Development of an Atmospheric Climate Model with Self-Adapting Grid and Physics

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Abstract.

This project was targeting the development of a computational approach that would allow resolving cloud processes on small-scales within the framework of the most recent version of the NASA/NCAR Finite-Volume Community Atmospheric Model (FVCAM). The FVCAM is based on the multidimensional Flux-Form Semi-Lagrangian (FFSL) dynamical core and uses a "vertically Lagrangian" finite-volume (FV) representation of the model equations with a mass-conserving re-mapping algorithm. The Lagrangian coordinate requires a remapping of the Lagrangian volume back to Eulerian coordinates to restore the original resolution and keep the mesh from developing distortions such as layers with overlapping interfaces.

The main objectives of the project were, first, to develop the 3D library which allows refinement and coarsening of the model domain in spherical coordinates, and second, to develop a non-hydrostatic code for calculation of the model variables within the refined areas that could be seamlessly incorporated with the hydrostatic finite volume dynamical core when higher resolution is wanted.

We also updated the aerosol simulation model in CAM in order to ready the model for the treatment of aerosol/cloud interactions.

1. Introduction

Cloud formation and aerosol-cloud interactions are small-scale processes that occur under non-hydrostatic, compressible conditions. Resolving the small-scale processes of cloud drop nucleation and non-hydrostatic convectively unstable advection throughout the global domain is computationally challenging and would require much finer grid resolution than is currently feasible. This motivates the development of new approaches to both reduce computational costs and achieve the desired accuracy.

In our work, we were targeting the development of a computational approach that would allow resolving cloud processes on small-scales within the framework of the most recent version of the NASA/NCAR Finite-Volume Community Atmospheric Model (FVCAM). The FVCAM is based on the multidimensional Flux-Form Semi-Lagrangian (FFSL) dynamical core and uses a "vertically Lagrangian" finite-volume (FV) representation of the model equations with a mass-conserving re-mapping algorithm. The Lagrangian coordinate requires a remapping of the Lagrangian volume back to Eulerian coordinates to restore the original resolution and keep the mesh from developing distortions such as layers with overlapping interfaces.

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The methods we developed in this project make use of techniques developed for adaptation of grid resolution to solve the equations of motion on a sphere for both hydrostatic and non-hydrostatic configurations. We developed algorithms for merging the hydrostatic and non-hydrostatic flows that need to be resolved when these two domains are joined. Our primary aim during this last year of our project is to couple the non-hydrostatic dynamical core to the hydrostatic dynamical core in CAM, to test and demonstrate the use of grid adaptation in the coupled model, and to write up the results for publication. We also obtained supplemental funding to complete several topics related to updating our aerosol model (and ice interactions of this model).

2. Adaptive Mesh Library (ABLCarT)

The need for accuracy and stability of the numerical calculations and for resolving small atmospheric phenomena like convection and clouds brings the interesting computer and atmospheric science problem of calculating vertical integrals over a distributed refined grid. To do this in an adaptive grid, the method needs to calculate the integrals across blocks distributed across multiple processors and between blocks with different refinement levels. This calculation also has to take into account the dependencies resulting from more refined neighbors. We call the process of calculating the vertical integral "directional scanning". We completed implementation of a "scanning" communication between computational blocks of the same and different sizes. We tested this new functionality of the ABLCarT library on a vertical advection problem, which evaluated the performance of the model with adaptation and for different fixed resolutions.

We used two pure advection tests with prescribed horizontal and vertical winds (Zubov et al. 1999, and Nair and Lauritzen, 2010) which tests the correctness of communication of all of the model's variables between the blocks as well as the accuracy of the adaptive method. The tests are also used to make sure that the interpolation subroutines that are "wired" into the model for the Lagrangian transport algorithm are not distorted during the adaptation. One of the important and very favorable aspects of the adaptive model simulation is that accuracy comparable to the static high resolution run can be obtained in less than half the computer time. Furthermore, depending on the specific problem, adaptation could potentially reduce the overall computer time by even more, e.g. if the problem required even higher levels of refinement.

3. Development of Lagrangian model nonhydrostatic dynamical core

In Chen et al. (2012), we present results from a non-hydrostatic extension for the Lin-Rood dynamical core (Lin and Rood 1996, Lin and Rood 1997, Lin 2004) using a generalized Lagrangian vertical coordinate. The multidimensional Flux-Form Semi-Lagrangian (FFSL) Lin-Rood dynamical core simulates the conservative, monotonic advection for prognostic variables, and uses a “vertically Lagrangian” finite-volume (FV) representation of the model equations with a mass conserving re-mapping algorithm. The Lagrangian coordinate requires a remapping to restore the original resolution and keep the mesh from developing distortions such as layers with overlapping interfaces. The horizontal numerical algorithm of the Lin-Rood dynamical core is based on the C-D grid. This FFSL FV algorithm has been adopted in several atmospheric transport models (e.g., CAM, GFDL). We use an unstaggered grid and build the method so it does not require any filtering of the acoustic waves. We test the method based on both an Eulerian and a Lagrangian formulation, using the 2-D warm bubble tests of Robert (1993) as well as his warm and cold interacting bubble test. We also test whether the results of this model can be merged with solutions in a pure hydrostatic version of the model using the Skamarock and Klemp (1994) gravity wave test.

4. Non-Hydrostatic Model.

Our model equations are the fully compressible FV Euler conservation equations in the flux form with a vertical Lagrangian coordinate with the model layers being material impenetrable surfaces and the bottom layer following the surface terrain. In our numerical representation of the model equations, we use an unstaggered grid. We use a 5-point interpolation scheme to calculate all grid cell interface values of each control volume, and we calculate the fluxes at the interfaces by solving the Riemann problem in both the horizontal and vertical directions. We developed a Light-Weighted Approximate Riemann Solver (LWARS) to use in both the horizontal and vertical directions. We show that the LWARS saves considerable computational time (up to 30%) in comparison with the Advection Upstream Splitting Method (AUSM^{+}-up) (Liou et al., 2006, Ullrich et al., 2010), but retains its accuracy.

5. Significance

In order to advance climate models through the improvement of convection and the representation of clouds and cloud/aerosol interactions, new numerical approaches are needed that lead to stable and accurate numerical solutions across regions with different physics and non-uniform grids. Adaptive methods offer an attractive framework for developing these solutions and to resolve features of interest more adequately. The key to the success of adaptive grid methods in meteorology lies in their parallel performance on high-speed supercomputers. We developed the LMARS algorithm, which is the best in its class in achieving ultra-low diffusivity and scalability and it offers an "out of box" conservational law, coupling non-hydrostatic dynamics with hydrostatic dynamics. The a-gridding system makes it the most elegant numerical scheme in its class.

6. Improvements to aerosol modeling and cloud interactions

We completed simulations of our hybrid-dynamical nitrate aerosol model coupled to our 2-mode sulfate dynamical aerosol model (with other aerosol types), in which the aerosols are not treated as fully internally mixed (the current CAM5 model treats all aerosol as internally mixed, in each size bin, and treats does not treat nitrate and ammonium) (Xu, dissertation, 2011). We also completed a set of simulations to examine the forcing by nitrate and ammonium aerosols and submitted a paper (Xu and Penner, 2012).

We completed simulations of a version of the model that treats soot aerosols from fossil and bio-fuel emissions using 3 different hygroscopicity categories (hydrophobic, hydrophilic, and hydroscopic). This treatment is of interest because the different categories have differing capabilities to act as ice nuclei. We have a paper prepared looking at the effects of this treatment in mixed phase clouds that is nearly ready to submit (Yun et al., 2012).

We extended our secondary organic aerosol model (Lin et al., 2012) to treat the formation of these aerosols as a result of aqueous reactions (Lin et al., 2011), and obtained results for the direct and indirect forcing of SOA as a result of this new mechanism. We hope to write up these results for publication over the summer.

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