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TURBULENCE CLOSURE AND CLOUD DYNAMICS IN CLOUD-RESOLVING SIMULATIONS OF BOUNDARY-LAYER CLOUD REGIMES

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1. Introduction

Parameterization of boundary-layer clouds is a particularly important problem for numerical weather prediction and climate models because of their impacts on the Earth's radiative budget and the general circulation of the atmosphere (Hartmann et al. 1992). Any parameterization has to properly represent the strong feedbacks between convection, cloud microphysics, radiation and the entrainment of the overlying air across the inversion. Two types of high-resolution models, i.e., large-eddy simulation (LES) and cloud-resolving models (CRMs), have been used to narrow the gaps between observations and parameterization development within the Global Energy and Water-cycle EXperiment (GEWEX) Cloud System Study (GCSS; Browning 1993).

LES models can explicitly resolve large turbulent eddies, but they are very expensive because they are three-dimensional (3-D) and use a very fine grid spacing in tens of meters. CRMs can use a much larger grid spacing in a few kilometers and their 2-D versions can be used to replace all cloud parameterizations in climate models (Khairoutdinov and Randall 2001).

Because of the coarse resolutions used in CRMs, the subgrid-scale (SGS) models have to be more sophisticated than in LESs. The most advanced SGS model in a CRM uses a third-order turbulence closure and a subgrid-scale condensation (SGSC) scheme (Sommeria and Deardorff 1977). Figure 1 illustrates how the SGS model works in a CRM. The mean fields control the higher moments through shear, buoyancy, and transport (Line 1). The second and third moments influence the mean fields in two ways: one is through the second moment divergence and convergence (Line 2); the other is through the SGSC, which influences the mean temperature and humidity directly (Line 5). Assuming a probability distribution function (PDF), the SGS temperature and humidity distributions are obtained (Line 3). If the PDF is appropriate, realistic condensation by SGS clouds will be obtained (Line 4). Since the feedback is a cycle, the entire system is closed.

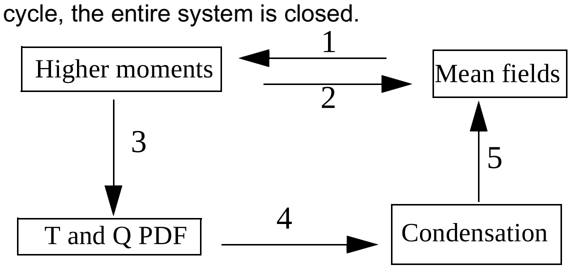

Fig. 1: A schematic diagram of the SGS model in a CRM.

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This study evaluates the ability of a 2-D CRM for simulating the boundary-layer cloud regimes against the LESs and limited observations and examines the importance of an SGSC scheme and the sensitivity to the vertical resolution used in the simulations.

2. Model description and design of the simulations

The Langley Research Center two-dimensional (LaRC2d) CRM, which is better known as the UCLA/CSU CRM (Krueger 1988; Xu and Randall 1995), is used in this study. The third-order turbulence closure is the most unique feature of this model, parameterizing both the boundary-layer and in-cloud turbulence. The SGSC scheme of Sommeria and Deardorff (1977) is included in the control simulations presented below.

Four cloud regimes are chosen for this study. They are from the following field experiments: the Atlantic Stratocumulus Transition EXperiment (ASTEX), the Barbados Oceanographic and Meteorological Experiment (BOMEX), the Atlantic Trade EXperiment (ATEX) and the Atmospheric Radiation Measurement (ARM). The first three are oceanic stratus (ASTEX) and stratocumulus (ATEX and BOMEX) regimes. The fourth one (ARM) is a continental stratus cumulus regime. Thus, this study provides a comprehensive comparison between CRM and LES results for the entire range of stratocumulus regimes that occur in the low and middle latitudes.

The configurations of the model, the initial and forcing conditions are identical to those used by the GCSS Working Group (WG) 1 intercomparison studies. The details of these designs are described in Duynkerke et al. (1999) for ASTEX, in Stevens et al. (2001) for ATEX, in Siebesma et al. (2002) for BOMEX and in Brown et al. (2002) for ARM. A horizontal grid size of 1000 m and a vertical grid interval of 100 m is used, which are much coarser than those used in LESs that participated in the GCSS WG 1 studies. For BOMEX, the initial sounding is slightly modified in order to produce a temporally steady simulation. In addition, the turbulent momentum fluxes at surface for ASTEX, ATEX and BOMEX are set to zero.

3. Results of the control simulations

The model simulates the thickness of the cloud layer and cloud fraction evolution well for the four cases (Fig. 2), with results similar to those of LESs. The model also realistically shows an unsteady evolution for the ARM case, and steady evolutions for the ATEX, BOMEX and ASTEX cases.

Snapshots of the cloud distributions in *x-z* cross sections (Fig. 3) show that the model captures the different characteristics of the four cloud regimes. The stratus (ASTEX) is shallow and overcast. The stratocumuli are narrow and deep in BOMEX. The transition-regime clouds (ATEX) are narrow at their bases but wide near their tops. The cloud top heights vary greatly for the ARM case, but cloud bases are flat.

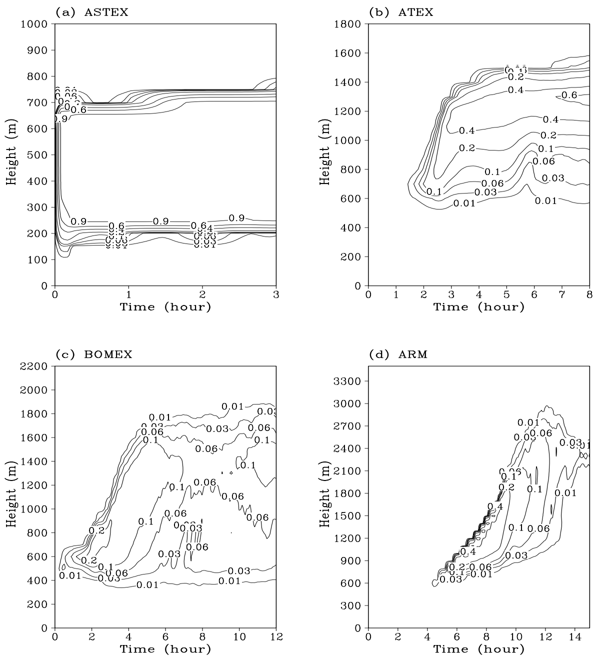


Fig. 2: Time-height cross sections of cloud fraction for the (a) ASTEX, (b) ATEX, (c) BOMEX and (d) ARM cases. Contours of 0.01, 0.03, 0.06, 0.1, 0.2, 0.4, 0.6 and 0.9 are plotted.

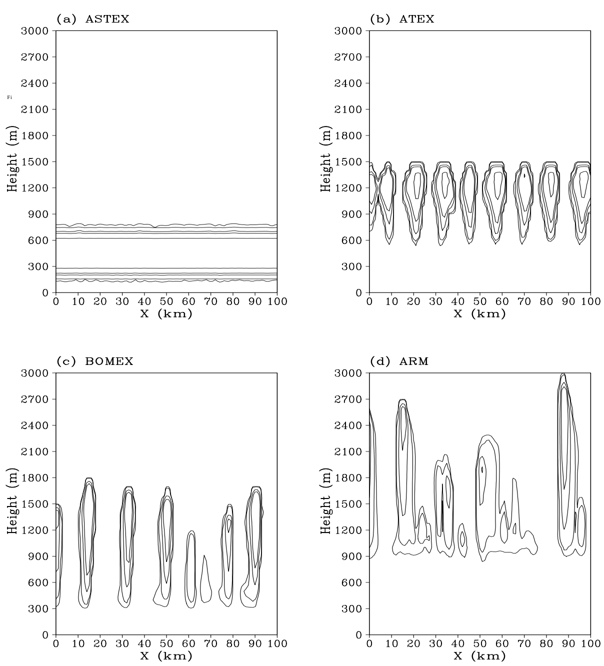


Fig. 3: *x-z* cross sections of cloud distribution for the (a) ASTEX at 3 h, (b) ATEX at 6 h, (c) BOMEX at 6 h and (d) ARM at 9 h. Contours of 0.01, 0.05, 0.3, 0.6 and 0.9 are plotted.Only a portion of the domain is shown for each snapshot.

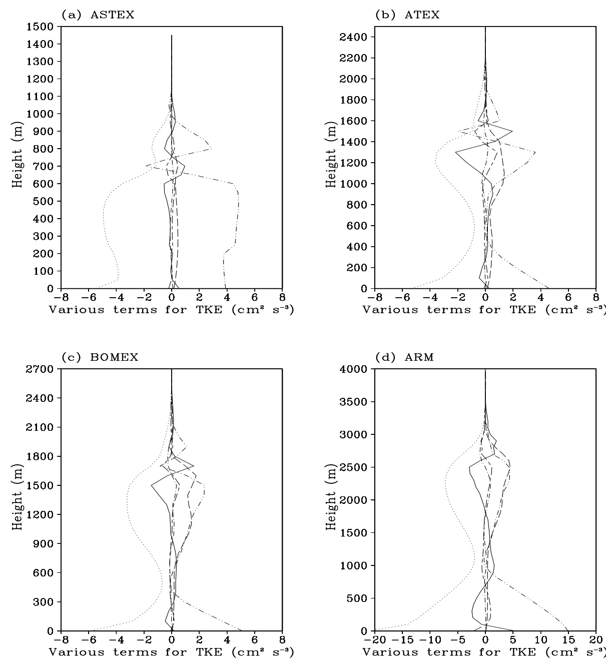


Fig. 4: Subgrid-scale TKE budget components for the four cases: turbulent transport (solid), buoyancy production (double-dotted and dashed), shear production (long dashed), mean wind transport (dotted and long dashed), pressure redistribution (short and long dashed) and dissipation (dotted).

The subgrid-scale turbulent kinetic energy (TKE) budget components are presented in Fig. 4. For ASTEX, the dominant terms in the TKE budget are the buoyancy production and turbulent dissipation. Both exhibit a "single layer" structure with comparable magnitudes. For the three cumulus cases, the TKE budget components are fairly similar except for the different heights of the maxima/minima, due to different heights and thicknesses of the cloud layers. Unlike the ASTEX case, both buoyancy production and turbulent dissipation profiles exhibit a "two layer" structure, i.e., a minimum below the cloud-base level. The structures of all TKE budget components within the cloud layer are very different among the three cases (Fig. 4). All of them are very similar to LESs except for some differences due to the coarser resolution [see Cheng and Xu (2002) for further details.].

The second-moment variables are shown in Fig. 5 for the BOMEX case. Both SGS (denoted by double primes) and resolved-scale (denoted by single primes) fluxes of liquid-water potential temperature and total water mixing ratio are presented. For BOMEX, the same "two-layer" structures exist except that the SGS fluxes of total water mixing ratios are not zero near the cloud base (Fig. 5b). This serves as the source of energy transport for the cloud layer from the subcloud layer. The interactions between the SGS and the resolved scale occur mainly in the upper portion of the cloud layer. The vertical velocity variances are the largest in the cloud layer, but a secondary maximum exists just above the surface (Fig. 5c), which is higher than the LESs, due to the neglect of surface turbulent momentum flux in the CRM simulations, mentioned in section 2.

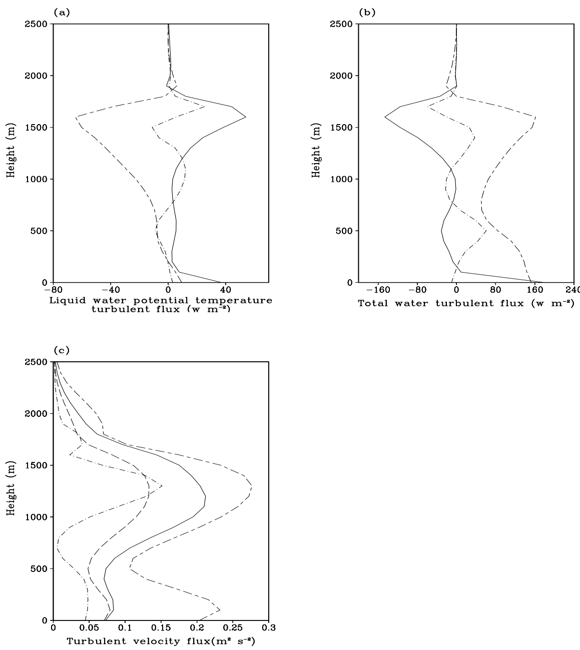


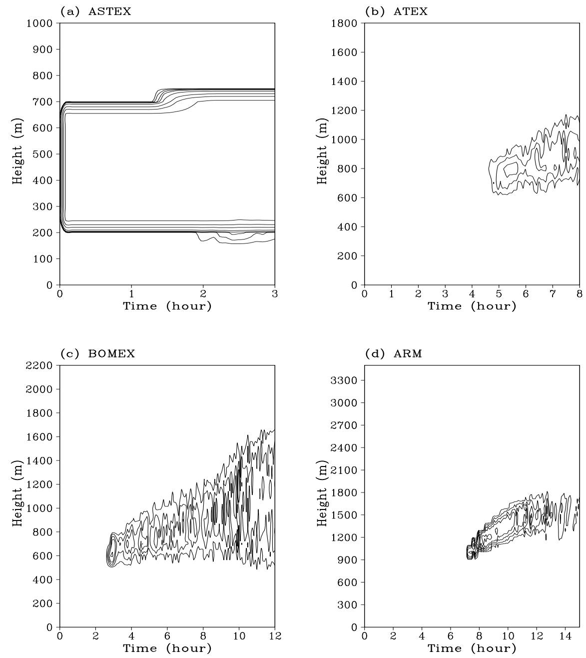
Fig. 5: Second moments for the BOMEX case between 5 and 6 h: *(a)* $\overline{w''\theta''_l}$ (short- and long-dashed), $\overline{u''\theta''_l}$ (solid) and $\overline{u'\theta_l'}$ (dotted-dashed), (b) same as in (a) except for total water mixing ratio; (c) $\overline{u''u''}$ (solid), $\overline{v''v''}$ (long dashed), $\overline{w''w''}$ (short- and long-dashed), and $\overline{u'u'}$ (dotted-dashed).

4. Sensitivity tests

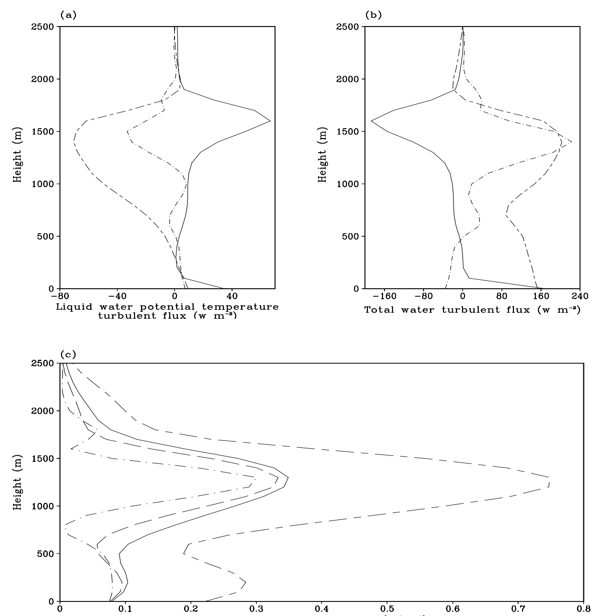
a. Sensitivity to the SGSC scheme

This sensitivity test was run by turning off the SGSC scheme. That is, a CRM grid is either totally cloudy or clear. This test is used to illustrate the importance of the SGSC scheme in the simulation of boundary-layer clouds with a coarse-resolution CRM.

The time evolutions of cloud fraction are shown in Fig. 6 for all four cases. Comparing to Fig. 2, it is obvious that there are no significant differences between the control and sensitivity simulations for ASTEX, but there are large differences for the three shallow cumulus cases. Firstly, the initiation of the first clouds in each simulation is delayed by 2 h in ATEX and BOMEX and 3 h in ARM. Secondly, the clouds are much thinner than those of the control simulations despite the fact that the cloud base heights are similar or slightly higher in the sensitivity simulations. Lastly, the cloud amount is drastically reduced in the sensitivity simulations. The maximum cloud amount is about 15% for all three cases, compared to 27% for BOMEX, 35% for ARM and 60% for ATEX of the control simulations.



ig. 6: Same as Fig. 2 except for the sensitivity simulations by urning off the SGSC scheme in the control simulations.



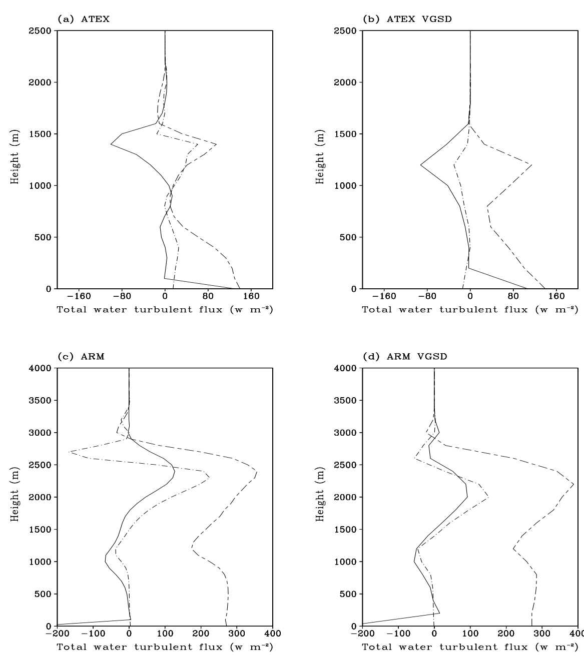
ig. 7: Same as Fig. 5 except for the sensitivity simulation of he BOMEX case between 11 and 12 h.

The second-moment fluxes are shown for the BOMEX case (Fig. 7). The averaging profiles are obtained for the time period between 11 and 12 h which has a comparable cloud depth as the time period between 5 and 6 h of the control simulation (Fig. 5). Compared to Fig. 5, the vertical profiles of all SGS and resolved scale fluxes are basically unchanged, except they have slightly larger magnitudes. The resolved scales are more actively involved in the sensitivity simulation (Fig. 7c).

In summary, the comparison between the control and sensitivity simulation reveals that both the SGS and the resolved scale have to be stronger so that they can cause the uneven change of the temperature and humidity within the domain to produce condensation in the sensitivity simulations.

b. Sensitivity to vertical resolution

In this set of simulations, the vertical grid size is doubled (VGSD simulation), compared to the control simulation. The differences between the VGSD and the control simulations are not as large as those between the control and sensitivity simulations presented in section 4a. However, a significant difference is that both the cloud base and top heights are lower in all four cases (not shown). The coarser resolution also smooths out the gradient at the top of the subcloud layer and increases the transport of water vapor from the subcloud layer to the cloud layer (compare Fig. 8a with b, c with d).



ig. 8: Same as Fig. 5b except for comparing the control (a, c) nd VGSD (b, d) simulations of ATEX and ARM cases.

5. Conclusions

This study presents some results from simulations of four distinct boundary-layer cloud regimes using a 2-D CRM with a third-order turbulence closure. The horizontal grid size used is 1 km, which is 15-30 times larger than those used in LESs. A subgrid-scale condensation (SGSC) scheme is used in the control simulations and compared to simulations without this scheme.

We find that the SGSC scheme makes no difference in the stratus simulation. However, the SGSC scheme has many effects on the other three regimes. The amount and depth of shallow cumulus clouds increase when the SGSC scheme is used, and agree well with observations. The simulations also provide mostly realistic profiles of subgrid-scale buoyancy production, turbulent transport, dissipation and turbulent fluxes, comparing well with limited observations and the LES studies. The resolved-scale kinetic energy production is dominated by buoyancy production, which has a maximum in the cloud layer and is near zero in the subcloud layer. Without the SGSC scheme, all simulations of shallow cumulus clouds are very different from observations and the LES studies.

When a coarser vertical resolution is used, the results do not change much except that the cloud top and cloud base are lower. This coarser resolution also redistributes the kinetic energy between the SGS and resolved scale. The vertical total water flux increases. These differences are most significant in the stratus simulation.

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