Large-eddy simulation and its application to study subgrid-scale transport for global cloud-resolving models

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1 Introduction

One crucial question to the subgrid-scale (SGS) problem in a global cloud-resolving model (GCRM) is how unresolved smaller-scale convection responds locally to resolved larger-scale convection. To study this response, we performed a benchmark simulation, which is a large-eddy simulation (LES) of a tropical deep convective system. The LES technique is specifically defined as a turbulence simulation tool where energy-containing, flux-carrying turbulent motions are explicitly calculated, while not-so-important small eddies are parameterized. Our benchmark simulation consists of 2048 x 2048 x 256 $\sim 10^9$ grid points (and is hence called Giga-LES) with a numerical domain of 204.8 km x 204.8 km x 27 km, which is large enough to cover a deep convective system. Its grid spacing is 100 m in horizontal directions and varies from 50 m to 100 m in the vertical (below $z \sim 18$ km), which is small enough to resolve energy-containing, flux-carrying turbulent eddies. The initial sounding, large-scale forcing, simulation setup, and overall cloud properties were reported in Khairoutdinov et al. (2009).

2 Spectral analysis of the Giga-LES

The power spectra of the vertical-velocity w and the co-spectra between w and q (the total water mixing ratio) of the Giga-LES flow field are shown as the contours in Fig. 1. The x axis is the wavelength L, ranging from 200 m (twice the horizontal grid spacing) up to 1024 km and the y axis indicates the height. The spectra are continuous across all convective scales. The peak scale of the w-spectra (top) increases almost linearly with height from the surface to about 4 km and then remains at $L =$ 5-10 km above it. These peak scales are close to the effective resolution of a typical GCRM. The wq-cospectra (bottom) show maxima over a broad range of scales in the lower layer and then peak at a few tens of kilometer scales in most of the deep cloud layer. This indicates that a significant portion of the vertical transport of moisture (and also heat and momentum, which are not shown here) is carried by motions smaller than the effective resolution of a typical GCRM.

3 *A priori* test of a mixed SGS scheme

Using the benchmark simulation, we split the flow field u_i into filter-scale (FS, $\tilde{u_i}$) and subfilter-scale (SFS, u_i') components, where the FS component is regarded as a surrogate for the GCRM-resolvable field and the SFS component as the GCRM-SGS field. We then performed *a priori* test of the following mixed SGS model, where the SGS flux of a variable c (where c represents heat, moisture or momentum) is expressed as:

$$\tau_{u_i c} = -K_h \frac{\partial \tilde{c}}{\partial x_i} + 2\left(\frac{\Delta_f^2}{12}\right)\left[\frac{\partial \tilde{u_i}}{\partial x}\frac{\partial \tilde{c}}{\partial x} + \frac{\partial \tilde{u_i}}{\partial y}\frac{\partial \tilde{c}}{\partial y}\right], \qquad (1)$$

*NCAR is sponsored by the National Science Foundation

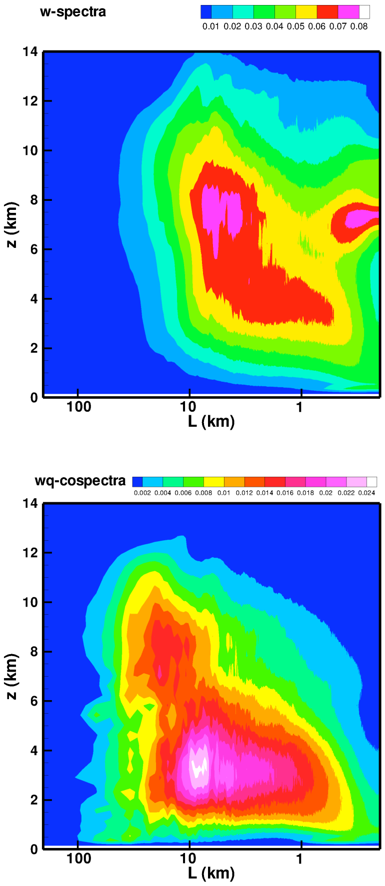

Figure 1: Vertical distributions of (top) the w spectra and (bottom) the $w-q$ cospectra from the Giga-LES.

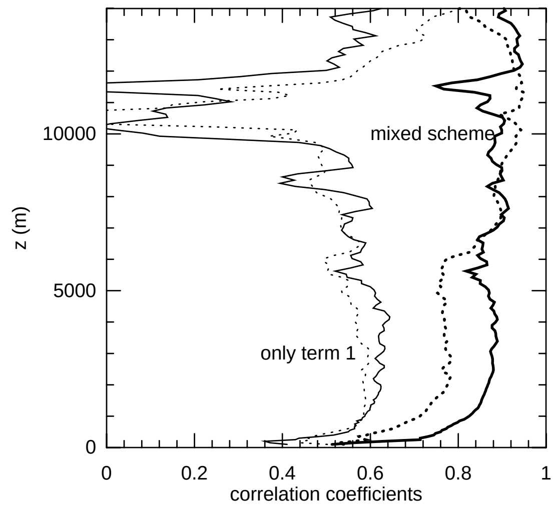

Figure 2: Correlation coefficients between the modeled and the LES-retrieved τ_{wq} with Δ_f= 4 km (solid curves) and 10 km (dotted curved).

The first term is the usual K-model commonly used in cloud-resolving models and the second term represents the effect from the largest SGS eddies, which are on the order of filter width or GCRM grid resolution (for derivation of the equation, see Moeng et al. 2010). The SFS fluxes retrieved from the Giga-LES are used as "truth" to evaluate the modeled fluxes estimated from Eq. 1. Figure 2 shows the spatial (point-by-point) correlations between the modeled and the LES-retrieved SFS fluxes (showing the vertical flux of moisture as an example) for two filter widths. The inclusion of the second term greatly enhances the correlation coefficients from about 0.6 to about 0.9 throughout most of the deep cloud layer. We also tested the mixed scheme for heat and momentum fluxes and found significant improvements in estimating these SGS fluxes, particularly the horizontal fluxes of scalars.

References

Khairoutdinov, M.F., S.K. Krueger, C.-H. Moeng, P.A. Bogenschutz, and D.A. Randall, 2009: Large-eddy simulation of maritime deep tropical convection, *J. Adv. Model. Earth Syst.*, **1**, 13pp.

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