Simulation of global cloudiness

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Abstract. We present a new model designed to simulate cloudiness over the entire Earth with a grid spacing of less than 5 km. The model uses a geodesic grid. Vertically propagating sound waves are filtered. The three-dimensional vorticity equation is integrated. The code can efficiently use tens of thousands of processors.

1. Introduction

During the 1960s, atmospheric general circulation models (AGCMs) had grid spacings of a few hundred kilometers and up to about 10 layers. The models included parameterizations of moist convection, stratiform clouds, radiation, and the boundary layer. In part because of limitations of computer power, they were typically run for a few simulated months, in perpetual-season mode.

Now, 40 years later, the AGCMs used for numerical weather prediction (NWP) have grid spacings about 10 times finer in the horizontal, implying about 100 times as many grid columns. The number of layers has increased to nearly 100 in some cases. As a result of advances in numerical methods, the time steps of today’s high-resolution NWP models are actually larger than those used by the lower-resolution models of the 1960s. The physical parameterizations of today’s models are more elaborate than those of the 1960s, but not dramatically so; they require perhaps 10 times more computation than their predecessors. Putting these factors together, we conclude that the most elaborate of today’s global NWP models use about $10^4$ times as much computer power as the AGCMs of the 1960s.

The AGCMs used for climate simulation today have horizontal grid spacings only slightly finer than those of the 1960s. Similarly, the number of layers has changed from $O(10)$ to perhaps 30 or so -- not a drastic increase. As mentioned above, parameterizations have become more complex, but not drastically so. We conclude that today’s AGCMs for climate simulation are only a few hundred times more expensive than their counterparts of the 1960s.

While these modeling changes have been going on, computer power has increased by about a factor of a million – from megaflops to teraflops. A typical laptop computer today is faster, has more memory and disk space, consumes much less power, is more reliable, is considerably easier to use, and costs much, much less than the cutting-edge Cray-1 of the 1970s.

How did we use the millionfold increase in computer power that has been achieved since the 1960s? For NWP models, we have argued above that increases in resolution and other changes have slowed the models down by about a factor of $10^4$. The additional factor of 100 needed to go from $10^4$ to a million can be accounted for in terms of shorter execution times (enabling operational use on a fixed schedule) and the introduction of forecast ensembles. For the AGCMs used for climate, we have argued that current models are a few hundred times slower than their predecessors. The additional factor of several thousand need to go from a few hundred to a million can be accounted for by much longer simulations -- centuries instead of months -- and by an increase in the number of simulations performed.

Over the next few decades, computers are expected to speed up by another factor of a million. What are we going to do with that next million? Although there are many worthwhile ways to spend it, we believe that a portion of it will be used to run very high-resolution models for both NWP and climate prediction.
simulation. The horizontal grid spacings of these models will be in the range 1 to 5 km, and the vertical structure of the atmosphere will be resolved using on the order of 100 layers. We refer to this new generation of global models as “global cloud-resolving models,” or GCRMs.

Because they have grid spacings comparable to the native scales of large clouds, GCRMs are free of the parameterizations of deep cumulus convection and stratiform cloudiness needed by conventional AGCMs. GCRMs also have no need for parameterizations of cloud overlap, or gravity-wave drag, because these can be explicitly simulated. GCRMs do still rely on parameterizations of cloud microphysics, turbulence, and radiation, but all three of these parameterization problems become much more tractable with the high resolution of a GCRM. In fact, a strength of GCRMs is that they are ideal vehicles for the implementation of more advanced parameterizations of microphysics, turbulence, and radiation. In addition, the cloud-scale statistics simulated by GCRMs can be compared directly with cloud-scale observations, which greatly simplifies the diagnosis of model deficiencies. Moreover, GCRMs are intrinsically more amenable to modularization than today’s AGCMs, simply because the various physical processes represented by the parameterizations are less inter-dependent on the cloud scale.

The transition from today’s AGCMs to GCRMs will be possible only after important changes in the formulations of the models. A decrease of the horizontal grid spacing by another factor of ten, together with the introduction of nonhydrostatic dynamics and major changes in parameterizations, will yield global NWP models with grid cells just a few kilometers across, at the coarse end of the “cloud-resolving” range. Taking into account the decrease in time step needed to permit simulation of the birth and death of individual large clouds, we can estimate that these cloud-resolving NWP models of the future will be about 1000 times as expensive as today’s high-resolution global NWP models. Such GCRMs will become marginally practical for operational global NWP within the coming decade, which means that now is the time to begin their development.

A GCRM has already been developed at the Frontier Research Center for Global Change (FRCGC), in Japan. The model has been tested on the Earth Simulator, with provocative results [1, 2]. The FRCGC’s GCRM, called NICAM (for “Nonhydrostatic Icosahedral Atmospheric Model”) is constructed on a geodesic grid based on the icosahedron, similar to the one that we had developed and published before NICAM development began (see Section 2). During the development of NICAM, FRCGC scientists consulted with our team at Colorado State University, especially about the geodesic grid. In January 2008, Dr. Hiroaki Miura of FRCGC began a two-year visit with us at CSU.

At the highest tested resolution, NICAM has cells 3.5 km across. It needs approximately one teraflop-day of computer power (about $10^{17}$ floating point operations) to simulate one day. A snapshot of just the prognostic (time-stepped) variables fills about 1 TB of memory. Model output can easily exceed 10 PB per simulated year. Because of its high computational cost, NICAM has been run with 3.5 km cell widths for just a few simulated weeks. The model has also been run with coarser grids.

2. Model design

2.1. Introduction

We are developing a new and unique global nonhydrostatic dynamical core, based on a geodesic grid (explained below), and suitable for use with grid spacings ranging from meters to hundreds of kilometers. The core is accurate in the Taylor-series sense, physically consistent, computationally robust, and designed to perform well on modern computer architectures.

Because the core is nonhydrostatic, it can be run with very high spatial resolution (grid spacings of meters), but it can also be using much coarser resolutions typical of current global numerical weather prediction and climate models (grid spacings on the order of tens or hundreds of kilometers). The core is therefore suitable for a wide range of applications. It is currently (June 2008) at a late stage of development.
We have not simply adapted a conventional nonhydrostatic model for use on a global domain. Our approach has been to go back to a blank piece of paper and ask, “What is the best way to build a dynamical core, given what we know in 2008?” The model that we are proposing is quite different from anything that has been done before. However, the closest single parallel is the NICAM, the model developed by the Frontier Research Center for Global Change [3-10, 11, 12]. Like NICAM, our global model is nonhydrostatic, and uses a geodesic grid. However, there are many major differences between our model and NICAM, as mentioned briefly in several places below.

2.2. Governing equations
Our GCRM uses what we call the Unified System system of equations derived by Arakawa and Konor (2008). The Unified System is a generalization of the “pseudo-incompressible system” of Durran (1989). It unifies the quasi-hydrostatic system with the anelastic system. Unlike the anelastic system, the Unified System does not use a reference state. As shown by Arakawa and Konor [11], the Unified System filters vertically propagating sound waves, while permitting the Lamb wave and giving accurate phase speeds for both inertia-gravity waves and Rossby waves. For comparison, NICAM uses the fully compressible system.

The Unified System is further modified to solve a parabolic equation, analogous to a diffusion equation, instead of solving an elliptic equation, which is required for any truly anelastic system. The equilibrium solution of the diffusion equation is of course identical to the solution of the elliptic equation. When a large diffusion coefficient is used together with a vertically implicit and horizontally iterative algorithm, there is no need to solve a global elliptic equation, as with the conventional anelastic system. The Unified System system has tested in the model of Jung and Arakawa (hereafter JA) [13], with good results. We are now carrying it forward into the global domain.

Following the approach of JA, our model is based on solution of the three-dimensional vector vorticity equation, rather than the vector momentum equation. The motivation for this choice is that vorticity is at the core of the meteorologically important dynamical processes over a wide range of scales. Large scales are dominated by strongly rotational quasi-geostrophic motion, which is closely related to the vertical component of the vorticity. On small scales, convection arises through the generation of horizontal vorticity by buoyancy. Because of the key roles played by vorticity on a wide range of spatial scales, the vector (three-dimensional) vorticity equation represents the meteorologically important dynamical processes much more directly and explicitly than the momentum equation. It is therefore advantageous to formulate the discrete equations of a numerical model by starting from the vector vorticity equation.

It is necessary to predict only two components of the three-dimensional vorticity vector. The third component can then be diagnosed (given a boundary condition), by using the mathematical identity \( \text{Div}(\text{Curl}) = 0 \). In practice, we predict the two components of the horizontal part of the vorticity vector and use the identity to diagnose the vertical component of the vorticity. We also predict the divergence of the three-dimensional velocity. The three-dimensional velocity field can then be reconstructed diagnostically. As shown by JA, when vector vorticity is predicted, the elliptic equation required to filter out sound waves is expressed in terms of the vertical velocity, rather than the pressure as in the usual anelastic models based on the momentum equation. Once this equation has been solved for the vertical velocity, the components of the horizontal velocity can be diagnosed from the horizontal components of the vorticity (given a vertical boundary condition). This makes formulation of the lower boundary condition over irregular terrain significantly simpler. For comparison, NICAM integrates the momentum equation.

We are formulating the first version of the GCRM using height as the vertical coordinate. In later versions of the dynamical core, we may test alternative vertical coordinates. In the first version of the model, the effects of topography will not be included. They will be introduced in the second version.
2.3. **Discretization of the sphere**

The GCRM will be constructed using the geodesic grid developed by Heikes and Randall [14, 15] and extended by Ringler et al. [16] and Ringler and Randall [17, 18]; see also Randall et al. [19]. An “exploded” depiction of a (very low-resolution) geodesic grid is shown in Fig. 1. Models based on geodesic grids are now being used by several major modeling groups around the world, including NOAA’s Earth System Research Laboratory in Boulder (http://fim.noaa.gov/), the U.S. Naval Postgraduate School [20], FRCGC in Japan, Richard Peltier’s group in Canada [21, 22], the Max Planck Institute for Meteorologie and the Deutsche Wetterdienst in Germany [23-25]), and the University of Reading in the UK [26]. The geodesic grid is well suited to use in high-resolution models. It is also being used in a variety of other applications (e.g., [27]).

An obvious strength of the geodesic grid is that all grid cells on the sphere are very nearly the same size. Variational “tweaking” of the grid [15] can improve the uniformity of the mesh. The largest cells anywhere on the grid are only about 5% larger in area than the smallest cells on the grid (e.g., [19]).

Because of the uniform cell size, computational stability for advection is not a major issue. For example, with a grid cell L km across, and an extreme wind speed of 100 m s\(^{-1}\), the allowed time step for advection is on the order of 10 L seconds. Computational stability for fast waves is discussed below.

![Figure 1. An “exploded” picture of a low-resolution geodesic grid. The grid can be divided into ten logically rectangular panels, as seen in the figure. Memory addressing can be organized using these panels.](image)
A second important property of the geodesic grid is that it is quasi-isotropic. As is well known, only three regular polygons tile the plane: equilateral triangles, squares, and hexagons. Figure 2 shows portions of planar grids made up of each of these three possible polygonal elements. On the triangular and square grids, some of the neighbors of a given cell lie directly across cell walls, while others lie across cell vertices. As a result, finite-difference operators constructed on these grids tend to use “wall neighbors” and “vertex neighbors” in different ways. For example, the simplest second-order finite-difference approximation to the gradient, on a square grid, uses only “wall neighbors”; vertex neighbors are ignored. Although it is certainly possible to construct finite-difference operators on square grids (and triangular grids) in which information from all neighboring cells is used (e.g., the Arakawa Jacobian, as discussed by Arakawa [28]), the essential asymmetries of these grids remain and are, unavoidably, manifested in the forms of the finite-difference operators. Hexagonal grids, in contrast, have the property that all neighbors of a given cell lie across cell walls; there are no “vertex neighbors.” As a result, finite-difference operators constructed on hexagonal grids treat all neighboring cells in the same way; in this sense, the operators are as symmetrical and isotropic as possible. A geodesic grid on the sphere has twelve pentagonal cells in addition to the many hexagonal cells; nevertheless each cell of the geodesic grid has only wall neighbors; there are no vertex neighbors anywhere on the sphere.

It is sometimes claimed that geodesic grids permit only second-order accurate finite-difference schemes. This is simply not correct. We are currently using third-order-accurate horizontal advection schemes, and we can easily construct schemes of arbitrarily high accuracy (in the Taylor-series sense) by numerically solving straightforward linear algebra problems.

2.4. Spatial differencing

The spatial differencing of the model is a modified version of that described by Jung and Arakawa (2008; hereafter JA). The modifications serve to adapt the scheme from JA’s Cartesian grid to the GCRM’s
geodesic grid. A sketch showing the horizontal and vertical staggering of the variables in a single hexagonal grid cell is given in figure 3. The horizontal staggering is designed to minimize the computational noise associated with computational modes. The horizontal staggering places vertical velocity, temperature, the divergence of the horizontal wind, and the associated velocity potential all at the centers of hexagonal (and pentagonal) cells. The tangential component of the horizontal vorticity vector is defined on the walls of the hexagons (and pentagons). The vertical component of the vorticity and the associated stream function are defined on the corners of the hexagons (and pentagons).

Again to minimize the noise associated with computational modes, we use the Charney-Phillips vertical staggering, in which temperature and the horizontal components of the vorticity are predicted at the same levels. The moisture variables are also predicted at those levels (for reasons discussed by Konor and Arakawa, 2000), and the vertical velocity is diagnosed there. For comparison, NICAM uses the Lorenz staggering in the vertical, and an unstaggered grid in the horizontal.

2.5. Time differencing
Because the Unified System filters vertically propagating sound waves, it permits relatively long time steps without the need for time splitting or vertically implicit time-differencing schemes. It thus simplifies the model.

We will test a new explicit horizontal differencing scheme for the wave equation (Konor and Arakawa, 2007). The idea underlying this scheme is very simple. The trapezoidal scheme permits large time steps, but at the cost of using information from all grid points in the entire global domain, thus requiring the solution of large matrix problems that create problems on parallel computer architectures. Far-away points actually contribute very little information to the solution, however. The new scheme

Figure 3. A sketch of the vertical and horizontal distributions of the variables in one hexagonal grid cell of the GCRM. Here \( \eta \) is the tangential component of the horizontal vorticity vector, defined on the cell walls. The other notation is conventional.
mimics the trapezoidal implicit scheme, but approximates it by using information only from relatively nearby points. The maximum Courant number for which computational stability is required is specified in advance; larger required Courant numbers imply larger required stencils. Details are explained by Konor and Arakawa [29]. We will use the new approach in the GCRM to permit large time steps in the presence of the fast-moving Lamb wave.

3. Status
Components of the GCRM are currently being tested on Franklin, a Cray XT-4 at the National Energy Research Supercomputing Center at the Lawrence Berkeley National Laboratory in Berkeley, California. We have already tested a high-resolution “kernel” of the model on 10,000 Franklin processors, with good scaling performance.

We expect to complete coding and preliminary testing of the dynamical cores before the proposed grant begins. Tests will be designed to establish numerical accuracy and stability, conservation properties, and parallel scaling performance. We will also be coupling the cores with our own suite of physical parameterizations, designed for use with cloud-resolving grid spacings.

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