Nonhydrostatic atmospheric modeling with a hybrid vertical coordinate

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The primary research goal of CMMAP is to better understand the effect of cloud processes on the global climate through the development of new atmospheric modeling methods. One area we are exploring is the benefit of using quasi-Lagrangian (QL) vertical coordinates in cloud resolving models (CRMs). In a PhD thesis project at Colorado State University, a model has been developed to examine the feasibility of using such a coordinate, and the possibility that it will lead to improved cloud simulations when implemented in a CRM.

CRMs typically use a fixed-in-space Eulerian vertical coordinate such as geometric height. The accurate representation of the vertical transport of water vapor, aerosols and chemical species across model surfaces can be difficult with such coordinates. The use of a QL coordinate virtually eliminates the computational error associated with vertical transport because coordinate surfaces approximate fluid material surfaces, and therefore the mass transport across model surfaces is minimal. There has been much success with QL coordinates in low-resolution, hydrostatic models that simulate large-scale motion (e.g., Konor and Arakawa 1997; Benjamin et al. 2004). However, the coordinate surfaces become very irregular when they are used in nonhydrostatic models that simulate the fine scale, turbulent motion characteristic of cloud-scale flow. The new model we have developed overcomes this problem by combining the features of QL and Eulerian coordinates. Our approach builds on the methods of Konor and Arakawa (1997) and uses techniques similar to those recently developed for nonhydrostatic models (He 2002; Zangl 2007).

The model uses a hybrid vertical coordinate which is a terrain-following height-based (Eulerian) coordinate near the bottom surface and transitions to a potential temperature (θ) coordinate with height. For adiabatic processes, air parcels conserve their value of potential temperature, so θ is a QL coordinate. At this time the model is dry, so clouds cannot yet be modeled. Nevertheless the model has been tested for the case of a breaking mountain wave, and it is able to represent turbulence on scales expected in cloud circulations.

An adaptive grid technique is used to prevent the QL coordinate surfaces from becoming too spatially irregular as the waves develop. This is done by allowing mass to cross model surfaces in such a way as to keep them smooth and to prevent layers from becoming too thin. As a result, in the locations where the flow is turbulent, the coordinate becomes Eulerian in nature, and some of the benefit of the QL coordinate is lost. However, this is necessary for the success of the simulation, and it only has a temporary and local effect. As the turbulence subsides, the adaptive grid is designed to return the coordinate to its original target value.

The test we performed is a 2-dimensional simulation of the 11 January 1972 Boulder, Colorado windstorm (Doyle et al. 2000). The horizontal domain is 220 km in extent with periodic boundary conditions and the horizontal grid size is 1 km. There are 125 model levels and the model top is a rigid lid at a height of 25 km. The Front Range is represented by a simple curve with a height of 2000 m.

The advantage of the QL coordinate in terms of the vertical transport of a passive tracer is shown in Figure 1. The initial tracer concentration is shown in the top left plot as a function of height (vertical axis) and horizontal distance (horizontal axis). The concentration has a value of one along four horizontal bands bounded by selected isolines of potential temperature (isentropes), and a value of zero elsewhere. At the top right is a scatter plot of the initial values of θ (vertical axis) versus tracer concentration (horizontal axis) for all model grid points. Since the flow over the mountain is adiabatic and the tracer is passive, the correlation between θ and tracer concentration should remain unchanged. The middle row of plots shows the result of a 75 minute simulation with a pure Eulerian coordinate. Dispersion error due to vertical transport is apparent in both the spatial distribution of tracer concentration as well as in the scatter plot. The bottom row shows that with the hybrid coordinate model, in the upper half of the domain where the coordinate is θ, the tracer concentration has maintained its initial correlation with potential temperature. This is due to the vertical mass flux being close to zero in θ-coordinates, and therefore producing little dispersion error.

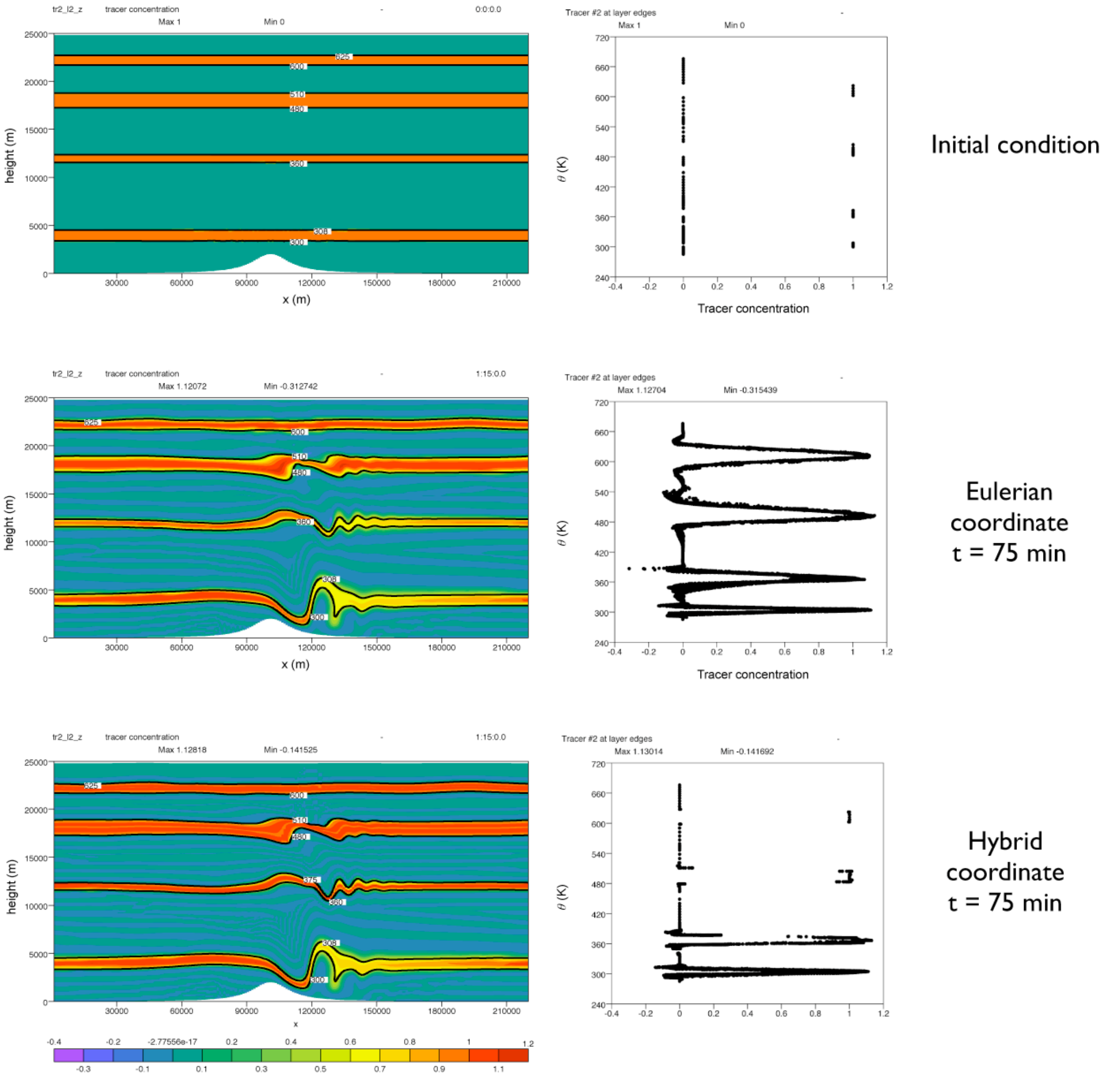

Figure 1. Tracer transport: Eulerian vs. hybrid coordinate.

Figure 2 shows that the hybrid-coordinate model is able to simulate the turbulent flow that develops as the mountain waves break. Isolines of potential temperature (black lines) and model levels (red lines) are shown at 3.5 hours into the simulation. Eulerian coordinate results are shown in the top plot, and hybrid coordinate results are in the bottom plot. The adaptive vertical grid of the hybrid-coordinate model performs as designed in that the coordinate surfaces remain smooth and evenly spaced in regions of wave breaking where the isentropes overturn. Here the coordinate is Eulerian in nature as the isentropes, which approximate streamlines, cross coordinate surfaces. Where the wave amplitude is small, the coordinate surfaces are quasi-Lagrangian in nature since they follow the isentropes.

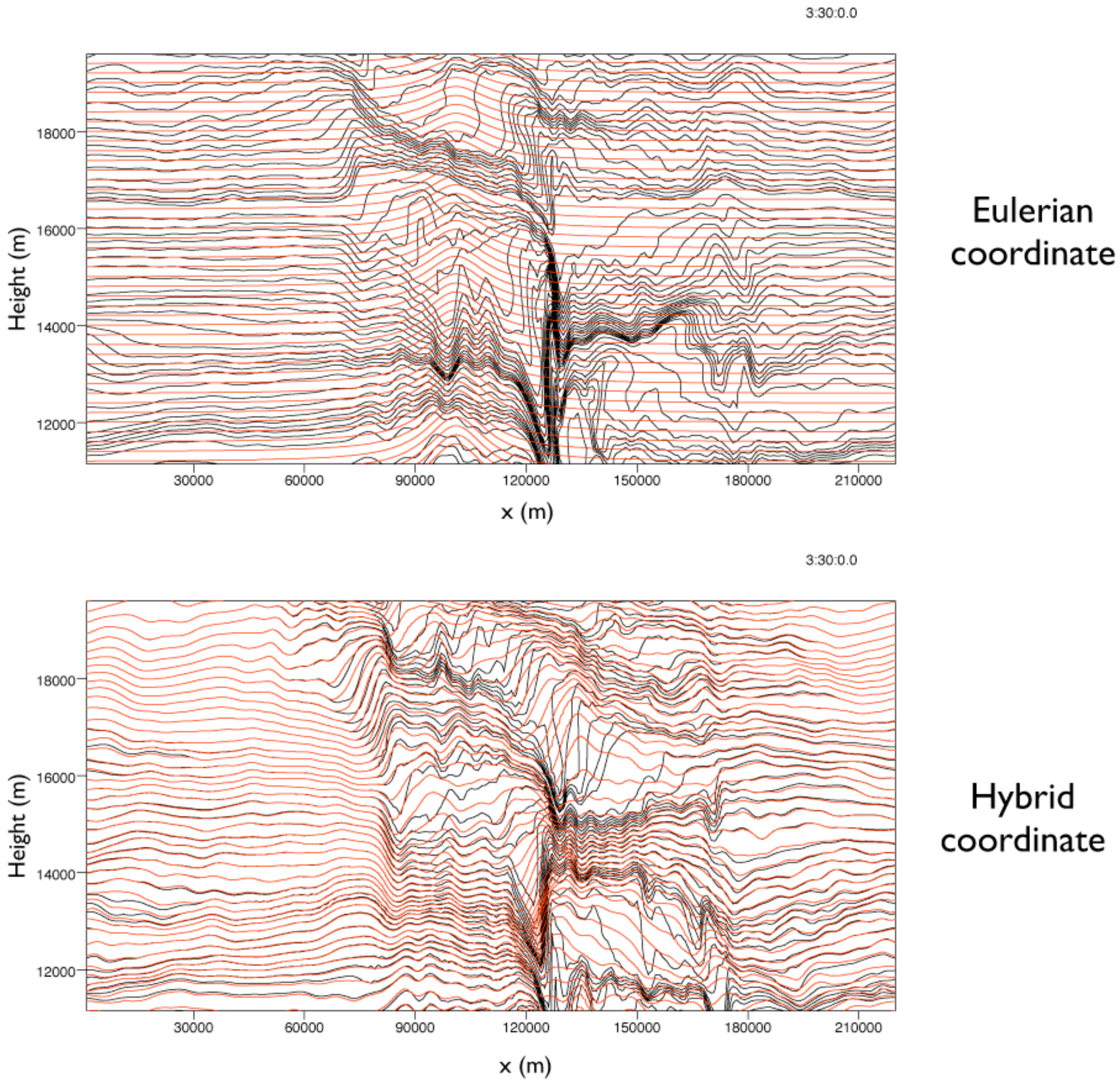

Figure 2. Position of isentropes (black lines) with respect to model coordinate surfaces (red lines) with an Eulerian coordinate model (top) and hybrid coordinate (bottom).

Initial tests indicate that there are potential benefits to using a hybrid vertical coordinate in cloud resolving models. The quasi-Lagrangian nature of the θ-coordinate improves the representation of vertical tracer transport which, when applied to moisture, could improve the simulated vertical cloud distribution. Since this distribution has a large impact on the atmospheric energy budget, a better representation of the role of clouds on climate may result.

REFERENCES

Benjamin, S. G., G. A. Grell, J. M. Brown, and T. G. Smirnova, 2004: Mesoscale weather prediction with the RUC hybrid isentropic-terrain-following coordinate model. *Mon. Wea. Rev.,* **132,** 473-494.

Doyle, J. D., D. R. Durran, C. Chen, B. A. Colle, M. Georgelin, V. Grubisic, W. R. Hsu, C. Y. Huang, D. Landau, Y. L. Lin, G. S. Poulus, W. Y. Sun, D. B. Weber, M. G. Wurtele, and M. Xue, 2000: An intercomparison of model-predicted wave breaking for the 11 January 1972 Boulder windstorm. *Mon. Wea. Rev.,* **128,** 901-914.

He, Z., 2002: A nonhydrostatic model with a generalized vertical coordinate. Ph.D. dissertations, University of Miami, 99pp.

Konor, C. S., and A. Arakawa, 1997: Design of an atmospheric model based on a generalized vertical coordinate. *Mon. Wea. Rev.,* **125,** 1649-1673.

Zangl, G., 2007: An adaptive vertical coordinate formulation for a nonhydrostatic model with flux-form equations. *Mon. Wea. Rev.,* **135,** 228-239.