Comparison of Low-order and Third-order Turbulence Closures in the Simulation of Shallow Cumulus Clouds

Anning Cheng[1,2], Kuan-Man Xu[2]

1. AS&M, Inc., 2. NASA Langley Research Center, Hampton, VA

1. Introduction

Multi-scale Modeling Framework (MMF) and global cloud resolving model (GCRM) will play an important role in addressing important climate issues, such as global warming. The difficulties associated with the parameterization of deep convective clouds can be avoided, but those associated with the parameterization of boundary-layer clouds remains.

Low-order turbulence closure (LOC) and third-order turbulence closure (TOC) are extensively used for parameterizations for boundary-layer clouds. Subgrid-scale turbulence transports of scalars are parameterized differently in the two types of closure.

2. Experiment Design

The BOMEX and ARM shallow cumulus cases are simulated with System for Atmospheric Modeling (SAM) CRM and the SAM LES (large-eddy simulation) to explore the sensitivity of the models to horizontal grid-size and subgrid-scale parameterizations.

- Control: The SAM LES (6.4 km x 6.4 km, dx, dy = 100 m, dz= 40 m)
- LOC SAM: dx = 250 m, 500 m, 1 km, 2 km and 4 km, dz = 40 m, with a domain size of 256 km
- TOC SAM: dx = 250 m, 500 m, 1 km, 2 km and 4 km, dz = 40 m, with a domain size of 256 km.

3. Results

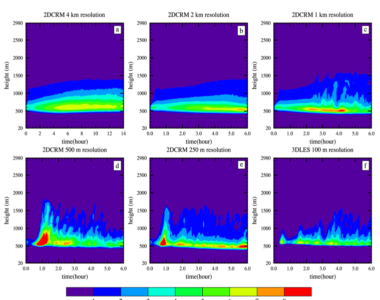

Fig. 1. Time-height cross section of cloud fraction simulated by SAM CRM with the Cheng-Xu third-order closure (TOC) for BOMEX. The horizontal grid sizes range from 4 km (a) to 250 m (e). Results from a large eddy simulation from the SAM LES are also shown in (f).

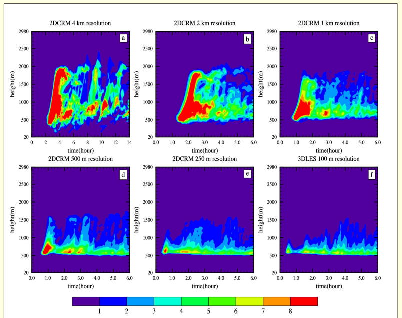

Fig. 2. Same as Fig. 1 except for simulations performed by the standard SAM with a low-order closure (LOC).

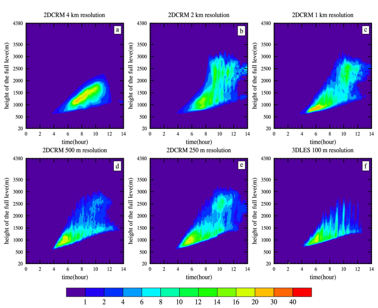

Fig. 3. Same as Fig. 1 (TOC) except for the ARM Case.

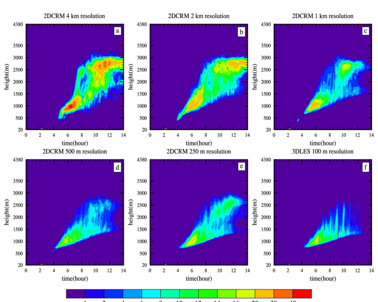

Fig. 4. Same as Fig. 2 (LOC) except for the ARM Case.

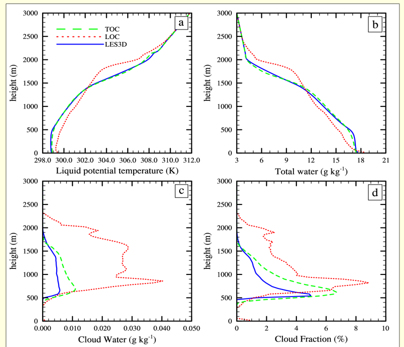

Fig. 5. Mean profiles of selected first-order variables averaged over the last 6 h of the BOMEX simulations. The grid size of the CRM used is 4 km.

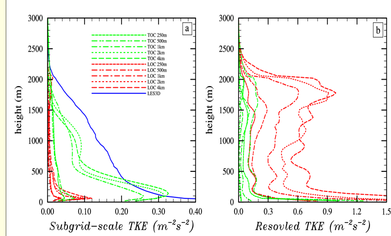

Fig. 6. Profiles of (a) subgrid-scale kinetic energy (TKE) and (b) resolved-scale kinetic energy from CRM simulations of the BOMEX case with different dx (250 m to 4 km) using the versions of SAM with LOC (red) and TOC (green) schemes, respectively. The 3D-LES profile (blue) is also shown in (a).

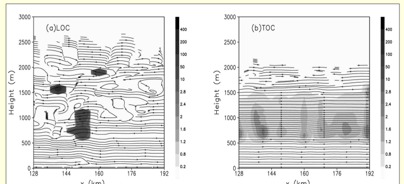

Fig. 7. Snapshot of the streamfunction fields overlapped with cloud water mixing ratio (g/kg) at the last hour of BOMEX. The vertical velocity was increased by ten times in order to show the circulation.

4. Conclusions

- The development of shallow cumuli is delayed with the increase of grid-size for LOC SAM. A lack of subgrid-scale transports causes
  - increased convergence of moisture and temperature near surface
  - accumulation of CAPE due to inhibition of shallow convection
  - producing convection through resolved-scale circulations
- The clouds from LOC SAM were mainly produced by the resolved-scale circulations. The horizontal scale of the resolved-scale circulations is approximately 20 km.
- The TOC SAM produced the proper subgrid-scale transports and cloud evolution at coarse resolutions, compared to 3D-LES. The cloud evolution is less resolution dependent.
- The total kinetic energies for coarse resolution runs are larger when convection occurs, due to stronger resolved-scale circulations.
- Inadequate subgrid-scale transports can result in unrealistic resolved-scale circulations, cloud evolution, and energy budget.

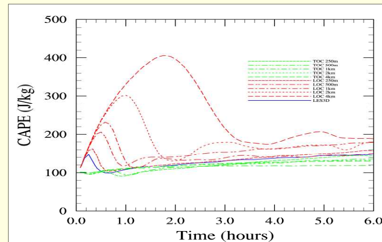

Fig. 8. Time series of convective available potential energy from BOMEX simulations (red, TOC; green, LOC; blue, LES).

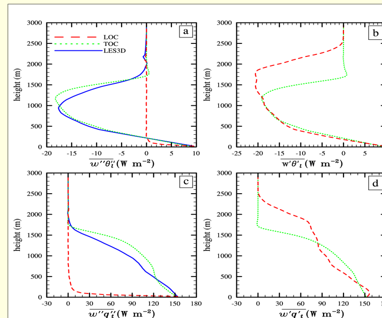

Fig. 9. Mean profiles of turbulence-scale and total transports averaged over the last 6 h for BOMEX 4 km (dx) simulations.