

Continuous Dynamic Grid Adaptation in a Global Atmospheric Model

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1. Abstract

The focus of this project is to extend development and testing of a global atmospheric model with continuous dynamic grid adaptation (CDGA) capability. The model is based upon the anelastic approximation for deep moist convection following Lipps and Hemler (1982) and uses nonoscillatory, forward-in-time (NFT) numerical schemes. It has options for either Eulerian (MPDATA scheme of Smolarkiewicz et. al., 2001) or semi-Lagrangian (Smolarkiewicz and Pudykiewicz, 1992) integrations. Options for either warm (rain only) or cold (rain and ice) moist thermodynamics using the cloud microphysical parameterization of Grabowski (1999) also exist.

The capability for grid adaptation derives from the model's formulation in terms of a generalized coordinate system that is homeomorphic with an *a priori* specified physical coordinate system such as Cartesian or spherical coordinates (Prusa et. al., 2001; Smolarkiewicz and Prusa, 2002). In particular, the horizontal coordinates on the sphere can be any transformation of latitude and longitude that preserves the topology of the specified physical coordinates. The vertical coordinate is treated separately with a time variable generalization of the terrain following transformation (Gal-Chen and Sommerville, 1975; Prusa et. al., 1996). One additional transformation applied to the vertical coordinate allows it to be further stretched in any time variable, nonuniform way that preserves its topology. The coordinate transformations may be either specified analytically or determined numerically.

2. Summary of work completed/underway

2a. Preliminary tests with analytical transformations

The generalized coordinates have been implemented throughout the dynamical core of the global model. Preliminary CDGA results for an idealized Held-Suarez climate (Held and Suarez, 1994) on the sphere show that analytically specified meridional grid stretching that moves points away from the poles substantially reduces the condition number of the elliptic operator (resulting from the solution of the pressure equation), leading to 20% smaller execution times. Thus the use of CDGA methods *does not* necessarily increase CPU time over that of a uniform grid of the same computational complexity. Global grids with enhanced equatorial or mid-latitude resolution are of high interest for numerous studies in the tropics and mid-latitudes. Also of interest is that maximum grid speeds of $\sim 10 \text{ ms}^{-1}$ appear feasible (in general, moving grid points adversely affect the Courant number stability condition, see Iselin et. al, 2002a) - demonstrating that grid adaptations can reasonably be expected to adapt to regionally sized flow features on the time scale of days.

CDGA shows expected effects on simulation accuracy (e.g., Fig. 1):

- (i) In regions of enhanced resolution, quantitative features such as field extrema and variances show improvements consistent with the second order accuracy of the numerical schemes employed, but

(ii) In regions of decreased resolution these features are overly dissipated compared to uniform grid results of the same computational complexity.

Qualitative features such as zonal jets also mirror these trends.

While useful for testing the model code and demonstrating the potential of CDGA, these preliminary global CDGA tests used only a meridional grid stretching. Such an adaptation scheme guarantees the presence of more accurate and less accurate zones in accord with the local meridional resolution. In order to achieve a more uniform global improvement, it is necessary to activate the fully two-dimensional horizontal stretching capability of the CDGA, and to allow the grid to respond to the simulated fields in order to track targeted flow features. In this way we hope to simulate the statistical variables of climate more accurately over the entire globe (i.e., in all zonal bands). The complexity of the required grid generator is beyond the simple analytical generators used in the preliminary tests, however.

2b. Preliminary tests with numerical transformations

First steps toward the numerical generation of a coordinate transformation were made using an innovative new grid generator that advects grid points using the NFT algorithms integral to our model. In our first test case, the model was applied to a regional, two-dimensional Cartesian domain to simulate the propagation of a gravity wave packet generated by a traveling deformation in the tropopause. The advected grid simulated a "nested grid" which is characterized by discontinuous metric terms as the grid suddenly changes resolution. This grid generation problem is equivalent to a propagating shock wave problem and represents an extreme test of the robustness of the CDGA machinery. We note that our NFT algorithms automatically guarantee the sharp propagation of these discontinuities without significant dissipation or dispersive waves *by design*. Results indicate that the gravity wave packet can be simulated with the same apparent accuracy of a high resolution, uniform grid solution using only 60% as many grid points and a nested grid of high uniform resolution following the immediate neighborhood of the traveling wave packet.

The use of NFT advection as a grid generator is noteworthy because typically grid generators are elliptic in nature. Our NFT advection generator has the advantages (compared to elliptic generators) of (i) efficiency, (ii) smoothness in time, and (iii) natural ability to impose limits on the minimum grid spacing. This last feature is enabled using the positive definiteness of the NFT algorithms, and is essential in preventing the collapse of the grid into a singularity.

2c. Simulation of geophysical turbulence

Work is also underway to extend the generalized coordinates throughout the thermodynamic and diagnostic routines of the model code. Of particular focus at present are the subgrid scale algorithms for turbulent LES simulations. The turbulent, idealized climate simulations of the preliminary tests were made using the *implicit* sub grid scale, or VLES (for Very Large Scale Simulations) option of our code. This option arises from the nonoscillatory character of our NFT algorithms. Its efficacy for use in simulating geophysical turbulence recently has been documented both with a book chapter (2001) and a journal publication (2002).

3. Future Directions

Our advection-based grid generator hinges upon the determination of a grid point advective velocity. In our 2D gravity wave example, this was straightforward to determine. In more general flows, where the grid should evolve so as to follow targeted

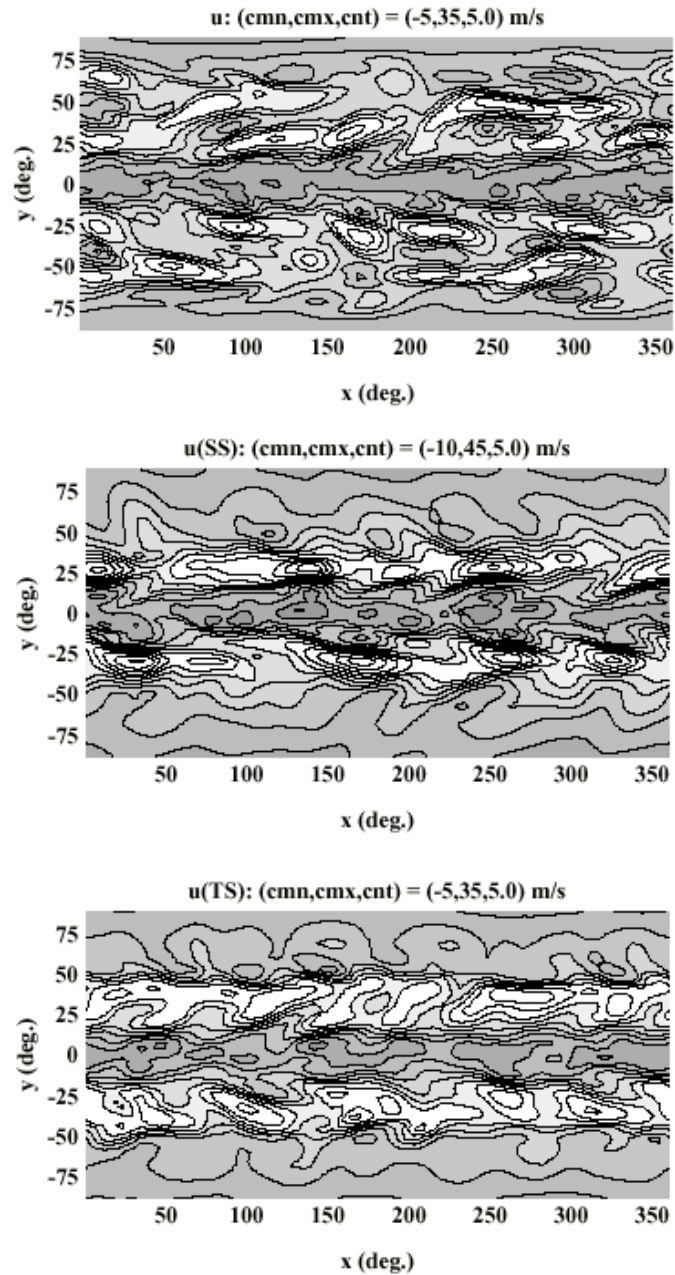


Figure 1 - Solutions for the instantaneous zonal (u) wind field in the horizontal plane at 7.2 km altitude after 3 years of simulating Held-Suarez flow. Plates from top to bottom show results using a static, uniform, 64 (lon) x 64 (lat) grid [U0], a static but meridionally stretched 130 x 32 grid with double the zonal resolution globally and double the meridional resolution in a broad equatorial region [SS], and a dynamic adaptive grid with 64 x 32 gridpoints [TS] simulations, respectively. Contour extrema (cmx, cmn) and intervals (cnt) are shown above each plate. Darker shades correspond to smaller wind values.

flow features, it is not clear how to define this advective velocity. One of our most immediate tasks is to develop this idea and a body of algorithms so as to make the advective grid solver capable for more general flows. A successful test of the generalized advective grid generator would show, for example, grid enhancement following baroclinic eddies around the globe.

A second immediate goal is to begin the application of the model to global simulations with regional emphasis, particularly South Africa. Once the model is operational in this application, we will add soil-moisture, planetary boundary-layer, and radiation schemes in order to make more realistic global simulations with regional emphasis. It is anticipated that the analytical grid generation technology developed in section 2a above is already adequate for these simulations. To assist with this work, a graduate student starting at Iowa State University this fall will be devoting her research time starting these simulations, assisting with analysis and porting additional model physics. An undergraduate with an Iowa State University Undergraduate Research Assistantship (ISU matches project funds on a 2.33:1 basis) will also assist with simulation.

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4. Publications/Papers Presented (Wholly or Partially Supported by the Grant)

4a. Journal Publications

- Smolarkiewicz, P.K., and J.M. Prusa, "VLES Modeling of Geophysical Fluids with Nonoscillatory Forward-in-Time Schemes", in press, *Int. J. Num. Methods in Fluids*, 24 pps, 2002.
- J.P. Iselin, J.M. Prusa, and W.J. Gutowski, "Dynamic Grid Adaptation Using the MPDATA Scheme", *Mon. Wea. Rev.*, **130**, pp. 1026-1039, 2002a.

- Prusa, J.M., Smolarkiewicz, P.K., and A.A. Wyszogrodzki, "Simulations of Gravity Wave Induced Turbulence Using 512 PE CRAY T3E", *Int. J. Applied Math. Comp. Sci*, **11**, pp. 883-897, 2001.

in review:

- Prusa, J.M., and P.K. Smolarkiewicz, "Mesh Adaptivity for Turbulent Geophysical Flows", to be submitted to *J. Comput. Physics*, June, 2002.
- J.P. Iselin, W.J. Gutowski, and J.M. Prusa, "Tracer Advection Using Dynamic Grid Adaptation and MM5", to be submitted to *Mon. Wea. Rev.*, June, 2002b.
- Prusa, J.M., M. Segal, B.R. Temeyer, W.A. Gallus Jr., and E.S. Takle, "Conceptual and Scaling Evaluation of Vehicle Traffic Thermal Effects on Snow/Ice Covered Roads", submitted to *J. App. Meteor*, Nov., 2001.

4b. Book Chapter

- Smolarkiewicz, P.K., and Prusa, J.M., 2001: Forward-in-Time Differencing for Fluids: Simulation of Geophysical Turbulence. In *Turbulent Flow Computation*. Ed. D. Drikakis and B.J. Geurts, Kluwer Academic Publishers, Boston, pp. 207-240; 265 pp.

4c. Conference Proceedings

- Prusa, J.M., and P.K. Smolarkiewicz, "Mesh Adaptivity for Geophysical Turbulence", *Proceedings 8th International Conference on Numerical Grid Generation, in Computational Field Simulations, June 2-6, Honolulu, HI, 10 pps, 2002.*

4d. Papers Presented

- P.K. Smolarkiewicz and J.M. Prusa, "Mesh Adaptivity for Geophysical Turbulence," *Workshop on Adaptive and High-Order Methods with Applications in Turbulence*, NCAR Geophysical Turbulence Program, Sept. 19-21, Boulder, CO., 2001.
- Prusa, J.M., and P.K. Smolarkiewicz, "Continuous Dynamic Grid Adaptation in a Global Atmospheric Model", *The 2002 Workshop on the Solution of Partial Differential Equations on the Sphere*, The Fields Institute, Aug. 12-15, Toronto, CANADA, 2002.