Towards an all-scale cloud-resolving model

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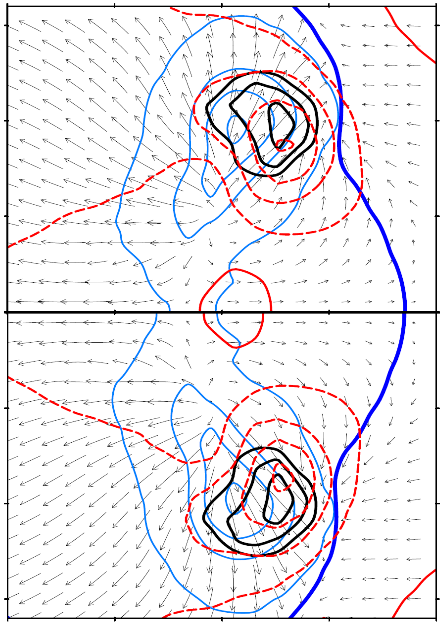
The goals: - to explore *moist* nonhydrostatic modeling across scales;
- to quantify the differences between compressible and soundproof models;

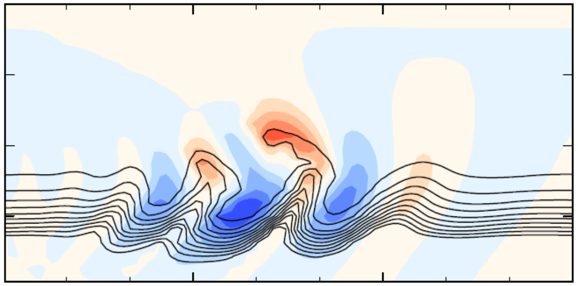
The tool: a consistent numerical framework of the EULAG model suitable for integrating the following equation sets:

- anelastic *(Lipps and Hemler, 1982)*
- pseudo-incompressible *(Durran, 1989)*
- fully-compressible *(explicit/implicit)*

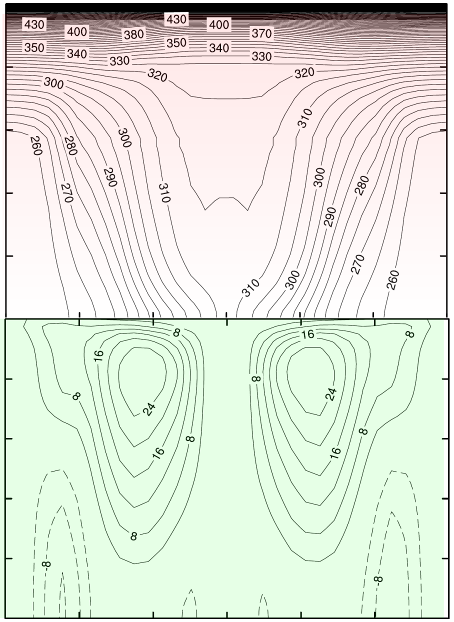
1. Deep convection



2. Weather



3. Climate



10 km — 10 000 km — 40 000 km

0.1 days — 10 days — 1000 days

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Introduction

This study explores nonhydrostatic moist modeling across scales, from small-scale cloud dynamics to planetary circulations, through a systematic comparison of model solutions obtained applying soundproof (i.e., anelastic or pseudo-incompressible) 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 facilitates 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 three distinct modeling problems: moist deep convection, moist baroclinic waves, and the Held-Suarez climate benchmark.

Moist dynamics and thermodynamics

Besides different formulations of the continuity equation, the most important differences between the soundproof (anelastic/ANES and pseudo-incompressible/PSIN) and compressible/COMP systems concern the momentum equation:

COMP $$\frac{d\boldsymbol{u}}{dt} = -c_p\theta_d\nabla\pi'_m \quad -\boldsymbol{g}\left(\frac{\theta'}{\theta_0}+0.61q'_v-q_c\right)\ -\boldsymbol{f}\times\boldsymbol{u}+\ldots$$

PSIN $$\frac{d\boldsymbol{u}}{dt} = -c_p\theta_d\nabla\pi' \quad -\boldsymbol{g}\left(\frac{\theta'}{\theta_0}+0.61q'_v-q_c\right)\ -\boldsymbol{f}\times\boldsymbol{u}+\ldots$$

ANES $$\frac{d\boldsymbol{u}}{dt} = -\nabla\left(c_p\theta_0\pi'\right)\ -\boldsymbol{g}\left(\frac{\theta'}{\theta_0}+0.61q'_v-q_c\right)\ -\boldsymbol{f}\times\boldsymbol{u}+\ldots$$

where $\theta_d=\theta(1+q_v/\epsilon)/(1+q_t)$ is the density temperature, π is the Exner function, q_v and q_c are the mixing ratios of water vapor and cloud water ($q_t=q_c+q_v$), and primes depict deviations from the hydrostatically balanced reference state denoted by the subscript *0*.

There are also significant differences in the way pressure (or pressure perturbation) enters the moist thermodynamics. The full pressure is needed for the saturated water vapor mixing ratio and, more importantly, for the conversion of the potential temperature into temperature for the saturated water vapor pressure. The full pressure combines the initial hydrostatically balanced base state (p_0), large-scale quasi-hydrostatic component (p_H) and nonhydrostatic perturbations (p'):

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

The scale analysis in Kurowski et al. (2013) suggests that pressure perturbations may have a non-negligible impact on the saturation adjustment for severe (e.g., tornadic) convection (because of significant p') and for large scale quasi-hydrostatic flows (because of significant p_H). Kurowski et al. (2013) also show that soundproof p'compares well with its compressible counterpart and can be used to reconstruct the full pressure required in the moist thermodynamics.

Moist deep convection

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

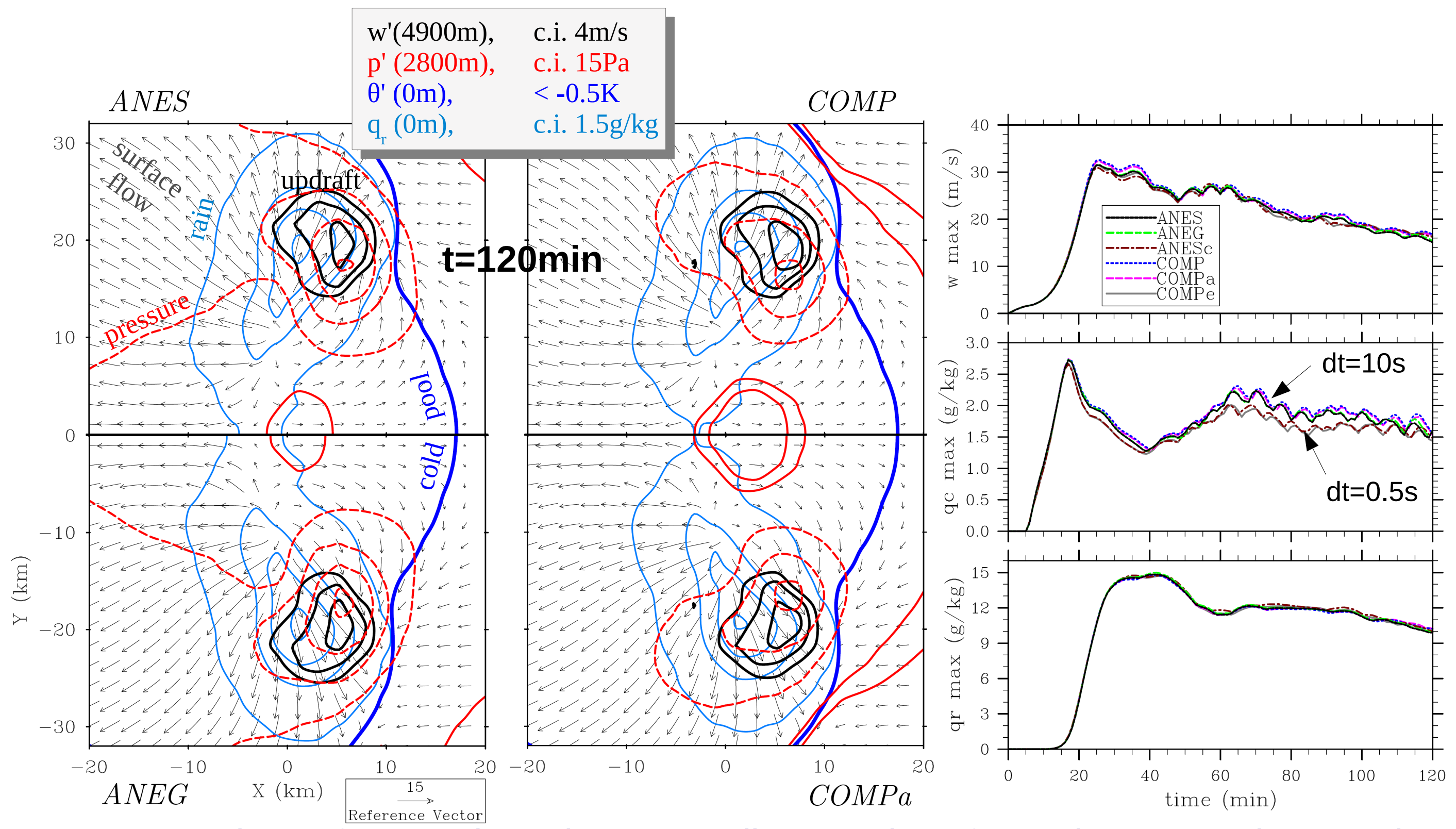

FIG 1. Comparison of anelastic and compressible solutions for Weissman and Klemp (1982). Six configurations have been tested: three compressible versions (COMP – standard implicit; COMPa – with the anelastic reference pressure, i.e. p'=0, COMPc – explicit with the acoustic time step) and three anelastic versions (ANES – standard anelastic; ANEG – generalized with p' included in moist thermodynamics; ANESc – with the acoustic time step).

Moist baroclinic wave

The moist baroclinic wave experiments follow the dry test of Jablonowski and Williamson (2006). The results from the dry EULAG test are presented in Smolarkiewicz et al. (2014). In the current test, we analyze a simplified setup for the moist baroclinic instability considering condensation/evaporation only. Initial surface relative humidity is set to 90% and it decreases exponentially with a 3km-height scale.

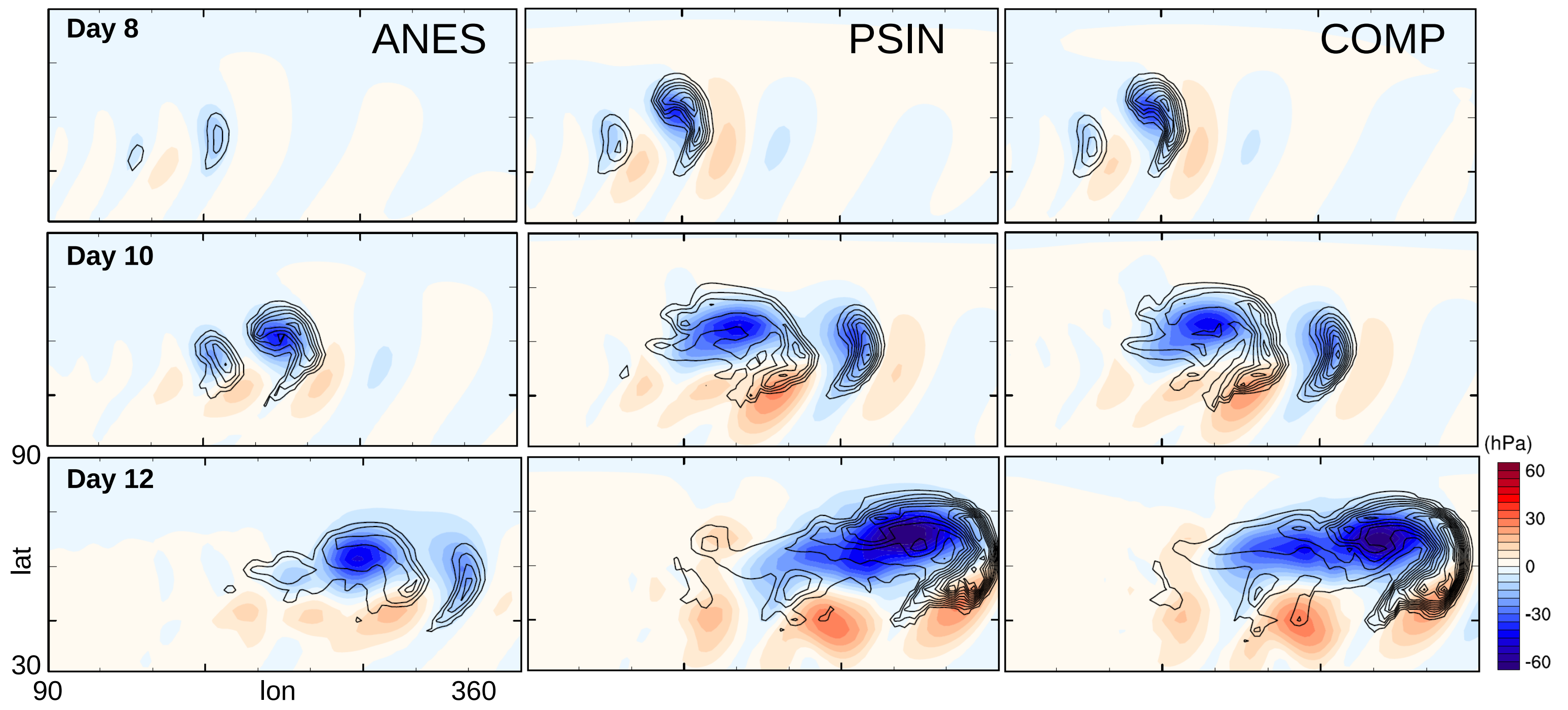

FIG 2. Comparison of the compressible (COMP), pseudo-incompressible (PSIN) and anelastic (ANES) solutions for the baroclinic wave development. Panels show surface pressure (color) and liquid water path (isolines, c.i.=1kg/m^2).

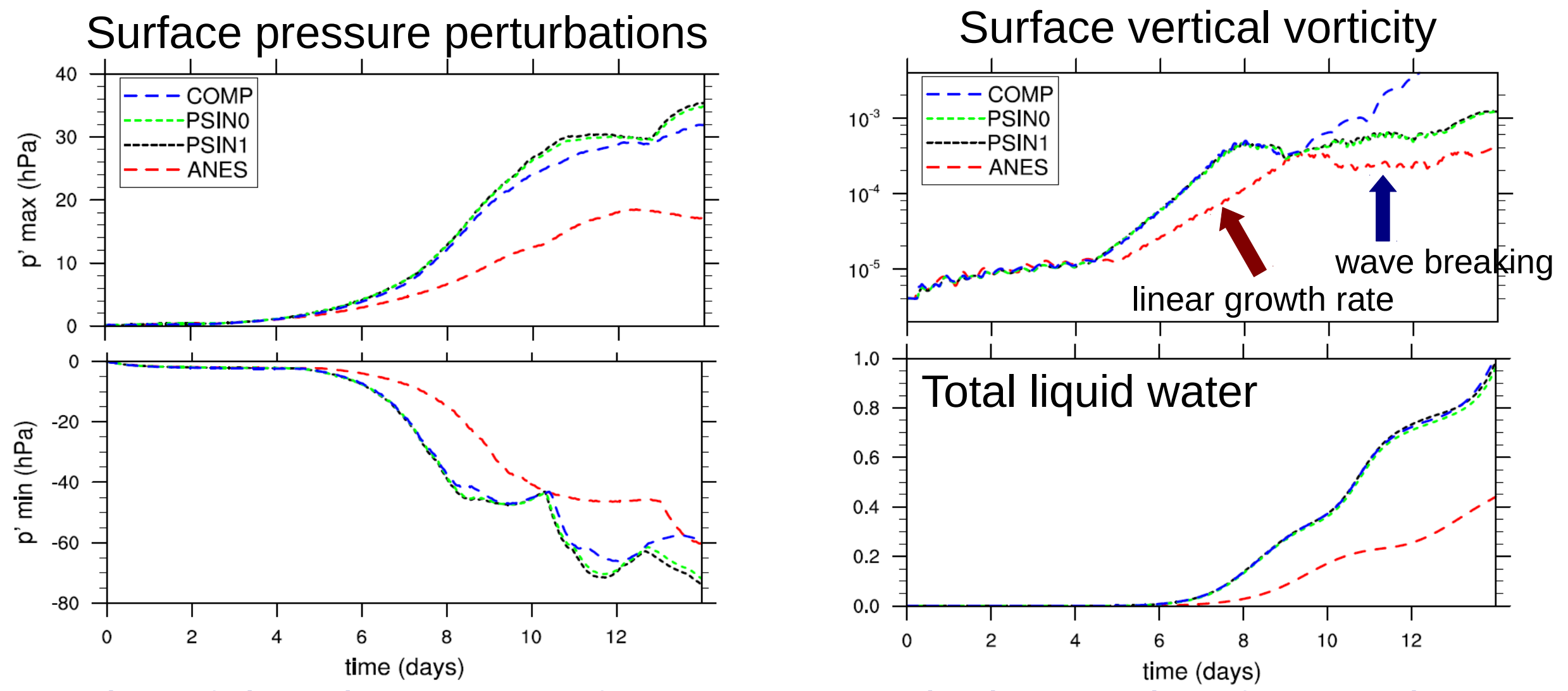

FIG 3. Evolution of domain extrema of pressure perturbations and surface vertical vorticity and total liquid water normalized to 1 at day 14 for COMP. PSIN1 and PSIN0 represent results for PSIN including (PSIN1) or neglecting (PSIN0) p' in moist thermodynamics.

Held-Suarez climate benchmark

The long-term comparison is based on the Held and Suarez (1994) dry setup. The atmospheric circulation on the Earth-like sphere is driven by the Newtonian relaxation of the local temperature to the prescribed zonally symmetric radiative equillibrium field.

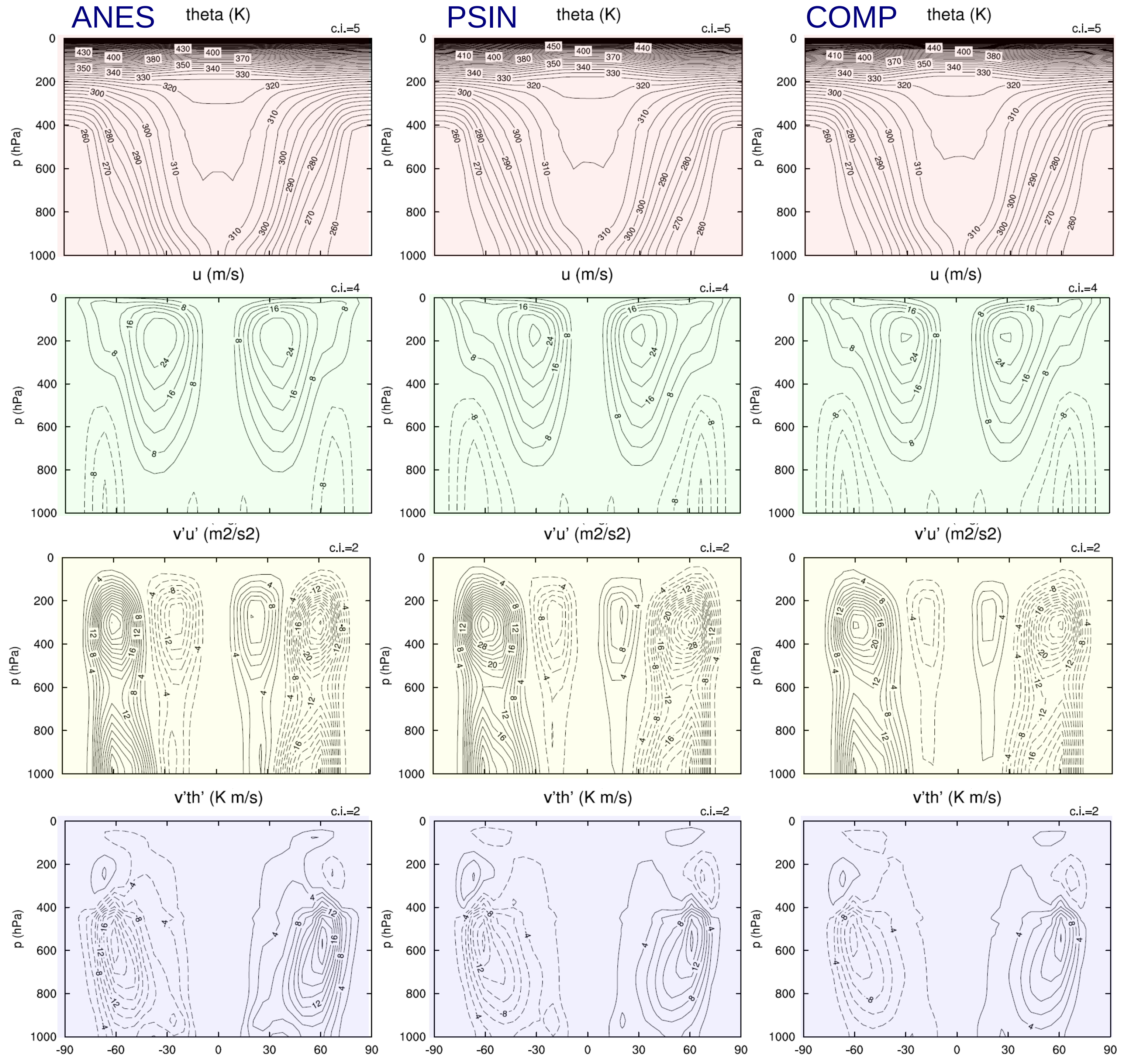

Fig. 4. Zonally averaged fields of the potential temperature, zonal velocity and meridional fluxes of the momentum and potential temperature for the 3rd year of the simulations from ANES, PSIN and COMP models.

Conclusions

- Anelastic approximation is sufficiently accurate for moist deep convection, but fails to correctly represent baroclinic wave development.
- Pseudo-incompressible model retains all terms in the momentum equation and provides improved anelastic solutions.
- Dry Held-Suarez climate benchmark yields similar equilibrium solutions, with comparable zonal fluxes, for both soundproof and compressible approaches.
- Our results show that pressure perturbations have insignificant impact on moist thermodynamics, for small-scale cloud evolution up to the supercell scale.
- Details of numerics and physics may significantly affect model solutions. One should be careful comparing results from different numerical codes.

References:

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