Responses of Subtropical Marine Stratocumulus Cloud to Perturbed Lower Atmospheres

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Abstract

Most global climate models (GCMs) suffer from prediction biases in their dynamic and thermodynamic structures in and around the boundary layer (BL). It remains unclear which of these biases within the large-scale conditions are crucial to the accurate reproduction of BL clouds. To develop a better understanding of the effects of variations in the simulated large-scale conditions, this paper uses large-eddy simulations to evaluate the effects of the fluctuation based on the latest GCM ensemble data on the prediction of a Californian stratocumulus under perturbed environments. The result indicates the relative importance of each component, and the most important factors controlling cloud behavior are the amplitudes of jumps in vapor and temperature across a BL top. The given variations in wind velocity and its vertical shear, large-scale subsidence, and surface heat fluxes have a lesser effect. This suggests that to reduce model biases predicted in GCMs, greater attention should be paid to the stratification structure across the BL top.


1. Introduction

Marine stratocumulus clouds are an important climatic element, especially with respect to their influence on the Earth’s radiative budget caused by their high solar albedo and significant coverage (Stevens 2005; Wood 2012). Consequently, a realistic representation of stratocumulus clouds within global climate models (GCMs) is required if we are to make accurate predictions of future climate change. However, at present, such boundary-layer (BL) clouds are poorly represented in GCMs (e.g., Bony and Dufresne 2005). The reason for this difficulty arises not only from the complexity associated with modeling BL processes, but also from model biases, such as in the predicted thermodynamic and dynamic structure in and around the BL used to generate clouds within their BL scheme, although these two elements are not independent of each other.

The techniques used in the parameterization schemes for BL processes have steadily been improved (e.g., Bretherton and Park 2009), whereas model biases remain problematic, and an improved understanding of the extent to which biases in the predicted structure of the lower atmosphere prevent the adequate prediction of BL clouds is still required. Such efforts could help to identify which model biases in the GCMs should be reduced first to generate a better representation of BL clouds.

Several studies have attempted to determine the response of various environmental parameters to stratocumulus clouds, including the sensitivity of thermal stratification across a BL top (Ackerman et al. 2004; Yamaguchi and Randall 2008; Lock 2009; Dussen et al. 2013; Noda et al. 2014), the influence of wind shear across a BL top (Wang et al. 2008), the role of subsidence (Blossey et al. 2013), and so on. Recent studies have extended our understanding of the roles of the thermodynamic environment and microphysical processes in the transition of stratocumulus to cumulus clouds that occurs from the subtropics to the tropics (Sandu and Stevens 2011; Chung et al. 2012).

Most of these previous studies have focused on assessing the importance of individual BL processes, and thus their relative importance in reproducing a BL clouds is not well understood. Consequently, further research is required to examine the relative impacts of these environmental factors on the behavior of individual forms of BL clouds.

Some studies have been conducted with the aim of clarifying the influence of changes in environmental conditions on such cloud behavior. Chlond and Walkau (2000) investigated stratocumulus observed over the North Atlantic region, and demonstrated the extent to which uncertainty in the realization of their large-eddy simulations (LES) could modulate the behavior of simulated stratocumulus. Recently Bretherton et al. (2013) extended this numerical approach to examine the responses of BL clouds under warmer atmospheric conditions (i.e., warmer temperature, more vapor, and weaker subsidence).

We focus here on a typical subtropical stratocumulus cloud, and investigate the key factors required to reproduce its basic behavior using LESs. There is large arbitrariness associated with selecting the fluctuation used in the sensitivity experiments, and we used the Coupled Model Intercomparison Project Phase 5 (CMIP5) model ensemble data to define the width of the predicted cloud environment in the BL.

2. Experimental design

To conduct the LESs, we used the nonhydrostatic model (NHM; Saito et al. 2001), and the subgrid-scale turbulent model was that proposed by Deardorff (1980). We used a simple liquid cloud scheme with saturation adjustment:

\[
q_c = \begin{cases} 
q_c - q_s, & \text{for } q_c - q_s > 0 \\
0, & \text{otherwise}
\end{cases}
\]

where \(q_c\), \(q_s\), and \(q\) are the mixing ratios (kg kg\(^{-1}\)) of cloud water, the sum of cloud water and vapor, \(q_c\), and saturation vapor, respectively. The experimental design of the LES essentially followed that in the DYCOMS-II model intercomparison study (Ackerman et al. 2009; herein, A09). The horizontal and vertical grid intervals were 50 and 5 m, respectively, following A09. The domain size was \(6.5 \times 6.5 \text{ km}^2\) horizontally, and 1.5 km vertically.

In this study, modification of the control experiment (CTL) from the A09 setup was twofold. First, for simplicity, the wind velocity at the initial state was modified to \((u, v) = (8.0 \text{ m s}^{-1}, 0 \text{ m s}^{-1})\) over the domain to examine the sensitivity of wind and the associated vertical shear. The wind velocity of 8.0 m s\(^{-1}\) corresponds to the approximate average of the initial wind velocity in A09. The geostrophic wind was set to the initial wind (i.e., \((8.0 \text{ m s}^{-1}, 0 \text{ m s}^{-1})\) for CTL) over the entire domain during the simulation with a Coriolis parameter of \(7.62 \times 10^{-5} \text{ s}^{-1}\) (A09).

Second, the surface fluxes were computed based on Monin–Obukhov’s similarity theory (Kondo 1975) to examine cloud
behavior under different stability conditions near the surface. In addition, the definition of the height of the BL top, $z_i$, was modified from that in A09 to the average of heights where the vertical jump in $q_v$ was at a maximum in each column.

To determine the extent of any differences caused by the slight modification of CTL from A09, we also conducted an experiment that followed A09 for reference (ORG). We conducted sensitivity experiments to examine the responses of the simulated clouds and the BL state to the environmental variations estimated from the CMIP5 ensemble data. We first considered the following six factors as possible major elements affecting the behavior of stratocumulus cloud: a jump in vapor and temperature across $z_i$, the strength of wind velocity (and its vertical shear near $z_i$), the strength of subsidence rates, and surface sensible and latent heat fluxes ($SHF$ and $LHF$, respectively). For these experiments, we examined cloud responses in perturbed lower atmospheres with a 20% magnitude. This value was selected based on the variance of the large-scale environment over areas of California (USA) stratocumulus clouds in the current GCMs within the present climate simulations of CMIP5 (Fig. S1). Figure 1 shows the sounding profiles used in the sensitivity experiments in CTL, $\Delta q^{20\%}$, $\Delta q^{35\%}$, $q^{+2.0K}$, $q^{+1.5K}$, $q^{+1.0K}$, $q^{0.5K}$, $q^{-0.5K}$, $q^{-1.0K}$, $q^{-1.5K}$, $q^{-2.0K}$, and $q^{-2.5K}$ for reference, where EIS indicates the estimated inversion strength (Wood and Bretherton 2006). Time integration was performed over six hours in these experiments, and the averages for the last two hours were analyzed. The experiment IDs and descriptions are summarized in Table 1.

### 3. Results

#### 3.1 Control and sensitivity experiments

Figure 2 compares the liquid water path (LWP) in CTL with the sensitivity experiments. The LWP in CTL is similar to that in ORG, although the former is marginally smaller by approximately 3% compared with ORG. A possible major reason for this slight difference is increased entrainment of overlying dry air in CTL during an earlier stage of the simulation. In fact, $z_i$ in CTL is slightly higher (by ca. 3%) than that in ORG (not shown). Thus, we conclude that the slight modification of CTL from ORG does not cause significant issues in the behavior of the typical stratocumulus cloud (DYCOMS-II).

The two major factors that change LWP are jumps in vapor and temperature across $z_i$. For the temperature jumps, the results are consistent with previous findings that the temperature stratification of the lower atmosphere strongly controls BL clouds (Klein and Hartmann 1993; Wood and Bretherton 2006). In addition, our results indicate that the variation in the jump in vapor causes a greater change in the LWP prediction than the jump in temperature when the fluctuation percentages of both elements are assumed to be 20%.

The other factors cause changes in the LWP to a similar degree, but less than those caused by changes in the vapor and temperature jumps across $z_i$. For wind velocity, a stronger (weaker) initial wind leads to more (less) LWP. A decrease (increase) in subsidence results in the increase (decrease) of LWP. Changes in LHF and SHF also affect the prediction of LWP. LWP increases when SHF increases. A decrease in SHF does not alter LWP greatly in this case. A decrease in LHF results in a decrease of LWP.

To investigate changes in BL structures in more detail, Fig. 3 compares $z_i$ and the total cloud cover (TCC; i.e., the cloud cover viewed from the domain top or bottom). Here, a cloudy grid is defined as a grid in which $q_v > 0$. An interesting finding here is that changes in TCC are closely correlated with those in LWP.

### 3.2 Sensitivity of humidity and temperature perturbations in the BL

In the previous section, we investigated the influence of changes in stratification across $z_i$, wind velocity, and surface heat fluxes. Another interesting issue is how humidity and temperature bias in the BL can cause differences in the cloud behavior in the LES configuration. This question motivated us to perform additional experiments that involved changing the initial vapor below $z_i$ constantly from 60% to 120% at an increment of 10%, and the initial value of $\theta_l$ below $z_i$ from $-2 K$ to $+2 K$ at an increment of 0.5 K. We hereafter refer to these experiments as $q_{ul}^{+0.5K}$, $q_{ul}^{+1.0K}$, $q_{ul}^{+1.5K}$, $q_{ul}^{+2.0K}$, and $q_{ul}^{+2.5K}$, similarly $\theta_l^{+2.0K}$, $\theta_l^{+1.5K}$, $\theta_l^{+1.0K}$, $\theta_l^{+0.5K}$, and $\theta_l^{-2.5K}$. We extended the time integration for a further six hours in these experiments and CTL to obtain a quasi-stationary state.

Figure 4 compares LWP averaged over the last two hours of

![Figure 1. Sounding profiles used as initial environments for the LESs, showing: (a) $q_v$ ($10^4$ kg kg$^{-1}$); (b) liquid water potential temperature ($K$); and (c) $q_c$ ($10^3$ kg kg$^{-1}$). Vapor profiles in (a) correspond to, from left to right, the $\Delta q^{20\%}$ (dotted line), CTL (solid line), and $\Delta q^{35\%}$ (broken line) experiments, respectively. Profiles of liquid water potential temperature in (b) correspond to, from left to right, the EIS $^{20\%}$ (broken line), CTL (solid line), and EIS $^{35\%}$ (dotted line) experiments, respectively. Thick lines show those used in A09.

![Figure 2. LWP (g m$^{-2}$) averaged over the last two hours of the simulations. Error bars are computed using data collected at intervals of 60 s during this period. The horizontal line shows the value of CTL.

<table>
<thead>
<tr>
<th>ID</th>
<th>Difference (compared with CTL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTL</td>
<td>n/a (control experiment)</td>
</tr>
<tr>
<td>ORG</td>
<td>Same as A09</td>
</tr>
<tr>
<td>$\Delta q^{20%}$</td>
<td>$q_v$ above $z_i$ decreased so that $\Delta q$ increased by 20%</td>
</tr>
<tr>
<td>$\Delta q^{35%}$</td>
<td>$q_v$ above $z_i$ increased so that $\Delta q$ decreased by 20%</td>
</tr>
<tr>
<td>EIS</td>
<td>$\theta_l$ above $z_i$ decreased so that $\Delta \theta$ increased by 20%</td>
</tr>
<tr>
<td>$u^{20%}$</td>
<td>$u$ increased by 20% (i.e., 9.6 m s$^{-1}$)</td>
</tr>
<tr>
<td>$u^{35%}$</td>
<td>$u$ increased by 20% (i.e., 6.4 m s$^{-1}$)</td>
</tr>
<tr>
<td>$W_{LS}^{20%}$</td>
<td>Large-scale subsidence increased by 20%</td>
</tr>
<tr>
<td>$W_{LS}^{35%}$</td>
<td>Large-scale subsidence decreased by 20%</td>
</tr>
<tr>
<td>$C_i^{20%}$</td>
<td>Exchange coefficient for SHF decreased by 20%</td>
</tr>
<tr>
<td>$C_i^{35%}$</td>
<td>Exchange coefficient for SHF increased by 20%</td>
</tr>
<tr>
<td>$C_{LHF}^{20%}$</td>
<td>Exchange coefficient for LHF decreased by 20%</td>
</tr>
<tr>
<td>$C_{LHF}^{35%}$</td>
<td>Exchange coefficient for LHF increased by 20%</td>
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</tbody>
</table>
these sensitivity experiments. As expected, a larger underestimation of BL vapor leads to less LWP and TCC. An interesting result here is that the overestimation of vapor leads to the underestimation of LWP, which is the opposite of what might be expected. To investigate the cause of this result, Figure 5 compares stratification between \( q_{\text{BL}}^{25\%} \) and \( q_{\text{BL}}^{-30\%} \), along with \( \theta_{\text{BL}}^{10\%} \) and \( \theta_{\text{BL}}^{-30\%} \). Compared with the result for \( q_{\text{BL}}^{25\%} \), large \( q_i \) at the initial state in \( q_{\text{BL}}^{25\%} \) is due to more vapor in the BL. The associated condensational heating produces much stronger stratification in the BL, as shown in the profile of virtual potential temperature, leading to reduced surface entrainment of overlying dry air in the BL (cloud dissipating process). On the other hand, a stronger turbulent mixing near the cloud top, driven by radiative cooling, enhances entrainment of overlying dry air in the BL (cloud dissipating process). As a result, cloud eventually decays more rapidly.

Figure 4 also indicates a large gap between \( q_{\text{BL}}^{10\%} \) and \( q_{\text{BL}}^{25\%} \). An additional sensitivity experiment in which the radiation process was cut off revealed that this difference was caused by stronger radiation-cloud feedback driven by the more humid condition of \( q_{\text{BL}}^{25\%} \) that allowed clouds to persist for longer.

For temperature perturbation in the BL, the influence of changes in \( \theta_i \) is less crucial compared with that in vapor (Fig. 4). As in \( q_{\text{BL}}^{25\%} \), strong stable stratification in the BL appeared in \( \theta_{\text{BL}}^{10\%} \) (Fig. 5). However, in this case, a large jump between the surface temperature and the temperature of the lower atmosphere causes an increased SHF, which acts to weaken stratification of the BL during the early stage of the simulation. As a result, the BL stratification in \( \theta_{\text{BL}}^{10\%} \) becomes similar to that in CTL by five hours, as does LWP thereafter. The stratification in the sensitivity experiment is due to stronger wind field (i.e., \( u^{+20\%} \)), although there is no vertical wind shear in the initial environment (Section 2). Increased wind shear acts to strengthen turbulent mixing across \( z_i \) (Wang et al. 2008), which enhances cloud evaporation. The increase in LWP for \( u^{+20\%} \) can be explained by the increased surface heat fluxes caused by the higher wind speed near the surface. The latter cloud-building process (i.e., the increase of surface heat fluxes) prevails against the former cloud-dissipating process (turbulent mixing near the cloud top). In fact, \( z_i \) in \( u^{+20\%} \) is higher than that in \( u^{-20\%} \) due to both processes (Fig. 3a).

For SHF, a stronger SHF acts to strengthen turbulent kinetic energy (TKE), not only near the surface, but over the BL, leading to a slight increase of LHF due to an increase in wind velocity near the surface, and a resultant increase in vertical vapor supply from the layer near the surface to the cloud layer. On the other hand, a higher SHF acts to decrease relative humidity, especially in the lower to middle levels of the BL; however, an increased LHF to the cloud layer prevails against this cloud-dissipating process, leading to the maintenance of more LWP in \( C_{\text{SHF}}^{-20\%} \). In contrast, the decrease in SHF does not alter LWP notably. As expected from consideration of the \( C_{\text{SHF}}^{+20\%} \) result, mean TKE in the BL of \( C_{\text{SHF}}^{-20\%} \) is weaker than that of CTL; however TKE around \( z_i \) is similar to that in CTL (not shown). Thus turbulent coupling in \( C_{\text{SHF}}^{-20\%} \) is presumably more pronounced than in \( C_{\text{SHF}}^{+20\%} \) and CTL. The increase in LHF does not lead to an increase in mean LWP due to the present setting. Under the range of subsidence variation in the present research, the impacts on LWP are not significant.

4. Discussion

Previous observational studies have shown that the stability in a lower atmosphere is an important factor controlling BL clouds (Klein and Hartmann 1993). Furthermore, Wood and Bretherton (2006) proposed a modified index, EIS, which can estimate the strength of the temperature jump across \( z_i \) more accurately. Our results emphasize the importance of the EIS concept and highlight the relative importance of the improved prediction of the jump in vapor across \( z_i \) among the other elements investigated.

In terms of perturbed wind velocity, one might readily expect that reduced wind velocity leads to less LWP because of less LHF. However, the mechanism whereby a stronger wind acts to increase LWP may not be straightforward. The vertical shear of horizontal wind develops rapidly across \( z_i \) in the early stage of the simulation, and the magnitude of the wind shear is greater in the stronger wind field (i.e., \( u^{+20\%} \)), although there is no vertical wind shear in the initial environment (Section 2). Increased wind shear acts to strengthen turbulent mixing across \( z_i \) (Wang et al. 2008), which enhances cloud evaporation. The increase in LWP for \( u^{+20\%} \) can be explained by the increased surface heat fluxes caused by the higher wind speed near the surface. The latter cloud-building process (i.e., the increase of surface heat fluxes) prevails against the former cloud-dissipating process (turbulent mixing near the cloud top). In fact, \( z_i \) in \( u^{+20\%} \) is higher than that in \( u^{-20\%} \) due to both processes (Fig. 3a).
In the present approach, we used the amplitude of the large-scale advection of heat following A09 to examine the influences of local environmental changes on a stratocumulus cloud. To be exact, however, this assumption does not match the heat balance in the real atmospheric BL, because the quasi-steady state of the BL is achieved by balancing the heat budget between local and large-scale environments. Thus, further efforts may be needed to strengthen the conclusions of the present research.

It is important to point out that one cannot directly connect the width of spreads in the LES result with possible errors in GCM because of a large gap between the GCM result and LES setting. For example, $Dq$ in CTL is $-4.45$ g kg$^{-1}$ (A09) while that in the GCM ensemble is $-2.3$ g kg$^{-1}$ (Fig. S1). Nonetheless we still consider the present result to be useful in the precision of stratocumulus simulations by GCMs: thermal stratification near a cloud top is the most important element controlling such clouds, and its prediction error should be prioritized. Such effort is expected to lead to better prediction of stratocumulus if a parameterization scheme for those stratocumulus in GCMs can predict cloud responses similar to those in the LESs. Improving the vertical resolution of GCMs will also be an important factor in improving the representation of the magnitude of the inversion jump, and so allow more accurate prediction of stratocumulus.

Several critical comments have been made in the previous LES studies of stratocumulus clouds (e.g., Stevens et al. 2003). The discrepancy in the present result with possible errors in GCM could be overcome by the extension of sensitivity studies to higher resolution experiments.

5. Summary

We conclude that the main factor controlling stratocumulus simulation at present is the magnitude of the jump in vapor across $z_i$, and that an additional important factor is the amplitude of the jump in temperature across $z_i$. The importance of the inversion jump itself has been well-recognized (e.g., Stevens 2002; Wood 2012), but our results reveal its relative importance in a typical stratocumulus case. The effects of the other elements in our experiments (wind velocity in and around the BL and associated vertical shear near $z_i$, subsidence, and surface heat fluxes) are similar to each other, but are all less than the impact of the vapor and temperature jumps across $z_i$. We also investigated the influences of vapor and temperature perturbations in the BL on stratocumulus cloud behavior, and found that perturbation of vapor leads to greater bias in LWP and TCC than does the perturbation of temperature.

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Supplement

Supplement 1 shows variance relative to the mean of large-scale conditions over the Californian stratocumulus environment in the CMIP5 multimodel ensemble data.

References


