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Multiscale modeling of the moist-convective atmosphere — A review

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A B S T R A C T

Multiscale modeling of the moist-convective atmosphere is reviewed with an emphasis on the recently proposed approaches of unified parameterization and Quasi-3D (Q3D) Multiscale Modeling Framework (MMF). The cumulus parameterization problem, which was introduced to represent the multiscale effects of moist convection, has been one of the central issues in atmospheric modeling. After a review of the history of cumulus parameterization, it is pointed out that currently there are two families of atmospheric models with quite different formulations of model physics, one represented by the general circulation models (GCMs) and the other by the cloud-resolving models (CRMs). Ideally, these two families of models should be unified so that a continuous transition of model physics from one kind to the other takes place as the resolution changes. This paper discusses two possible routes to achieve the unification. ROUTE I unifies the cumulus parameterization in conventional GCMs and the cloud microphysics parameterization in CRMs. A key to construct such a unified parameterization is to reformulate the vertical eddy transport due to subgrid-scale moist convection in such a way that it vanishes when the resolution is sufficiently high. A preliminary design of the unified parameterization is presented with supporting evidence for its validity. ROUTE II for the unification follows the MMF approach based on a coupled GCM/CRM, originally known as the "super-parameterization". The Q3D MMF is an attempt to broaden the applicability of the super-parameterization without necessarily using a fully three-dimensional CRM. This is accomplished using a network of cloud-resolving grids with gaps. The basic Q3D algorithm and highlights of preliminary results are reviewed. It is suggested that the hierarchy of future global models should form a "Multiscale Modeling Network (MMN)", which combines these two routes. With this network, the horizontal resolution of the dynamics core and that of the physical processes can be individually and freely chosen without changing the formulation of model physics. Development of such a network will represent a new phase of the history of numerical modeling of the atmosphere that can be characterized by the keyword "unification".

Contents

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1. Introduction

As illustrated in Fig. 1, clouds and their associated physical processes strongly influence the atmosphere in the following ways (Arakawa, 1975):

- By coupling dynamical and hydrological processes in the atmosphere through the heat of condensation and evaporation and through redistributions of sensible and latent heat and momentum;
- By coupling radiative and dynamical-hydrological processes in the atmosphere through the reflection, absorption, and emission of radiation;
- By influencing hydrological processes in the ground through precipitation; and
- By influencing the couplings between the atmosphere and oceans (or ground) through modifications of radiation and planetary boundary layer (PBL) processes.

It is important to note that most of these interactions are two-way interactions. For example, the amount of latent heat release through condensation is strongly coupled with the motion so that the heat of condensation is a result of the motion as well as a cause of the motion. Thus, although the release of latent heat is a dominant component of the atmosphere's sensible heat budget, it is not correct to say that the atmospheric motions are “forced” by the heat of condensation (see Emanuel et al., 1994). Similar situations exist for all of the two-way interactions shown in Fig. 1.

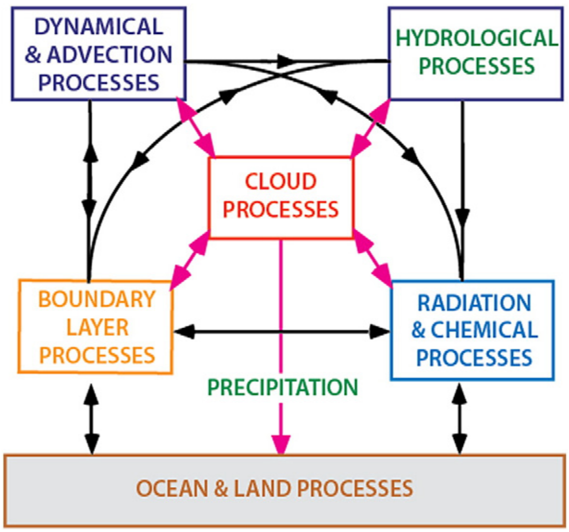

Fig. 1. Interactions between various processes in the climate system. Taken from Arakawa (2004), his Fig. 1.

Convectively active clouds play the central roles in these interactions and the problem of cumulus parameterization has always been at the core of our effort to improve numerical modeling of the atmosphere. In spite of the accumulated experience over the past decades, however, our progress in this aspect of atmospheric modeling has been especially slow (Randall et al., 2003). Besides the basic question of how to pose the problem, there are a number of uncertainties in modeling moist-convective processes as reviewed by Arakawa (2004). Even more seriously, we have not established a sufficiently general framework for representing the multiscale effects of moist-convective processes. Before the satellite age, we used to see the atmosphere through weather charts. Now we can also see the atmosphere via satellites as in the example shown in Fig. 2. Here we see lots of details as well as large-scale features. This by itself gives us the feeling that atmospheric modeling must inevitably be multiscale modeling.

In numerical modeling, we have to truncate the continuous system somewhere in the spectrum. This artificially separates the spectrum into the resolved scales, for which the local and instantaneous effects are simulated, and the unresolved scales, for which only the statistical effects can be considered through parameterization. Numerical models typically treat these two scales as separate modules as shown in Fig. 3. For the two-way interactions to take place between these modules, the loop in the figure must be closed requiring closure assumptions.

Fig. 2. An example of satellite cloud images showing clusters of clouds. Taken from http://goes.gsfc.nasa.gov/pub/goes/color_goes11d1.jpg.