Application of 3-D spherical shell adaptive mesh refinement to an atmospheric model with a vertical Lagrangian coordinate

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Abstract. Here we present an application of a 3D adaptive mesh refinement (AMR) tool to a stratospheric tracer advection in a spherical coordinate system enriched by a new v-scan routine which allows conservation of the vertical integral of meteorological variables. Until now 3-D AMR tools did not take into account the separate tracking of vertical integrals. The latter is crucial to the atmospheric studies where refinement and coarsening routines in the vertical direction change the grid resolution of atmospheric pressure and geopotential height.

1. Introduction

Previously, mesh adaptation was applied to different representations of the Navier–Stokes equations. First, Skamarock et al. (1989) and Skamarock and Klemp (1993) applied their adaptive grid techniques for 3D limited-area models in Cartesian coordinates. Later, Behrens (1998) applied AMR techniques with an adaptive grid to a shallow water model in Cartesian coordinates while Hess (1999) used a grid based on a block-structured data layout. Bacon et al. (2000) and Boybeyi et al. (2001) formulated an adaptive non-hydrostatic regional model based on unstructured, triangulated grids with rotated Cartesian coordinates. Later, this model was used within a formulation with a spherical geometry (Gopalakrishnan et al. 2002, Bacon et al. 2003). There are a few shallow water models with statically adaptive grids developed using a spherical geometry (Ruge et al. 1995, Fournier et al. 2004, Barros and Garcia 2004). The dynamic AMR methods for shallow water models in spherical geometry were introduced by Jablonowski (2004) and Lauter et al. (2007). Most mesh adaptation methods were developed for models with numerical representation based on the finite-volume class of numerical schemes, and thus they all had desirable properties such as conservation and monotonicity.

In this paper we apply AMR methods to the shallow water equations in a spherical geometry with a Lagrangian vertical coordinate (Jablonowski et al. 2006, Penner et al. 2007). It uses the MPI-based communication library (Adaptive Block library for Locally Cartesian Topologies, ABLCarT) to control grid adaptation, particularly in the horizontal x-y direction (Oehmke 2004). The main requirement for the block structure in the library is that every block consists of the same number of grid cells no matter what their actual spatial size, which is consistent with the needs of the finite-volume approach. In this paper we use the 3D version of ABLCartT, enriched by a new functionality that allows conservation of the vertical integral of meteorological variables.

2. Vertical Mesh Adaptation.

Previously ABLCarT, in its 2D formulation, was used in a dynamical core that adapted its grid resolution (either dynamically or statically) in the horizontal direction (Jablonowski et al. 2006, Oehmke et al. 2008). From the library's viewpoint the model's computational grid is viewed as a collection of individual blocks that are independent data units. Each block is a rectangular unit with additional ghost cell regions around its boundaries. Thus, the information from adjacent blocks is

shared to allow computations requiring information from a block's neighbors. A choice of four ghost cells in each direction satisfies the requirements of the parabolic piecewise method (PPM) solution technique, widely used in atmospheric science. All ghost cells are at the same resolution as the parent block. The flow solver is individually applied to all blocks within the grid before ghost cells are updated.

Previously the library was solely applied in the horizontal direction so that the entire vertical column was contained in a single block. However, the spherical grids used to represent phenomena on Earth often need to treat the vertical dimension differently than those in the horizontal direction. For example, atmospheric pressure at a point is determined by the integral of the atmospheric mass above it, and thus is based on calculations that need to be sequenced in a particular order along a specific integration path. Further, each value along the integral is needed to determine the pressure at each cell, not just those at the bottom. This requires that variable information be sent top-down from each adaptive block to the blocks directly below (or above, in other cases), and this must be done (logically) sequentially above each point on the sphere, though it can be done in parallel across all surface points.

To perform vertical integration we have developed a *vertical scan* operation (v-scan) in ABLCarT, which allows computing along vertical paths in the correct order across blocks transparent to their resolution and processor location. To use v-scan the user specifies how the integration (summation) is to be performed in each block, and what information is passed between the blocks, while the library ensures that the operations are performed in the correct order, no matter where the blocks are located. In computer science a *scan* operation is normally used to describe an operation on a single vector (vertical cells above a point on the sphere) rather than on many such vectors in parallel. The ABLCarT performs the v-scan in strict sequential order, so there is no assumption that the operation be commutative or associative.

The 3D refinement involves a large increase in the complexity of the code, but its modular design allows this complexity without extensively altering the user's interface. Data access functions hide lower level implementation details, and adaptation modules are constructed so that each type of change to a block is handled separately and transparently to processor location, allowing the developer to concentrate on one neighbor interaction at a time. The user interfaces are encapsulated so that the library functions such as sphere creation, communication, adaptation, etc., work similarly on 3D and 2D spherical shells.

3. The Stratospheric Tracer Advection

The Brewer-Dobson circulation (BDC) in the stratosphere is a prominent feature of the atmospheric dynamics, which within the stratosphere (10–50 km) carries trace gases from equator to pole. We use an advection test (Zubov et al. 1999) which imitates the BDC with prescribed horizontal and vertical winds. The simplicity and transparency of the test enable us to check whether the model's interpolation subroutines that are "wired" into the Lagrangian vertical transport are not distorted by the v-scan, and that communication of all of the needed variables between the blocks in both the horizontal and vertical directions during grid adaptation is correct.

The prescribed circulation has a closed cell in each hemisphere, which is anti-symmetrical about the equator. The winds are set to zero at the poles and on the upper and lower boundaries, thus the model domain is closed to transport and the total mass of a conservative species should not change in time. The initial species distribution was prescribed to be constant within the rectangle between 32.5°S(N) to 12.5°S(N) in latitude and 19.75 km to 25.75 km in height, with a mixing ratio of 1.6 ppmv, and zero everywhere else. Initially, the 10–50 km vertical domain of the model was subdivided into 0.5 km-thick layers, and the 90S-to-90N latitudinal domain was subdivided into 5° steps. The time step, Δt was set to be 10,041 s (2.8 hr), which satisfies the Courant-Friedrich-Levy (CFL) criterion. The tracer makes one revolution around the center of the circulation cell in about 3 to 4 months.

We performed a few "adaptive runs" using the ABLCarT library. First, we have started with the initial resolution of 40 (levels) and 72 latitudes and used 2 levels of dynamic refinement ($40 \times 72 \times 2$)

by applying a prescribed threshold value of 10^{-15} ppmv on the concentration of the tracer in a grid cell. Figure 1 presents the adaptation of the tracer advection at various time steps. Then, we compared the adaptive run with a static high resolution run of 160 vertical levels and 288 points in the latitudinal direction (160 × 288 × 0). Also, we compared our results to an adaptive run with an initial resolution of 80 vertical levels and 144 latitudinal points with one level of refinement (80 × 144 × 0). We found that with the respective initial tracer distribution for the adaptive and high resolution runs, the integrals of the tracer in the horizontal and vertical directions in all three runs correspond to each other, showing that the adaptive transport has the same accuracy as the high resolution run.

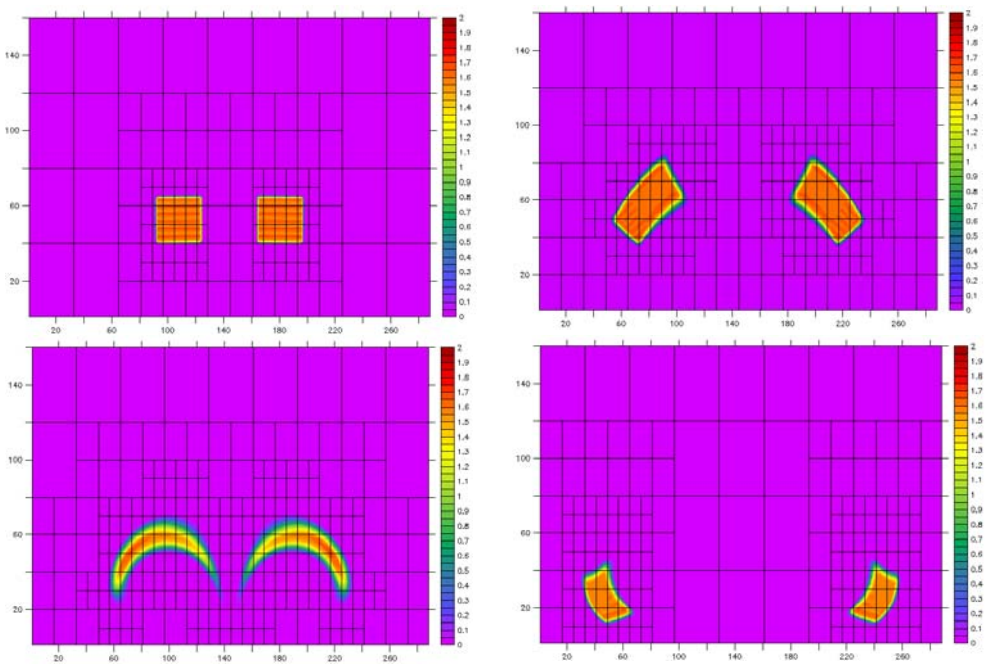

Figure 1. The tracer distribution at different times. Clockwise: days 1, 10, 25, and 100. The wire shows the refinement levels.

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, dynamic refinement could reduce the overall computer time by even more, e.g., if the problem required even higher levels of refinement. Similar reductions are realized in the memory required.

4. Conclusions

We have implemented and tested the three-dimensional parallel adaptive block mesh library (ABLCarT) within the dynamical core of a spherical model with a vertical Lagrangian coordinate. The introduction of a new vertical adaptation feature (v-scan) to the library was a challenging task due to the sequential nature of the vertical atmospheric calculations along a specific integration path. This introduces new geometric configurations of adjacent blocks with differing resolution and the concomitant numerical conservation equations. Applying the ABLCarT with v-scan to a pure advective tracer transport test, we demonstrated that the dynamical mesh adaptation works properly, and gives results equivalent to the refined non-adaptive case.

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