Simulation of Boundary-Layer Cumulus and Stratocumulus Clouds Using a Cloud-Resolving Model with Low- and Third-order Turbulence Closures

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Abstract

The effects of subgrid-scale (SGS) condensation and transport become more important as the grid spacings increase from those typically used in large-eddy simulation (LES) to those typically used in cloud-resolving models (CRMs). Incorporation of these SGS effects can be achieved by a joint probability density function approach that utilizes higher-order moments of thermodynamic and dynamic variables. This study examines how well shallow cumulus and stratocumulus clouds are simulated by two versions of a CRM implemented with low-order (1.5-order) and third-order turbulence closures (LOC and TOC). Resolution sensitivities of the closure are studied by refining the grid spacing from control simulation (with standard CRM grids of 4 km) to simulations with much finer meshes in the horizontal.

In our simulations cumulus clouds are mostly produced through SGS transport processes while stratocumulus clouds are produced through both SGS and resolved-scale processes in the TOC version of the CRM at standard resolution. In contrast, the LOC version of the CRM requires resolved-scale circulations to produce both cumulus and stratocumulus clouds, as SGS transports within cloud layer remain small in this model. The mean profiles of thermodynamic variables, cloud fraction and liquid water content exhibit significant differences between the two versions of the CRM, with the TOC results agreeing better with the LES than the LOC results. The characteristics, temporal evolution and mean profiles of shallow cumulus and stratocumulus clouds are weakly dependent upon the horizontal grid spacing used in the TOC CRM. However, the ratio of the SGS to resolved-scale fluxes becomes smaller as the horizontal grid spacing decreases. The subcloud-layer fluxes are mostly due to the resolved scales when horizontal grid spacings approach the depth of this layer. The overall results of the TOC simulations suggest that the 1-km grid spacing is a good choice for CRM simulation of shallow cumulus and stratocumulus.

1. Introduction

Higher-order turbulence closure (HOC) and low-order turbulence closure (LOC) schemes, where closure assumptions are made on different orders of correlation terms, are extensively used to simulate planetary boundary-layer (PBL) turbulence and clouds, and deep convective clouds. The state-of-the-art third-order closure (TOC) schemes, which are a subset of HOC schemes, can well simulate stratocumulus, shallow cumulus clouds and shallow cumulus-to-stratocumulus transition (e.g., Golaz et al. 2002b; Lappen and Randall 2001b;
Cheng and Xu 2006). The LOC schemes such as the K-theory (1st order) and prognostic turbulence kinetic energy (TKE; 1½-order) schemes can also simulate these clouds rather well, but only if the counter-gradient transport of scalars (e.g., Wang 1993; Bechtold et al. 1995; Lock et al. 2000; Grenier and Bretherton 2001) and/or subgrid-scale (SGS) condensation (e.g., Sommeria and Deardorff 1977; Mellor 1977) are appropriately represented. For decades, cloud-resolving models (CRMs) have used both types of closures (e.g., Soong and Tao 1980; Krueger 1988a) to parameterize SGS processes for simulating deep convective clouds. Bryan et al. (2003) found that simulations using LOC with 1-km grid spacing did not produce equivalent squall-line structure and evolution as compared to the higher-resolution simulations. They argued that a minimum grid spacing of $O(100\text{ m})$ is required to perform adequate simulations.

The HOC schemes have traditionally been based on the assumption that a somewhat inaccurate approximation for the higher-order correlation terms will predict the lower-order moments adequately well (Lumley and Khajeh-Nouri 1974; André et al. 1976; Bougeault 1981a, b; Krueger 1988a). However, Cheng et al. (2004) argued that a physically consistent formulation of third-order moments is important for the simulation of shallow cumulus clouds since a traditional quasi-Gaussian-based closure is unable to simulate this and other boundary-layer cloud types (e.g., Krueger and Bergeron 1994). Recent approaches to higher-order closure have emphasized the relationship between selected moments and the assumption of an underlying form to the distribution of fluctuations and their correlations (Lappen and Randall 2001a; Golaz et al. 2002a; Larson and Golaz 2005; Cheng and Xu 2006). Such an approach provides a physically consistent treatment for all moments.

There are two types of LOC schemes. The first type was originally justified for large-eddy simulation (LES) wherein the grid-spacing (typically less than 100 m) falls within the inertial sub-range of three dimensional turbulence (Smagorinsky 1963; Deardorff 1973, 1980), but is also extensively used in CRMs (e.g., Soong and Tao 1980; Khairoutdinov and Randall 2003; Petch 2006), for which such justifications do not exist and the merits of such an approach have little physical justification. Petch (2006) identified 200 m as a required horizontal grid length to adequately simulate the transition from shallow to deep convection. Other types of LOC schemes, which are typically used as parameterizations in large-scale models and developed and improved with LES results, are typically combined with a mass flux and SGS condensation schemes to properly simulate shallow cumulus clouds and stratocumulus clouds (e.g., Grenier and Bretherton 2001; Bretherton et al. 2004), as well as other modifications in order to simulate stratocumulus clouds (e.g., Lock et al. 2000; Bechtold et al. 1995).

Deardorff (1978) found that the LOC and HOC produce similar simulations of diffusion of a pollutant released at a particular time in homogeneous turbulence. He also pointed out that HOC might be advantageous to use when the turbulence is not homogeneous and driven by buoyancy. Direct comparisons of HOC with LOC (as SGS closures) in simulations of boundary-layer clouds are difficult owing to the inhomogenous and buoyancy-driven turbulence. One difficulty of such comparisons is that the effect of SGS condensation, which is typically negligible in the LOC scheme used in LESs, becomes more important as the grid spacing increases. This effect cannot be adequately formulated with the low-order moments unless the variances of thermodynamic variables are parameterized in terms of their vertical gradients (Bechtold et al. 1995). On the other hand, an HOC scheme uses an SGS condensation scheme to calculate liquid water content and cloud fraction (e.g., Bougeault 1981a, b; Lappen and Randall 2001a; Golaz et al. 2002a).

The cloud fraction and condensation then follow naturally from the attributes of the joint probability density function (pdf) assumed to characterize the thermodynamic properties. A proper pdf with non-zero skewness can produce reasonable profiles of cloud fraction and liquid water content of shallow cumulus (Bougeault 1981a, b; Golaz et al. 2002b; Cheng and Xu 2006). Another difficulty is that LOC and HOC schemes as SGS closures are rarely implemented in the same CRM. Existing CRMs almost always use an LOC with the conspicuous exception of the UCLA-LaRC (University of California at Los Angeles-Langley Research Center) CRM used here (Krueger 1988a; Xu et al. 2002). The HOC schemes are mostly implemented in a single-column model (SCM) framework as PBL ensemble-average models (e.g., Bougeault 1981b; Lappen and Randall 2001a; Golaz et al. 2002a), which parameterize the effects of turbulence and clouds and neglect the horizontal variability of turbulence and have been compared with their LOC counterparts extensively (e.g., Bechtold et al. 1996;...
The recently proposed MMF (Multi-scale Modeling Framework; Randall et al. 2003) approach, which uses a two-dimensional CRM to replace all cloud and turbulence parameterizations at every grid point of a conventional general circulation model (GCM), provides a good venue to further improve turbulence closure in the embedded CRM because all cloud regimes over the globe must be simulated by the CRM. The embedded CRM uses a horizontal grid size of 1–4 km (typically the larger). This grid spacing is too large to resolve any turbulence variability although stratocumulus clouds are simulated near the west coasts of the continents where subsidence prevails (Khairoutdinov et al. 2005). The CRM in this MMF includes a 1½-order turbulence closure (Khairoutdinov and Randall 2003). The LOC does not parameterize SGS condensation so that cloud condensation occurs only at the CRM grid scale. In particular, shallow cumulus clouds are not realistically represented by the large grid-spacing CRM. The seasonal-mean cloud fraction results from averaging the binary (0 or 1) cloud amount over all CRM grid cells within a grid point of the parent GCM.

The overarching goal of this study is to improve the simulation of boundary-layer clouds in the MMF. This may be achieved by implementing a TOC scheme in the CRM that is used for the MMF and then comparing the simulated results with those obtained using the same CRM with an LOC scheme. The two objectives of the present study are as follows. We will examine how well shallow cumulus and stratocumulus are simulated by two versions of the CRM with the standard MMF grid spacing of 4 km and a vertical resolution higher than used in an MMF. We will also compare what roles the SGS and resolved-scale processes play between the two versions of the CRM by refining the grid spacing from control simulation with much finer meshes in the horizontal direction. The second objective will be important for selecting appropriate grid spacings for a future MMF that implements an improved CRM, global cloud-resolving models (Miura et al. 2005) and cloud-resolving regional numerical weather prediction models. These two objectives are achieved by comparing CRM simulations with the LOC and TOC schemes against LES simulations for a few cases derived from field data as part of the GEWEX (Global Energy and Water-cycle Experiment) Cloud System Study (GCSS) initiative.

It is expected that there will be significant differences in the simulated cloud and turbulence characteristics when the LOC and TOC schemes are used in the same CRM, due to the vastly different representations of SGS processes between the two schemes. We are not aware of a similar study that compares CRM simulations with HOC and LOC schemes implemented in the same CRM, although intercomparison studies have compared simulations among CRMs with different types of turbulence closures (e.g., Xu et al. 2002, 2005; Grabowski et al. 2006) and SCM intercomparison studies of boundary-layer clouds have revealed some differences between the LOC and HOC schemes (Bechtold et al. 1996; Zhu et al. 2005). In the context of improving the CRM component of the MMF, this is a unique investigation.

Three diverse boundary-layer cloud cases are simulated in this study. They are the BOMEX (Barbados Oceanographic and Meteorological Experiment, a marine shallow cumulus case; Siebesma et al. 2003), the ATEX (Atlantic Trade Wind Experiment, an intermediate case; Stevens et al. 2001), and the ASTEX (Atlantic Stratocumulus Transition Experiment, a stratocumulus case).

Section 2 introduces the CRM, the LOC and the TOC schemes. Section 3 describes the experiment design. The results from the two versions of the CRM are compared with those from LES in Section 4. Summary and conclusions are presented in Section 5.

2. Model description

A full description of the System for Atmospheric Modeling (SAM) CRM can be found in Khairoutdinov and Randall (2003). This CRM is embedded in an MMF (Khairoutdinov and Randall 2001). The model uses a fully staggered Arakawa C-type grid for the finite-difference representation of the anelastic model equations. The advection of momentum is computed with second-order finite differences in the flux form with kinetic energy conservation. The advection of scalars is monotonic with non-oscillatory options. One-moment bulk microphysics scheme of Kessler (1969) is used in SAM for liquid-phase clouds. Ice cloud microphysics and radiation schemes are not used in this study.

SAM includes a typical 1½-order closure scheme, which predicts TKE and parameterizes the SGS transports by turbulence. The 1½-order closure scheme is the same as described by Deardorff.
The double prime denotes the SGS perturbation from the CRM grid mean while the single prime to appear shortly refers to the local deviation from the CRM domain average unless mentioned otherwise. The overbar denotes the Reynolds averaging for SGS perturbations or domain averaging for both SGS and total fluxes shown in Section 4.

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order moments. The SAM CRM with IPHOC is about 25% more expensive than the standard SAM CRM. The IPHOC scheme has been tested in the UCLA/LaRC CRM, where it has improved the simulation of shallow cumulus clouds and produces a gradual transition from shallow to deep convection (Cheng and Xu 2006).

3. Experiment design

The benchmark experiments for all three cases use the LES version of SAM with a horizontal domain of 6.4 km × 6.4 km, a horizontal grid spacing of 100 m and a vertical grid spacing of 40 m. The exception is the ASTEX case, in which a smaller vertical grid spacing of 25 m is used to better resolve the shallow inversion layer above the top of the stratocumulus clouds. These simulations are treated as benchmarks for comparing the performance of the LOC and IPHOC versions of the CRM because the results of SAM LES boundary-layer cloud simulations are close to the consensus of LES inter-comparison studies (Stevens et al. 2001; Siebesma et al. 2003).

We also performed a series of 2-D CRM simulations with the LOC and the IPHOC schemes for each case by only varying the horizontal grid spacing, but using a fixed horizontal domain of 256 km (x direction) and the LES vertical resolution described above. The largest horizontal grid spacing is 4 km that is used in the control simulation, which is the largest CRM grid spacing used in the original MMF (Khairoutdinov and Randall 2001). A 1-km grid spacing has also been used in an MMF (Marchand; personal comm. 2007). Apart from the control simulation, four alternate horizontal grid spacings of 2 km, 1 km, 500 m and 250 m are explored. The smallest grid spacing (250 m) is still much larger than that used in the LES, but it can partially resolve cumulus-scale circulations. A list of the experiments described is given in Table 1. Additional information on the configurations of each case will be described in Section 4. For simplicity, we refer to the CRM with the IPHOC scheme as the IPHOC, and the CRM with the LOC scheme as the LOC in the rest of this paper.

4. Results

In this section, results from three boundary-layer cloud cases will be presented with an emphasis on the simulated cloud profiles, vertical transports and mean thermodynamic structures. More detailed results will be shown for the BOMEX case...
Table 1. Summary of experiments performed in this study. The cloud-resolving model (CRM) with the low-order turbulence closure is denoted by LOC while the CRM with the intermediately-prognostic higher-order closure is denoted by IPHOC. CRM is run in 2D while the large-eddy simulation (LES) is run in 3D. See text for further details.

<table>
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<th>Hours</th>
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and for the resolution sensitivity of the IPHOC simulations because the differences between the LOC and IPHOC simulations in the other two cases are largely similar to those in the BOMEX case.

a. Shallow cumulus – the BOMEX case

BOMEX took place in the Caribbean region between 22 and 30 June 1969. It is a purely shallow cumulus case, no trace of the stratocumulus clouds or mesoscale circulations were involved. Following the prescription of Siebesma et al. (2003), surface fluxes, large-scale subsidence and radiative cooling are prescribed in order to simulate a quasi-steady state. Because both the diameter and depth of individual clouds are less than 1 km, the CRM simulations are not expected to resolve the shallow cumul-
li for the specified grid spacings except perhaps for the 250-m grid spacing. A detailed description of this case and results from LESs and observations can be found in Siebesma et al. (2003).

1. Cloud evolution and vertical fluxes

The simulated spatial distributions of clouds within the 2-D domain are fundamentally different between the LOC and IPHOC simulations. In the IPHOC simulations, there are partially cloudy grids with a maximum grid cloud amount of ~10%. This is in contrast to the LOC simulations which contain a few percent of cloudy grids with large cloud water contents that are produced by the resolved-scale circulations (not shown). This is partly due to the lack of an SGS condensation scheme in the LOC.

The evolution of cloud fraction from the IPHOC is shown in Fig. 1. All simulations were run for 6 h, although the 2- and 4-km grid-spacing LOC simulations need a longer integration to achieve a steady state (Figs. 2a, b). The cloud base and cloud top are located at approximately 500 m and 1500 m, respectively, in all IPHOC simulations. The largest cloud fraction is located at the bottom of the cloud layer and decreases gradually towards the cloud top. This is because most of the thinnest clouds were located near the bottom of the cloud layer and they did not grow very high, due to the large entrainment associated with these clouds. The cloud fraction is less than 10% most of the time. These are the typical characteristics of the BOMEX shallow cumulus clouds simulated by LESs (Jiang and Cotton 2000; Siebesma et al. 2003). These results are relatively insensitive to the horizontal grid spacing except that short-term fluctuations over the cloud layer increase as the grid spacing decreases. This suggests that the influence of resolved-scale circulations increases as the grid size decreases, because these circulations are better resolved in the finer grid-spacing simulations. The temporal fluctuations probably indicate that life cycles of a few simulated cumulus clouds within the 2-D domain may be coherent. This feature also appears in

Fig. 1. Time evolution of domain-averaged cloud fraction (%) from the IPHOC version of the CRM (a−e) and LES (f) for the BOMEX case. Horizontal grid-spacings of (a) 4 km, (b) 2 km, (c) 1 km, (d) 500 m, and (e) 250 m were used in the CRM simulations. Values greater than 8% are included in the darkest shading area.
The LOC simulations also reproduce the general characteristics of the BOMEX cloud fractions, particularly, in the fine grid-spacing (0.25–1 km) simulations. As in the IPHOC simulations, the LOC results, where cloud fraction is determined from averaging of binary cloud amount, converge to that of the 3-D LES as the horizontal resolution increases (Fig. 2). There are, however, three major differences between the LOC and IPHOC simulations. First, the evolution of cloud fraction from the LOC depends greatly upon the horizontal resolution. For example, the highest clouds extend to 2000 m for the 4-km and 2-km grid-spacing simulations, 1800 m for the 1-km grid-spacing simulation, and 1600 m for the 500-m grid-spacing simulation, respectively. All of them are higher than the height of 1500 m simulated by the LES. Secondly, the life cycle of each cloud event is longer in the larger grid-spacing simulations, e.g., 2–3 hours for the 4-km grid-spacing simulation. Third, the maximum cloud fractions for the larger grid-spacing simulations are higher than those of the smaller grid-spacing simulations. These features are related to the inability of the LOC to deal with the small-scale processes and the slow response of resolved-scale circulations to the instability created by the deficiency of the LOC scheme (Fig. 3b). It can be expected that this deficiency is less pronounced at the high-resolution simulations because the small-scale processes can be marginally resolved. Thus, the instability in the LOC simulations is very sensitive to the horizontal grid spacing. For the IPHOC simulations, the small-scale processes are parameterized through SGS transport and condensation using pdfs obtained from the means, variances, co-variances, and the third-order moments. Therefore, the instability does not vary much with time in any of the IPHOC simulations and is similar to that of the LES (Fig. 3a).

The transition from a smooth to a highly fluctuating state in IPHOC cloud fraction seen from Figs. 1a–e suggests that there is a change in the partitioning of the resolved-scale and the SGS transports as the grid spacing changes. This can be seen clearly in the vertical profiles of SGS ($\bar{w}\bar{q}$) and total transports of $\theta_l$ and $q_t$, as denoted by $\bar{w}\theta_l$, $\bar{w}q_t$, averaged over the last three hours of the simulations (Fig. 4). The initial spinup period is excluded. The total fluxes (Figs. 4b, d) are relat-

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**Fig. 2.** Same as Fig. 1 [panels (a)–(e)] except for the LOC version of the CRM.
Fig. 3. Time series of the convective available potential energy (CAPE) from (a) the IPHOC and (b) the LOC versions of the CRM, and LES for the BOMEX case. Horizontal grid spacings ranging from 250 m to 4 km were used in the CRM simulations.

Fig. 4. Vertical transports of $\theta_l$ and $q_t$ averaged over the last three hours of the LES and IPHOC simulations of the BOMEX case. The subgrid-scale transports ($w'\theta_l$, $w'q_t$) are shown in (a) and (c) while the total transports ($\overline{w'\theta_l}$, $\overline{w'q_t}$) are shown in (b) and (d).
tively less sensitive to resolution because the SGS model is carrying an increasing portion of the transport as the grid is coarsened. Another interesting result is how the vertical profiles of these fluxes change as the grid spacing increases. A two-layer structure, i.e., the subcloud and cloud layers, is easily identified in the SGS flux profiles of the high-resolution simulations (Figs. 4a, c). It is now well appreciated that the turbulent statistics of the subcloud layer (which in this case is about 500 m) is relatively insensitive to the circulations in the cloud layer. Hence while the unsaturated thermal overturning within the subcloud layer is mostly resolved by the 250-m and 500-m grid-spacing simulations, it is only partially simulated by the 1-km and 2-km grid-spacing simulations. At the lowest 0.2 km, i.e., the lowest portion of the subcloud layer or the near-surface layer, the SGS fluxes are significant at the high-resolution simulations. This is also well captured by all LOC simulations (not shown). That is, $\overline{w'\theta_y'}$ and $\overline{w'q_{li}'}$ from the LOC simulations are nearly zero for the layer above 0.2 km (similar to the 250-m IPHOC run shown in Fig. 4) and show little dependency on the grid spacing. The profiles of the resolved-scale fluxes resemble the profiles produced from the LES, except for the larger magnitudes in the cloud layer (not shown) due to the overestimated cloud top heights in the LOC simulations (Figs. 2a–c). Therefore, the resolved-scale transports are required to compensate for the lack of SGS vertical transports in all LOC simulations, which are due to the deficiencies in the LOC scheme discussed earlier.

2. Mean thermodynamic profiles

This section describes the mean vertical structures of thermodynamic variables in relation to the simulated characteristics of shallow cumulus

![Fig. 5. Mean profiles of (a) liquid-water potential temperature, (b) total water mixing ratio, (c) cloud water content and (d) cloud fraction averaged over the last three hours of the BOMEX IPHOC and LES simulations. Horizontal grid sizes of 250 m, 500 m, 1 km, 2 km and 4 km are used in the IPHOC simulations.](image-url)
discussed earlier. Shallow cumulus clouds have a three-layer thermodynamic structure: a well-mixed subcloud layer, a conditionally unstable cloud layer, and a weak inversion layer above cloud top. These structures are well simulated by both the LES and IPHOC and are relatively insensitive to the horizontal grid spacing, as seen from the $\theta_l$ and $q_t$ profiles shown in Figs. 5a, b.

To illustrate the impact of 2-D resolved-scale circulations in the LOC simulations on the thermodynamic structures, the vertical profiles of $\theta_l$ and $q_t$ (Figs. 6a, b) from both the IPHOC and LOC simulations are contrasted. The 1-km grid-spacing simulations are chosen for this comparison. As discussed earlier, the turbulent transports in the LOC are very weak. So the 2-D resolved-scale flows produce artificially strong transports to substitute for the lack of SGS transports. Thus, the thermodynamic structures of the LOC simulation, which show weaker vertical gradients than the LES and IPHOC counterparts, must deviate more greatly from those of the LES than the IPHOC simulation in order to balance the prescribed forcing.

As shown in Fig. 1, the temporal evolutions of cloud fraction differ among the IPHOC simulations with different horizontal grid spacings. The steady state in the 4-km grid-spacing simulation is not reached until 10 h (not shown). To a lesser extent, this is also true in the 2-km grid-spacing simulation. Because of this, the mean cloud fractions averaged over the last three hours of these two simulations are slightly higher than the LES and the higher-resolution simulations (Fig. 5d). On the other hand, the liquid water contents in the upper cloud layer of these coarser-resolution simulations are lower than their higher-resolution counterparts (Fig. 5c). There is no systematic dependency of the departures from LES on the grid spacing. Fortunately, the difference is less than 50% of the benchmark LES value between any pair of simulations.

Fig. 6. Same as Fig. 5 except for the 1-km grid-spacing simulations with IPHOC and LOC versions of the CRM and the LES simulation.
This is much smaller than the 10-fold difference in liquid water path among SCMs with different turbulence closures (Zhu et al. 2005). This result suggests that it is difficult to simulate the liquid water content even when \( \theta_l \) and \( q_t \) profiles are very similar between simulations (Figs. 5a, b). Compared to the differences between the LOC and IPHOC 1-km grid spacing (Figs. 6c, d), the resolution sensitivity of the IPHOC simulations is insignificant.

b. Stratocumulus - the ASTEX case

ASTEX took place over the area near the Azores and Madeira Islands in the Atlantic Ocean off North Africa on 1–28 June 1992 (Albrecht et al. 1995). A stratocumulus case with no drizzle was configured based upon the ASTEX observations (de Roode and Duynkerke 1997), which represented a typical stratocumulus-topped boundary layer. The prescription of de Roode and Duynkerke (1997) is followed. The observed cloud deck has a thickness of 400 m, extending from 300 m to 700 m. The temperature jump is 5.5 K at the inversion. The simulations are initiated with an adiabatic cloud liquid water profile, with a peak value of ~0.7 g kg\(^{-1}\). They are prescribed with surface sensible and latent heat fluxes. A simple, interactive radiation scheme is included; the radiative flux is diagnosed from the predicted liquid water content, but there is no clear sky cooling. Each simulation lasts for 3 h, beginning at 0400 UTC 13 June 1992.

The overall evolution of cloud fraction from all three (LOC, IPHOC and LES) simulations is very similar and they do produce realistic overcast cloud deck between 300 and 700 m. Minor differences can be noticed at the bottom and the top of cloud layer, however (Fig. 7). Since the simulated cloud characteristics are insensitive to the grid spacing, only the 1-km grid-spacing LOC and IPHOC simulations are shown in Figs. 7b, c. The cloud bases in the IPHOC simulation and the cloud tops in the LOC simulations are somewhat lower than the LES (Fig. 7a) although they are within the uncertainties of measurements. This result can be seen from the averaged vertical profiles over the last two hours of the IPHOC simulations (Fig. 8d). The LOC results for this case will not be described below because the discrepancies in the SGS and total flux profiles are similar to those noted in Section 4a while the mean thermodynamic profiles are largely similar to those simulated by the IPHOC.

The differences in the \( \theta_l \) and \( q_t \) profiles among the five IPHOC and one LES simulations (Figs. 8a, b) are due mainly to the differences in the total transports (Fig. 9), which is caused indirectly by the cloud top entrainment, since the radiative cooling, surface fluxes, and large-scale subsidence are nearly identical (not shown). As in the BOMEX cumulus case, most transports are carried by the subgrid scales in the coarser 1-, 2- and 4-km grid-spacing simulations but are carried by the resolved scales, which are the differences between the right and left panels of Fig. 9, in the finer 250- and 500-m grid-spacing simulations.
grid-spacing simulations. The size of eddies largely determines whether or not the subgrid scales are the dominant player in the boundary-layer circulations. Since these eddies cannot be resolved in the 1-, 2- and 4-km grid-spacing simulations, this explains why the SGS fluxes in the cloud layer are relatively larger for these three simulations (Figs. 9a, c). Because the subcloud layer (below 300 m) is a part of the stratocumulus-topped boundary layer, the SGS fluxes at this region of the vertical profiles are large. This feature is present for all IPHOC simulations. This is a major distinction from the BOMEX case discussed earlier.

The maximum liquid water content was also underestimated by the IPHOC (Fig. 8c) since the sharp q_i inversion of the ASTEX stratocumulus is not captured in the three coarser-resolution simulations (Fig. 8b). There are spurious \( w'\theta' \) fluxes in the layer immediately above the cloud top that may be produced by the non-monotonic advection scheme of \( \theta \) or those of the turbulence closure (Fig. 9a) although the negative peak at the top of the cloud layer is well produced. This result is consistent with the lack of sharp peaks in the three simulations in question. This result agrees with Zhu et al. (2005). They showed that some SCMs tend to smooth out the sharp jumps of \( \theta \) and q_i at the cloud top and have larger gradients in \( \theta \) and q_i within the mixed layer. They suspected that the SCM inversion structure depends on details of its turbulent parameterization, in particular, the cloud top entrainment.

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Fig. 8. Same as Fig. 5 except for the ASTEX case. The profiles were obtained from the averages over the last two hours of the IPHOC and LES simulations. The dots represent observations (de Roode and Duynkerke 1997).
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variance and skewness of $\theta_i$ and $q$, within this thin layer produced by the IPHOC closure (not shown). This inherent difficulty also appears in the simulations of Golaz et al. (2002b), in which the IPHOC turbulence closure shares the double-Gaussian pdf description of SGS fluctuations.

c. Intermediate trade cumulus − the ATEX case

ATEX took place in the northwest tradewind region of the Atlantic in February 1969. Clouds were observed in a transition region from shallow cumulus to stratocumulus. The observations were based on three ships that drifted for about three weeks in this region, with intensive observations being concentrated in the lowest 4 km of the atmosphere (e.g., Augstein et al. 1973). The intercomparison of LES model simulations for this case found that the cloud amount is sensitive to the numerical algorithms among the participating models (Stevens et al. 2001). The configuration outlined for this intercomparison case is used in the present study. Specifically, both radiation and surface fluxes are interactive. The sea surface temperature is prescribed to be 298 K. An exception to the intercomparison configuration is that the simulated domain-averaged wind profile is nudged to its initial profile with a nudging time scale of 4 h (Xu and Randall 1996). This helps to minimize the differences in the calculated surface turbulent fluxes between simulations.

As in the BOMEX case, the model-generated cloud spatial distributions and resolved-scale circulations within the 2–D domain are quite different between the LOC and IPHOC simulations (not shown). For a given grid spacing, the resolved-scale circulations simulated by both versions of the CRM are, as discussed later, much stronger than those in the BOMEX case due to stronger (and

Fig. 9. Same as Fig. 4 except for the ATEX case. The profiles were obtained from the averages over the last two hours of the LES and IPHOC simulations. The dots represent observations (Roode and Duynkerke 1997), which are compared to the total fluxes.
interactive) radiative cooling at the cloud top. This difference between the two cases can help understanding the results presented below.

The LES-simulated cloud fraction of the ATEX case exhibits characteristics of both shallow cumulus and stratocumulus clouds (Fig. 10f). There are two maximum centers of cloud fraction at the bottom and the top of the cloud layer. The cloud fraction at the bottom of the cloud layer is less than 10%. Shallow cumulus clouds contribute to this secondary maximum. These clouds were produced when positively buoyant air parcels near the surface, which were driven by surface sensible and latent heat fluxes, reached the lifting condensation level. The cloud fraction near the cloud top is about 40%, which is mainly composed of stratocumulus clouds driven by cloud top cooling.

The IPHOC simulation (Figs. 10a–e) reproduced both the stratocumulus (30–40% at the top of the cloud layer) and shallow cumulus maxima (5–10%). While these features were produced through the entire integration period of finer grid-spacing simulations (250 m and 500 m), they were only produced for the first half of the 8-h integration with the coarser grid-spacing simulations (1-, 2- and 4-km). Note that the 4-km grid-spacing simulation did not achieve a quasi-steady state until 14 h (not shown) and the steady state was not reached within 8 h in the 2-km grid-spacing simulations, either. The cloud fraction minimum in the middle of the cloud layer for the quasi-steady state was not reproduced well when the grid spacing was larger than 1 km, due presumably to the weak cloud-top entrainment.

The LOC simulations produced slightly higher cloud bases and larger cloud amounts than the 3D-LES and IPHOC simulations, especially when grid spacings are large. The delay for onset of shallow cumulus and stratocumulus clouds increased as the horizontal grid spacing increased (Figs. 11a–e). The mechanism for this delay is the same as that described for the BOMEX case, i.e., due to the inability of the LOC scheme to deal with the small-scale processes within the cloud field. At the larger horizontal grid spacings, it takes longer to develop the resolved-scale circulations in response to the build-up of the instability produced from the prescribed large-scale cooling (see Fig. 3b). In nature, cloud-radiation interactions drive both resolved-scale and SGS circulations at the top of the cloud.

Fig. 10. Same as Fig. 1 except for the ATEX case.
layer and contribute to the maximum cloud fraction there. In the LOC simulations, stratocumulus clouds appear well after shallow cumuli have occurred, which suggests that the stratocumulus clouds are initially produced from resolved-scale circulations. Sufficient moistening at the upper part of the cloud layer then occurs and cloud-top radiative cooling further strengthens the resolved-scale circulations. This may explain the overestimated cloud fractions in the large grid-spacing simulations.

There are two major similarities between the ATEX and BOMEX cases regarding the SGS and total fluxes (Figs. 4 and 12). First, the magnitudes of $\overline{w'' \theta''}$ and $\overline{w'' q''}$ increase while the magnitudes of $\overline{w' \theta'}$ and $\overline{w' q'}$ are relatively insensitive as the grid spacing increases. An exception is that the 250-m grid-spacing simulation has larger magnitudes of $\overline{w'' \theta''}$ and $\overline{w'' q''}$ near the cloud top layer than those of 500-m and 1-km grid-spacing simulations. Second, the total fluxes within the subcloud layer are dominated by those of the resolved scales for all IPHOC simulations except for the 4-km grid-spacing case. The most significant differences from the BOMEX case are that both $\overline{w'' \theta''}$ and $\overline{w'' q''}$ contribute less to the total transports in the cloud layer (Fig. 12). This is due to the presence of the interaction of stratocumulus clouds with radiation in the ATEX case, which drives the resolved-scale circulations more readily.

For the ATEX case, the sounding within the cloud layer is more well-mixed (Figs. 13a, b) than in the BOMEX case, but more stratified than in the ASTEX case. The unstable cloud layer and the well-mixed subcloud layer can be distinguished from the mean vertical profiles of $\theta$ and $q$ produced by both the IPHOC and LES simulations. However, the $q$ profile in the subcloud layer of the LOC 1-km grid-spacing simulation deviates more from the LES than the corresponding IPHOC simulation. This is similar to the BOMEX case (Fig. 6b), and is due to the lack of SGS transports (not shown). In order to compensate for this, the model overproduces the 2-D resolved-scale transports. Consequently, the magnitudes of the cloud water content and cloud fraction are greatly overestimated (Figs. 13c, d). Contrasting to the LOC simulations, overestimates of both the cloud fraction and liquid water content are small for the IPHOC simulations (Figs. 13c, d), although they depend somewhat

![Fig. 11. Same as Fig. 2 except for the ATEX case.](image)
upon the grid spacing (not shown). In particular, overestimates appear in the middle of the cloud layer, with the largest differences occurred in the 2- and 4-km grid-spacing simulations. Overestimates for the 250- and 500-m grid-spacing simulations are similar to those of the 1-km grid-spacing simulation (Figs. 13c, d). In combining with the flux profiles shown in Fig. 12, which shows almost no difference in the subcloud-layer fluxes among the 250-m, 500-m and 1-km grid-spacing simulations, one may argue that the 1-km grid spacing is a good choice for the coarsest “acceptable” resolution. A similar argument can be made for the BOMEX case, based upon all the parameters examined. This chosen grid spacing is larger than the 100−200 m identified by both Bryan et al. (2003) and Petch (2006) using CRMs with an LOC. The larger grid length helps improving the computational performance of the CRM simulations (see Section 2). Thus, the implementation of the TOC, instead of an LOC, can allow for the realistic CRM simulations of the boundary-layer clouds with a larger grid size.

5. Summary and conclusions

This study has examined how well shallow cumulus and stratocumulus clouds are simulated by two versions of a CRM implemented with low-order and third-order turbulence closures (LOC and TOC) and what roles the SGS and resolved-scale processes play as the horizontal grid spacing of the CRM increases from 250 m to 4 km. CRM simulations were performed in the 2D framework. The 2D framework is similar to that employed in the MMF with a domain size of 256 km, but different from that employed in the MMF because horizontal grid spacings ranging from 250 m to 4 km and higher vertical resolutions were used. These simulations have been compared with benchmarks obtained from LES simulations. The major conclu-
The detailed findings can be summarized as follows.

In our simulations, the initiation and evolution of boundary-layer clouds in the two versions of the CRM are significantly different when typical CRM grid spacings (> 1 km) are used. The LOC version of the CRM requires the resolved-scale circulations to produce both shallow cumulus and stratocumulus clouds and the simulated clouds undergo large temporal fluctuations at coarse resolutions, as SGS transports within cloud layer remain small in this model. This is related to the inability of the LOC to deal with small-scale processes and the slow response of resolved-scale circulations to the instability created by the deficiencies of the LOC scheme and the imposed large-scale cooling.

On the other hand, the IPHOC version of the CRM produces shallow cumulus clouds mostly through SGS processes and stratocumulus clouds through both SGS and resolved-scale processes. There is no delay in the initiation of shallow cumulus clouds, due to adequately formulated SGS transports. These differences in the cloud initiation and evolution between the two versions of the CRM also appear in the intermediate trade cumulus case since models start without any cloud for both cases. The ASTEX stratocumulus case does not show such differences because clouds are initially specified. At high resolutions, as expected, the simulated cumulus and stratocumulus undergo similar evolutions for both versions of the CRM. They show high-frequency temporal variations and reasonably similar vertical structures, as in the LES, due to the increased amplitudes of resolved-scale transports and adequate simulations of subcloud-layer circulations. The differences are, however, still not negligible between the two versions of the CRM because SGS condensation is not
produced in the LOC version.

The various characteristics of the quasi-steady or mean thermodynamic states, including cloud properties, exhibit significant differences between the two versions of the CRM, with the TOC results agreeing better with the LES than the LOC results. The results from the 1-km grid-spacing simulations with the two versions of the CRM were extensively compared to illustrate the differences between the two versions of the CRM. Their differences for all three cases are much greater than those between the TOC simulations with different horizontal grid spacings, despite of some discrepancies in the simulations resulted from shortcomings of the HOC such as the cloud top entrainment noted by Golaz et al. (2002b) and Zhu et al. (2005).

For all three cases, the partitioning between the resolved-scale and SGS fluxes from the IPHOC is reasonable. The magnitudes of SGS fluxes increase while the magnitudes of resolved-scale decrease as the grid spacing increases. The total fluxes, which are relatively insensitive to grid spacing, are solely due to the SGS fluxes for the coarsest resolution (4 km) simulation while they are mostly due to the resolved-scale fluxes for the highest resolution (250 m) simulation. At relatively high resolutions, the resolved scales are responsible for most transports within the subcloud layer of cumulus and stratocumulus clouds. This may be an important factor in choosing an acceptable resolution, along with the other characteristics of the simulations. A 1-km grid spacing can be a good choice, because a significant fraction of the total fluxes comes from the resolved scale in the subcloud layer while the parameterized SGS fluxes in the cloud layer are reasonably large. This chosen grid spacing is larger than the 100–200 m identified by both Bryan et al. (2003) and Petch (2006) using CRMs with an LOC to simulate deep convection and transition to deep convection. Thus, the incorporation of a TOC, instead of an LOC, in a CRM allows for the realistic simulation of the boundary-layer clouds with a larger grid size. The choice of the appropriate vertical grid spacing is being explored in on-going work.

As the computational power increases, MMFs and global CRMs will play an important role to address important climate issues. The difficulties in parameterization of deep convective clouds can be avoided in such models, but those in the parameterization of boundary-layer clouds remain. One can see the impacts of the different turbulence closure schemes on cloud evolution, resolved-scale circulation, vertical transport of $\theta$, and $q$, and the mean thermodynamic profiles presented in this study. Many aspects of cloud evolution and thermodynamic structures from the IPHOC are comparable to the benchmark LES results. It will be interesting to study the impact of the IPHOC in a global model because there are significant uncertainties in cloud feedbacks associated with boundary-layer clouds in traditional climate models (Bony and De Fresse 2005).

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