Final Technical Report for the U.S. Department of Energy Award DE-SC0006748 (SciDAC)
"Multiscale Simulation of Moist Global Atmospheric Flows"
W. W. Grabowski (PI) and P. K. Smolarkiewicz (co-PI)
Period of Performance: Sept. 15, 2011 – January 14, 2015

The overarching goal of this grant was to include phase changes of the water substance that accompany moist atmospheric flows into the all-scale atmospheric model based on soundproof equations and to advance the application of unstructured meshes used in our recent dry simulations to moist global flows. A postdoctoral researcher (Dr. Marcin Kurowski) was hired in summer 2012 after international search. Dr. Kurowski was involved in model development and numerical tests of the moist version of the EULAG model. Below we report specific activities and accomplishments during the project.

In collaborative research between Grabowski, Kurowski, and Smolarkiewicz, a moist version of the unified fully-compressible and anelastic model EULAG was developed and a range of numerical tests featuring moist flows were performed and analyzed. These tests include moist thermals rising in the stable-stratified environment (Grabowski and Clark, *J. Atmos. Sci*. 1991) and in the moist-neutral environment (Bryan and Fritsch, *Mon. Wea. Rev*. 2002), moist flow over a mesoscale topography (Grabowski and Smolarkiewicz, *Mon. Wea. Rev*. 2002), deep convection in a sheared environment (Weisman and Klemp, *Mon. Wea. Rev*. 1982), moist extension of the baroclinic wave on the sphere of Jablonowski and Williamson (*Q. J. R. Met. Soc*. 2006) and the moist extension of the Held-Suarez climate benchmark (Held and Suarez, *Bull. Amer. Met. Soc*., 1994). These developments formed the basis of two papers published and one submitted to *J. Atmos. Sci*. (Kurowski et al. 2013, 2014, 2015). In addition, numerous conference talks were presented over the course of the project. The highlight of the project is the development of the moist implicit compressible model that can be run applying time steps as long as the anelastic model, that is, limited only by the CLF stability of the fluid flow and not by the speed of acoustic modes that typically limit the stability of the explicit compressible models. Applying various versions of the EULAG model (anelastic, pseudo-incompressible and either explicit or implicit compressible) in the same numerical framework (based on the nonoscillatory-forward-in-time integration and the MPDATA advection scheme) allows for an unprecedented comparison between various model options and straightforward evaluation of the impact of various physical parameterizations on the model solutions.

The summary of key findings of the three papers is presented below.

Kurowski, M. J., W. W. Grabowski, P. K. Smolarkiewicz, 2013: Towards multiscale simulation of moist flows with soundproof equations. *J. Atmos. Sci.*, 70, 3995-4011.

This paper discusses the incorporation of phase changes of the water substance that accompany moist atmospheric flows into the all-scale atmospheric model based on soundproof equations. A specific issue involves developing a theoretical basis and practical implementation to include pressure perturbations associated with atmospheric circulations, from small scale to global, into representations of moist thermodynamics. In small-scale modeling using soundproof equations, pressure perturbations are obtained from the elliptic pressure solver and are typically excluded from the moist thermodynamics. This paper argues that in larger-scale flows, at least the hydrostatic component of the pressure perturbation needs to be included be- cause pressure variation in synoptic weather systems may affect moist thermodynamics in a way comparable to the temperature variations. As an illustration, two idealized test problems are considered: the small-scale moist thermal rising in a stratified environment and the moist mesoscale flow over idealized topography. The paper compares numerical solutions obtained with a fully compressible acoustic mode–resolving model and with two versions of the anelastic model, either including or excluding anelastic pressure perturbations in moist thermodynamics. The two versions of the anelastic model are referred to as the generalized and standard anelastic. In agreement with the scaling arguments, only negligible differences between anelastic and compressible solutions are simulated. Incorporation of the anelastic pressure perturbations into moist thermodynamics paves the way for future studies where larger-scale moist dynamics will be considered.

Kurowski, M. J., W. W. Grabowski, P. K. Smolarkiewicz, 2014: Anelastic and compressible simulation of moist deep convection. *J. Atmos. Sci.*, 71, 3767-3787.

The authors compare anelastic and compressible solutions for two moist deep convection benchmarks, a two-dimensional thermal rising in a saturated moist-neutral deep atmosphere, and a three-dimensional supercell formation. In the anelastic model, the pressure applied in the moist thermodynamics comes from either the environmental hydrostatically balanced pressure profile in the standard anelastic model or is combined with nonhydrostatic perturbations from the elliptic pressure solver in the generalized anelastic model. The compressible model applies either an explicit acoustic-mode-resolving scheme requiring short time steps or a novel implicit scheme allowing time steps as large as those used in the anelastic model. The consistency of the unified numerical framework facilitates direct comparisons of results obtained with an- elastic and compressible models.

The anelastic and compressible rising thermal solutions agree not only with each other but also with the previously published compressible benchmark solution based on the comprehensive representation of moist dynamics and thermodynamics. In contrast to earlier works focusing on the formulation of moist thermodynamics, the authors emphasize the compatibility of the initial conditions and document their impact on the benchmark solutions. Anelastic and compressible supercell solutions agree well for various versions of an- elastic and compressible models even for cloud updrafts reaching 15% of the speed of sound. The non- hydrostatic pressure perturbations turn out to have a negligible impact on the moist dynamics. Numerical and physical details of the simulations, such as the advection scheme, spatial and temporal resolution, or parameters of the subgrid-scale turbulence, have a more significant effect on the solutions than the particular equation system applied.

Kurowski, M. J., W. W. Grabowski, P. K. Smolarkiewicz, 2015: Anelastic and compressible simulation of moist dynamics at planetary scales. *J. Atmos. Sci.* (submitted).

Moist anelastic and compressible numerical solutions to the planetary baroclinic instability and climate benchmarks are compared. The solutions are obtained applying a consistent numerical framework for discrete integrations of the various nonhydrostatic flow equations. Moist extension of the baroclinic instability benchmark is formulated as an analog of the dry case. Flow patterns, surface vertical vorticity and pressure, total kinetic energy, power spectra, and total amount of condensed water are analyzed. The climate benchmark extends the baroclinic instability study by addressing long-term statistics of an idealized planetary equilibrium and associated meridional transports. Short-term deterministic anelastic and compressible solutions differ significantly. In particular, anelastic baroclinic eddies propagate faster and develop slower owing to, respectively, modified dispersion relation and abbreviated baroclinic vorticity production. These eddies also carry less kinetic energy and the onset of their rapid growth occurs later than for the compressible solutions. However, the differences between the two solutions are sensitive to initial conditions as they diminish for large-amplitude excitations of the instability. In particular, on the climatic time scales the anelastic and compressible solutions evince similar zonally averaged flow patterns with the matching meridional transports of entropy, momentum and moisture.