, 0.76, 0.79, 0.82, 0.845, 0.87, 0.892, 0.912, 0.932, 0.952, 0.97, 0.984, 0.994, 1.0. In ResV, the model atmosphere is divided into 26 vertical layers with the interfaces $\sigma = 0.0, 0.03, 0.04, 0.054, 0.072, 0.097, 0.13, 0.165, 0.205, 0.255, 0.31, 0.37, 0.43, 0.49, 0.55, 0.61, 0.67, 0.72, 0.76, 0.80, 0.84, 0.88, 0.92, 0.95, 0.976, 0.994, 1.0.

3. The results

a. Control simulation

The large-scale mean surface condition over the southeast Pacific during August and September (AS) 1999 is dominated by the subtropical anticyclonic circulation with southeasterly trade winds off the west coast of South America, as seen from the Quick Scatterometer (QuikSCAT) satellite measurements shown in Fig. 1b. The southeasterly trade winds accelerate on their way toward the equator, giving rise to large-scale divergence and subsidence, favoring the formation and maintenance of MBL clouds off the west coast of South America (Fig. 1c). To the north of the equator there is an east–west elongated cyclonic shear zone, where the
Fig. 1. (a) Model interior domain and topography contoured in 0.5, 1, 2, 3, and 4 km (light, medium, and heavy shadings show the orography higher than 0.5, 2, and 4 km) and 2-month mean SST over the ocean (contour interval 1°C); (b) QuikSCAT-satellite-measured 2-month mean surface winds with contours showing wind speed in m s⁻¹; (c) TMI-observed 2-month mean column-integrated cloud liquid water (10⁻² mm), with contours shown at 0.03, 0.06, 0.09, 0.12, 0.15, 0.20, and 0.25 mm (light and heavy shadings show values larger than 0.06 and 0.15 mm, respectively); (d) TMI-observed 2-month mean rainfall with contours shown at 1, 4, 8, 16, 24, 32 mm day⁻¹ (light and heavy shadings show daily rainfall larger than 8 and 16 mm, respectively).
mean ITCZ is located, as seen from Tropical Rainfall Measuring Mission (TRMM) rainfall (Fig. 1d).

The control run reproduced the seasonal mean precipitation (Fig. 2a) and column-integrated cloud liquid water content (Fig. 3a) quite well in spatial distribution and magnitude in most of the model domain compared to the TRMM Microwave Imager (TMI) measurements (Fig. 1c). In particular, the model simulated low clouds with little precipitation over large subtropical regions of the southeast Pacific and northeast Pacific and high
cloud water contents with significant precipitation in both the ITCZ region north of the equator and to the southwest corner in the domain where the Southern Hemisphere storm track is located. Compared to Part I, the latest model version 1.2 improved the simulation of MBL clouds in the coastal region off South America, but it still overestimated the clouds in the equatorial region west of the Galapagos Islands.

Figures 4a and 5a show, respectively, the zonal (along 10°S) and meridional (along 95°W) cross sections of cloud liquid water mixing ratio (shaded) and virtual potential temperature (contours) together with the $d\theta_p/dp = 8 \text{ K (100 hPa)}^{-1}$ contour (thick dashed curves), which is a weak criterion for the temperature inversion layer. In the zonal direction (Fig. 4a), the well-mixed MBL (vertically constant $\theta_p$) is very shallow, with a strong temperature inversion west of South America. The boundary layer cloud deck is topped by the temperature inversion, both increasing in height toward the west. As already discussed in Part I and WXWX, there are different cloud regimes east and west of 105°W. To the east, the well-mixed MBL is
fig. 3. The model-simulated 2-month mean column-integrated cloud liquid water (10^{-2} mm; areas with larger than 0.08 and 0.16 mm are lightly and heavily shaded) in experiments (a) CTL, (b) NoSC, (c) SCDh, (d) CNh, (e) QCh, and (f) L2C. Contours shown are 0.03, 0.06, 0.09, 0.12, 0.15, 0.20, and 0.25 mm.

topped by a dense cloud deck and capped by a strong temperature inversion layer. The low-level (below about 700 hPa over the ocean) cloud amount is large (Fig. 6a). These features are typical of MBL SCu clouds (Albrecht et al. 1995; Bretherton and Wyant 1997; Stevens et al. 1998; Bretherton et al. 2004). To the west, there is a stable layer between the mixed layer and a weak temperature inversion layer above, indicating a decoupled MBL structure and a transition from the SCu to trade cumulus regime (Krueger et al. 1995; Wyant et al. 1997; Stevens et al. 1998).

In the meridional direction (Fig. 5a), the temperature inversion height shows a general northward decreasing trend from 20°S to the equator, mainly due to the distribution of subtropical subsidence (not shown) that prevents the inversion height from following the underlying SST (Fig. 1a). The cloud base, however, shows little change in height with latitude except for being lower over the equatorial cold tongue. Near the strong SST front north of the equator (Fig. 1a), the cloud top rises rapidly as air moves northward toward warmer SSTs (Fig. 5a).
b. Effect of shallow convection

Shallow cumulus convection affects the PBL structure by venting air from the surface mixed layer through the stable layer toward the free atmosphere. Over the subtropical oceans, the vertical transport of heat, moisture, and momentum by shallow convection deepens the boundary layer and enhances surface evaporation, counteracting the warming and drying effects of the large-scale subsidence associated with the Hadley circulation and maintaining a quasi-steady state of the inversion layer and SCu clouds (Norris 1998; Siebesma et al. 2003). The detrainment at the top of cumuli allows a
cloud layer to form in the stable layer between the surface mixed layer and inversion. The longwave cooling and/or evaporation of cloud droplets enhances turbulent mixing there, further helping entrain dry and warm inversion air into the MBL. Thus, shallow convection plays an important role in deepening the cloud-topped MBL, drying the subcloud layer, and destabilizing the thermal structure of the cloud layer (Tiedtke 1989). Because of its subgrid-scale nature, the effect of shallow cumulus convection is parameterized in our model based on the mass flux scheme of Tiedtke (1989).

With the parameterized shallow convection turned off in the NoSC run, the simulated MBL structure is quite different from that in CTL. Rainfall is enhanced in the western Atlantic ITCZ region, while it is reduced both in the Pacific ITCZ region (Fig. 2b) and along the Andes. The inversion layer is lower, with a much thicker cloud layer (Figs. 4b and 5b) than in CTL (Figs. 4a and
5a). Boundary layer clouds over most of the oceans in the model domain are excessive (Fig. 3b) compared to TMI observations. Low-level cloudiness increases considerably in the whole model domain (Fig. 6b). There is significant drizzle reaching the sea surface (Fig. 2b). In NoSC, the decoupled MBL does not occur, the inversion layer is lower, and the well-mixed MBL becomes deeper in the western model domain (Fig. 4b). These results from the NoSC run are consistent with those from an experiment of MB04b without the use of shallow convection (see their Fig. 5).

Without shallow convection, the mixing between the cool and moist MBL and the warmer and drier air above is reduced, keeping the boundary layer shallower, moister, and much more cloudy. In addition, the denser cloud layer in NoSC can cause larger cloud albedo (Fig. 7b) and stronger cloud-top cooling, which would result in stronger compensating descending motion just above the cloud layer (not shown). This cloud–radiation feedback also plays a role in keeping both the inversion and cloud layers lower in NoSC than that in CTL.
Because of stronger trapping of water vapor in the boundary layer, the atmospheric column in NoSC is drier by more than 10%–20% than in CTL over most of the tropical eastern Pacific, especially in the equatorial cold tongue and subtropical regions (Fig. 8b). The drying mostly occurs above the cloud layer in the free atmosphere (Fig. 9). Interestingly, the atmospheric column in NoSC is also much drier (about 10%–15%) over most of South America than in CTL, which seems to be related to the reduced rainfall along the Andes.

The experiment NoSC is an extreme case to explore the effect of shallow convection on the boundary layer and clouds. In the Tiedtke’s (1989) mass flux scheme, several parameters are poorly constrained by observa-
sections, including the fractional entrainment and detraining rates, and the fraction of detrained cloud water penetrated into the inversion layer. We performed an additional sensitivity experiment, SCDh, in which the fraction of the detrained cloud water penetrated into the stable layer is reduced by half to 0.15 from the default value 0.30 used in CTL. Although the overall patterns of the simulated precipitation (Fig. 2c) and the column-integrated cloud liquid water content (Fig. 3c) are similar to those in CTL, cloud liquid water content (Figs. 3c, 4c, and 5c) and low-level cloudiness (Fig. 6c) are both higher than in CTL because of reduced evaporation of detrained cloud water at the cloud top. The atmospheric column in SCDh is drier (Figs. 7c and 9). The drying is about one-third of that in NoSC. These results indicate that accurate representation of the cloud-top penetrative mixing is critical to the shallow convective parameterization, consistent with MB04b, who used a quite different shallow convection scheme and a different atmospheric model.
c. CDNC and drizzle effects

CDNC affects the droplet size. Smaller CDNC leads to larger cloud droplets with the same cloud water mixing ratio, and vise versa. Larger droplets reflect less solar radiation, resulting in a smaller cloud albedo. In nature, this CDNC-induced change in droplet size also affects drizzling/precipitation efficiency. Our current microphysics parameterization, however, does not take this CDNC effect into account (Wang 1999). We plan to replace the Kessler (1969) scheme with a more physically based scheme in the future to include this effect.

In CNh, CDNC is reduced to 50 cm$^{-3}$ from the standard value of 100 cm$^{-3}$ used in CTL over the ocean. Cloud albedo is reduced by 10%±15% on average in CNh compared to that in CTL (Figs. 7a and 7c), consistent with MB04b, who reported a 10%±12% reduction in surface shortwave cloud radiative forcing by halving CDNC. This reduction in cloud albedo does not significantly affect precipitation (Fig. 2d), cloud water content (Figs. 3d, 4d, and 5d), or low-level cloudiness (Fig. 6d).

Drizzle helps dissipate clouds. When drizzle is allowed to occur at a lower threshold mixing ratio of cloud water in QCh, more cloud water in the cloud layer is converted into drizzle/rainwater. As a result, the simulated cloud water content is reduced considerably over the whole model domain (Figs. 3d, 4d, and 5d), with a 10%−20% reduction in cloud albedo (Fig. 7e). Changes in low-level cloudiness are insignificant however (Fig. 6e). The overall rainfall (Fig. 2e) seems to be little affected by the change in precipitation parameterization. This insensitivity of precipitation to changes in low-level clouds is due to the use of prescribed SST. In coupled models, the feedback between SST and low clouds is important for convection in the ITCZ north of the equator (Philander et al. 1996; Ma et al. 1996).

d. Sensitivity to subgrid vertical mixing

The IPRC-RegCM uses the $E-e$ turbulence closure scheme that computes the evolution of eddy kinetic energy and its dissipation rate. In L2C, this prognostic turbulent mixing scheme is replaced with the diagnostic level 2 turbulence closure scheme. The simulated boundary layer structure and clouds are similar to those in CTL, but both the inversion layer and the cloud base become higher, especially near the South American coast (Figs. 4f and 5f). Local minima in column-integrated cloud water content and in low-level cloudiness occur in the coastal region off Chile (Figs. 3f, 4f, and 6f), indicating that the very shallow boundary layer is not well represented by the level 2 turbulence closure scheme. The overall low-level cloudiness (Fig. 6f) is underestimated in most of the model domain compared to that in CTL (Fig. 6a). The reduction in low-level cloudiness is accompanied by the increased atmospheric-column water vapor over the tropical eastern Pacific and the South American continent in L2C (Fig. 8f). These results indicate that the level 2 closure scheme overestimates the vertical mixing across the cloud top, thereby deepening the boundary layer and moistening the atmospheric column (Fig. 9). Our implementation of the level 2 closure scheme does not take into account the effect of the temperature inversion on the mixing length, which is a function of height with an asymptotic value of 100 m (Blackadar 1962). The mixing length may be improved by taking into account the stratification effect, in particular in regions where the boundary layer is very shallow. Potential sensitivity of boundary layer cloud simulation to turbulent mixing parameterization has also been reported recently by MB04b using MM5.

The IPRC-RegCM version 1.2 employs a nonlocal turbulence closure scheme (Langland and Liou 1996) that includes countergradient flux of heat and moisture to mimic the entrainment of dry and warm air from the overlying inversion when the surface layer is unstable. This effect is usually small on a fully developed mixed layer but can sometimes increase the deepening rate of a mixed layer. A supplementary experiment is performed in which this nonlocal effect is turned off. The results from this supplementary experiment (not shown) are quite similar to those from the control experiment except for a slight increase in low-level cloudiness due to the reduced vertical mixing across the boundary layer top. Thus the nonlocal mixing is secondary in our model.

e. Sensitivity to model resolution

The low cloud deck is only a few hundred meters thick and requires a sufficient number of vertical levels
in a model to resolve. In ResV the number of vertical levels is reduced to seven below 800 mb, a resolution that is still slightly higher than most of current GCMs. Although the simulated precipitation, column-integrated cloud water content and the low-level cloudiness (Figs. 10a–c) are comparable to those in CTL, both the inversion layer and boundary layer clouds (Figs. 10e and 10f) are substantially lower than in CTL. In particular, the cloud base now touches the ocean surface in the coastal region off South America (Fig. 10e). The cloud top is well below the inversion base, indicative of few cumulus clouds penetrating into the inversion layer (Figs. 10e and 10f). It seems that the reduced vertical resolution could not resolve the sharp temperature inversion layer or the vertical gradient of longwave radiative flux in the upper cloud layer, underestimating the vertical penetrative mixing into the inversion layer. Most GCMs have slightly poorer vertical resolutions than in ResV, and in these GCMs, the cloud base is generally too low, touching the sea surface in some models (Bretherton et al. 2004, their Fig. 10). The ResV results indicate that poor vertical resolution is a possible
cause of poor low cloud simulation. Our results also suggest that examination of only the vertically integrated variables, such as the column cloud water content (Fig. 10b), low-level cloudiness (Fig. 10c), and cloud radiative forcing, is insufficient to evaluate the realism of boundary layer cloud simulations. A further examination of the vertical structure of clouds is equally important.

With a much coarser horizontal resolution ($2^\circ$) in ResH, the model not only loses the details in distributions of the simulated precipitation, cloud liquid water content, and low-level cloudiness, but also the boundary layer structure (Fig. 11). Both the inversion and cloud layers are considerably lower than in CTL. The maxima in the column-integrated cloud liquid water content and the low-level cloudiness are shifted offshore to about $100^\circ$W (Figs. 11b and 11c). The cloud regime transition and the decoupled boundary layer structure (Fig. 11e) are unclear.

The ResH run overestimates cloudiness and cloud liquid water content possibly because of a lack of condensation and cloud variability on the subgrid scale in our cloud microphysics scheme that was originally developed for a high-resolution tropical cyclone model (Wang 1999, 2001). Clouds are subject to large subgrid-scale variability, which increases with the grid size. Ig-
noring these effects may underestimate the drizzling and overestimate cloud water content. This may become substantial at the coarse resolutions (Wood et al. 2002; Zhang et al. 2003). A more physically based drizzle parameterization that takes into account subgrid variability is needed to further investigate the sensitivity of cloud simulation to horizontal resolution. Besides the changes in resolved or unresolved physics, the coarse-resolution model does not adequately resolve the high Andes and underestimates the effects of these mountains on the MBL structure and clouds (Xu et al. 2004).

MB04b used MM5 and performed a similar sensitivity study by contrasting simulations at 200- and 60-km grids. Their coarse-resolution run, however, resulted in a sizable reduction in shortwave cloud radiative forcing, with a significant decrease in cloud water content and a warmer subcloud layer in the coastal region over the subtropical northeast Pacific. The vertical structure of the simulated boundary layer was unchanged in their simulation, in contrast to large changes in response to reduced horizontal resolution in our model (Fig. 11). MB04b indicated that since the horizontal diffusion dominates the boundary layer moisture budget in the coarse-resolution simulation, the impact of horizontal resolution is unrelated to the PBL and cumulus convection parameterizations. Since a similar cloud microphysics parameterization is used in MB04b but with the opposite results, it seems that the lack of subgrid effects is not the reason for the contrasting sensitivity to horizontal resolution between MM5 and our model. Some other processes are responsible for this model dependency on MBL structure and clouds, and these need to be further explored.

4. Conclusions and discussion

The IPRC–RegCM (version 1.2) is used in this study to investigate what model aspects are critical to the realistic simulation of MBL SCu clouds over the subtropical southeast Pacific. With the standard settings, the model captures major features of the MBL in the region, including a well-mixed MBL near the coast, a capping temperature inversion, SCu clouds, a cloud regime transition into a decoupled MBL in the west over warmer waters. A series of numerical sensitivity experiments are performed to investigate the impact of physical parameterizations and model resolution on the simulation of boundary layer structure and clouds.

With the shallow cumulus parameterization turned off, boundary layer clouds are increased but the decoupled boundary layer over warm water almost disappear. Because of the suppressed mixing between the boundary layer and the free troposphere, the atmospheric column becomes drier than that in the control experiment. With the reduced fraction of the detrained cloud water penetrated into the inversion layer (which is part of the shallow convection parameterization), the major features of the boundary layer structure are retained while both the liquid water content and low-level cloudiness are increased considerably. Reducing the cloud droplet number concentration increases cloud droplet size and reduces the cloud albedo, while cloud water content and low-level cloudiness are little affected. Lowering the cloud water threshold for autoconversion of cloud water into drizzle/rainwater decreases cloud water content considerably but has less effect on boundary layer structure and low-level cloudiness.

Using a simplified level 2 turbulent closure scheme with a constant asymptotic mixing length overestimates the vertical mixing across the boundary layer top, reducing the boundary layer clouds and resulting in a moister atmospheric column. The removal of the non-local closure in the $E$–$v$ turbulent closure scheme affects little the boundary layer structure and clouds except for a slight increase in low-level cloudiness.

The simulated boundary layer structure and clouds are very sensitive to both the vertical and horizontal resolutions. Reducing the vertical resolution in the lower troposphere produces a cloud base and inversion layer that are too low and close to the sea surface, a typical problem in global model simulations as discussed in Bretherton et al. (2004). With a much coarser horizontal resolution ($2^\circ \times 2^\circ$ instead of $0.5^\circ \times 0.5^\circ$), the model simulated excessive boundary layer clouds with too low a cloud base. Subgrid-scale condensation and cloud variability need to be considered when using a large grid box, which is not included in the simple Kessler (1969) scheme used in the model. We note that MB04b reported an opposite sensitivity to the model horizontal resolution using a similar bulk cloud microphysics scheme and MM5, suggesting that other feedback processes may be responsible for this model dependency.

The results from this study, together with those reported by MB04b using MM5, provide strong evidence that adequate model physics, in particular shallow convection, turbulent mixing, precipitation/drizzle parameterizations, and sufficient vertical and horizontal resolutions are critical to a realistic simulation of subtropical MBL clouds. The problem in simulating MBL clouds with GCMs might be partly due to poor model resolutions that do not resolve the sharp temperature inversion and sharp gradients in the longwave radiative flux in the upper cloud layer. Poor horizontal resolution may distort various feedback processes for the boundary layer and clouds. Furthermore, our results indicate that the examination of only the vertically integrated variables, such as the column cloud water content, low-level cloudiness, and cloud radiative forcing, may be insufficient to evaluate the realism of boundary layer cloud simulations. A further examination of the vertical structure of the boundary layer is equally important.

Several aspects of our regional atmospheric model also need to be improved in areas such as subgrid-scale condensation (e.g., Zhang et al. 2003) and subgrid cloud variability (Bechtold et al. 1993; Wood et al. 2002) in the cloud microphysics scheme, which may help make
the model less resolution dependent. These improvements can help reassert the model sensitivity to horizontal resolution. As a related issue, previous large-eddy simulations (LESs) suggest that the fractional entrainment/detrainment rates used in the Tiedtke (1989) scheme are about one order of magnitude too small compared to LESs (Siebesma and Cuijpers 1995; Stevens et al. 2001; Siebesma et al. 2003). While this is not expected to affect our conclusions, further validation of these poorly constrained parameters in the shallow cumulus parameterization will no doubt help improve the simulation of subtropical MBL clouds.

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