LES MODEL SIMULATIONS OF CCN IMPACTS ON STRATOCUMULUS MICROPHYSICS AND DYNAMICS

Keun Yong Song and Seong Soo Yum

Department of Atmospheric Sciences, Yonsei University, Seoul 120-749, Korea

1. INTRODUCTION

The marine stratocumulus topped boundary layer (STBL), which prevails in the subtropical regions where the subsidence inversion associated with the descending branch of the Hadley-Walker cell dominates, is thought to be an important component of the climate system [Randall et al., 1984]. Especially, understanding the impact of the anthropogenic cloud condensation nuclei (CCN) on the cloud microphysics and dynamics of these clouds is a key to accurately assess the climatic impact of these clouds since the cloud radiative properties are determined by these properties.

Observations have shown that the diurnal evolution of marine stratocumulus to be characterized by an ascending cloud base [Vernon, 1936; Hignett, 1991]. For the daytime clouds, decoupling between the cloud layer and the surface plays an essential role in the dynamics of the STBL [Turton and Nicholls, 1987]. Here we focus on the diurnal variation of STBL, especially concerning the CCN effects on cloud. An LES model with size resolving microphysics [Kogan et al., 1995] is employed and the stratocumulus development for the three CCN loadings (maritime, continental and extreme continental) are examined.

2. MODEL SETUP

2.1. LES MODEL DESCRIPTION

The dynamical framework of the 3D LES model follows Moeng [1984]. The LES implementation uses a subgrid scheme adapted from Deardorff [1970], predicting the turbulent kinetic energy in order to evaluate eddy mixing coefficients. A 24-band solar radiation package [Slingo and Shrecker, 1982] is mounted for the shortwave radiative process calculation Longwave radiation parameterization is based on a greybody approximation for cloud drops [Herman and Goody, 1976]. The absorption coefficients for cloud drops are defined using parameterized expressions for cloud drop concentration and effective radius [Moeng and Curry, 1990].

Corresponding author’s address: Keun Y. Song, Yonsei University, Dept. of Atmospheric Sciences, South Korea, Email: doitsky@yonsei.ac.kr
2.2. MODEL SETTING AND METEOROLOGICAL CONDITIONS

There are 40 grid points in x and y, and 50 in z. The grid spacing is 75 m in horizontally and 25 m in the vertical, to make the total domain size 3 km X 3 km X 1.25 km. Total simulation time is 6 hrs. The model is set up with surface temperature of 290 K. The roughness length is 0.0002 m. The initial wind field was set to be equal to zero in all grid points but thermal impulses at two locations initiate the air motion. Initial thermodynamic sounding is assumed to have inversion at 662.5 m (Fig. 1).

2.3. INITIAL CCN DATA

The cumulative CCN concentrations at 1% supersaturation are 163, 1023 and 5292 cm^{-3} for the three CCN loading, maritime, continental, and extreme continental, respectively.

3. RESULTS

3.1. CCN IMPACTS ON CLOUD MICROPHYSICS, DYNAMICS, AND RADIATION

Fig. 2. Various cloud properties averaged over the last 4 h of simulations as a function of CCN loading; (a) cloud droplet concentration ($N_c$), (b) effective radius ($R_e$), (c) cloud optical depth (COD), (d) albedo, (e) cloud top and base height, and (f) cloud geometric depth for the daytime clouds.

Fig. 3. Same as Fig. 2 except for the nocturnal clouds.

The cloud droplet number concentration, cloud optical depth, and albedo increase but the cloud droplet effective radius decreases with the increase of CCN concentration for
both the daytime and nocturnal clouds (Figs. 2 and 3). High CCN concentration enhances cloud reflectivity (albedo) by increasing the cloud droplet number concentration, leading to a cooling effect (Table 1). Notable is that the cloud depth (top height-base height) decreases with CCN concentration for the daytime clouds (Fig. 2f). This is mainly due to the lifting of cloud base as CCN loading increases (Fig. 2e). For daytime clouds, decoupling of the cloud layer from the surface (discussed later) leads to dryness below the cloud base and strong evaporation of cloud drops in this region eventually leads to the lifting of the cloud base. The point is that this is more significant for the clouds with higher CCN concentration since evaporation is more effective for these clouds due to the smaller drop sizes (Fig. 2b). This is consistent with Lohmann and Lesins’s [2003] satellite observation: cloud base height of maritime clouds is 100 hPa higher than those of continental clouds and polluted clouds were thinner than clean clouds. Since the cloud albedo depends on both the cloud droplet sizes and the cloud thickness these competing effects partly cancel each other out, making it more complex to assess indirect aerosol effects.

On the other hand, cloud thickness does not show a significant trend with CCN loading for the nocturnal clouds (Fig. 3f). Especially for the maritime cloud, strong drizzling (Fig. 4) leads to the collapse of cloud top (Fig. 3e). Light drizzling in the daytime maritime cloud, however, does not seem to affect the cloud top height.

Unlike the maritime clouds, there was virtually no surface precipitation for the continental and extreme continental clouds. Yum and Hudson [2002] provided evidence for the fact that marine stratocumulus clouds have higher drizzle liquid water content for more maritime. vanZanten et al. [2005] also showed that the precipitation rate increased with cloud drop diameter from the aircraft observation of stratocumulus topped marine boundary layers off the California coast.

Fig. 4. Time series of surface precipitation rate and cloud geometric depth for the three CCN loadings.
3.2. CONTRAST BETWEEN DAYTIME AND NOCTURNAL CLOUDS

Cloud droplet concentration and cloud amount are consistently smaller for the daytime clouds than for the nocturnal clouds regardless of CCN loading. Daytime cloud thicknesses are also shallower than those of the nocturnal clouds for each airmass type (Fig. 5). Solar heating of the cloud layer and continued entrainment and evaporation near cloud base are responsible for the negative buoyancy flux below the bottom of the cloud layer for the daytime clouds. This leads to the decoupling of the cloud layer from the surface layer. The main effect of decoupling is to virtually cut off the cloud layer from the moisture source of the sea surface. Since entrainment drying is no longer balanced by moisture flux from the sea surface, the clouds will not be able to maintain the form before the decoupling; cloud base height rises and cloud thickness becomes thinner for the daytime clouds but no such trend is shown for the nocturnal clouds (Fig. 5). This is consistent with Turton and Nicholls [1987] observation.

3.3. CLOUD RADIATIVE FORCING (CRF)

Cloud radiative forcing (CRF) at the top of the atmosphere is calculated from the model results. The cloud radiative forcing, $C$, is defined

$$C = C_{\text{cloudy}} - C_{\text{clr}},$$

where $C_{\text{cloudy}}$ is the stratocumulus cloudy-sky net heating and $C_{\text{clr}}$ is the clear-sky net heating [Ramanathan, 1989]. The domain average of cloud radiative forcing for maritime, continental, and extreme continental clouds are shown in Table 1 for the daytime clouds. An anthropogenic net CRF can be defined as the difference in net CRF between maritime and polluted clouds. This is $-103.5$ W m$^{-2}$ for the extreme continental, indicating a significant cooling effect on the global radiation balance.

Wilcox et al. [2006] estimated shortwave cloud forcing for the in-situ measurements during the Cloud Indirect Forcing Experiment (CIFEX) in North Pacific oceanic clouds.
average value of cloud radiative forcing for all overcast samples was -110.3 W m⁻², and the averages for the clean and polluted clouds are -103.9 W m⁻² and -113.6 W m⁻² at the top of atmosphere, respectively. But the strongest shortwave cloud radiative forcing was about -200 W m⁻². The CRF values in this study are generally larger than this measurement but are close to Hanson and Gruber [1982], who calculated average values of shortwave, longwave, and net stratocumulus cloud radiative forcing for Northern hemisphere: -228.3, 8.2, and -185.4 W m⁻².

Table 1. Shortwave cloud radiative forcing (CRF) at the TOA for maritime, continental, and extreme continental cases.

<table>
<thead>
<tr>
<th>case</th>
<th>N_{CCN}</th>
<th>CRF_{SW}</th>
<th>CRF_{LW}</th>
<th>CRF_{NET}</th>
</tr>
</thead>
<tbody>
<tr>
<td>mari.</td>
<td>163</td>
<td>-204.1</td>
<td>7.5</td>
<td>-196.6</td>
</tr>
<tr>
<td>cont.</td>
<td>1023</td>
<td>-283.3</td>
<td>7.6</td>
<td>-275.7</td>
</tr>
<tr>
<td>ex.</td>
<td>5292</td>
<td>-308.0</td>
<td>7.9</td>
<td>-300.1</td>
</tr>
</tbody>
</table>

Here, N_{CCN} is CCN number concentration.

4. Acknowledgments

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5. REFERENCES


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