Anelastic and compressible simulation of moist deep convection

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Introduction

This study is part of our exploration of the nonhydrostatic moist modeling across scales, from small-scale cloud dynamics to planetary circulations, through a systematic comparisons of model solutions obtained applying soundproof (anelastic) and fully-compressible equations using the nonoscillatory-forward-in-time EULAG model. The model allows consistent integrations of various sets of the governing equations with only small differences in the numerics (Smolarkiewicz et al. 2014). Such an approach allows a confident quantification of impacts of mathematical differences on simulation results.

After testing small-scale cloud dynamics and orographic flows (Kurowski et al. 2013), this study compares results from two moist deep convection benchmarks. Deep convection is an example of a nonhydrostatic atmospheric flow that involves multiscale dynamics and extreme ranges of the temperature, pressure and humidity accompanied by strong vertical velocities. All these pose key questions about the efficacy of anelastic modeling of moist deep convection.

Moist dynamics and thermodynamics

Besides different formulations of the continuity equation, the most important differences between the anelastic (ANES) and compressible (COMP) systems concern the momentum equation:

COMP $$\frac{d\mathbf{u}}{dt} = -c_p\theta_d\nabla\pi'_m + \mathbf{g}\left(\frac{\theta_d'}{\theta_0}\right) + \ldots$$

ANES $$\frac{d\mathbf{u}}{dt} = -\nabla\left(c_p\theta_0\pi'\right) + \mathbf{g}\left(\frac{\theta_d'}{\theta_0}\right) + \ldots,$$

where θ_d is the density potential temperature, θ_0 denotes the hydrostatic horizontally homogeneous reference state, π and π_m are the dry and moist Exner functions, respectively, and all perturbations are derived with respect to the reference state.

Another important difference involves the treatment of pressure in the moist thermodynamics (i.e., formulation of the saturated water vapor mixing ratio and the conversion of θ to T):

$$p(x,y,z,t) = p_0(z) + p_H(x,y,z) + p'(x,y,z,t).$$

A scale analysis in Kurowski et al. (2013) suggests that pressure perturbations may have a significant impact on the saturation adjustment for severe (e.g. tornadic) circulations ($p' \neq 0$) and for large scale quasi-hydrostatic flows ($p_H \neq 0$). Kurowski et al. (2013) also show that the soundproof p' compares well with its compressible counterpart and can be used to reconstruct the full pressure in the anelastic system. However, experiments so far show only insignificant influence of p' on moist model results.

model acronym	governing equation set	Δt	p'	treatment of sound waves
ANES	*anelastic*	Δt_a	N	n/a
ANEG	*anelastic*	Δt_a	Y	n/a
ANESc	*anelastic*	Δt_c	N	n/a
COMP	*compressible*	Δt_a	Y	*implicit*
COMPa	*compressible*	Δt_a	N	*implicit*
COMPe	*compressible*	Δt_c	Y	*explicit*

TAB 1. EULAG model versions used in this study with an explanation of main differences in the governing equation sets, model timesteps (where "a" and "c" subscripts refer to the anelastic and acoustic compressible time step sizes), whether pressure perturbations p' are included in/excluded from (Y/N) moist thermodynamics, and how sound waves are treated in the compressible model.

2D case: moist-neutral convection

The first simulation set is the two-dimensional benchmark of Bryan and Fritsch (2002) designed for testing moist thermodynamics. The test assumes a moist-neutral saturated environment in which convection is initiated with a warm bubble. The moist processes are limited to condensation/evaporation only.

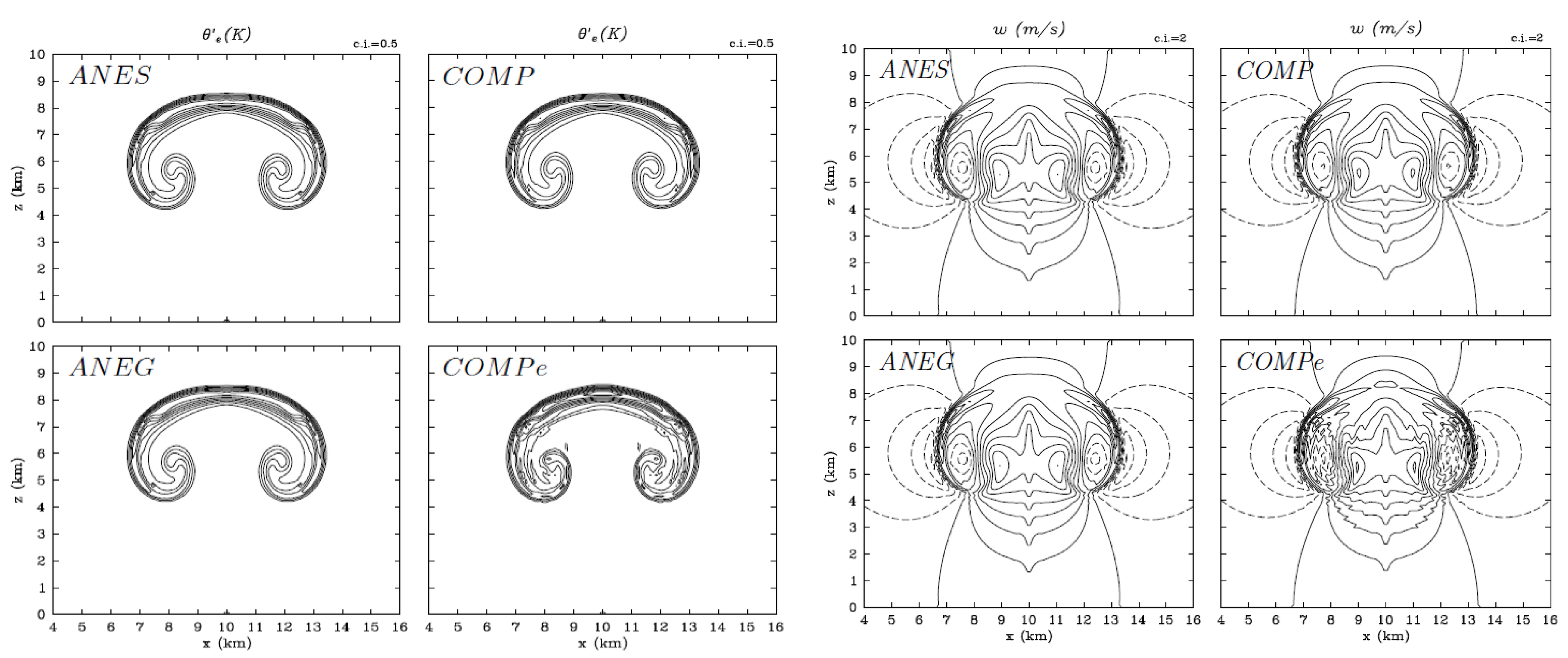


FIG 1. Comparison of anelastic and compressible solutions for the Bryan and Fritsch (2002) test at t=1000 s applying environmental profiles derived using EULAG's moist physics. All solutions agree (see Table 2) with those from Bryan and Fritsch (2002) who applied a comprehensive representation of moist thermodynamics. The main difference between various simulations comes from different time stepping that leads to different realizations of the advection-condensation problem. This results in more noisy solutions for smaller time steps.

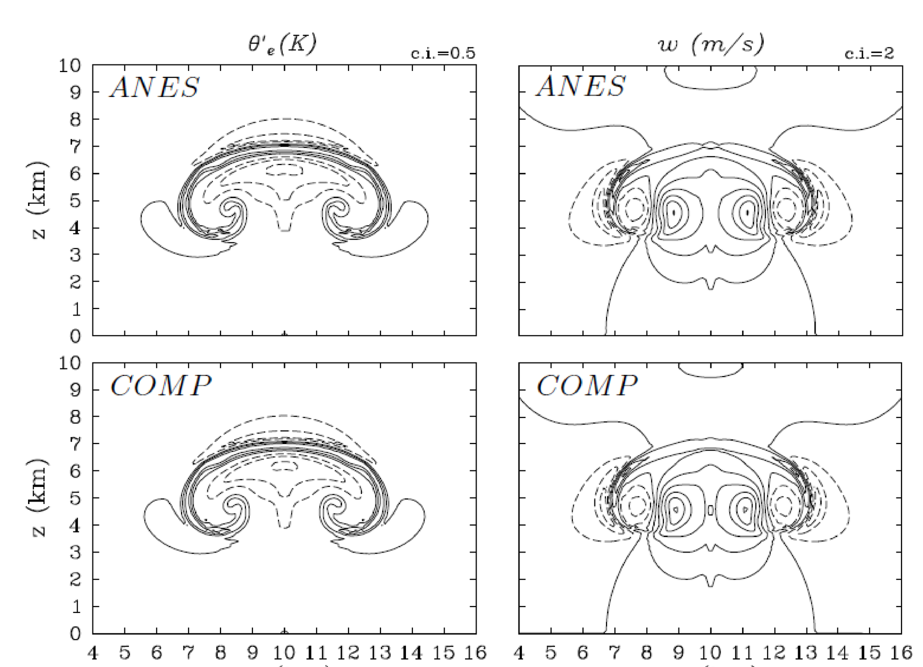


FIG 2. As in Fig. 1, but for the environmental profiles defined using energy equations from Bryan and Fritsch (2002) which are inconsistent with those in EULAG. The solutions are now significantly different. The main reason is the violation of compatibility conditions, that is, deriving environmental profiles with one set of equations and applying a different set in the model physics. The environmental state is now seen as slightly stable (see temperature perturbations below and above the thermal in left panels).

MODEL	θ'_e *min* [K]	*max* [K]	*avg* [K]	*std* [K]	w *min* [m/s]	*max* [m/s]	*std* [m/s]	p' *min* [Pa]	*max* [Pa]	*std* [Pa]	Z_{mean} [m]	Z_{top} [m]
BF02	-0.31	4.10	0.119	0.486	-9.93	15.71	3.34	-93.5	49.0	18.4	6450	8535
ANES	-0.17	4.07	0.127	0.515	-10.15	16.14	3.60	-107.0	51.0	20.2	6564	8655
COMP	-0.16	4.10	0.129	0.518	-10.00	16.30	3.54	-98.0	51.3	18.9	6580	8629
ANEG	-0.17	4.06	0.127	0.515	-10.15	16.14	3.60	-107.0	51.0	20.2	6564	8655
COMPa	-0.16	4.11	0.129	0.518	-10.00	16.30	3.54	-98.0	51.3	18.9	6580	8630
COMPe	-0.55	5.17	0.129	0.533	-9.64	16.35	3.44	-94.2	54.3	18.1	6604	8701
ANESc	-0.57	5.14	0.129	0.534	-9.66	16.32	3.54	-103.4	55.4	19.2	6640	8751

TAB 2. Comparison of Bryan and Fritsch (2002, BF02) and anelastic/compressible EULAG solutions for the moist-neutral benchmark at time of 1000s. Z_{mean} denotes the mean height of the bubble, whereas Z_{top} is the height of bubble top on the axis of symmetry. Model gridlength is 100m.

3D case: supercell formation

As an example of severe convection characterized by strong updrafts (~0.1 Ma), a large vertical extent, and intense vorticity dynamics, Weissman and Klemp (1982) supercell benchmark has been selected following Kurowski et al. (2011).

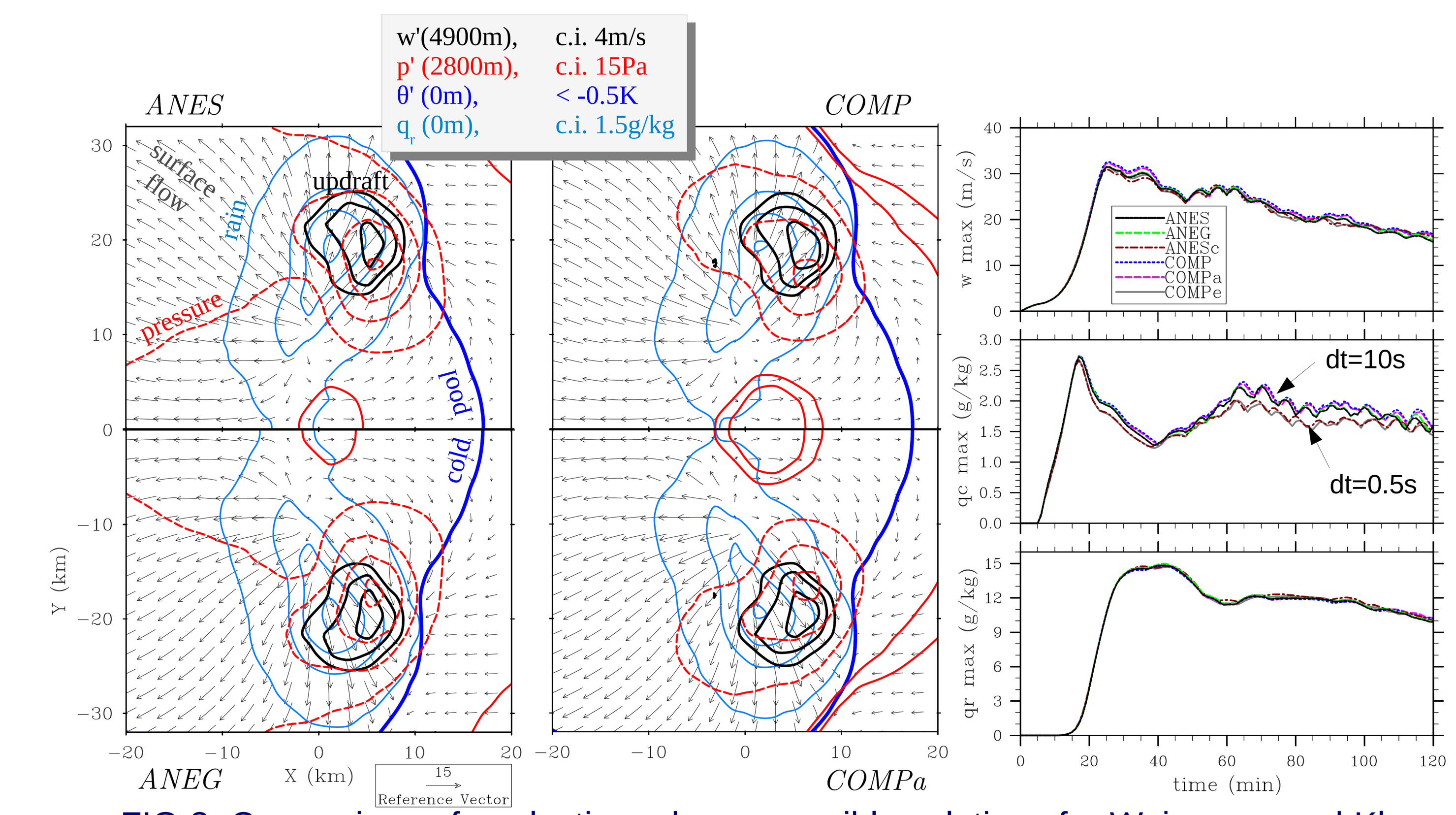
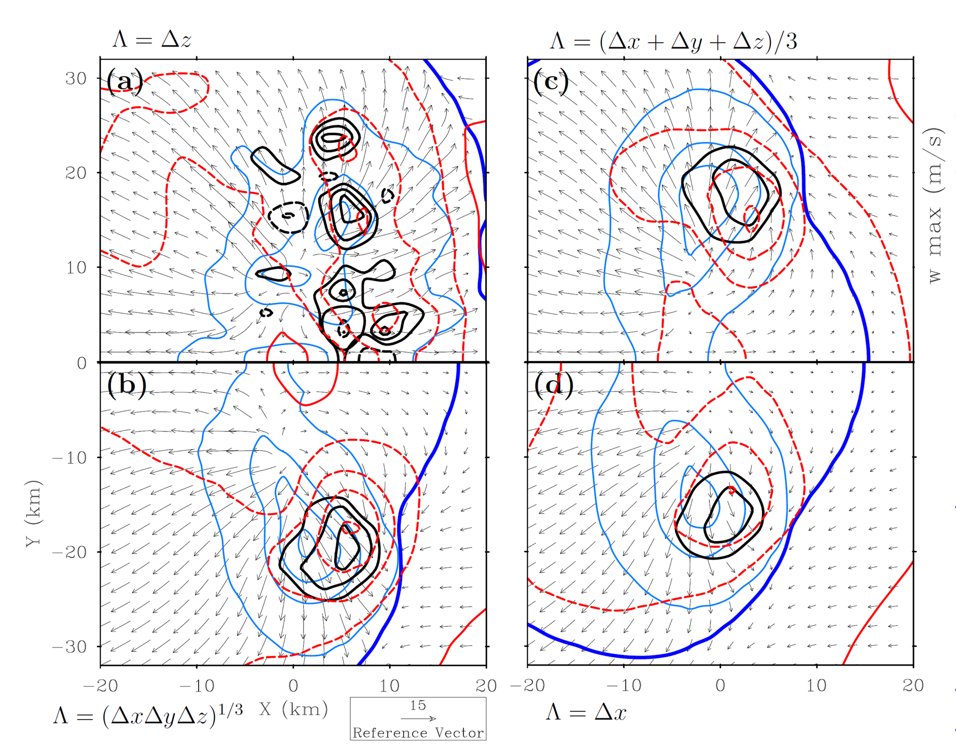


FIG 3. Comparison of anelastic and compressible solutions for Weissman and Klemp (1982) test at t=120 min. Only half of the solution is shown, either the left (upper panels) or the right (lower panels) supercell.



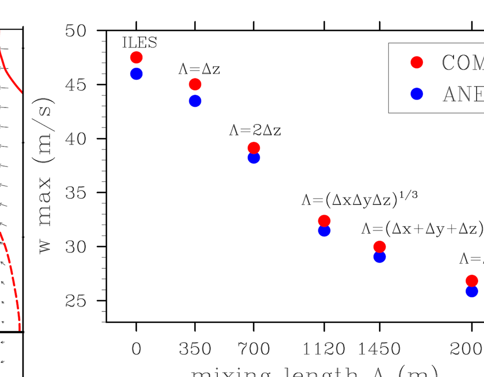


FIG 4. Comparison of four ANES solutions at 120 min applying different mixing length in the subgrid-scale model (panels to the left) and the maximum vertical velocity as a function of the mixing length for anelastic and compressible solutions (panel above).

Conclusions

- Anelastic approximation remains accurate for moist deep convection, even for updraft velocities close to 0.2 Ma.
- The sensitivity in the Bryan and Fritsch (2002) benchmark highlights the significance of the compatibility conditions and not the impact of the formulation of moist thermodynamics.
- The nonhydrostatic pressure perturbations in deep convection have an insignificant impact on the moist thermodynamics.
- Numerics and physics significantly affect model solutions. Meaningful comparisons of the type presented here are only possible when applying identical numerical frameworks and physical parameterizations.

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