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Multiscale eddy simulation for moist atmospheric convection: Preliminary investigation

Samuel N. Stechmann [a,b]

[a] Department of Mathematics, University of Wisconsin-Madison, USA
[b] Department of Atmospheric and Oceanic Sciences, University of Wisconsin-Madison, USA

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ABSTRACT

A multiscale computational framework is designed for simulating atmospheric convection and clouds. In this multiscale framework, large eddy simulation (LES) is used to model the coarse scales of 100 m and larger, and a stochastic, one-dimensional turbulence (ODT) model is used to represent the fine scales of 100 m and smaller. Coupled and evolving together, these two components provide a multiscale eddy simulation (MES). Through its fine-scale turbulence and moist thermodynamics, MES allows coarse grid cells to be partially cloudy and to encompass cloudy–clear air mixing on scales down to 1 m; in contrast, in typical LES such fine-scale processes are not represented or are parameterized using bulk deterministic closures. To illustrate MES and investigate its multiscale dynamics, a shallow cumulus cloud field is simulated. The fine-scale variability is seen to take a plausible form, with partially cloudy grid cells prominent near cloud edges and cloud top. From earlier theoretical work, this mixing of cloudy and clear air is believed to have an important impact on buoyancy. However, contrary to expectations based on earlier theoretical studies, the mean statistics of the bulk cloud field are essentially the same in MES and LES; possible reasons for this are discussed, including possible limitations in the present formulation of MES. One difference between LES and MES is seen in the coarse-scale turbulent kinetic energy, which appears to grow slowly in time due to incoherent stochastic fluctuations in the buoyancy. This and other considerations suggest the need for some type of spatial and/or temporal filtering to attenuate undersampling of the stochastic fine-scale processes.

1. Introduction

Models of atmospheric dynamics must focus on a limited range of scales and physics, due to limited computational resources. For example, simulations of cloud systems of $O(100)$ *kilometers* must use grid spacings of $O(100)$ *meters* [1–3]. With such grid spacings, a great deal of subgrid-scale processes must be represented in some way. Subgrid-scale turbulence is typically represented via a large eddy simulation (LES) framework, and other key ingredients are thermodynamics and cloud microphysics involving subgrid-scale water substance: vapor, liquid droplets, phase changes, droplet collision/coalescence, etc. [4–6].

E-mail address: stechmann@wisc.edu.
URL: http://www.math.wisc.edu/~stechmann/.

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In models of subgrid-scale cloud processes, traditional approaches are computationally inexpensive but physically unsatisfying—if not inadequate—in several ways. First, as one example, a grid cell must be either entirely saturated or entirely unsaturated. It has long been realized that this is unrealistic for grid spacings of $O(100)$ m [7,8]. While some interesting work has been proposed to mitigate this issue [9,10], no method has yet been generally accepted. Second, as another example, subgrid-scale turbulence typically interacts very weakly—if at all—with subgrid-scale thermodynamics and cloud microphysics. A great deal of work has examined the effect of turbulence on droplet collisions [11–13] and the thermodynamic impact of turbulent mixing of cloudy and clear air [14–17]; and these effects are being incorporated into some interesting new subgrid-scale parameterizations [18–20]. In short, as illustrated by these examples, the intermingling of different processes on different scales has received increasing attention, and it is becoming apparent that new theoretical and computational tools are needed [21,22].

The main purpose of this paper is to investigate a multiscale modeling approach to cloud dynamics. Instead of the typical "grid scales" and "subgrid-scales", the multiscale framework involves a "coarse-scale" grid, a "fine-scale" grid, and two models: on the coarse scales of >100 m is an LES model, and on the fine scales of <100 m is a stochastic, one-dimensional turbulence (ODT) model [23–27]. Coupled and evolving together, these two components form a multiscale eddy simulation (MES).

A key goal of the multiscale approach is to include more realistic fine-scale behavior—in particular, to allow fine-scale regions of cloudy and cloud-free air to mix turbulently. Previous works [28–30] have shown the importance of the finite time scales of such mixing—as opposed to slow mixing or instantaneous mixing scenarios—and some studies [15–17,31] investigated such mixing with a predecessor of the ODT model. If the fine-scale mixing and its thermodynamic impact are represented more realistically, it is expected that, in turn, the coarse-scale behavior will be more realistic as well.

Multiscale modeling has been a successful approach in many related scientific areas. Problems such as turbulent combustion involve multiscale phenomena with chemical reactions interacting with turbulent fluid dynamics [32], which are similar to the issues of phase changes and droplets in cloud dynamics. In fact, LES and ODT have been used in both combustion and atmospheric science [26,33,34] and models that combine LES and ODT dynamics have been proposed previously for combustion [35] and for general turbulent flows [36,37]. The multiscale framework of the present paper is different from these previous approaches and is similar in spirit to the "superparameterization" approach that has been used for much larger scales of atmospheric dynamics [38–42]. On the fine scales, a 1D or 2D reduced-dimensional model is used, and it uses periodic boundary conditions within each coarse cell. This configuration simplifies the multiscale coupling and is well-suited for massively parallel computations in an "embarrassingly parallel" setup. It may also be a useful framework for other scientific areas with similar challenges, such as turbulent combustion, ocean dynamics [43,44], or bubbles in the ocean [45].

Besides multiscale computational models, multiscale asymptotic models have also been useful for elucidating interactions between different scales. In atmospheric science, many such models have been investigated for elucidating interactions between clouds, their environment, and the larger-scale circulation [46,47]. In particular, those most related to the present investigation are [48] and [49], which investigate boundary layer clouds—stratocumulus and shallow cumulus clouds, respectively.

Among the various cloud regimes that could be modeled with the multiscale framework, the particular focus of the present paper is shallow cumulus clouds. These clouds are "shallow" as opposed to "deep" in the sense that they extend vertically only a few kilometers above the Earth's surface [50]. Moreover, they are somewhat simple in the sense that they do not involve ice and they often do not rain; nevertheless, they still involve the challenges of turbulent mixing and vapor–liquid phase changes over a large range of scales, which makes them well-suited as a test case for MES.

From a broader perspective, the multiscale framework is ultimately aimed at enhancing our understanding of clouds and their role in the climate system [51,52]. In this capacity, clouds play an important role in both the Earth's radiation budget and hydrological cycle. A remarkable range of scales is involved: microscale aerosols and liquid droplets affect macroscale cloud properties such as size, lifetime, propensity to rain, and ability to scatter or absorb electromagnetic radiation [22,53–56]. Further complicating matters, all of these microscale and macroscale processes are intricately linked with turbulent mixing. While this complicated setting is the ultimate motivation, here we use a simplified setup that neglects intricate radiation, aerosol, and precipitation effects and instead focuses on the pervasive turbulent mixing that make these effects so perplexing. Furthermore, the turbulent mixing of ODT is used here for its effect on buoyancy alone, and not for use as a stochastic model of fine-scale turbulent fluxes. Instead, a Smagorinsky closure is retained for modeling the effect of "subgrid-scale" turbulent fluxes on the coarse-scale flow field. In principle, ODT could be used for this purpose in place of the Smagorinsky model, but a preliminary investigation presented formidable challenges in this direction, and we leave this as an interesting direction to pursue further in the near future. In short, the ODT model will be used here to investigate only the impact of fine-scale mixing on the buoyancy in non-precipitating clouds.

The paper is organized as follows. In Section 2, the multiscale model is described, including both the LES and ODT components and their coupling to form the MES. In Section 3, a one-way coupled version of MES is examined in which the coarse LES model affects the fine ODT model but not vice versa; this configuration provides a simplified view of the fine-scale dynamics, and it allows a comparison of coarse and fine scales on a cell-by-cell basis. Then, in Section 4, the full MES model is investigated where two-way coupling is allowed between coarse and fine scales; and MES statistics are compared with LES. Finally, in Section 5, conclusions are summarized and future directions are discussed.

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