RECENT ADVANCES IN THE DEVELOPMENT OF NEXT-GENERATION GLOBAL MODELING SYSTEMS.

P. A. Ullrich, *University of California Davis, Davis, CA (paullrich@ucdavis.edu)*.

Introduction

At the core of any planetary modeling system is the dynamical core, the module responsible for solving the equations of fluid motion. Although the dynamical equations governing atmospheric motion have been known for over a century, novel numerical discretizations continue to be developed that can more accurately (and efficiently) resolve these motions. Historically, the vast majority of investment on global models has been directed at modeling the Earth's atmosphere, but the next few years promise to be particularly exciting for the planetary atmospheres community. There has been growing diversity in the modeling ecosystem, as modeling centers worldwide invest in new global modeling tools. Earth system models have been increasingly adopting the unapproximated non-hydrostatic atmospheric equations, which makes these models applicable at high horizontal resolutions and able to better incorporate steep topography and generalized equations of state. Massively parallel systems are now available that combine hundreds of thousands of processors, and the performance of these systems is growing at an exponential rate (Fig. 1). New hardware paradigms have similarly been gaining traction: for example, graphical processing units (GPUs) have been shown to dramatically reduce the time and cost of simulations. New software technologies have also been developed, including quasi-uniform grids and mesh refinement that can be used to improve resolution of key planetary features. With these developments in mind, this paper aims to describe some of these new technologies in the context of the ongoing work of modeling centers worldwide.

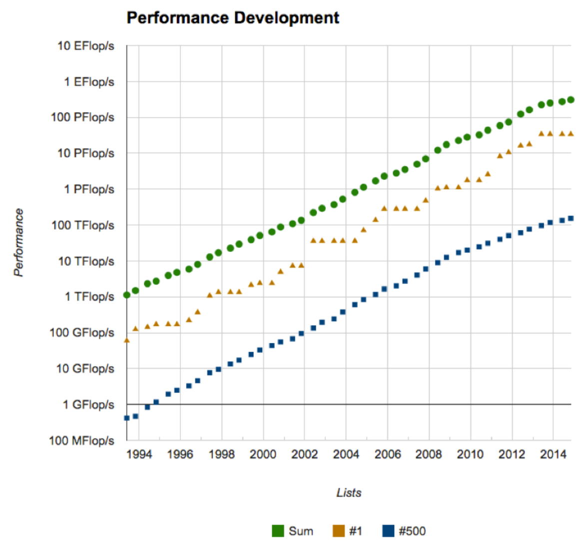

Figure 1: Performance of the top 500 world-wide supercomputers over the period 1993-2015 (measured in floating point operations per second). Note the logarithmic y-axis, indicating exponential growth over time. Source: top500.org

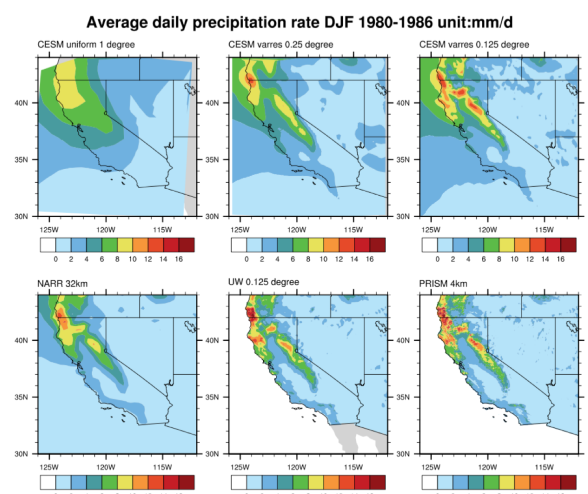

Figure 2: The effect of mesh resolution (top row) on precipitation rate over California, compared with three reference datasets (bottom).

The need for high resolution

It is widely acknowledged that Earth system models will need high resolution to accurately model the global atmosphere. Most modern climate modeling systems are run at typical resolutions of 110km (1 degree) global resolution, which is largely insufficient for resolving regional-scale features. On the Earth, tropical cyclones, atmospheric rivers and orographically driven precipitation are not resolved at these coarse scales. Consequently, questions on anticipated changes to regional climate and extreme weather over the next century have been left largely unanswered. With the increasing availability of large-scale supercomputing systems, model simulations are now available at 28km resolution (1/4°)

and finer. There is clear improvement in the use of these high-resolution modeling systems for representing regional climate: Figure 2 depicts the seasonally-averaged winter precipitation over a 7-year integration period along with three reference datasets obtained from gridded data and reanalysis. The topographic features that drive much of California's regional climate only appear in the precipitation fields at (1/4°). Further improvement is apparent at the higher (1/8°) resolution.

A growing ecosystem of global models

Dozens of global atmospheric models are in use today, with target applications ranging from experimental science to operational forecasting. Although global climate models are still several years away from reaching non-hydrostatic scales (10km resolution and finer) over the whole globe, there has been an increasing push to unify climate models with global weather prediction models, which are now operational at 3km global resolution. Further, new technologies such as variable-resolution have meant that parts of the globe can now be simulated at these extremely high resolutions. This push has led modeling centers to develop non-hydrostatic models which use the unapproximated equations of fluid motion, and are more readily applied to planetary atmospheres. The following list includes many of the major international modeling efforts that now use the non-hydrostatic equations or are actively developing non-hydrostatic dynamical cores.

- **GFDL FV3 (FV-Cubed) model:** (Geophysical Fluid Dynamical Laboratory, Princeton, NJ) The GFDL FV3 model uses a staggered finite-volume method on the cubed-sphere grid with floating Lagrangian layers and a free upper boundary. [6, 7]

- **High-Order Method Modeling Environment (HOMME) models:** (Sandia National Laboratory, Albequerque, NM) A set of hydrostatic models built on finite-element-type compact methods, including spectral element and discontinuous Galerkin in the horizontal and second-order finite-differences with hybrid η coordinate in the vertical. Non-hydrostatic capability is now being developed in HOMME, with an anticipated completion date of 2016. [2, 13]

- **Icosahedral Non-hydrostatic (ICON) GCM:** (Max-Planck Institute for Meteorology, Hamburg, Germany and DWD) Initially, ICON was developed as a hydrostatic prototype model, but has recently been updated to use the full non-hydrostatic equations. This model uses a finite-difference method on an icosahedral grid with Arakawa C-grid staggering and hybrid η vertical coordinate. [15, 3]

- **ECMWF Integrated Forecast System (IFS) model:** A non-hydrostatic model using the spectral transform method with semi-Lagrangian transport and built on the reduced latitude-longitude grid. The hydrostatic IFS has been in operational use for decades, but has more recently been extended to a non-hydrostatic dynamical core. It is now being run (in weather prediction mode) at resolutions of 3km and finer. [16]

- **Global Environmental Multiscale (GEM) model:** An implicit second-order semi-Lagrangian model using an Arakawa C-grid and hydrostatic-pressure based vertical coordinate, and built on a latitude-longitude grid. [18]

- **Model for Prediction Across Scales (MPAS):** (NCAR, LANL/DOE) A new non-hydrostatic global model designed to supercede the Weather Research and Forecasting (WRF) model. Uses conservative 2nd-order finite-differences on a icosahedral hexagonal mesh with Arakawa C-grid staggering, height-based vertical coordinate and 3rd-order split-explicit Runge-Kutta time integration. [10]

- **Non-hydrostatic ICosahedral Atmospheric Model (NICAM):** Developed in cooperation with the Center for Climate System Research (CCSR, Japan). This non-hydrostatic atmospheric model uses 2nd-order finite-differences on an icosahedral grid with horizontally unstaggered variables and vertically staggered vertical velocity. The vertical coordinate is height-based. [14]

- **Non-hydrostatic Icosahedral Model (NIM):** (Earth System Research Laboratory, NOAA) A Riemann-solver-based finite-volume model on an icosahedral hexagonal grid with monotonic Adams-Bashforth third-order multistep time integrator and height-based vertical coordinate. [4]

- **UK Met Office Unified Model:** A non-hydrostatic model using a conservative finite-difference approach on a latitude-longitude grid with height-based vertical coordinate. Both the shallow and deep-atmosphere equations as well as the hydrostatic and non-hydrostatic equations are supported in this model. [1, 12]

Although some may perceive multiple simultaneous modeling efforts to be a waste, there are unmistakable benefits to diversity in the modeling ecosystem. First, it is worth emphasizing that there is no "correct" model design, since all models represent an approximation to reality. Second, since the third climate model intercomparison project, it has been the case that the mean model behavior actually outperforms any individual model in representing the Earth system (see Fig. 3). This observation is surprising, but indicative that any choices that are made during the model design process can incorporate biases that can somehow be cancelled when examined in light of all multi-model ensemble.

Quasi-uniform grids

Recently, atmospheric dynamical cores have tended away from the regular latitude-longitude (RLL) grid due to the convergence of grid lines at the North and South poles. Numerical constraints typically require that the time-step size be proportional to the smallest grid cell size, meaning that the small triangular cells at the poles of the RLL grid make high-resolution simulations untenable. Consequently, global models have been increasingly moving towards quasi-uniform grids such as the icosahedral [9, 17] or cubed-sphere grids [8]. This choice has allowed for the design of models which can be run at very fine resolutions on large-scale parallel computing systems. These grids were an elegant solution to the pole problem, but in many cases were not competitive with existing models until the advent of distributed supercomputing. As a consequence, uniform grids were largely not used in operational atmospheric models until the mid-1990s. A depiction of the RLL grid, cubed-sphere grid and geodesic grid can be seen in Fig. 4.

Variable resolution grids

Recent advances in global Earth system modeling have focused on the development of variable-resolution global climate models (VRGCMs) as a means for better understanding interactions between the global and regional scale, and to improve climate projections over a limited area. VRGCMs utilize a global coarse resolution grid which is refined over a specific area of interest; hence, these models often require only a small fraction of the computing power of uniform resolution models to resolve fine-scale features (see Fig. 6). These efforts are now beginning to come to fruition, and have led to Earth system models which both correctly capture regional-global interactions and reach the resolutions needed to understand regional climate change. Some of the large modeling groups now developing and evaluating variable-resolution models include HOMME, MPAS and GFDL FV3.

Adaptive mesh refinement

Although computational power has increased substantially in recent years, large parallel systems are still required to properly resolve many important atmospheric features. In order to reduce the computational burden of these fine-scale simulations, the next generation of

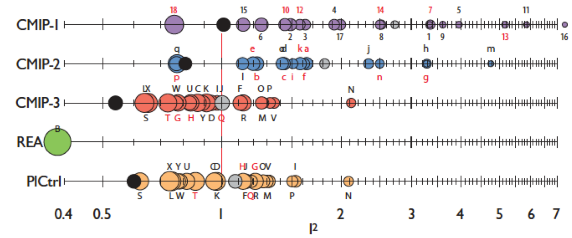

Figure 3: Model performance from CMIP-1, CMIP-2 and CMIP-3. Circles represent the performance metric for the model (models closer to reality are to the left). The model mean is denoted in black. Similar results to CMIP-3 have been reported for the more recent CMIP-4 and CMIP-5 projects. Source: Climate Models: An Assessment of Strengths and Limitations (USCCSP, 2008).

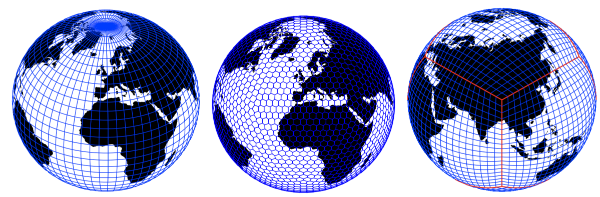

Figure 4: Left: A latitude-longitude mesh. Center: An icosahedral (geodesic) mesh. Right: A cubed-sphere mesh.

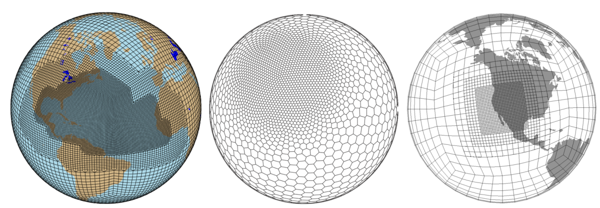

Figure 5: Left: A conformal cubed-sphere mesh. Center: A Voronoi tessellation grid. Right: A non-conformal cubed-sphere mesh.

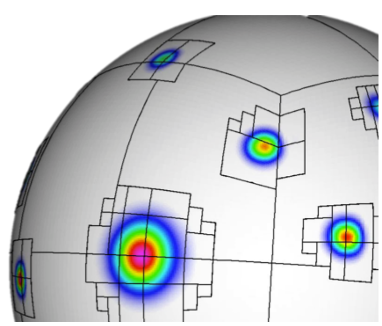

Figure 6: An example of the Chombo adaptive mesh refinement is used on the non-conformal cubed-sphere grid to automatically track advected features. Black lines around features indicate the edges of high-resolution zones (courtesy of Hans Johansen, Lawrence Berkeley National Laboratory).

atmospheric models will likely need to rely on adaptive mesh refinement (AMR). Mesh refinement refers to the addition of grid elements to regions with small-scale features so as to reduce errors that arise due to insufficient resolution. Static mesh refinement, such as the variable-resolution strategy described earlier, requires that the grid does not change in time. AMR is similar, but allows the grid to change over the process of the simulation. Research on AMR for global modeling is ongoing, with recent work highlighting its potential [11, 5].

References

[1] T. Davies, M. J. P. Cullen, A. J. Malcolm, M. H. Mawson, A. Staniforth, A. A. White, and N. Wood. A new dynamical core for the Met Office's global and regional modelling of the atmosphere. *Quarterly Journal of the Royal Meterological Society.*, 131(608):1759–1782, 2005.

[2] A. Fournier, M. A. Taylor, and J. Tribbia. The spectral element atmosphere model (SEAM): High-resolution parallel computation and localized resolution of regional dynamics. *Monthly Weather Review*, 132(3):726–748, 2004.

[3] A. Gaßmann. Non-hydrostatic modelling with the ICON model. Presentation at ECMWF Non-Hydrostatic Workshop, Reading, U.K., Nov. 8-10, 2010., 2010.

[4] M. W. Govett, J. Middlecoff, and T. Henderson. Running the NIM next-generation weather model on GPUs. *IEEE International Symposium on Cluster Computing and the Grid*, pages 792–796, 2010.

[5] P. McCorquodale, P. Ullrich, H. Johansen, and P. Colella. An adaptive multiblock high-order finite-volume method for solving the shallow-water equations on the sphere. *Communications in Applied Mathematics and Computational Science*, 10(2):121–162, 2015.

[6] W. M. Putman and S.-J. Lin. A finite-volume dynamical core on the cubed-sphere grid. In N. V. Pogorelov, E. Audit, P. Colella, and G. P. Zank, editors, *Numerical Modeling of Space Plasma Flows: Astronum-2008*, volume 406, pages 268–276. Astronomical Society of the Pacific Conference Series, 2009.

[7] W. M. Putman and M. Suarez. Mesoscale weather and climate modeling with the global non-hydrostatic Goddard Earth Observing System Model (GEOS-5) at cloud-permitting resolutions. *AGU Fall Meeting Abstracts*, December 2009. Abs. # A42B-08.

[8] R. Sadourny. Conservative finite-difference approximations of the primitive equations on quasi-uniform spherical grids. *Monthly Weather Review*, 100:136–144, 1972.

[9] R. Sadourny, A. Arakawa, and Y. Mintz. Integration of the nondivergent barotropic vorticity equation with an icosahedral-hexagonal grid for the sphere. *Monthly Weather Review*, 96:351–356, 1968.

[10] W. C. Skamarock, J. Klemp, M. Duda, S.-H. Park, L. Fowler, T. Ringler, J. Thuburn, M. Gunzburger, and L. Ju. Global Non-Hydrostatic Modeling Using Voronoi Meshes: The MPAS Model. Presentation at ECMWF Non-Hydrostatic Workshop, Reading, U.K. Nov. 8-10, 2010., 2010.

[11] A. St-Cyr, C. Jablonowski, J. M. Dennis, H. M. Tufo, and S. J. Thomas. A comparison of two shallow-water models with nonconforming adaptive grids. *Monthly Weather Review*, 136:1898–1922, 2008.

[12] A. Staniforth and N. Wood. Aspects of the dynamical core of a nonhydrostatic, deep-atmosphere, unified weather and climate-prediction model. *Journal of Computational Physics*, 227:3445–3464, March 2008.

[13] M. A. Taylor, J. Edwards, and A. St.Cyr. Petascale atmospheric models for the community climate system model: New developments and evaluation of scalable dynamical cores. *Journal of Physics Conference Series*, 125:012023, 2008.

[14] H. Tomita and M. Satoh. A new dynamical framework of nonhydrostatic global model using the icosahedral grid. *Fluid Dynamics Research*, 34(6):357 – 400, 2004.

[15] H. Wan. Developing and testing a hydrostatic atmospheric dynamical core on triangular grids. Technical Report 65, *Reports on Earth System Science*, Max-Planck Institute for Meteorology, Hamburg, Germany, 2009. ISSN 1614-119.

[16] N. Wedi, P. Benard, K. Yessad, A. Untch, S. Malardel, M. Hamrud, G. Mozdzynski, M. Fisher, and P. Smolarkiewicz. Non-hydrostatic modeling with IFS: current status. Presentation at ECMWF Non-Hydrostatic Workshop, Reading, U.K., Nov. 8-10, 2010., 2010.

[17] D. L. Williamson. Integration of the barotropic vorticity equation on a spherical geodesic grid. *Tellus*, 20(4):642–653, 1968.

[18] K.-S. Yeh, J. Côté, S. Gravel, A. Méthot, A. Patoine, M. Roch, and A. Staniforth. The CMC MRB Global Environmental Multiscale (GEM) Model. Part III: Nonhydrostatic Formulation. *Monthly Weather Review*, 130:339–356, 2002.