

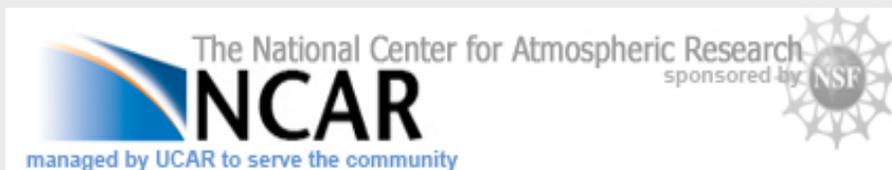
Anelastic and compressible simulation of deep moist convection

Wojciech W. Grabowski¹,
Marcin J. Kurowski^{1,2} and Piotr K. Smolarkiewicz³

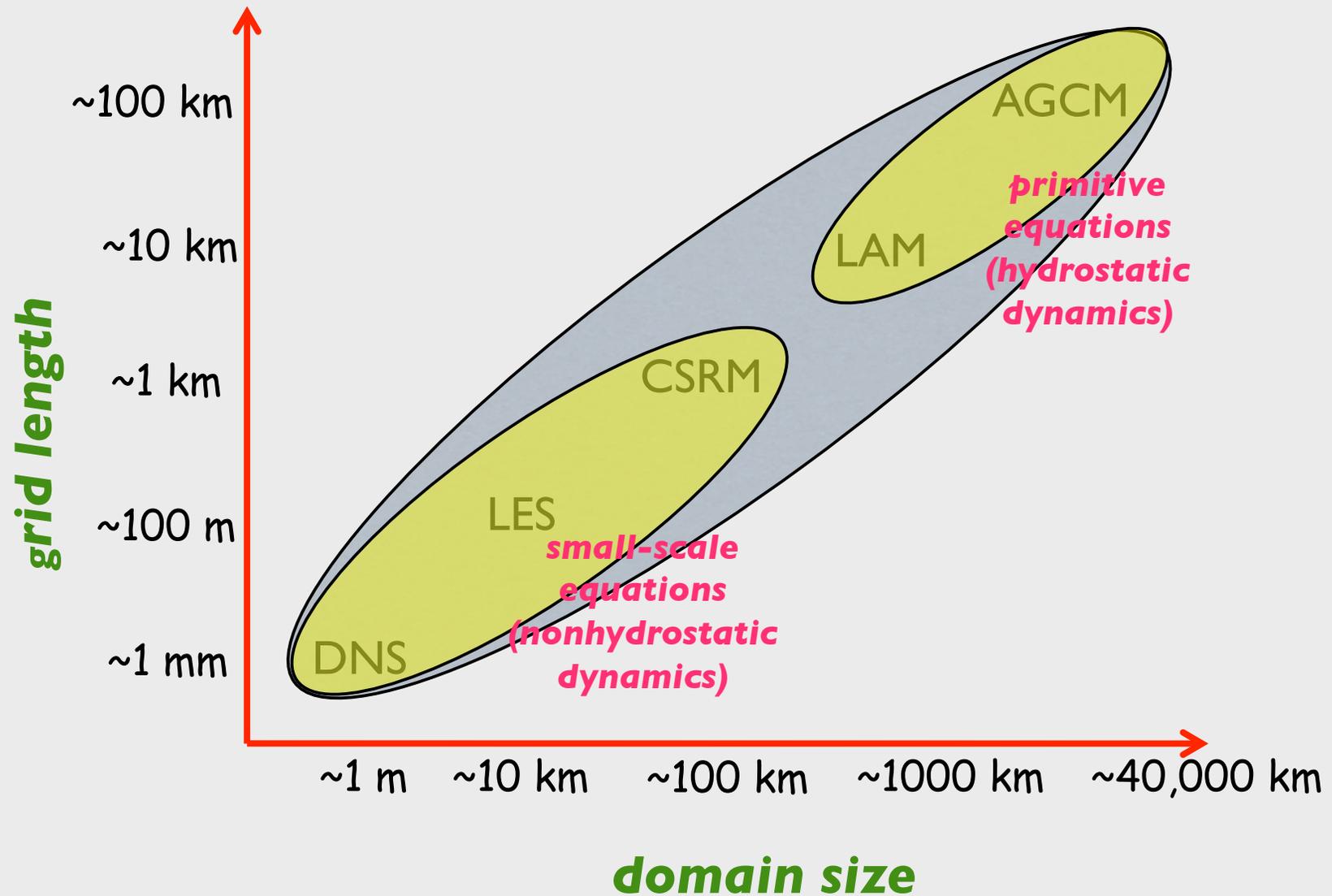
¹NCAR, Boulder, USA

²IMWM, Warsaw, Poland

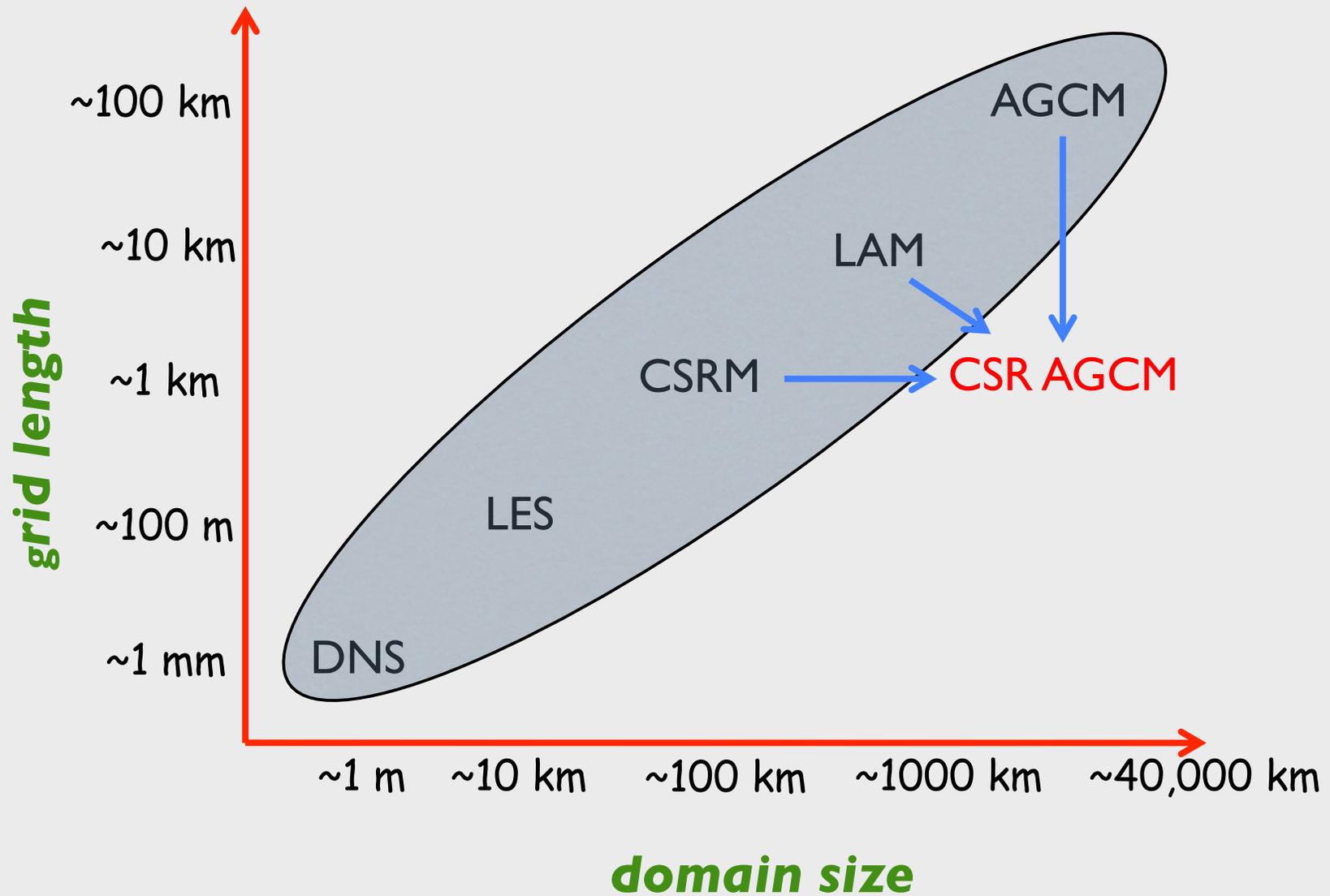
³ECMWF, Reading, UK



Atmospheric fluid dynamics models: from microscale to climate...

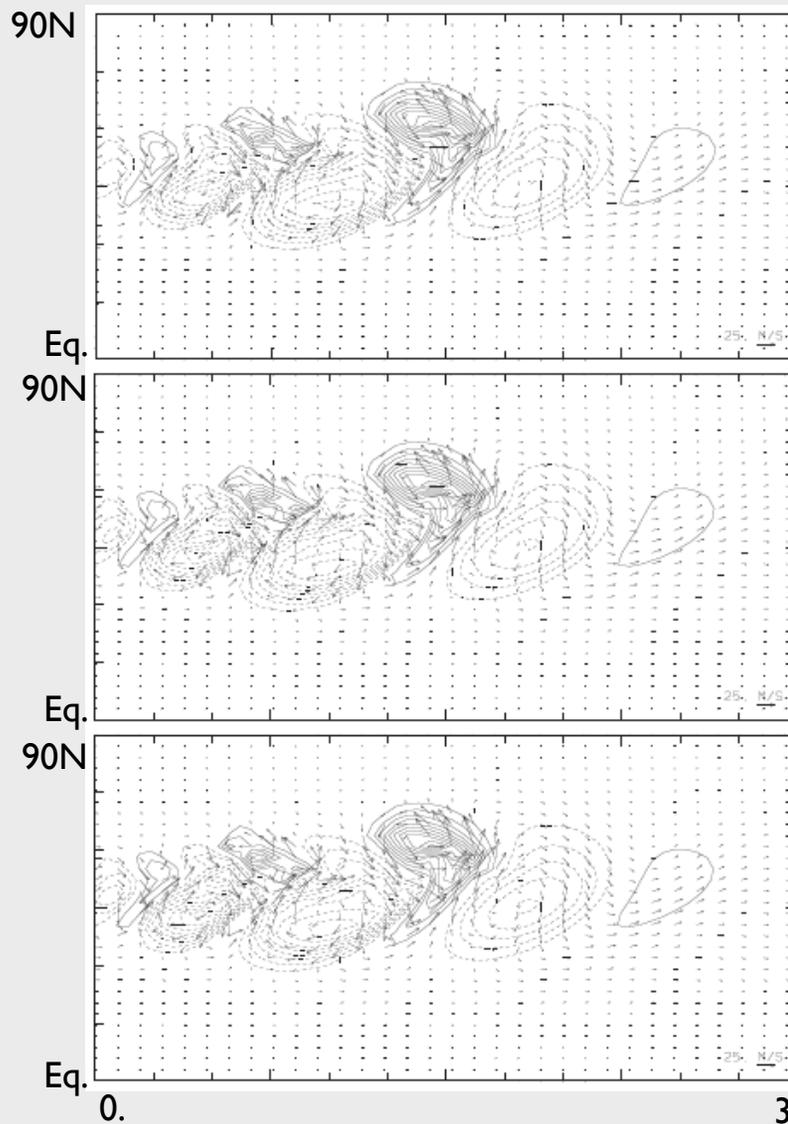


Emerging numerical weather prediction and climate models:



EULAG nonhydrostatic flow solver: anelastic, pseudo-incompressible,
compressible (explicit, **implicit** wrt to sound waves)

Day 8
solutions



compressible, implicit (1), dt=300s

compressible, implicit (2), dt=150s

compressible, explicit, dt=2s

Smolarkiewicz, P. K., C. Kuhnlein, and N. P. Wedi: 2014: A consistent framework for discrete integration of soundproof and compressible PDEs of atmospheric dynamics. *J. Comput. Phys.* (submitted).

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.

Kurowski, M. J., W.W. Grabowski, P. K. Smolarkiewicz, 2014: Anelastic and compressible simulation of moist deep convection. *J. Atmos. Sci.* (to be submitted).

model acronym	governing equation set	Δt	p'	treatment of sound waves
ANES	<i>anelastic</i>	Δt_a	N	-
ANEG	<i>anelastic</i>	Δt_a	Y	-
ANESc	<i>anelastic</i>	Δt_c	N	-
COMP	<i>compressible</i>	Δt_a	Y	<i>implicit</i>
COMP _a	<i>compressible</i>	Δt_a	N	<i>implicit</i>
COMP _e	<i>compressible</i>	Δt_c	Y	<i>explicit</i>

Δt_a – anelastic time step (e.g, 4s)

Δt_c – compressible time step (e.g., 0.25s)

Moist test cases:

- Moist thermals
- Moist mesoscale orographic flow
- Moist deep convection: the supercell

I. Moist thermals in moist-neutral atmosphere (following Bryan and Fritsch *MWR* 2002)

A Benchmark Simulation for Moist Nonhydrostatic Numerical Models

GEORGE H. BRYAN AND J. MICHAEL FRITSCH

Department of Meteorology, The Pennsylvania State University, University Park, Pennsylvania

(Manuscript received 6 February 2002, in final form 29 April 2002)

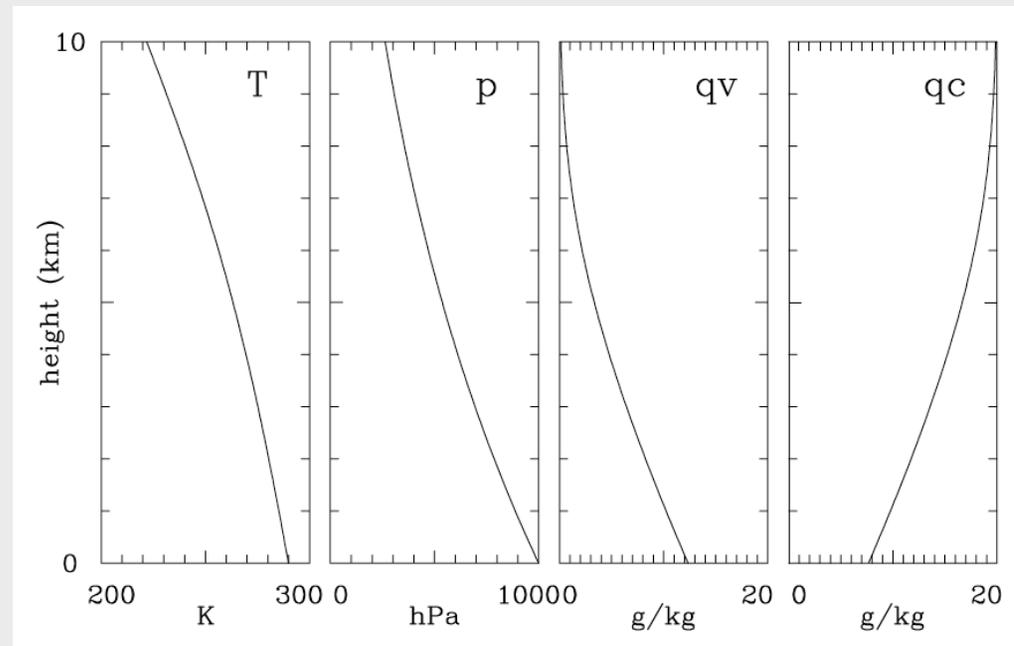
Condensation/evaporation only:

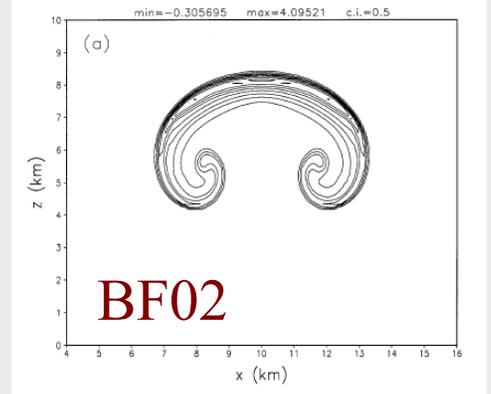
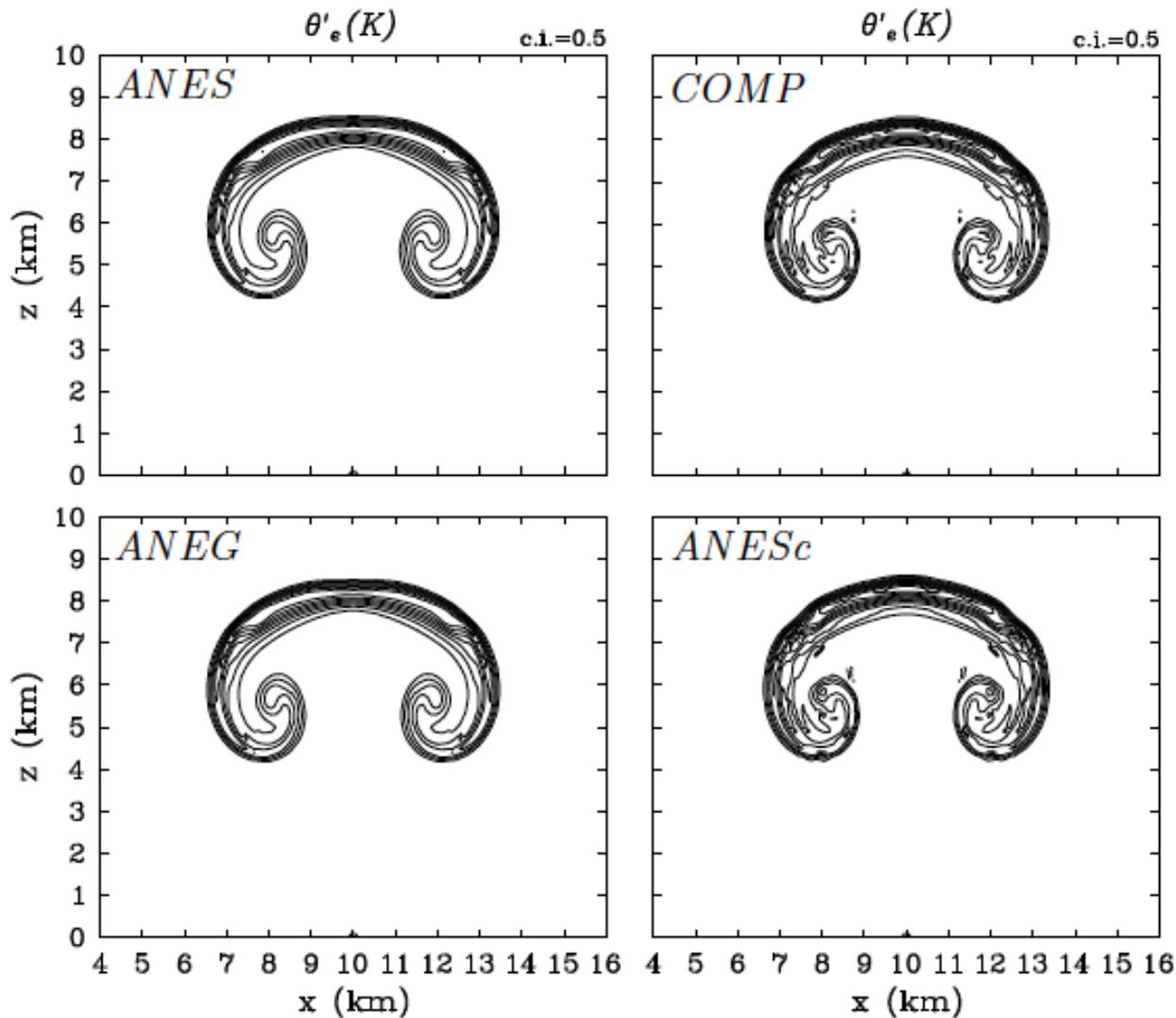
$$\Theta_e = 320 \text{ K}, q_t = 20 \text{ g kg}^{-1}$$

Θ_e - equivalent potential temperature

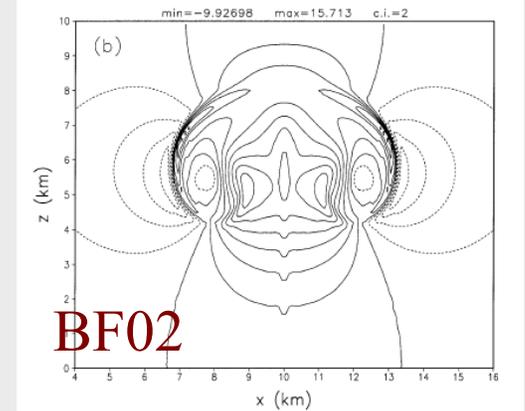
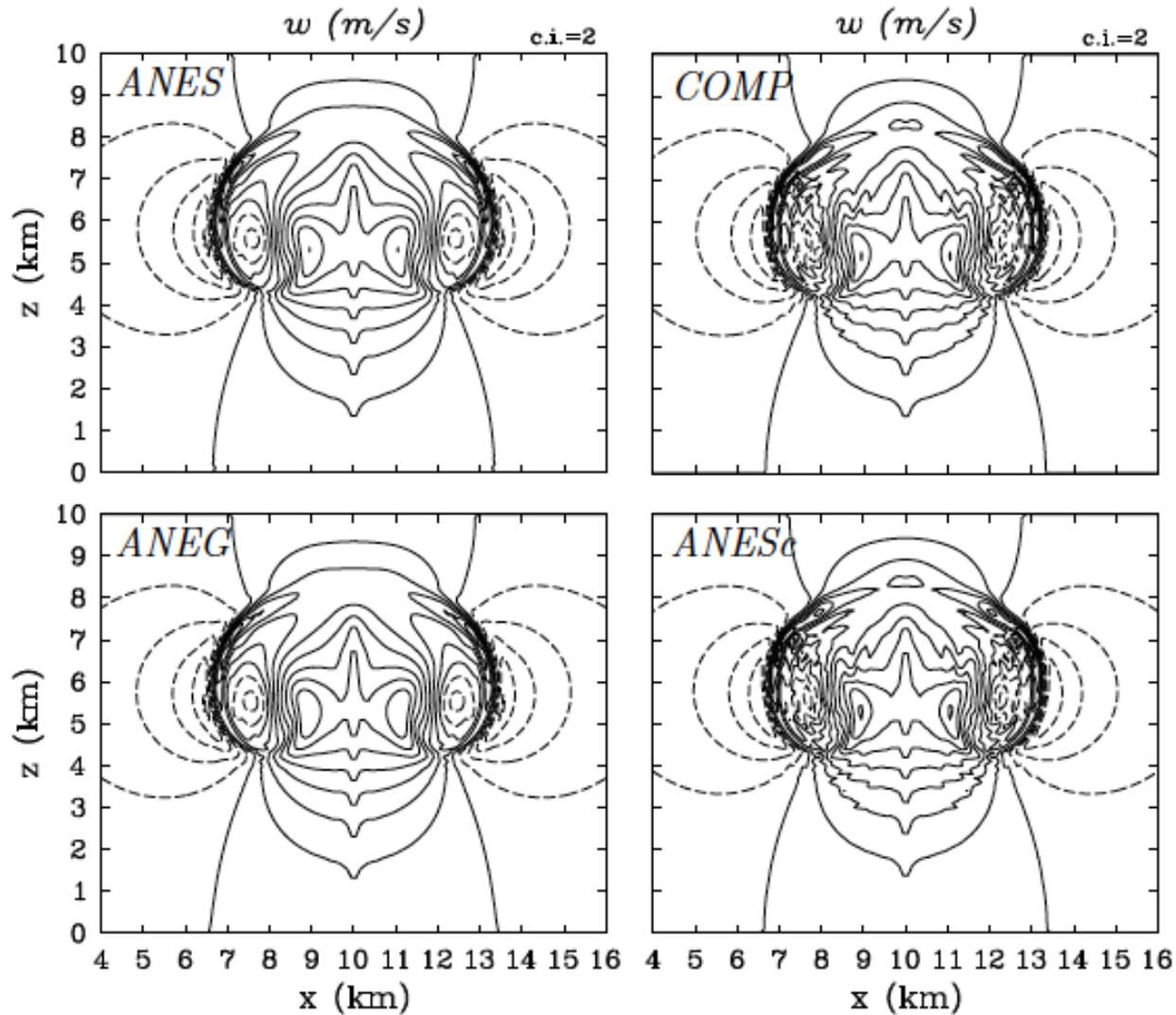
q_t - total water

$$\theta_e = T \left(\frac{p_d}{p_{00}} \right)^{-R/(c_p + c_{pl}r_d)} \exp \left[\frac{L_v r_v}{(c_p + c_{pl}r_t)T} \right]$$





Solutions applying moist-neutral profiles derived applying EULAG's moist thermodynamics...



Solutions applying moist-neutral profiles derived applying EULAG's moist thermodynamics...

2. Supercell simulations (following Weisman and Klemp *MWR* 1982)

The Dependence of Numerically Simulated Convective Storms on Vertical Wind Shear and Buoyancy

M. L. WEISMAN AND J. B. KLEMP

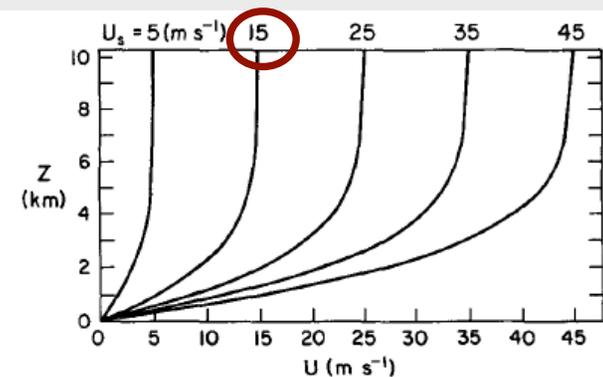
...analytically prescribed environmental profiles and initial perturbations...

Acta Geophysica

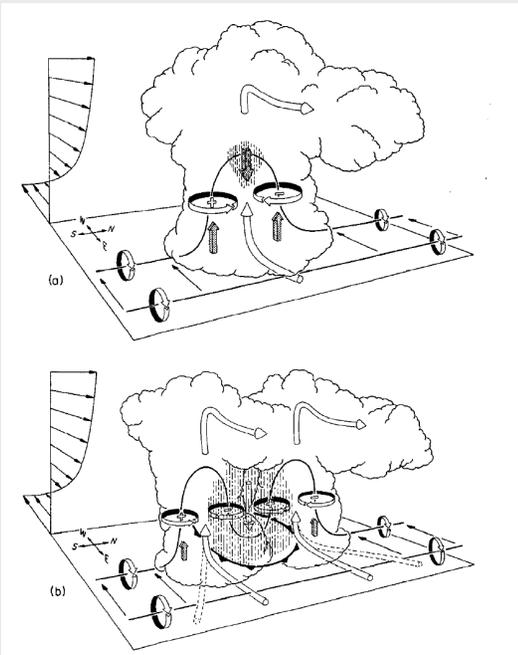
vol. 59, no. 6, Dec. 2011, pp. 1267-1293

Testing the Anelastic Nonhydrostatic Model EULAG as a Prospective Dynamical Core of a Numerical Weather Prediction Model Part II: Simulations of Supercell

Marcin J. KUROWSKI, Bogdan ROSA, and Michał Z. ZIEMIAŃSKI



IMPORTANT: periodic lateral boundary conditions (and also increased horizontal domain) are used in EULAG simulations, replacing open conditions in WK82...



Rotunno 1981

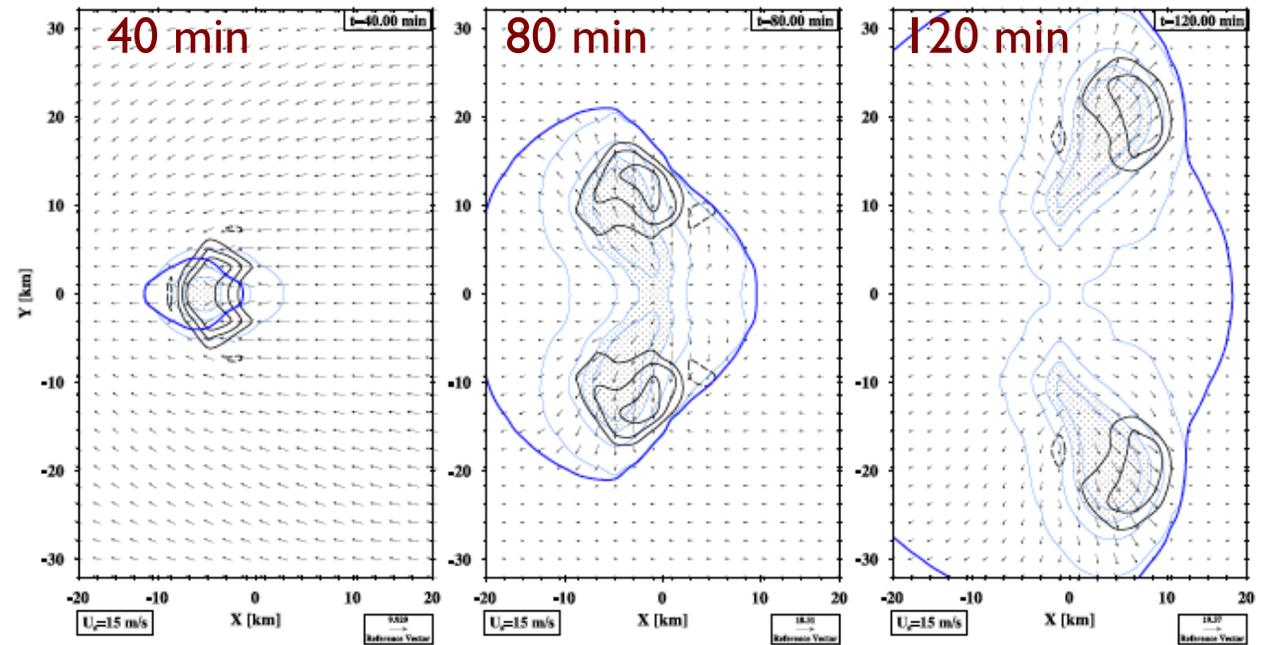


Fig. 10. Time evolution of horizontal flow at 75 m (black vectors), vertical velocity at 4900 m (black lines, dashed for negative values), surface precipitation (light blue lines), and a cold front defined as the edge of a cold pool ($\Delta\theta = -1$ K) at the surface (bold blue line). Dotted area marks region of $q_r > 2$ g/kg at the ground. Vertical velocity is contoured every 5 m/s for positive values and 2 m/s for negative values. Surface precipitation is contoured every 1 g/kg. The results are plotted for $U_s = 15$ m/s.

Kurowski et al. AG 2011

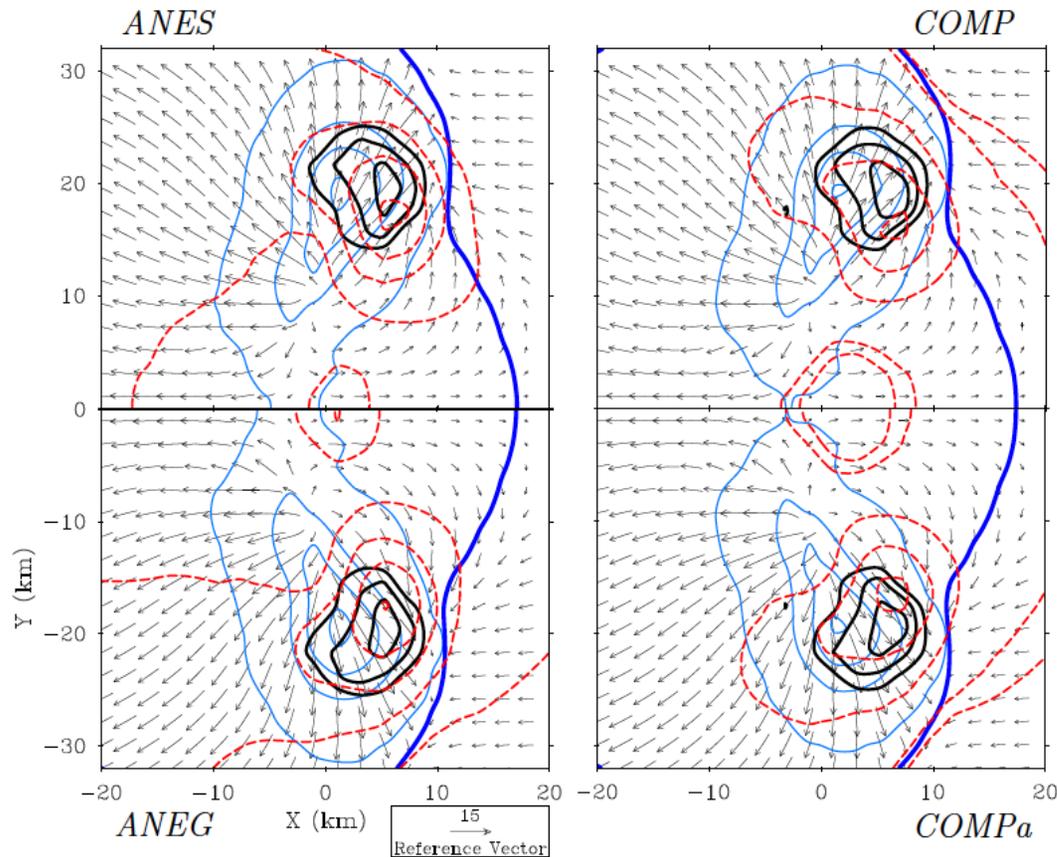
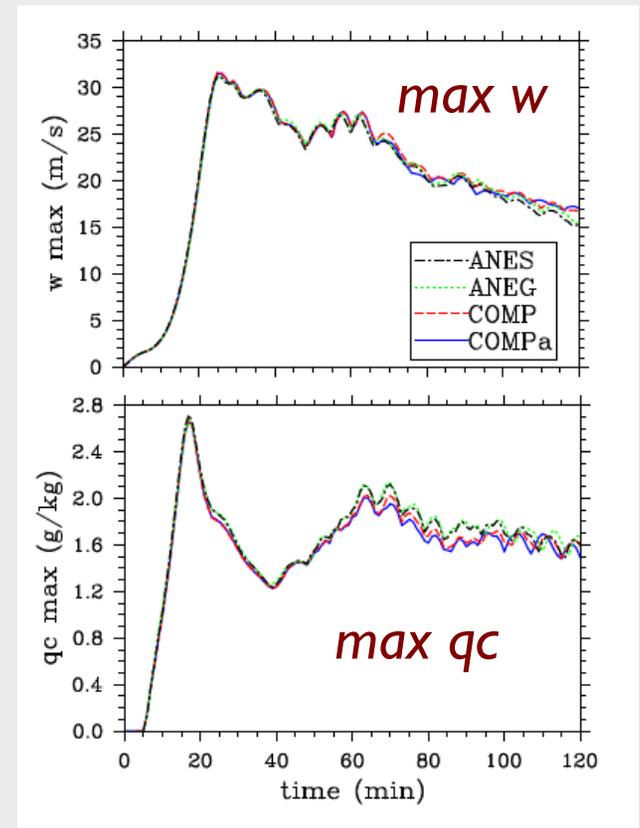
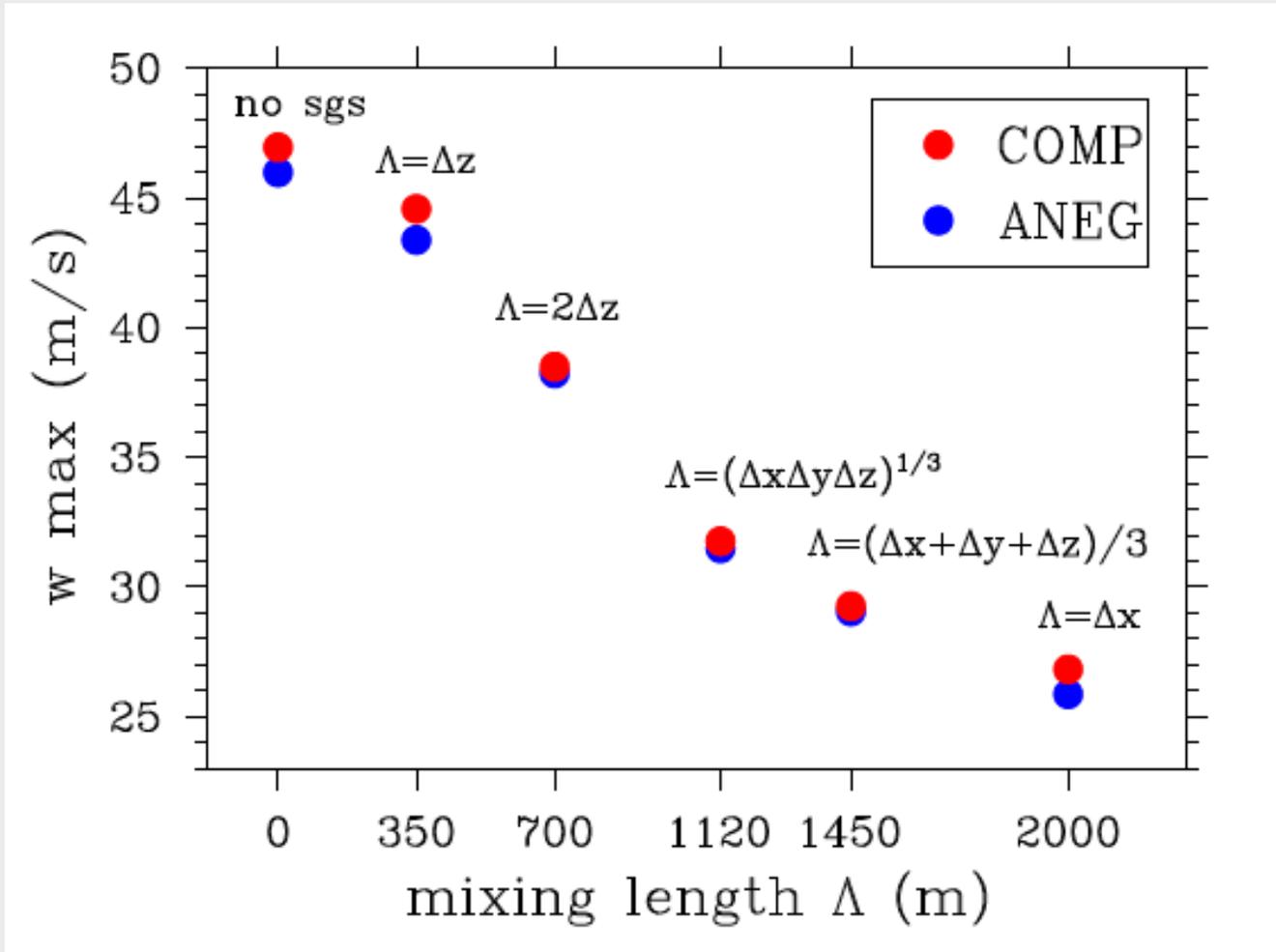


FIG. 4. Comparison of four different EULAG solutions (ANES, ANEG, COMP, and COMPa) after 120 min from the WK82 storm splitting experiment for the $U_s=15$ m/s case. Each panel represents horizontal cross section through the supercell and shows the surface rain mixing ratio (light blue lines; contours at 0.1, 1.5, 3, 4.5 g/kg), surface cold pool edge (defined by the $\theta' = -0.5$ K contour; thick dark blue line), updraft strength at 4900 m (black solid lines; contour interval of 4 m/s), and pressure perturbations at 2800 m (red lines, contour interval of 15 Pa). Positive/negative values marked with solid/dashed lines. Arrows show surface horizontal flow. As in WK82, the mean flow of 12 m/s was subtracted from the x-component of horizontal velocity. Only half of the solution is shown for each model.



Since solutions are almost perfectly symmetric, we only show left/right cell in upper/lower panels...



Solutions for a set of sensitivity simulations for COMP and ANEG models are quite similar as well....

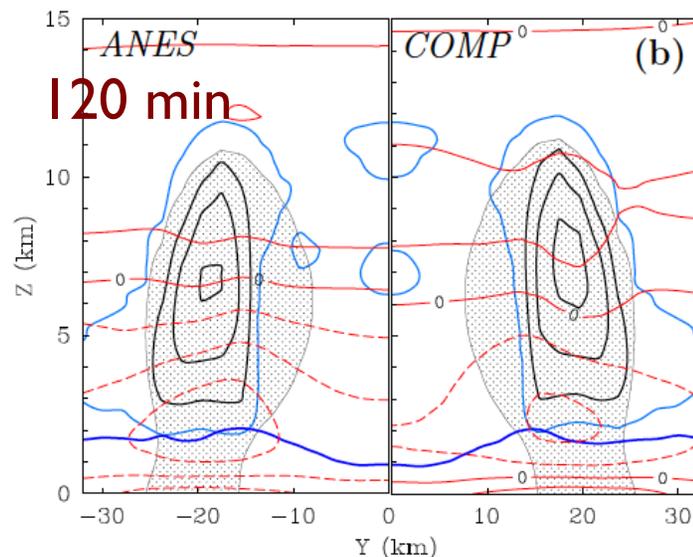
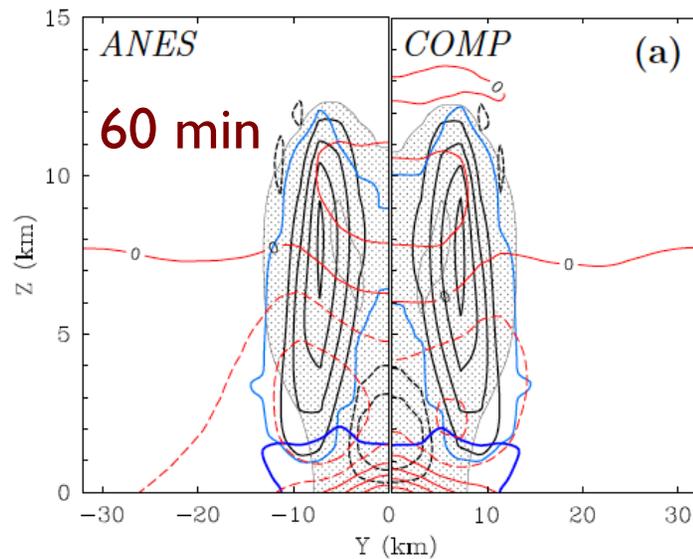
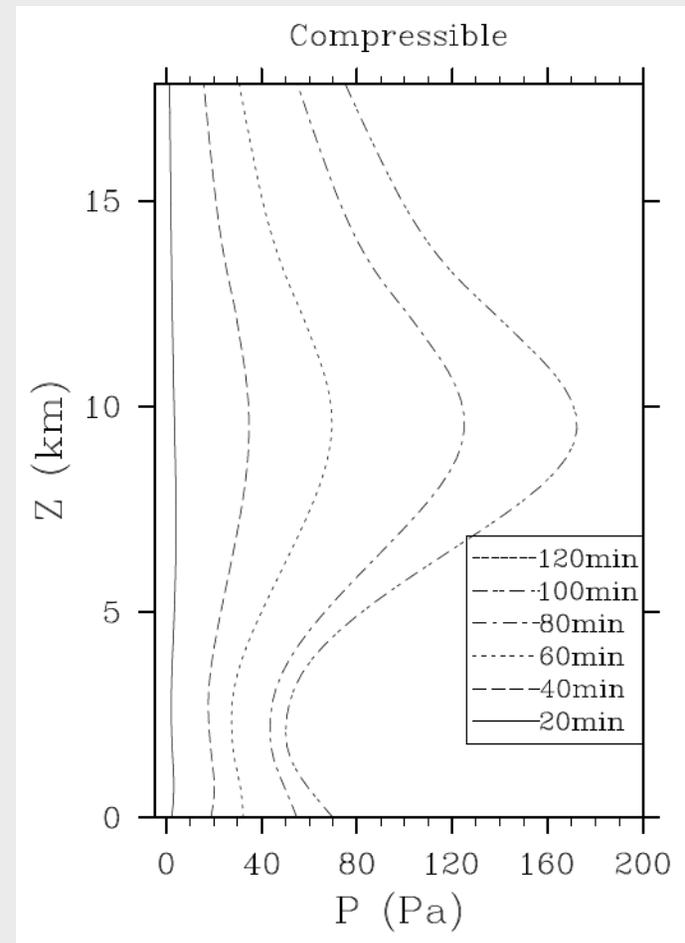
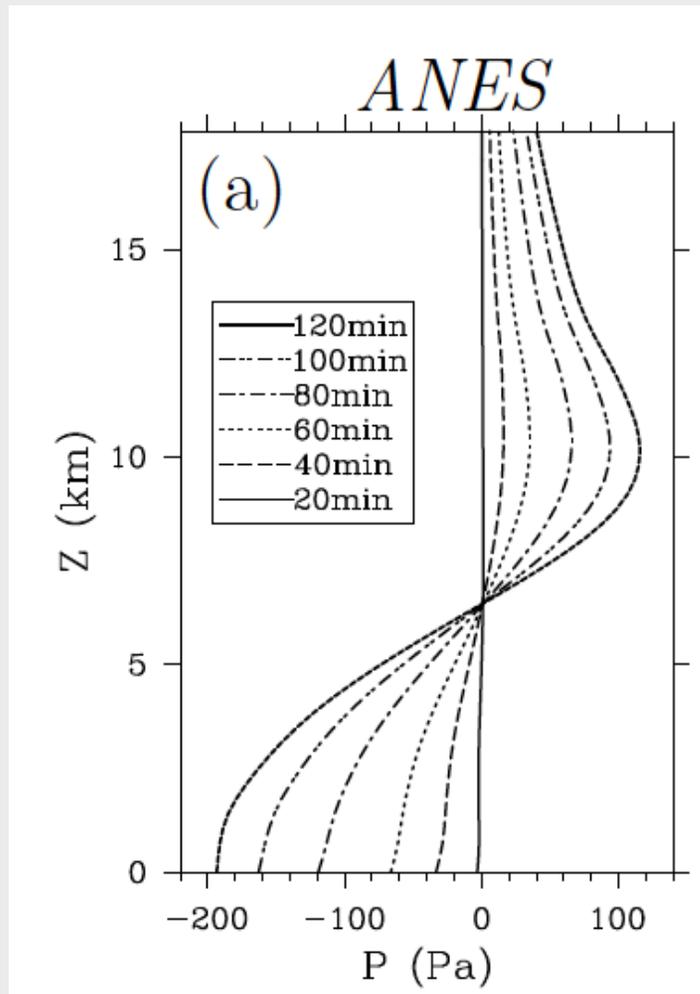


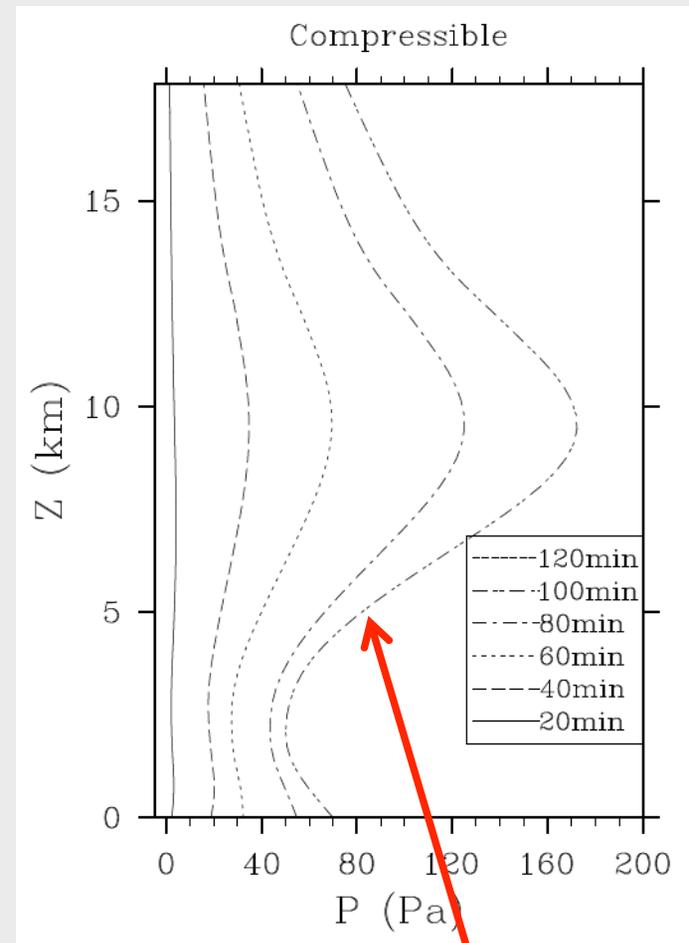
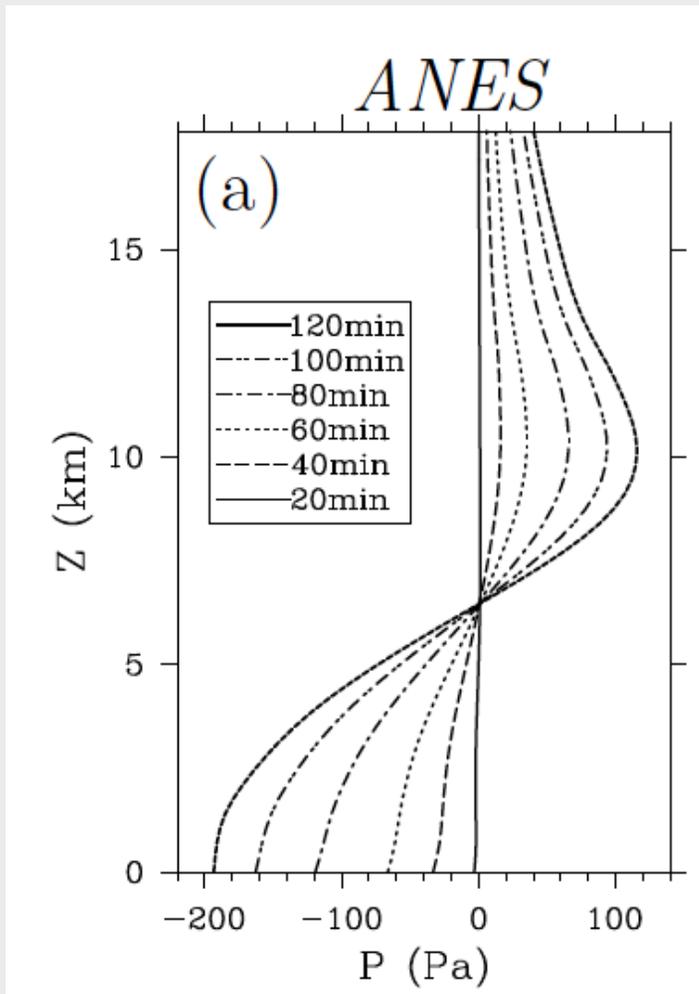
FIG. 5. Similar to Fig. 4, but for the vertical cross sections ($y - z$) through the convective cores for anelastic (ANES) and fully compressible (COMP) solutions at 60 min (a) and 120 min (b). Black contours are vertical velocity every 5 m/s, shaded regions show presence of rain water with $q_r > 1$ g/kg, light blue isolines mark the cloud edge ($q_c > 0.1$ g/kg), dark blue thick line indicates location of the near-ground cold pool ($\theta' = -0.5$ K) and red lines are pressure perturbations contoured with 40 Pa interval and negative values dashed. Only half of the solution is shown for each model.

Main point: all fields match pretty well between ANES and COMP models except for the pressure fields (red contours).

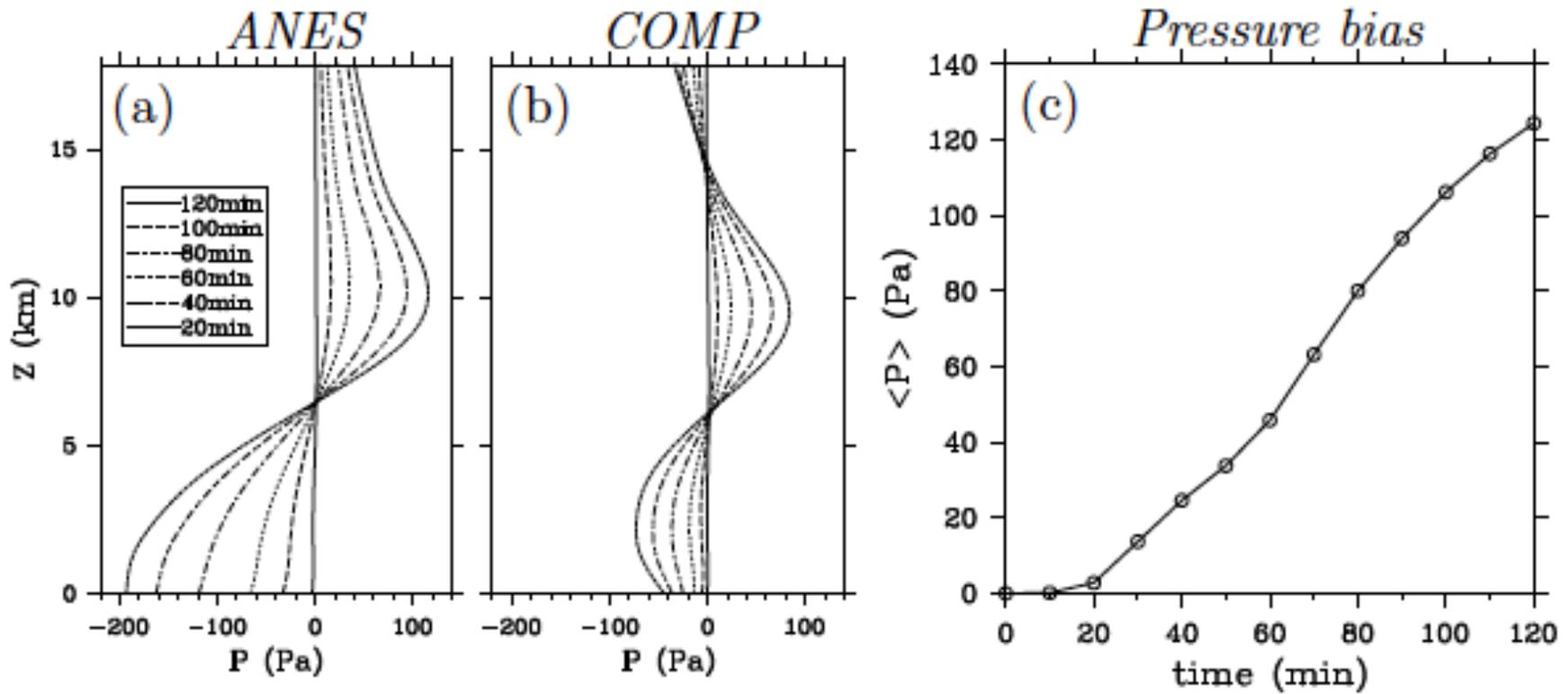
Why?



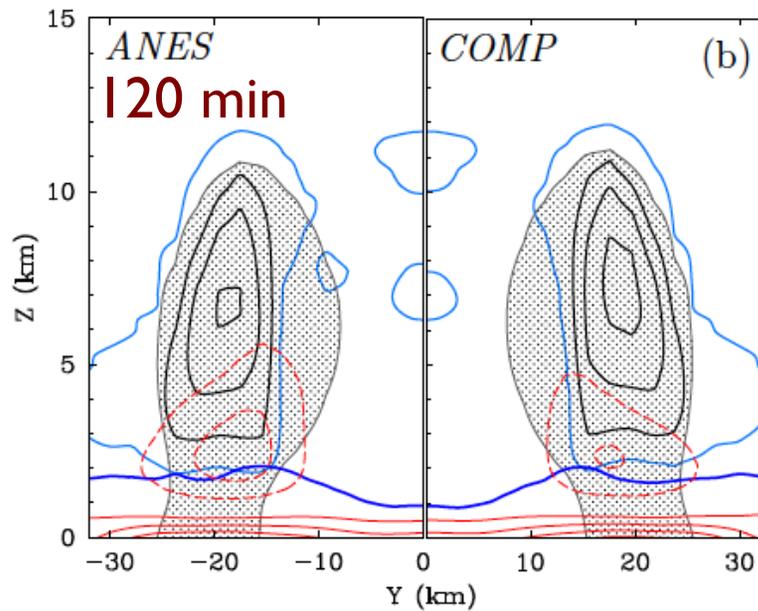
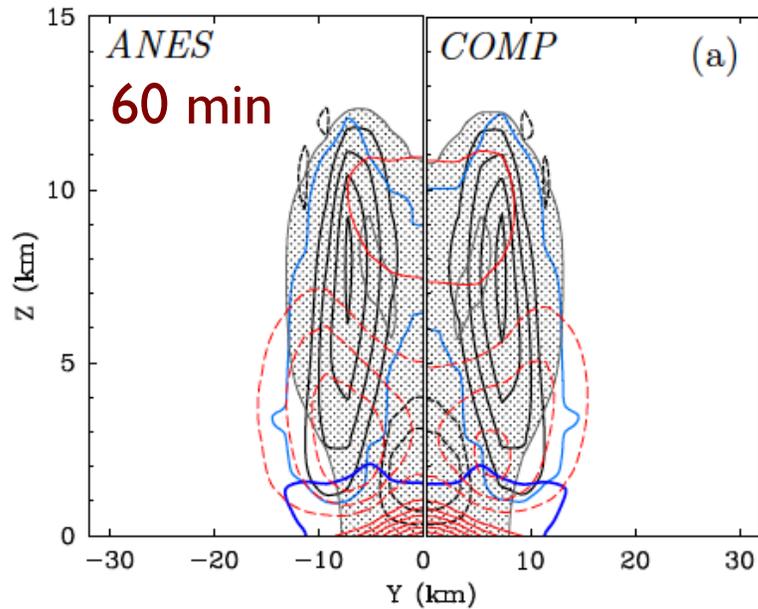
Profiles of the domain-averaged perturbation pressure fields for ANES and COMP models: response to the latent heating...



If we average vertically each profile, then we get the pressure bias in the COMP model. We can subtract it...



Profiles of the domain-averaged perturbation pressure fields for ANES and COMP models with COMP pressure bias subtracted: response to *horizontally-averaged* latent heating...



Solutions with the horizontally-averaged pressure perturbations removed.

Now pressure fields match nicely...

1. In the compressible system, the pressure bias develops because of the mean heating of the periodic domain...

2. Different mean pressure profiles develop because of the differences in the way hydrostatic balance is established in the anelastic and compressible systems (“boundary condition” and the hydrostatic balance equation)...

Although interesting, these have no effect on the supercell dynamics...

Table 1: Comparison of total wall clock times for two-dimensional Bryan and Fritsch (2002) and three-dimensional Weisman and Klemp (1982) experiments for ANES, COMP and COMPe models.

model acronym	Δt [s]	total time [s]
BF02 (on 2 processors)		
ANES	4	20
COMP	4	30
COMPe	0.25	297
WK82 (on 128 processors)		
ANES	10	57
COMP	10	55
COMPe	0.5	538

Next:

- moist baroclinic wave test;
- moist Held-Suarez idealized climate test;
- aquaplanets...