Testing of a New Dynamical Core at CSU

David A. Randall

Department of Atmospheric Science, Colorado State University
Fort Collins, Colorado, 80526 USA
randall@atmos.colostate.edu

1 Introduction

Since 2001, work has been underway to create coupled atmosphere, ocean, sea ice, and land surface models in a unified framework. The project involves Colorado State University (CSU), the University of California at Los Angeles (UCLA), the Naval Postgraduate School (NPGS), and the Los Alamos National Laboratory. (LANL). All of the sub-models use geodesic grids, as explained in Section 2. In addition, the atmosphere and ocean sub-models use quasi-Lagrangian vertical coordinates. The various sub-models are coupled in a way that takes advantage of their similar grids.

2 Geodesic grids

For about ten years now (Heikes and Randall, 1995 a, b), we have been pursuing a new approach to climate simulation that is based on the use of geodesic grids, which are generated by starting from an icosahedron. The construction of a variationally optimized geodesic grid is discussed in detail by Heikes and Randall (1995 a, b). Geodesic grids avoid the “pole problem” that arises on latitude-longitude grids, in which the meridians (lines of constant longitude) converge to points at the two poles.

Geodesic grids give almost homogeneous and quasi-isotropic coverage of the sphere (e.g., Randall et al., 2000, 2002). They were first tried in the 1960s (Williamson, 1968, 1969, 1970; Sadourny et al., 1968; Sadourny and Morel, 1969; Sadourny, 1972), and there is now widespread interest (Baumgardner and Frederickson, 1985; Masuda and Ohnishi, 1986; Heikes and Randall, 1995 a, b; Stuhne and Peltier, 1996, 1999; Thuburn 1997; Majewski et al., 2002; Randall et al., 2000; Ringler et al., 2000; Ringler and Randall, 2002 a, b; Randall et al., 2002; Tomita. and Satoh, 2004). As shown in Fig. 1, a geodesic grid can be ‘”cut” into ten rectangular panels. Each of these corresponds to a pair of triangular faces from the original icosahedron. Each panel is logically rectangular.

A geodesic grid can be considered to consist of hexagons and twelve pentagons, or it can be considered to consist of triangles. We use the hexagonal-pentagonal grid because of its higher symmetry. We define the vorticity, divergence, mass, and temperature on this grid, without any staggering. This arrangement was called the Z-grid by Randall (1994). The Z-grid allows a realistic simulation of geostrophic adjustment, regardless of the ratio of the grid size to the radius of deformation. In addition, it is free of computational modes. To solve the elliptic equations for the stream function and velocity potential, we use a multi-grid method (Fulton et al., 1986).

Our atmosphere and ocean sub-models both use the hexagonal-pentagonal Z-grid, although generally the ocean grid is finer than the atmosphere grid. The atmosphere model uses the Z-grid in its pure form. At

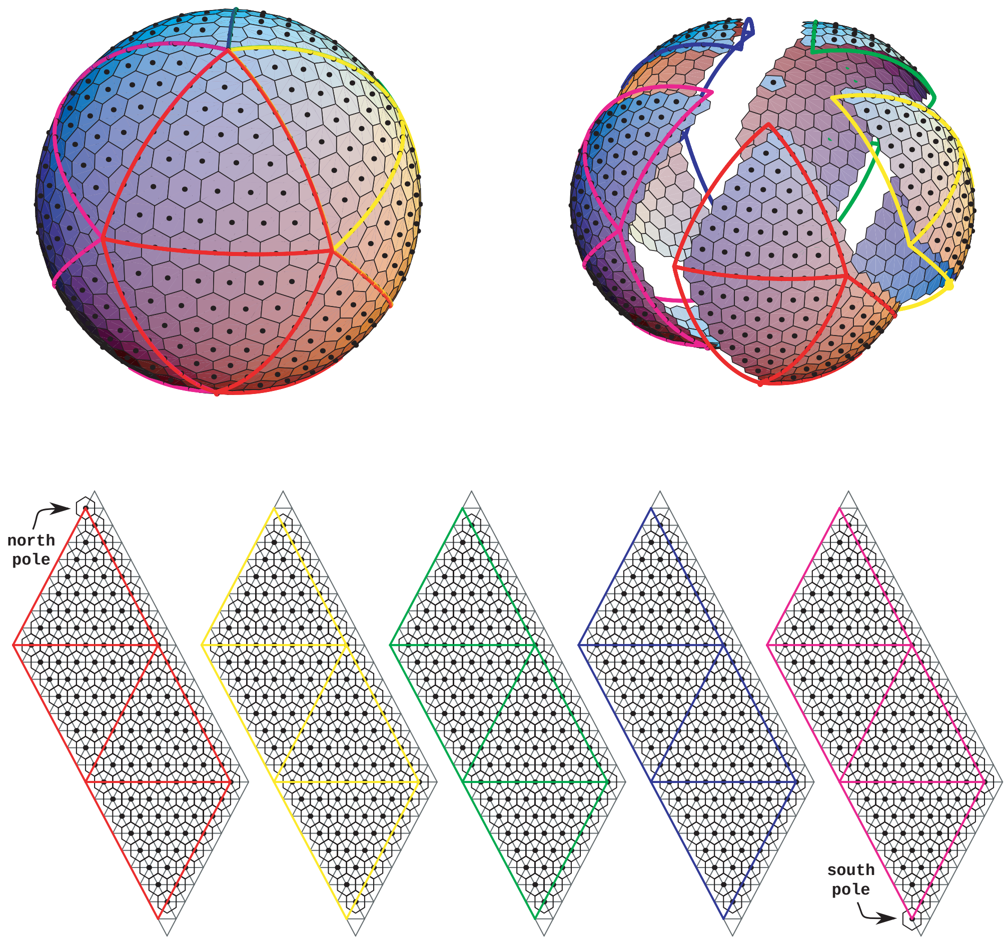

Figure 1: *A spherical geodesic grid can be "cut" into logically rectangular panels, which offer a convenient way to organize the data in the memory of a computer.*

present, the ocean model predicts the horizontal momentum vector in a manner that is consistent with the Z-grid. This approach, which was called the ZM-grid by Ringler and Randall (2001 b), introduces computational modes, but empirically they do not seem to be causing serious problems in the ocean model.

Our horizontal differencing scheme is Eulerian, conservative and second-order accurate. Recently we have introduced a third-order scalar advection scheme that is based on the ideas of Takacs (1985). We have also added an option for sign-preserving or monotone flux-corrected transport (Zalesak, 1979). The atmosphere and ocean models both use a biharmonic diffusion on momentum only.

The models use third-order Adams-Bashforth time differencing. In the ocean model, we are using the "reduced-gravity" approach of Jensen (1996, 2001), which allows long time steps without subcycling, without solving an elliptic problem, and with minimal communication overhead.

The Z-grid dynamics has been extensively tested in the spherical shallow-water framework (e.g., Heikes and Randall, 1995 a; Ringler and Randall, 2002 a), and as discussed by Heikes (2002) several three-dimensional global versions of the model have also been extensively tested in the framework suggested by Held and Suarez (1994). A three-dimensional version of the model with a full suite of physical parameterizations was tested by Ringler et al. (2000).

3 Vertical coordinates

Konor and Arakawa (1997) discuss a hybrid vertical coordinate, ζ, that reduces to θ away from the surface, and to σ near the surface. This hybrid coordinate is designed to combine the strengths of θ and σ coordinates, while avoiding their weaknesses. Following Konor and Arakawa (1997), define

$$\zeta = F(\theta, p, p_S) \equiv f(\sigma) + g(\sigma)\theta, \qquad (1)$$

where $\sigma \equiv \sigma(p, p_S)$ is a modified sigma coordinate, defined so that it is (as usual) a constant at the Earth's surface, and (not as usual) increases upwards, e.g., $\sigma \equiv \frac{p_S - p}{p_S}$. If we specify $f(\sigma)$ and $g(\sigma)$, then the hybrid coordinate is fully determined.

We require, of course, that ζ itself increases upwards, so that

$$\frac{\partial\zeta}{\partial\sigma} > 0. \qquad (2)$$

We also require that

$$\zeta = \text{constant for } \sigma = \sigma_S, \qquad (3)$$

which means that ζ is σ-like at the Earth's surface, and that

$$\zeta = \theta \text{ for } \sigma = \sigma_T, \qquad (4)$$

which means that ζ becomes θ at the model top (or lower). These conditions imply, from (1), that

$$g(\sigma) \to 0 \text{ as } \sigma \to \sigma_S, \qquad (5)$$

$$f(\sigma) \to 0 \text{ and } g(\sigma) \to 0 \text{ as } \sigma \to \sigma_T. \qquad (6)$$

Now substitute (1) into (3), to obtain

$$\frac{\partial f}{\partial\sigma} + \frac{dg}{d\sigma}\theta + g\frac{\partial\theta}{\partial\sigma} > 0. \qquad (7)$$

This is the requirement that ζ increases monotonically upward. Any choices for f and g that satisfy (5)-(7) can be used to define the hybrid coordinate.

Here is a way to do that: First, choose $g(\sigma)$ so that it is a monotonically increasing function of height, i.e.,

$$\frac{dg}{d\sigma} > 0 \text{ for all } \sigma. \qquad (8)$$

We also choose $g(\sigma)$ so that the conditions (5)-(7) are satisfied. Obviously there are many possible choices for $g(\sigma)$ that will meet these requirements.

Next, define θ_{min} and $\left(\frac{\partial\theta}{\partial\sigma}\right)_{min}$ as lower bounds on θ and $\frac{\partial\theta}{\partial\sigma}$, respectively, i.e.,

$$\theta > \theta_{min} \text{ and } \frac{\partial\theta}{\partial\sigma} > \left(\frac{\partial\theta}{\partial\sigma}\right)_{min}. \qquad (9)$$

When we choose the value of θ_{min}, *we are saying that we have no interest in simulating situations in which* θ *is actually colder than* θ_{min}. For example, we could choose θ_{min} = 10 K. This is not necessarily an ideal choice, for reasons to be discussed below, but we can be sure that in our simulations θ will exceed 10 K everywhere at all times, unless the model is in the final throes of blowing up. *Similarly, when we choose the value of* $\left(\frac{\partial\theta}{\partial\sigma}\right)_{\min}$*, we are saying that we have no interest in simulating situations in which* $\left(\frac{\partial\theta}{\partial\sigma}\right)$ *is actually less stable (or more unstable) than* $\left(\frac{\partial\theta}{\partial\sigma}\right)_{\min}$. We can choose $\left(\frac{\partial\theta}{\partial\sigma}\right)_{\min}$, i.e., a value of $\left(\frac{\partial\theta}{\partial\sigma}\right)_{\min}$ that corresponds to a statically unstable sounding. Further discussion is given below.

Now, with reference to the inequality (7), we write the following equation:

$$\frac{\partial f}{\partial\sigma} + \frac{dg}{d\sigma}\theta_{\min} + g\left(\frac{\partial\theta}{\partial\sigma}\right)_{\min} = 0\,. \tag{10}$$

Recall that $g(\sigma)$ has already been specified in such a way that (8) is satisfied. If the equality (10) is satisfied, then the inequality (7) will also be satisfied, i.e., ζ will increase monotonically upward. *This will be true even if the sounding is statically unstable in some regions, provided that (9) is satisfied.*

Eq. (10) is a first-order ordinary differential equation for $f(\sigma)$, which can be solved subject to the boundary condition (6).

A pure sigma-coordinate model will predict temperature. A pure theta-coordinate model will predict the pseudo-density. A hybrid coordinate model must predict both, i.e., the hybrid coordinate model predicts “too much.” This is OK. Too much is better than not enough. Nevertheless, we must take care that the predicted temperature and pseudo-density fields are consistent with each other and remain so through time. Konor and Arakawa show that this requirement leads to an expression for the vertical mass flux as seen by the hybrid coordinate. The vertical mass flux takes the expected forms in the special cases of a pure sigma-coordinate and a pure theta-coordinate.

We use the hybrid coordinate discussed above to represent the “free atmosphere” above the top of the planetary boundary layer (PBL). The PBL top is a coordinate surface of the model (Suarez et al., 1983), and a fixed number of model layers, typically four, are allocated to represent the PBL’s internal vertical structure.

In principle, the solutions of a continuous model are independent of the choice of vertical coordinate. The solutions of a vertically discrete model can be strongly affected by the choice of vertical coordinate, however. Our hybrid-coordinate atmosphere uses the “Charney-Phillips” grid, or CP grid (Arakawa and Moorthi, 1988; Arakawa and Konor, 1996), in which the temperature and winds are predicted at different levels. The pseudo-density is predicted at the same levels as the wind. The water vapor mixing ratio is predicted at the same levels as the temperature, since the conversion of water vapor to liquid represents a heating (Konor and Arakawa, 2000).

Recently A. Arakawa and C. Konor (personal communication, 2004) have been exploring the possibility of generalizing the hybrid coordinate so that it follows the equivalent potential temperature wherever possible. This makes the coordinate more nearly Lagrangian when the air is saturated. When the air is dry but stably stratified, and away from the Earth’s surface, the coordinate reverts to potential temperature. Near the Earth’s surface and wherever the potential temperature decreases upward, the coordinate reverts to sigma.

Our intention is to represent the vertical structure of the ocean in much the same way as in the atmosphere model. The ocean model has been coded to use the “Arbitrary Lagrangian Eulerian” method. At present, the model layers are remapped to surfaces of constant depth once per hour. In the near future we intend to alter the model to follow isopycnal surfaces where feasible. This work is being carried out in collaboration with scientists at LANL.

4 Current status of the hybrid-coordinate geodesic atmosphere and ocean models

As discussed above, the Z-grid geodesic dynamics has been extensively tested in both shallow-water and three-dimensional configurations, including tests with full atmospheric physics. The hybrid-coordinate geodesic atmosphere model has also been extensively tested in a "dry-dynamics" mode. Recently, the hybrid-coordinate geodesic atmosphere model has been endowed with a full set of physical parameterizations similar to those used by Ringler et al. (2000). This very large job was just completed within the last two months. The full-physics model is currently being debugged.

The geodesic ocean model has been running successfully since the summer of 2003. Multi-decade simulations have been performed at various resolutions, using observed atmospheric forcing. We have also performed a short coupled run, in which the ocean model was coupled to an earlier (sigma-coordinate) version of the geodesic atmosphere model, using the coupler described below. The results are quite encouraging.

5 Sea-ice and land-surface submodels

A geodesic sea-ice model has been developed by Don Stark of the NPGS, Todd Ringler of CSU, and Bill Lipscomb of LANL. Sea-ice is represented on the ocean model's grid. The model uses the elastic-viscous-plastic rheology developed by Hunke and Dukowicz (1997), modified for the geodesic grid. The thermodynamics processes of the ice are modeled following Bitz and Lipscomb (1999). We are experimenting with a remapping algorithm for sea-ice transport (Lipscomb and Ringler, personal communication, 2004).

The land-surface model is the third-generation version of the Simple Biosphere Model (SiB), originally developed by P. Sellers and colleagues (e.g., Sellers et al., 1996), and further developed by A. S. Denning and colleagues of CSU. The land-surface model uses the same grid as the ocean and sea-ice models.

6 Coupler

There are very important exchanges of energy, mass, and momentum across the Earth's surface. For example, water evaporates from the ocean and appears as water vapor in the atmosphere. In a climate model, these fluxes are computed by an interface routine called a "coupler." One of the attractions of using geodesic grids for both the atmosphere and the ocean models is that it greatly simplifies the design of an efficient, parallel coupler.

For dynamical reasons, ocean GCMs require higher horizontal resolution than atmosphere GCMs. To ensure satisfactory coupling of the ocean and the atmosphere, the air-sea fluxes due to turbulence must be computed at the higher resolution of the ocean model. The various atmospheric variables needed to compute these fluxes must be interpolated from the atmosphere model's coarse grid to the ocean model's fine grid. The fluxes must then be averaged back to the coarser atmosphere grid, in such a way that the globally averaged surface flux is the same on both grids. We use the methods developed by Jones (1999).

In addition, atmospheric fluxes due to precipitation and radiation, computed on the atmosphere model's coarse grid, must be interpolated to the fine grid of the ocean model in such a way that the globally averaged surface flux is the same on both grids. Similar comments apply to communications between the atmosphere and land-surface models. The coupler consists of the computational machinery needed to perform these various steps. A coupler which must be designed to facilitate communications and interactions among the various sub-models.

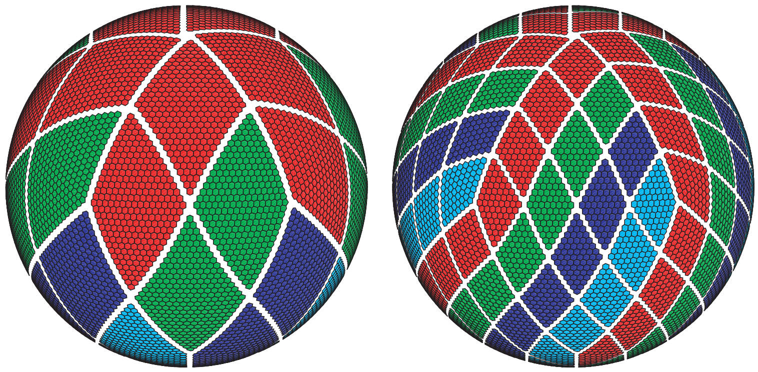

Figure 2: A two-dimensional field decomposed into 40 logically square blocks of data (left) and into 160 logically square blocks of data (right).

A two-dimensional field on the spherical geodesic grid can be represented using a data decomposition that consists of a collection of logically rectangular two-dimensional arrays. Figure 2 depicts two examples of such data structures. In Figure 2 a we decompose the grid into 40 blocks, while in Figure 2 b we use 160 blocks. In our model, each process "owns" one or more (generally more) blocks of the atmosphere grid and one or more corresponding blocks of the surface grid. Atmosphere blocks and surface blocks very nearly coincide, i.e. each atmosphere block is underlain by essentially one nearly congruent surface block. Each process owns N atmosphere points and M surface points, *where N and M are the same for all processes*. Multiple blocks that belong to a process need not necessarily be geographically contiguous. We can load-balance the global model by allocating blocks to processes in such a way that similar "mixes" of land and ocean points are assigned to all processes.

Further discussion of the coupler is given by Randall et al. (2002).

7 Conclusions

In summary, we have created an architecturally unified global modeling framework based on geodesic grids and quasi-Lagrangian vertical coordinates, including models of the atmosphere, ocean, sea ice, and land surface. More information about the model can be found on our web site (http://kiwi.atmos.colostate.edu/DOE_Cooperative_Agreement/).

Our primary focus at present is completing the debugging of the full-physics atmosphere model. Once this has been done, we will carry out extensive tests of the atmospheric model. We fully expect that various problems will be encountered with the radical new formulation.

As soon as the atmosphere model is giving satisfactory results, we will perform annual-cycle simulations with the full coupled system. Undoubtedly additional problems will be encountered at this stage.

The most important output of our work is the new knowledge that will come as we learn to overcome the various problems, and explore the behavior of our new modeling system.

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