FINAL REPORT

Research Performed at Colorado State University under DOE Contract DE-FG02-04ER63848 "Formulation of Moist Dynamics and Physics for Future Climate Models"

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Overview

In this project, one of our goals is to develop atmospheric models, in which innovative ideas on improving the quality of moisture predictions can be tested. Our other goal is to develop an explicit time integration scheme based on the multi-point differencing (MED) that does the same job as an implicit trapezoidal scheme but uses information only from limited number of grid points. Below we discuss the work performed at Colorado State University toward these goals during the funding period indicated above.

1. Development of a PBL parameterization based on a predicted depth with multiple layers

In this project, we propose the development of a multi-layer variable-depth PBL parameterization, in which a bulk formulation based on a mixed-layer is used for the effect of penetrative large eddies while a K-closure type formulation is added for the effect of diffusive small eddies that couple the layers within the PBL. With this hybrid approach, the simulated profiles are allowed to deviate from the well-mixed profiles. The deviations are expected to be small for a convectively active PBL while they can be significantly large for a convectively inactive PBL. The multi-layer parameterization allows vertical shear of wind within the PBL. In this way, the model can capture the effect of the low-level vertical shear on the thermal field even when the PBL is very deep.

To implement the parameterization into a model, the PBL top is selected as a model coordinate, through which vertical mass fluxes due to physical processes such as PBL-top entrainment and cumulus mass flux are allowed. The PBL depth is prognostically determined from PBL-top mass flux and the convergence of the horizontal mass fluxes within the PBL. A modified sigma coordinate is used between the PBL-top and the surface. Thermodynamic quantities and momentum are predicted on a Charney-Phillips type vertical grid.

We have completed the basic development of the PBL parameterization and have successfully tested the parameterization in our limited area generalized vertical coordinate model (see Konor and Arakawa, 2005). The parameterization is also implemented to an atmospheric general circulation model (AGCM). A paper presenting the performance of the parameterization in that AGCM is being prepared.

2. Development of a dynamical core based on a quasi-Lagrangian vertical coordinate

One of the goals of this work is to make use of quasi-Lagrangian vertical coordinates in atmospheric models. It is expected that such a vertical coordinate positively impacts the predicted distribution of moisture in an atmospheric model. To meet that goal, the dynamical core of the model we have been developing is based on a generalized vertical coordinate. In the free atmosphere, the vertical coordinate is a hybrid combination of sigma and quasi-Lagrangian isentropic types. Within the PBL, a modified sigma coordinate is used. The vertical grid structure of the model is carefully selected to reflect the effects of condensation heating on the effective stability. The horizontal discretization of the dynamical core uses a geodesic grid on a sphere. We incorporated CSU's physics package into the dynamical core to build a new AGCM. This model is a part of the Coupled Colorado State University Model, which is being developed with a funding from the DOE under a cooperative agreement.

To examine the performance of the atmospheric model with the full physics, we made aqua-planet simulations with perpetual January conditions. At this stage, our tests focus on the impact of the quasi-Lagrangian isentropic coordinate to the simulated moisture field. For that purpose, we prepared two different configurations of the model, which differ only in their vertical coordinate. The first model configuration virtually uses a sigma type coordinate through out the atmosphere, which is called the "mostly sigma" model. The second model configuration uses an isentropic coordinate in the middle troposphere and above, which is called "mostly isentropic" model. Typical vertical distributions of the coordinate surfaces in both configurations are presented in Fig. 1.

Vertical coordinate of "mostly sigma" model ***Vertical coordinate of "mostly sigma" model***

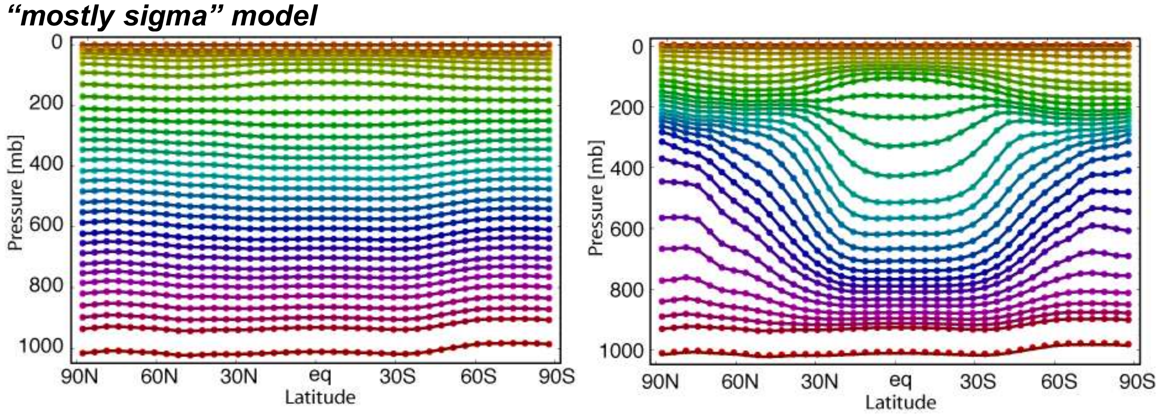

Fig. 1. North-South cross-sections of zonal mean coordinate surfaces at the initial time of the simulations with (a) the "mostly sigma" model and (b) the "mostly isentropic" model. The lowest surface corresponds to Earth's surface and the second coordinate surface from the bottom is the PBL-top. For the cases we discuss here, the PBL is a single layer.

We performed three-month long simulations with these two model configurations. The simulated zonally mean temperature, zonal wind, water-vapor mixing ratio, cloud-ice mixing ratio and cloud-liquid water mixing ratio are presented in Fig. 2. Note that the presented are also time-averaged fields for the last 30-day period of

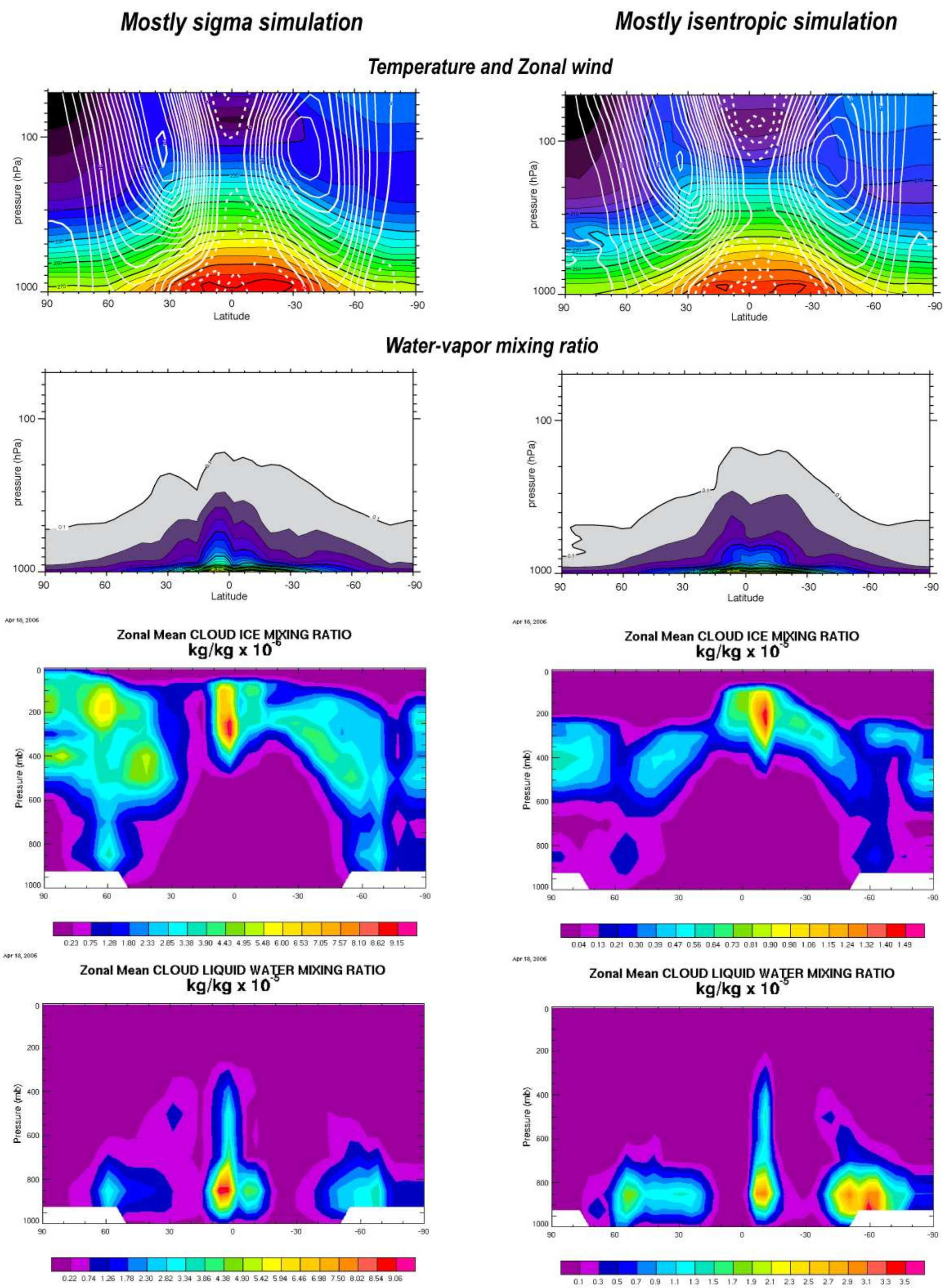

Fig. 2. North-South cross-sections of zonal mean fields. The left and right columns show results from the "mostly sigma" and "mostly isentropic" simulations, respectively.

a three-month long run. These figures show that the moisture appears more confined to the lower levels and there is much less cloud-ice in the winter hemisphere at upper troposphere and lower stratosphere in the mostly isentropic simulation than that in the mostly sigma simulation. This is consistent with the use of a quasi-Lagrangian isentropic coordinate, which minimizes vertical computational diffusion.

3. Development of an explicit time integration based on the MED

To be able to use long time steps in the integration of the atmospheric models, we propose a new explicit time integration scheme that is equivalent to an implicit trapezoidal scheme. The explicit scheme uses the multi-point differencing (MED) that requires information from the grid points within a limited domain of dependence, the size of which varies with the Courant number. This scheme with a time step corresponding to the large Courant number for the fastest moving wave is an alternative to the semi-implicit scheme. Since the semi-implicit scheme requires information from all the grid points in the domain, the explicit scheme based on the MED approach is expected to be more computationally efficient than the semi-implicit scheme, particularly for models with high horizontal resolution. We also develop a procedure to apply the scheme to an arbitrary horizontal grid, by which the scheme can be applied to the geodesic grid. The tests of the scheme in a shallow-water model with a geodesic grid on a sphere is on the way. The basic design of the scheme and its application to the shallow-water equations on square and hexagonal grids are presented by Konor and Arakawa (2006). Here we show an example of the simulation of surface waves obtained by using the explicit time integration scheme on a square grid (see Fig. 3). The time-step used in these simulations corresponds to the Courant numbers equal to and larger than one.

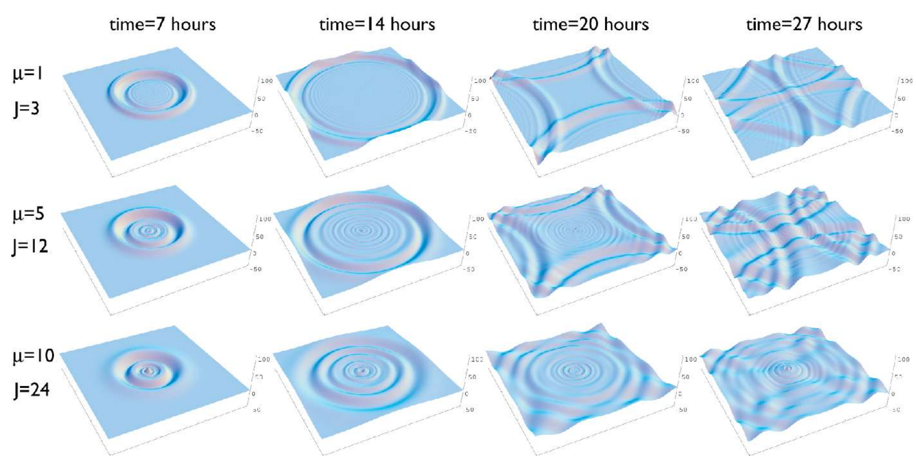

Fig. 3. Simulations of surface wave propagation obtained from the shallow-water model with the explicit time integration scheme based on the MED. In these simulations, the fluid depth is H=10 km and grid distance is d=100 km. The time-step is determined from $\Delta t \equiv \mu\delta/\sqrt{\gamma H}$***, where*** μ ***is the Courant number and g is the gravitational acceleration. The square domain of dependence contains*** $(2J+1)^2$ ***grid points.***

We are preparing a paper that describes the application of the MED approach to the wave equation on the rectangular and geodesic grids. Additionally, we are working on the application of the MED approach to the advection equation, which is an alternative to the semi-Lagrangian advection scheme. A version of the MED is successfully applied to terms responsible for the fastest moving waves in an three-dimension hydrostatic atmospheric model with a generalized vertical coordinate. The application to 3-D models will be finalized with incorporating the MED scheme into the horizontal advection process.

References

Konor C. S. and A. Arakawa, 2005: Incorporation of moist processes and a PBL parameterization into the generalized vertical coordinate model. Colorado State University Atmospheric Science note **765**. 75 pp. Available from http://kiwi.atmos.colostate.edu/group/csk.

Konor C. S. and A. Arakawa, 2006: Multi-point explicit differencing (MED) for efficient time integrations of the wave equation. Colorado State University Atmospheric Science note **769**. 51 pp. Available from http://kiwi.atmos.colostate.edu/group/csk.