A geodesic atmospheric model with a quasi-Lagrangian vertical coordinate

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Abstract. The development of the Coupled Colorado State Model (CCoSM) is ultimately motivated by the need to predict and study climate change. All components of CCoSM innovatively blend unique design ideas and advanced computational techniques. The atmospheric model combines a geodesic horizontal grid with a quasi-Lagrangian vertical coordinate to improve the quality of simulations, particularly that of moisture and cloud distributions. Here we briefly describe the dynamical core, physical parameterizations and computational aspects of the atmospheric model, and present our preliminary numerical results. We also briefly discuss the rational behind our design choices and selection of computational techniques.

1. Introduction
The geodesic atmospheric model with a quasi-Lagrangian vertical coordinate is being developed as a part of the “Coupled Colorado State Model (CCoSM)”. The CCoSM consists of coupled atmosphere, ocean, sea ice, and land surface components. A coupler provides the communications between the components.

Each component of CCoSM is based on geodesic grids [1]. The geodesic grid eliminates the pole problem while providing approximately homogeneous resolution and isotropic distribution of grid points over the entire sphere. The advantages of using the geodesic grid are enhanced with the use of vorticity-divergence equations. The atmosphere and ocean models make use of quasi-Lagrangian vertical coordinates. The atmospheric component uses the generalized vertical coordinate configured as a hybrid isentropic-sigma type in the free atmosphere [2]. The isentropic surfaces, which are surfaces of constant potential temperature, are quasi-Lagrangian surfaces in the atmosphere because the potential temperature is entirely conserved for adiabatic motion and nearly conserved under diabatic processes. Because of the reduced truncation errors due to minimized vertical advection with a quasi-Lagrangian coordinate, it is expected that the model predicts the moisture and, therefore, cloud distribution more accurately than is possible with a pressure based coordinate model. This type of model has obvious advantages for consistent simulations of climate because atmospheric processes such as radiation are greatly effected by the cloud distribution.

In our model, the planetary boundary layer (PBL) is separated from the free atmosphere by a material surface, which is referred to as the PBL-top. Only physical parameterizations within the PBL determine the mass exchange between the PBL and the free atmosphere. This treatment is
advantageous to effectively simulate the processes, such as PBL-top cloud formation and dissolution, confined or originated near the PBL-top.

The atmospheric model combines this dynamical core with the physics package previously developed at CSU. All components have been parallelized using MPI and ported to a variety of computational platforms.

2. Dynamical Core of the Atmospheric Model
In this section we will describe the dynamical core of the atmospheric model and computational aspects.

2.1. Horizontal structure
We use a geodesic grid similar to that proposed by [3] and [4]. Our geodesic grid is constructed from an icosahedron by recursively bisecting and subdividing each triangular face and projecting the new vertices to the sphere. The polyhedra generated through this process progressively approximate a sphere. A Voronoi cell is associated with each vertex. These cells are the control volumes for our finite-volume operators. The positions of the bisection grid points are then adjusted to optimize the order of accuracy of the finite-difference operators. This is discussed in [5].

The horizontal differencing follows [6]. The model predicts momentum in the form of vorticity and divergence without staggering to maintain the advantages of the Z-grid discussed by [7]. Vorticity and divergence are scalar quantities; hence this formulation avoids the difficulties associated with vector-valued functions near the poles. We diagnose a streamfunction and velocity potential each time step using a pair of elliptic equations. This is done with multigrid on the spherical geodesic grid. The multigrid solver consumes approximately 15% of CPU time. Considerable effort has been applied to optimize this piece of code to perform well in a parallel computing environment.

2.2. Vertical structure
We use the generalized vertical coordinate introduced by [2], which is essentially designed to combine a sigma-coordinate at and near Earth’s surface with an isentropic coordinate aloft. The coordinate is defined for smooth and quick transition from sigma to isentropic. In this way, we take advantage of the terrain-following sigma coordinate near the surface, and a quasi-Lagrangian isentropic coordinate throughout the majority of the model atmosphere.

The vertical discretization of the generalized vertical coordinate model becomes identical to that of the isentropic coordinate model designed by [8] when the vertical coordinate is selected as potential temperature. Therefore, it maintains the advantages of that isentropic coordinate model. On the other hand, when the generalized vertical coordinate is selected as sigma or any function of pressure, the vertical structure of the model mimics a model based on the Charney-Phillips vertical grid, which excludes disadvantages of the Lorenz-grid. Consistent with this staggering, mass, vorticity and divergence are defined within the model layer and potential temperature and tracers are defined at layer interfaces.

A selectable number of layers at Earth’s surface is assigned as the planetary boundary layer (PBL) and the depth of the PBL is predicted through a mass budget equation including the effects of PBL-top entrainment, cumulus mass flux and horizontal mass convergence within the PBL [9]. The PBL-top is treated as a material surface in the absence of entrainment and cumulus mass flux. With this treatment, the PBL-top discontinuity particularly seen in the temperature and moisture fields can be easily maintained in the discrete model. It is shown that this type of PBL is beneficial in realistically simulating the PBL-top clouds, which play an important role in coupled atmospheric-oceanic systems.

3. Numerical Tests with the Dry Dynamical Core
Recently [10] have proposed a test case for dynamical cores. The initial condition for the test is comprised of a zonally symmetric jet centered at 45N and 45S, balanced thermal and mass fields and a
superimposed small-amplitude perturbation of wind. The initial conditions are prescribed as analytic functions of longitude, latitude and pressure, so they can be readily applied to the geodesic grid and hybrid vertical coordinate without the need for interpolation. This disturbance is expected to evolve to resemble an extratropical disturbance as shown by [10].

We have performed tests suggested by [10] with our dynamical core using various resolutions and model parameters. Here we present results with 40962 cells and 163842 cells and 27 vertical layers. These correspond to approximately 120 km and 60 km horizontal resolutions, respectively. For the cases presented here, we did not include any explicit horizontal diffusion. Temperature and relative vorticity fields simulated using the resolutions above and interpolated to 850 mb at day 9 are presented in figure 1. The model with both resolutions produce a realistic evolution of the extratropical disturbances while the model with high resolution better captures fine scale structure associated with the wave development.

**Figure 1.** Simulated temperature (left column) and vorticity (right column) interpolated to 850 mb at day 9. Upper and lower rows show fields obtained by 40642 cells and 163842 cells resolutions, respectively.

4. Model Physics
The physics package has been developed at CSU for more than a decade. Cumulus convection is parameterized following the Arakawa-Schubert approach with a prognostic closure [11] and multiple cloud-base levels [12]. The stratiform cloud parameterization involves prediction of four condensed-water species in addition to water vapor, and is based on the work of [13]. The radiation parameterization is based on the work of [14] and [15]. The optical properties of the clouds are determined using the predicted distribution of condensed water. The PBL parameterization combines the effects of large convective and small diffusive eddies to determine the turbulence fluxes in a multi-layer framework, and is based on the work of [9].

5. Aquaplanet Simulations
To demonstrate the performance of the model with full physics, we have simulated the climate of an aqua-planet with perpetual January conditions. In this simulation the planet is entirely covered with ocean and the zonally symmetric sea surface temperatures are prescribed from January conditions. In the simulations, we use 2562 cells in the horizontal with 32 layers in the vertical.

Here we show two simulations with different vertical coordinate configurations. In the first simulation, we use a “mostly sigma” vertical coordinate, which covers the troposphere with a sigma coordinate and becomes isentropic in the stratosphere and above. In the second simulation, we use a
“mostly isentropic” coordinate, which completes its transition from the sigma to isentropic in the lower troposphere. The vertical distribution of the vertical coordinate surfaces for the “mostly sigma” and “mostly isentropic” simulations at the initial time is shown in the left upper and lower panels of figure 2, respectively. Three-month long simulations are performed with both models and selected zonally averaged fields are shown in figure 2. The upper and lower panels show results from the mostly sigma and mostly isentropic simulations, respectively. The figure shows that the moisture is more confined to the lower layers in the “mostly isentropic” simulation than in the “mostly sigma” simulation. Additionally, there is less cloud ice in the winter stratosphere in the “mostly isentropic” simulation than in the “mostly sigma” simulation. These differences are expected between a coordinate with enhanced quasi-Lagrangian characteristics such as the “mostly isentropic” coordinate and an ordinary “mostly sigma” coordinate.

Figure 2. Initial coordinate surfaces (left column) and simulated fields from the “mostly sigma” (upper panel) and “mostly isentropic” (lower panel) models. The middle and right columns are the water-vapor mixing ratio and the cloud-ice mixing ratio, respectively.

6. Ongoing research
The current data structure decomposed the geodesic grid into logically rectangular blocks that were mapped to 2D square arrays. These arrays use conventional (i,j) indexing. There is a single row of ghost cells along the parameter of each block. This single row limits the size of the computational stencil and prevents higher-order operators. We now are testing a new model with a more extensible data structure. This data structure uses linked lists to connect neighboring grid points, which allows for any number of ghost points.

A new time integration scheme called multi-point differencing (MED) scheme is being constructed by [16], which is an explicit scheme that mimics the implicit trapezoidal scheme except that it uses information from local grid points. Our next version of the dynamical core will use the new data structure and the MED time-integration scheme.

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