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Title: Development of the First Nonhydrostatic Nested-Grid Grid-Point Global Atmospheric Modeling System on Parallel Machines

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Development of the First Nonhydrostatic Nested-Grid Grid-Point Global Atmospheric Modeling System on Parallel Machines

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Abstract

This is the final report of a three-year, Laboratory Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). Evaluating the importance of global and regional climate response to increasing atmospheric concentrations of greenhouse gases requires a comprehensive global atmospheric modeling system (GAMS) capable of simulations over a wide range of atmospheric circulations, from complex terrain to continental scales, on high-performance computers. Unfortunately, all of the existing global circulation models (GCMs) do not meet this requirement, because they suffer from one or more of the following three shortcomings: (1) use of the hydrostatic approximation, which makes the models potentially ill-posed; (2) lack of a nested-grid (or multi-grid) capability, which makes it difficult to consistently evaluate the regional climate response to the global warming, and (3) spherical spectral (opposed to grid-point finite-difference) representation of model variables, which hinders model performance for parallel machine applications. The end product of our research is a highly modularized, multi-grided, self-calibratable (for further parameterization development) global modeling system with state-of-the-science physics and chemistry. This system will be suitable for a suite of atmospheric problems: from local circulations to climate, from thunderstorms to global cloud radiative forcing, from urban pollution to global greenhouse trace gases, and from the guiding of field experiments to coupling with ocean models. It will also provide a unique testbed for high-performance computing architecture.

Background and Research Objectives

In order to estimate potential environmental impacts of global change on hydrology, agriculture, and other societal resources, we need climate model results on the scale, at least, of watersheds (i.e., tens of kilometers). This requires a significant jump in climate simulations from their current horizontal resolution of hundreds of kilometers. This also requires a gain in computational capabilities of 10^2 to 10^3. Furthermore, there is an often-overlooked factor that makes the situation even more problematic. That is, as we translate those resolutions mentioned above into commonly used spherical coordinates in global climate models (GCMs), we have to move from current 5° latitude by 5° longitude

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resolution to 0.5° by 0.5° resolution. The latter requires very small Courant numbers because of small circumferences in the polar regions. In the extreme, the longitudinal grid size is about 500 m at 89.5° N or S. With upper air wind speeds of tens of m/s, a time-step on the order of 10 seconds (versus current 10^3 seconds) is required for the model integration. This increases the necessary gain in computational capabilities to 10^4 to 10^5, a number, which does not include the requirement for better physics in a fine-resolution model.

To circumvent this problem, we should not just rely on the increasing capabilities of new computer architectures since they can easily be consumed by increasingly improved model physics alone. Instead, we need to have a comprehensive and consistent multi-grid capabilities in a spherical-coordinate grid-point GCM. So, the nested-grids can be placed over any areas of interest, particularly the continental landmasses, at comparatively high horizontal resolutions, say, tens of kilometers, for detailed regional climate simulations. In addition, the limited-area domain can be further nested for the computations up to very high (1 km by 1 km) horizontal resolution. Meanwhile, the grid-point GCM itself can retain a modest horizontal resolution, say, 2.5° by 2.5° that is sufficient enough over the relatively homogeneous oceans and for communication with the fine-resolution limited areas. The nested-grid capabilities will be based on a two-way interface technique, which is essential to allow small-scale disturbances to feed back into large-scale circulations. This is extremely important for rough terrain regions such as the western United States.

In contrast to many existing "spectral" GCMs, including the current Los Alamos GCM, our global atmospheric modeling system (GAMS) is a spherical-coordinate "grid-point" GCM, which is superior because it can more realistically retain topographically and diabatically induced wave motions. In fact, the spectral GCMs tend to smooth out local forcings through Fourier harmonic operations, which is not desirable for the proposed two-way interface. Furthermore, because all the grids used in the models are logically connected three-dimensional meshes, they are well suited for the communication characteristics of parallel machines such as the Cray T3D or T3E and the SGI Blue Machines at LANL. The computation algorithm in GAMS is based on "nearest-neighbor" grid communication. In contrast, the use of spectral techniques, as mentioned previously, to represent horizontal transport does create the need for communications beyond nearest neighbors; in this case to all grid points.

Importance to LANL's Science and Technology Base and National R&D Needs

This research falls into the Laboratory's core competency of *Earth and Environmental Systems*, which states "The focus should be on approaches that integrate the Laboratory's broad knowledge base, experience, and skills to predict the behavior of earth and environmental system processes, especially where this leads to a quantitative understanding of how positive or negative human actions affect the system processes." Our project research is designed particularly for a better quantitative understanding of climate and environmental changes.

This GAMS capability will also be valuable to U.S. companies in understanding their interaction with the environment. It is clear that from recent collaborative research and development activity that partnerships with the national laboratories are vital to the "greening" of industry. Cray Supercomputers and Thinking Machines Companies are currently establishing ties with LANL to study global models on their massively parallel processors.

Scientific Approach and Accomplishments

The regional atmospheric modeling system (RAMS) limited-area model is a highly flexible modeling system, capable of simulating a wide variety of regional-scale phenomena (Pielke, et al., 1992). The model framework for our study incorporates a three-dimensional, terrain-following, nonhydrostatic version of the code. The simulation includes topography derived from a 5-minute global data set with a silhouette-averaging scheme that preserves realistic topography heights. Nonhydrostatic equations are used so that nested grids capable of resolving cloud-scale phenomena can eventually be implemented. At the surface, temperature and moisture fluxes are determined from the surface energy balance, which includes both short- and long-wave fluxes, latent and sensible fluxes, and subsurface heat and moisture conduction from a soil model. A microphysical parameterization describes the physical processes leading to the formation and growth of precipitation particles within model generated clouds. It is intended that the rain and snowfields derived from this parameterization will be coupled to a detailed surface hydrology model.

We have carefully chosen a global advection operator for the GAMS model. The operator will not only compute the advection of variables in the three dimensions, but also avoid the numerical problems associated with the Courant number (e.g., Kao et al., 1992 a and b) due to the geographical poles. The model has two options: the joining domain method and the reduced grid method. The former is numerically straightforward and couples two or more subdomains of the globe together. Each subdomain is represented by a transformed Cartesian grid so that uniform grid size can be used near the pole regions. The simplest example would be to join two hemispheric domains, each one represented by a separate polar stereographic transformation. The two domains would exchange information at the lateral boundaries (along the equator) by appropriate spatial interpolation to common locations. A slightly more complicated example would be to divide the Earth domain into more equal parts, say, 6. But, the smaller size of each domain would keep distortion due to map transformation at a smaller rate. The reduced grid method is based upon the spherical coordinate system with less grid points near the poles. A variety of methods for constructing the reduced grids are possible. We have extensively experimented with the simplest one, which merges cells of the regular mesh so that the nodes of the reduced grid retain their original locations.

In addition to the implementation of one of the above global operators into RAMS, we also added the stratosphere and its associated physics to the model. We have incorporated a radiative transfer routine that can be used for the stratospheric thermal structure and trace gas constituents. The gravity wave drag associated with the high stability in the lower stratosphere is also incorporated. The lower boundary conditions in terms of sea surface temperature, orography, and vegetation data have been compiled. The intrinsic difference between the hydrostatic and nonhydrostatic global models has been studied as a first attempt. The nested grid capabilities and their interface with larger-scale domains will be thoroughly tested in future studies. Finally, we have successfully ported the code to a Cray T3E parallel machine at NERSC.

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