# DEVELOPMENT OF A UNIFIED AND FLEXIBLE FRAMEWORK FOR ATMOSPHERIC MODELS

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## I. Introduction

In addition to a number of uncertainties in formulating individual processes, there are fundamental problems in conventional models of the atmosphere: *artificial separation of processes* and *artificial separation of scales* (Arakawa 2004). Due to the existence of these problems, the link between local weather and global climate is poorly represented in conventional models. The purpose of this paper is to point out that now time is ripe to seek a unified and flexible modeling framework that can represent the link more closely. The framework must be based on nonhydrostatic equations, with explicit formulations of cloud-scale processes and a good control of systematic errors. Development of such a framework represents a new pathway of atmospheric modeling,

## 2. Artificial separation of processes

As the solid lines in Fig. 1 show, climate and NWP models have a modular structure, in which different physical processes interact only through dynamics core (and surface conditions). Consequently, most of the direct interactions shown by the dashed lines, which involve small scales, are missing.

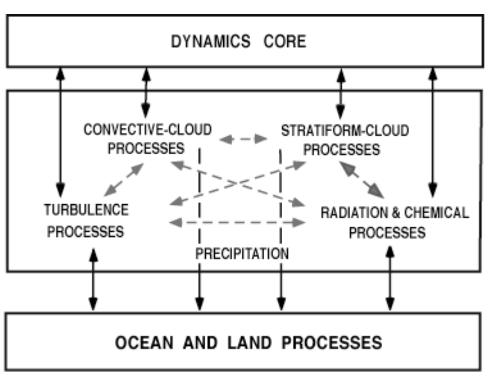


Figure 1

*Example 1: Cloud-radiation interactions*

The importance of the effect of fractional cloudiness on radiation is well recognized, although usually only its collective effect is considered. The importance of the feedback of radiation on fractional cloudiness, on the other hand, is not well recognized.

*Example 2: Cloud-turbulence interactions*

The effect of cumulform clouds on boundary-layer turbulence is usually neglected and the effect of horizontal inhomogeneities in the boundary layer on cumuliform clouds is almost always ignored. Examples of these interactions simulated by a cloud-resolving model will be presented at the Workshop.

## 3. Artificial separation of scales

In a discrete model, truncation introduced for computational purpose artificially separates the spectrum of atmospheric processes into *resolved processes*, for which local and instantaneous effects are explicitly formulated, and *unresolved processes*, for which only their statistical effects are considered through parameterization. This separation is nothing to do with the existence or nonexistence of a spectral gap in nature. Figure 2 illustrates the spectrum of atmospheric processes and three families of models currently being used: General Circulation Models (GCMs) including conventional NWP models, Cloud-Resolving Models (CRMs), and Large-Eddy Simulation (LES) models.

These families of models have been developed with different objectives, by people with different expertise, and tuned for different ranges of the atmospheric spectrum. At present, the gaps between these families represent fundamental obstacles in further development and broader applications of atmospheric models. Especially when coupled with oceanic GCMs, climate simulations are quite sensitive to uncertainties in the formulation of cloud and associated processes. Moreover, the use of a physically more justifiable formulation of those processes does not necessarily improve overall results unless other parts of the model are retuned. Optimum tuning, however, is usually model-dependent and, therefore, experience at a particular modeling center is not necessarily shared by other centers.

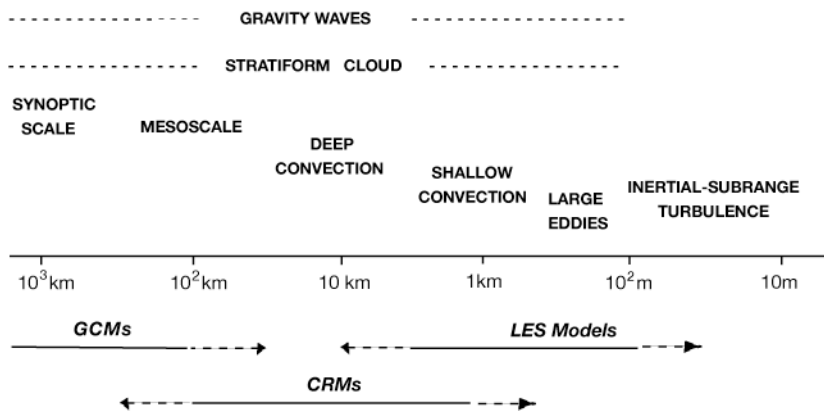


Figure 2

## 4. Problems in downscaling

The target we are aiming at is a unified and flexible framework for atmospheric models. One may wish to approach this target by downscaling GCMs. Obviously, the dynamics must eventually be switched to the nonhydrostatic system. This is analogous to the switching from quasi-geostrophiic models to primitive-equation models, which occurred in 1960s. The merits of this switch include

- Computational convenience in including those effects that are usually omitted in quasi-static models;
- Relaxing hydrostatic adjustment;
- Correct prediction of the vertical structure and vertical propagation of small-scale gravity waves.
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- After all, it is necessary for a unified framework.

Application of a nonhydrostatic model to quasi-static motions requires ability to simulate hydrostatic adjustment, which takes place through vertical dispersion of sound waves by buoyancy, as geostrophic adjustment takes place through horizontal dispersion of gravity waves by rotation. Then, to have a good dispersion property in the vertical, the choice of vertical grid is important, as the choice of horizontal grid is important for geostrophic adjustment. For the z-coordinate, a vertical grid similar to the Charney-Phillips grid for the quasi-static models has the best dispersion property (Thuburn and Woodlings 2004).

Downscaling of GCMs has much more serious problems in model physics. Justification for using a discrete model relies on the hope that its solution converges to the solution of the original system as the resolution is refined. The convergence problem for atmospheric models is, however, quite different from the standard convergence problem in numerical analysis: in our problem, *the governing equation is modified rather than approximated* through the use of parameterizations. As Jung and Arakawa (2004) and Arakawa (2004) emphasized, sources required for correct prediction of averaged fields are not averages of the local and instantaneous real sources. This is because the averaged effects of all other processes induced by the real source must also be included in the required sources. These effects are highly scale-dependent in the mesoscale range. Existing cumulus parameterizations fail to reproduce such scale dependency.

## 5. Development of a multi-scale modeling framework (MMF)

Inclusion of the scale dependence of required sources in the conventional framework of cumulus parameterization is an extremely challenging task. Improvement of weather and climate prediction models, however, cannot be delayed until all of the scientific problems are solved. In the mean time, computer technology is rapidly advancing. Taking together, now time is ripe to seek a unified and flexible framework that can provide a closer link between local weather and global climate. We call such a framework Multi-Scale Modeling Framework (MMF), which is in spirit an extension of the super-parameterization approach (Grabowski 2001, Khairoutdinov and Randall 2001, Randal et al. 2003). Our requirement for the MMF is two-fold: *unified*, which requires that the model physics be essentially the same for all options, and *flexible*, which requires that it can be run either in a global CRM mode or in less-expensive modes for practical applications. The merits of such a framework is (1) convergence to a global 3D CRM is guaranteed, and

(2) currently over-spread modeling efforts can be unified along the line of improving CRMs.

The key to the success of the MMF approach crucially depends on how we can generate less-expensive versions of CRMs while using essentially the same model physics. Feasibility of running a limited number of experiments with a very expensive global CRM can hardly be called "success" by itself. In our field, there are a number of issues to be studied with numerical models of the atmosphere, from day to day changes of local weather to century to century global change, requiring long-term integrations or many integrations under different initial/boundary conditions with different model parameters and different model configurations.

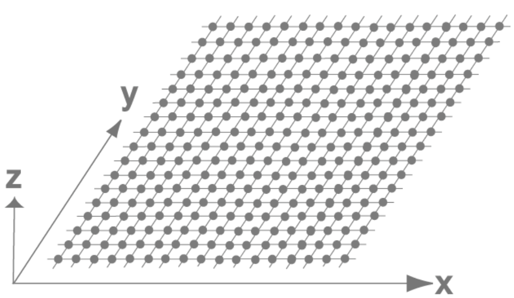


Figure 3a

The standard way of generating less expensive versions of a numerical model is through the use of a larger grid size. In the case of CRMs, however, the use of a grid size larger than, say, a few kilometers means that the cloud-scale resolution is completely lost and, therefore, inclusion of a cloud parameterization is a necessity. In this case, mathematical and physical errors are mixed. Figures 3a and 3b illustrate grid points in the original CRM and its low-resolution version, respectively.

If we wish to stay with essentially the same model physics, we have no other choice than using essentially the same grid size at least locally. If grid points fill the entire space more or less uniformly, we have a global CRM. A less-expensive version then means the use of a network in which grid points only partially fill the space. The distribution of grid points can be quasi-random or systematic as shown in Fig. 3c. Here the same (3D) prognostic algorithm is applied to all grid points shown by the dark dots. Values at neighboring points shown by the gray dots necessary for advection calculation can be determined by a combined regression-interpolation technique. In this approach, the error is a mixture of mathematical and sampling errors, which can be made arbitrarily small by using a denser distribution of grid points. There are several ways of systematically increasing the number of grid points. Figure 3d shows an example.

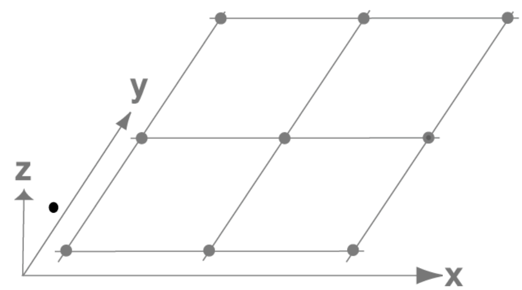


Figure 3b

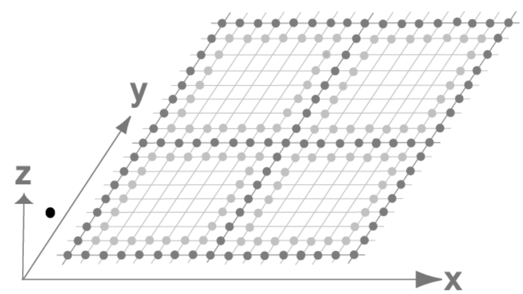


Figure 3c

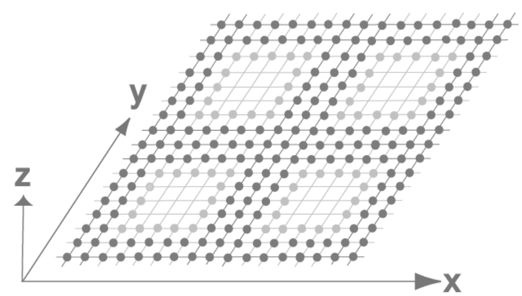


Figure 3d

If we have a less-expensive version of a global 3D CRM, in principle it can replace GCMs entirely. It is better, however, to use it as a replacement for parameterizations in GCMs, by constructing a coupled GCM-CRM system as illustrated in Fig. 3e. (Here heavy lines represent walls of GCM grid boxes.) This is because GCMs have more uniform and more isotropic grid-point distributions for large-scale flow, and using a network with a relatively small number of CRM grid points per each GCM box can be justified only when it is used to provide a statistical sample of small-scale events within the box. Also, compatibility with GCMs with conventional parameterizations can be maintained in this way.

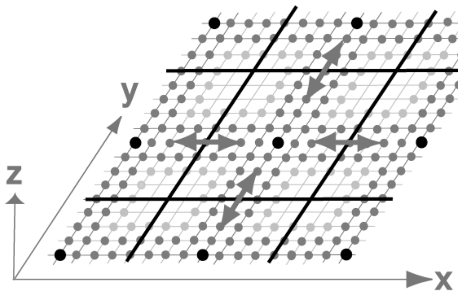


Figure 3e

## 6. Conclusion

It is possible to construct a multi-scale modeling framework (MMF) for future climate models, which has the following merits:

1) Convergence to a global 3D CRM without changing model physics;

2) Unification of modeling efforts along the line of improving CRMs;

3) Verifications possible for two ranges of the spectrum: GCM results against large-scale observations and CRM results against small-scale observations.

Development of such a framework represents a new era in the history of numerical modeling of the atmosphere, called by Arakawa (2000) Third Phase. Fist and Second Phases are characterized by *simplification* and *diversification*, respectively, while Third Phase would be characterized by *unification* (see Fig.4).

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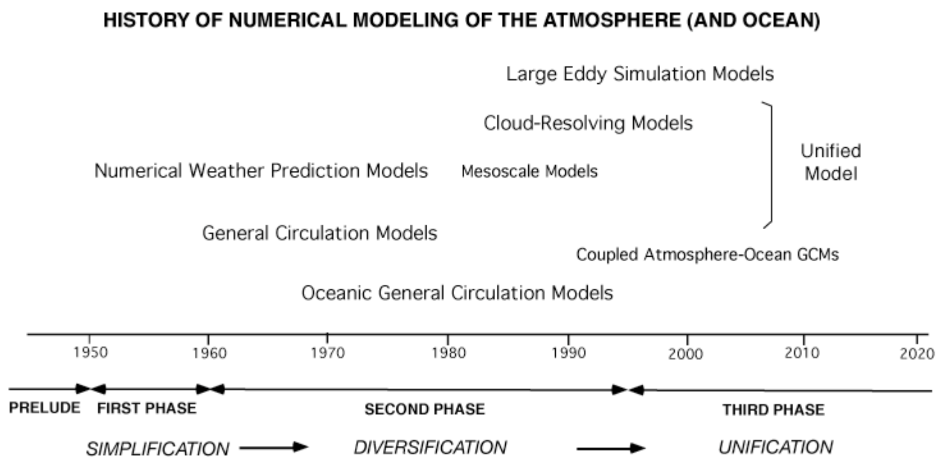


Figure 4

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