Recent progress in CELO Priority Project

Bogdan Rosa and Damian Wójcik

Institute of Meteorology and Water Management
National Research Institute
Warsaw, Poland

COSMO General Meeting
5th-8th September 2016

Tasks and outline

Task 1: Integration of EULAG DC with COSMO framework
The most recent version of COSMO-EULAG compressible (CE-C) has been developed based on COSMO ver. 5.1. Thus, some physical parameterizations of the new implementations are already consistent with the model ICON. These include *microphysics* and *radiation*.

Task 2: Consolidation and optimization of the EULAG DC formulation
Consolidation and optimization of CE-C are a part of Task 5 in the updated CELO project plan.

Task 3: EULAG DC code restructuring and engineering
Due to the limited human resources, the implementation of tailored restart subroutine in the CE has not been done yet.

Tasks and outline

Task 4: Optimization and testing of COSMO with EULAG DC (B. Rosa and D. Wójcik)

- Moist benchmark test - Weisman and Klemp (*MWR*, 110, 1982)
- Modeling of daytime convective development using C-RK and CE-C/A

Task 5: Integration and consolidation of the EULAG compressible DC with COSMO framework (D. Wójcik and B. Rosa)

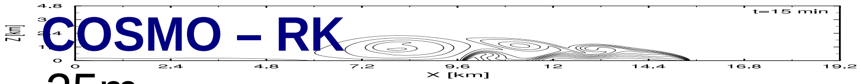
- **Integration of the consistent formulation of EULAG within CE**
- **Evaluation of idealized tests with compressible CE (CE-C)**
  - Cold density current (Straka et al., 1993)
  - Linear gravity waves (Skamarock et al., 1994)
  - Dry orographic flows (Klemp et al. (1977), Bonaventura (2000))
  - Moist orographic flows (Kurowski et al., 2013)

Cold density current : a reassessment

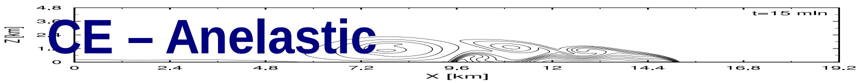
Straka, J. M., Wilhelmson, Robert B., Wicker, Louis J., Anderson, John R., Droegemeier, Kelvin K., Numerical solutions of a non-linear density current: A benchmark solution and comparison *International Journal for Numerical Methods in Fluids*, (**17**), 1993

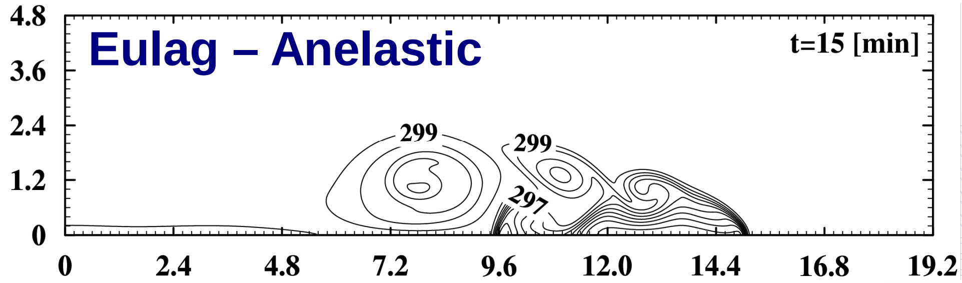
Experiment configuration:

- isentropic atmosphere, θ(z)=const (300K)
- open lateral boundaries
- free-slip bottom b.c.
- **constant subgrid mixing, K=75m²/s**
- domain size 51.2km x 6.4km
- bubble min. temperature -15K
- bubble size 8km × 4km
- no initial flow
- integration time 15 min
- isotropic grid



25m



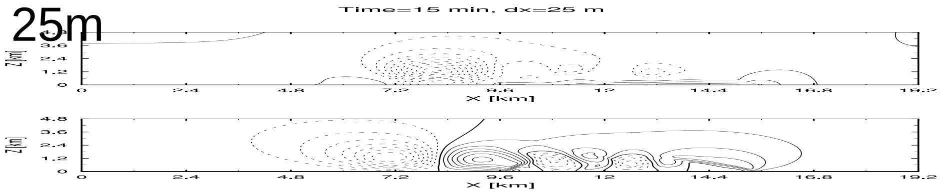


The sequence of figures confirms that the solutions obtained with 4 different models are in quantitative agreement.

Cold density current : P’ and W

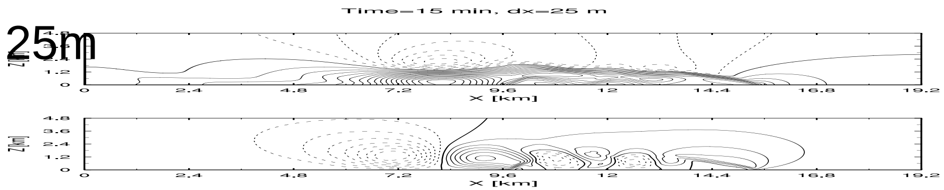
Cosmo – RK P’

25m

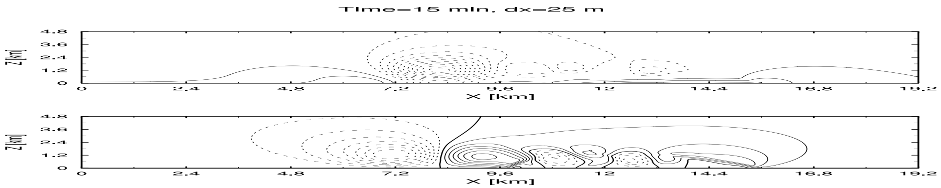


Cosmo – RK W

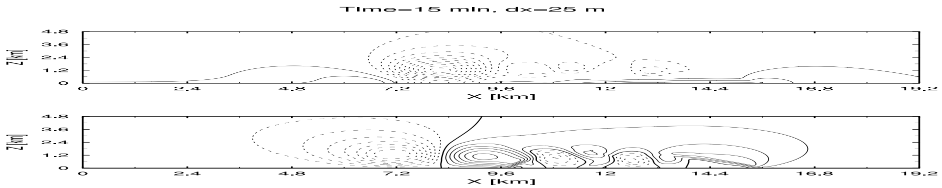
25m



CE – C P’



CE – C W

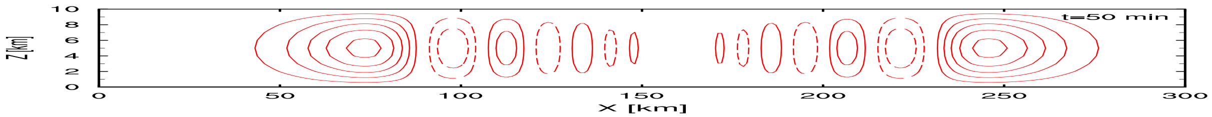


Parameter	**RK**		**CE-C**	
	Δx = 25 m	Δx = 100 m	Δx = 25 m	Δx = 100 m
P'_{max} [hPa]	2.0	1.7	1.9	1.6
P'_{min} [hPa]	-5.6	-5.5	-5.8	-5.6
W_{max} [m/s]	12.7	13.6	13.1	12.9
W_{min} [m/s]	-15.8	-15.9	-15.9	-15.5

The spatial distribution and magnitude of extreme values of the pressure perturbation are similar in both CE-C and COSMO-RK solutions.

Linear gravity wave : short channel

Skamarock W. C. and J. B. Klemp : Efficiency and Accuracy of the Klemp-Wilhelmson Time-Splitting Technique *MWR*, vol. **122**, 1994.



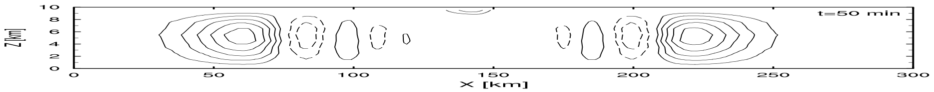
Short channel :

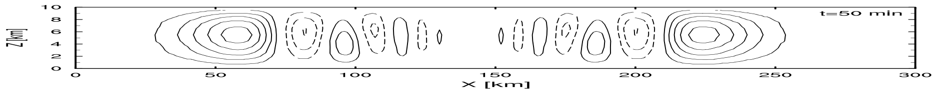
- Dry flow
- 2-D domain (XZ)
- Periodic b.c. in X
- Domain size 300 km x 10 km
- Free-slip upper and bottom b.c.
- $N_{B\text{-}V} = 0.01\ s^{-1}$
- Ambient flow U= 20 m/s
- The inertia-gravity waves are excited by an initial Θ perturbation (warm bubble) of small amplitude $\Delta\Theta_0 = 10^{-2}$ K
- Coriolis force acts on the ambient flow perturbation
- Integration time equals 50 minutes
- Isotropic grid ($\Delta x=\Delta z=1$ km)

Analytical solution - potential temperature perturbation at t=50 min

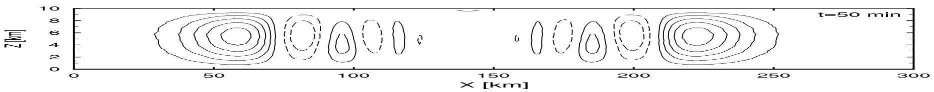
Linear gravity wave: short channel

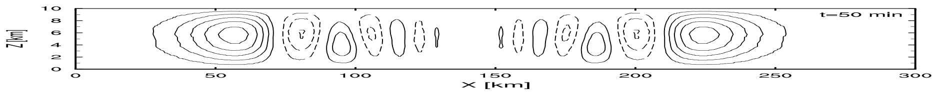
CE-C | RK



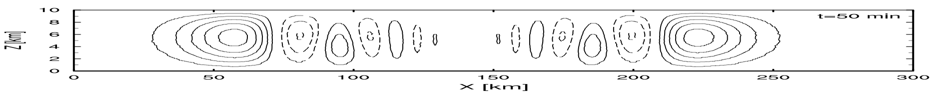


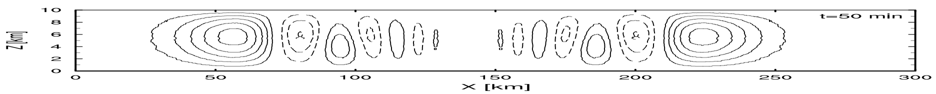
Δx=Δz=1km





Δx=Δz=0.5km





Δx=Δz=0.25km

The figures show spatial distribution of the potential temperature perturbation.

Dry orographic flows

Linear hydrostatic flow :

- Δx = 3km, Δz = 250 m
- h_0 = 1m, a = 16km
- U = 32 m/s
- N = 0.0187 s^{-1}

Nonlinear hydrostatic flow :

- Δx = 2.8km, Δz = 200 m
- h_0 = 800m, a = 16km
- U = 32 m/s
- N = 0.02 s^{-1}

Linear nonhydrostatic flow :

- Δx = 0.1km, Δz = 250 m
- h_0 = 100m, a = 0.5km
- U = 14 m/s
- N = 0.0187 s^{-1}

Nonlinear nonhydrostatic flow :

- Δx = 0.2km, Δz = 100 m
- h_0 = 900m, a = 1km
- U = 13.28 m/s
- N = 0.02 s^{-1}

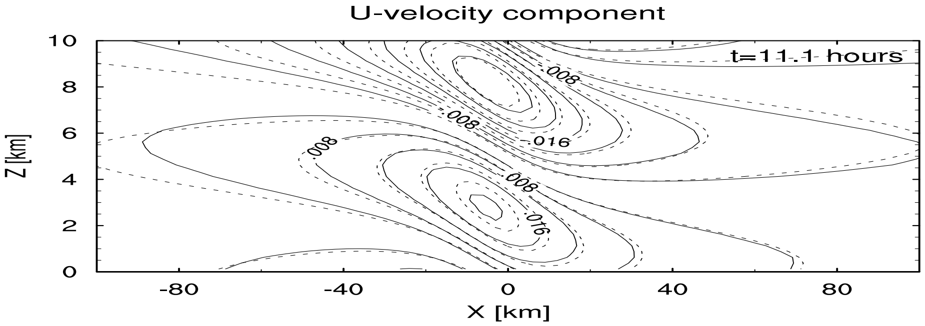
Klemp, J. B. and D. K. Lilly : Numerical Simulation of Hydrostatic Mountain Waves, *JAS*, vol. 35, 1977.

Bonaventura L. : A semi-implicit semi-Lagrangian scheme using the height coordinate for a nonhydrostatic and fully elastic model of atmospheric flows, JCP, vol. 158, 2000.

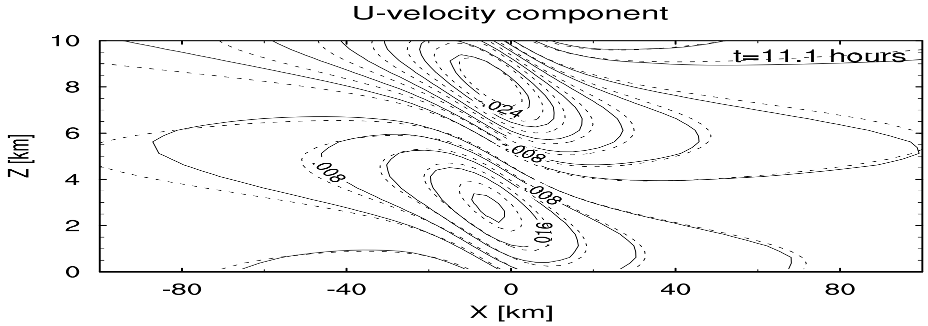
Pinty, J.P., R. Benoit, E. Richard, and R. Laprise : Simple tests of a semi-implicit semi-Lagrangian model on 2D mountain wave problems, MWR, vol. 123, 1995.

Linear hydrostatic flow: U after 11.1 h.

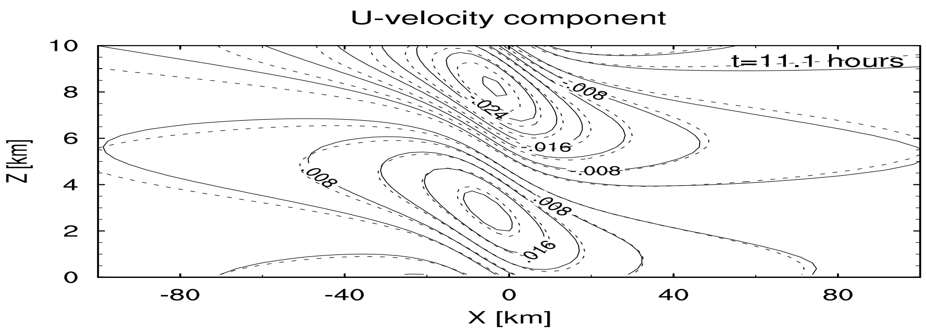
CE-C-Implicit



CE-C-Explicit



RK

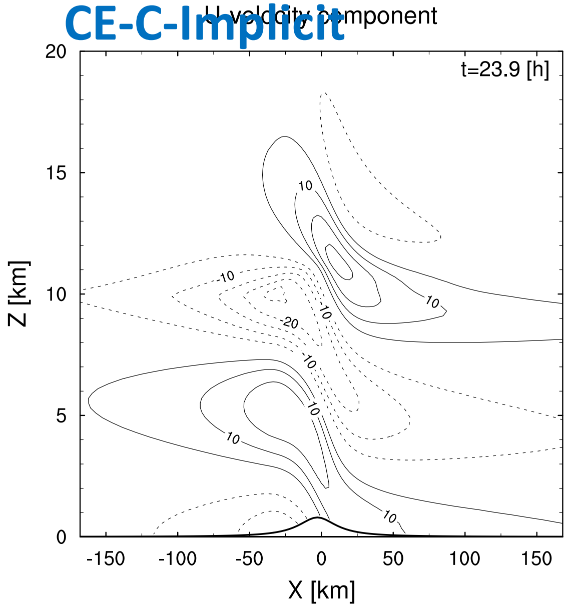


Solid lines - U component of velocity computed using different numerical models/approaches.

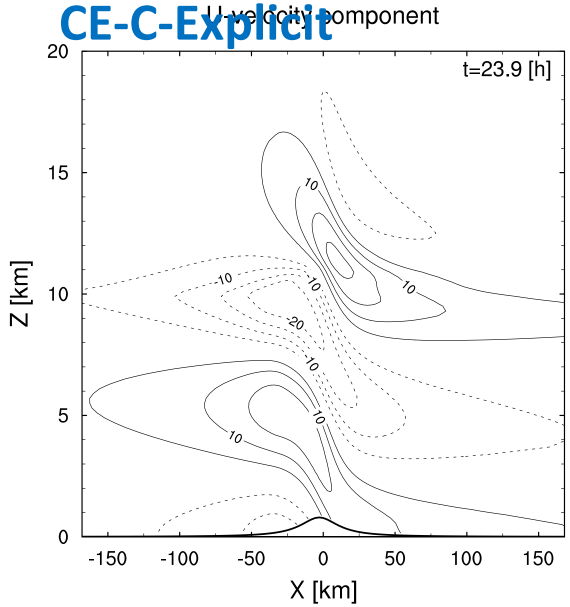
The plots confirm consistency between numerical solutions and the analytical formula (dashed lines).

Nonlinear hydrost. flow : U after 23.9 h.

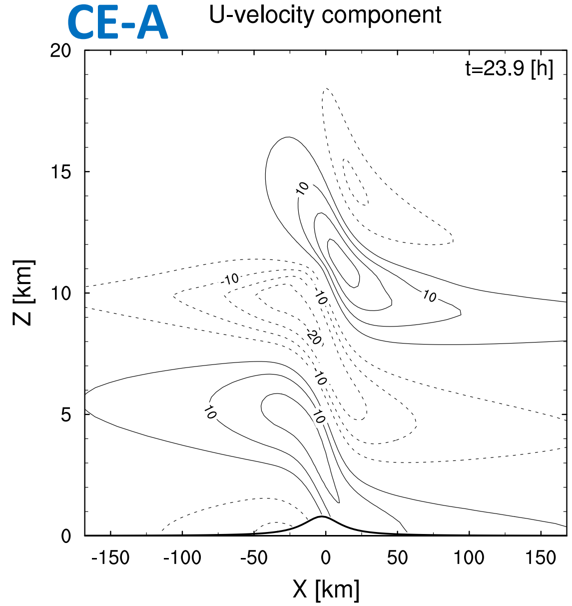
CE-C-Implicit



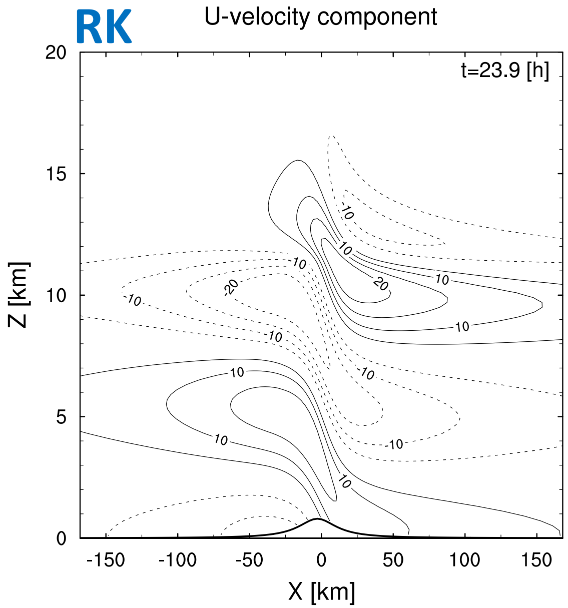
CE-C-Explicit



CE-A



RK



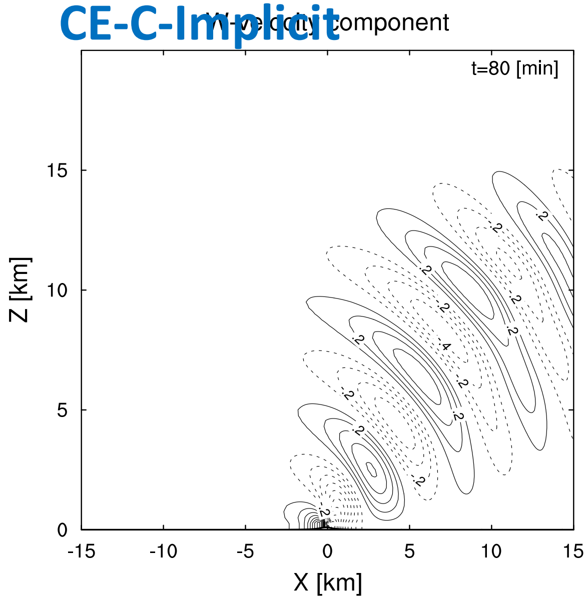
The series of figures present U component of velocity. The simulations have been performed using different numerical approaches and different codes.

All solutions are in good quantitative agreement, nevertheless, several small–scale differences are still observed.

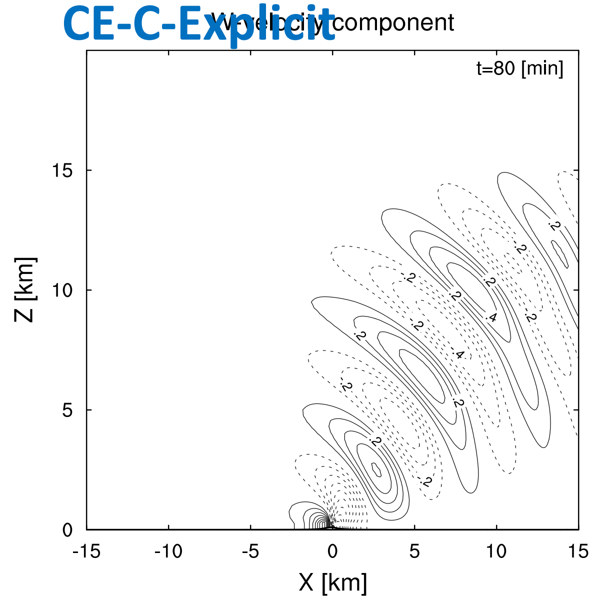
The differences in the stratosphere may result from different configuration of the sponge layer.

Linear nonh. flow : W after 80 min.

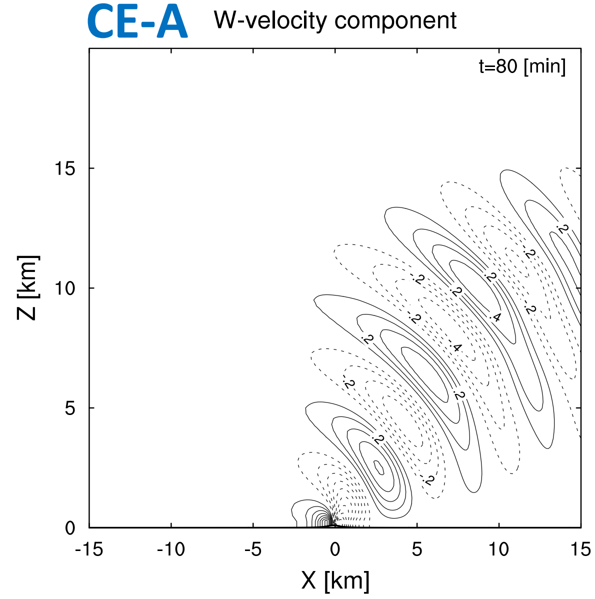
CE-C-Implicit



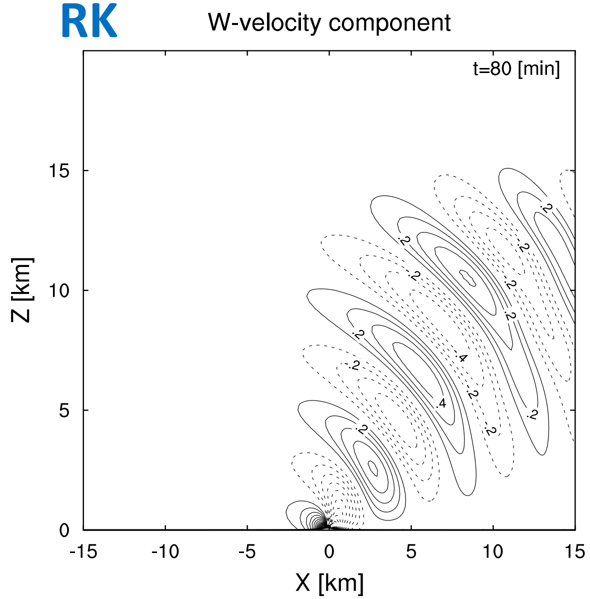
CE-C-Explicit



CE-A



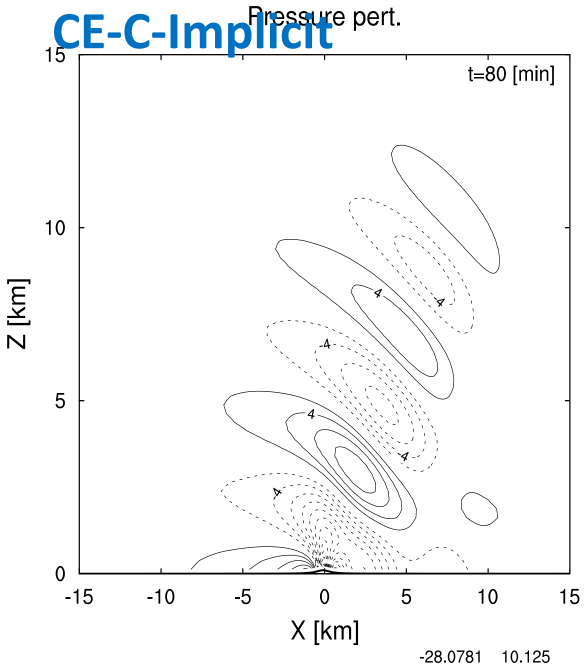
RK

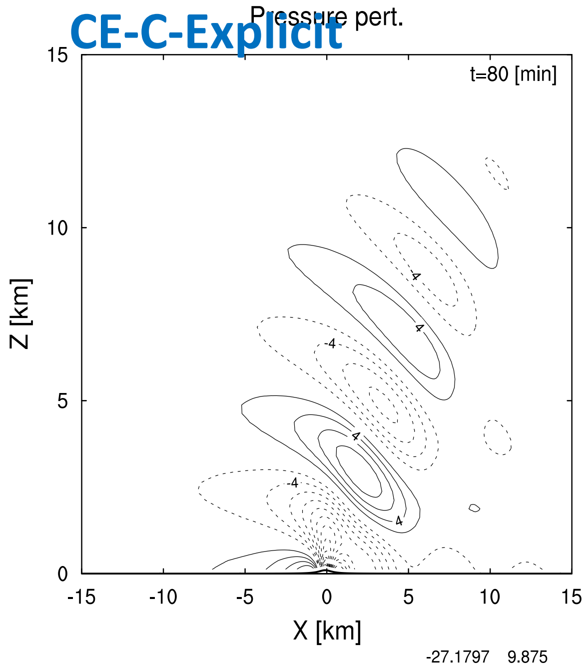


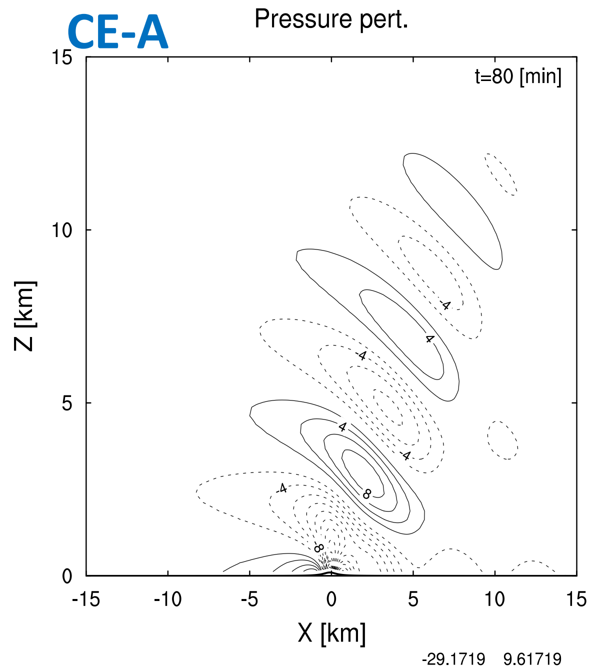
Spatial distribution of the vertical velocity perturbation.

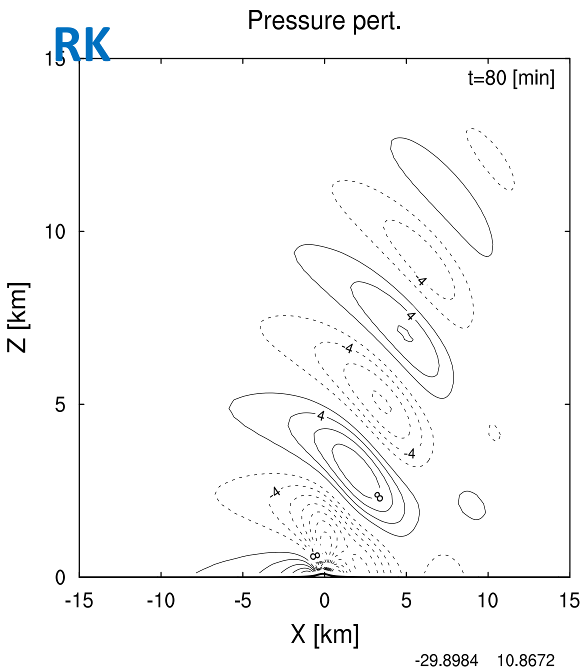
The results confirm high consistency of the numerical results (W) computed with different models.

Linear nonh. flow : P’ after 80 min.







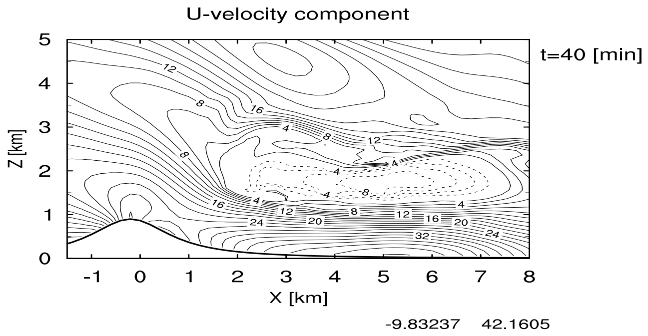


	P'_{min} [Pa]	P'_{max} [Pa]
RK	-29.9	10.9
CE-A	-29.2	9.6
CE-C-Expl.	-27.2	9.9
CE-C-Impl.	-28.1	10.1

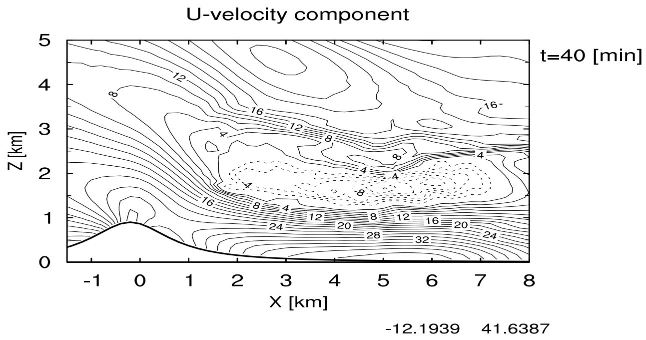
The results are in good qualitative and quantitative agreement.

Nonlinear nonh. flow : U after 40 min.

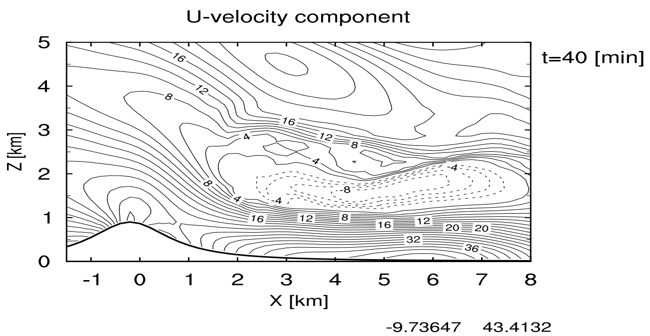
CE-C-Implicit



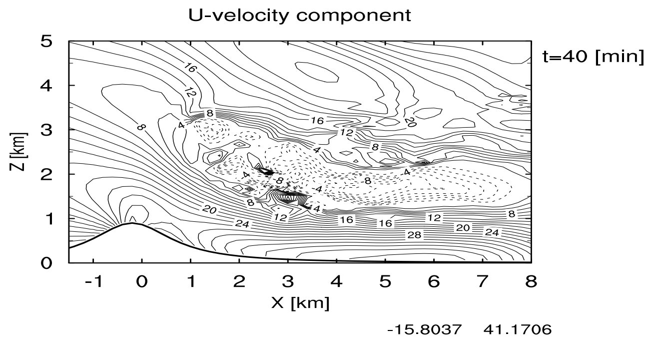
CE-C-Explicit



CE-A



RK



Summary – dry idealized experiments

- The most recent version of COSMO-EULAG with the compressible dynamical core has been tested in a set of benchmark idealized experiments. These include seven dry and one moist simulations (not presented here).

- In general the results obtained with CE-C are in good agreement with the reference solutions.

- A few bugs in the CE-C were found and corrected.

- Some differences between CE-C and COSMO-RK solutions are still present and have to be diagnosed.

Moist benchmark test - Weisman and Klemp (*MWR*, 110, 1982)

The experiment reproduces the development and evolution of a three-dimensional supercell over a flat terrain.

Domain height: 23 km
Flat levels above: 11 km
Vertical coordinate: Gal-Chen
Exponent in the Gal-Chen formula 2.6

Grid resolution:
Vertically 64 levels
Horizontally Δx=Δy=2km
Mesh size 100x100 grid points

Boundary conditions: periodic

Microphysics parameterization:
graupel-scheme (4)

Vertical turbulent diffusion:
1-D TKE based diagnostic closure

Environmental potential temperature and relative humidity are given by analytical formulas.

Initial conditions:

- Axial symmetric thermal perturbation of horizontal radius 10km and vertical radius 1.4km.
- Center of the thermal is located 1.4km above ground level
- Temperate excess 3° C at the center of the thermal and decreases gradually to 0° C at the edge.

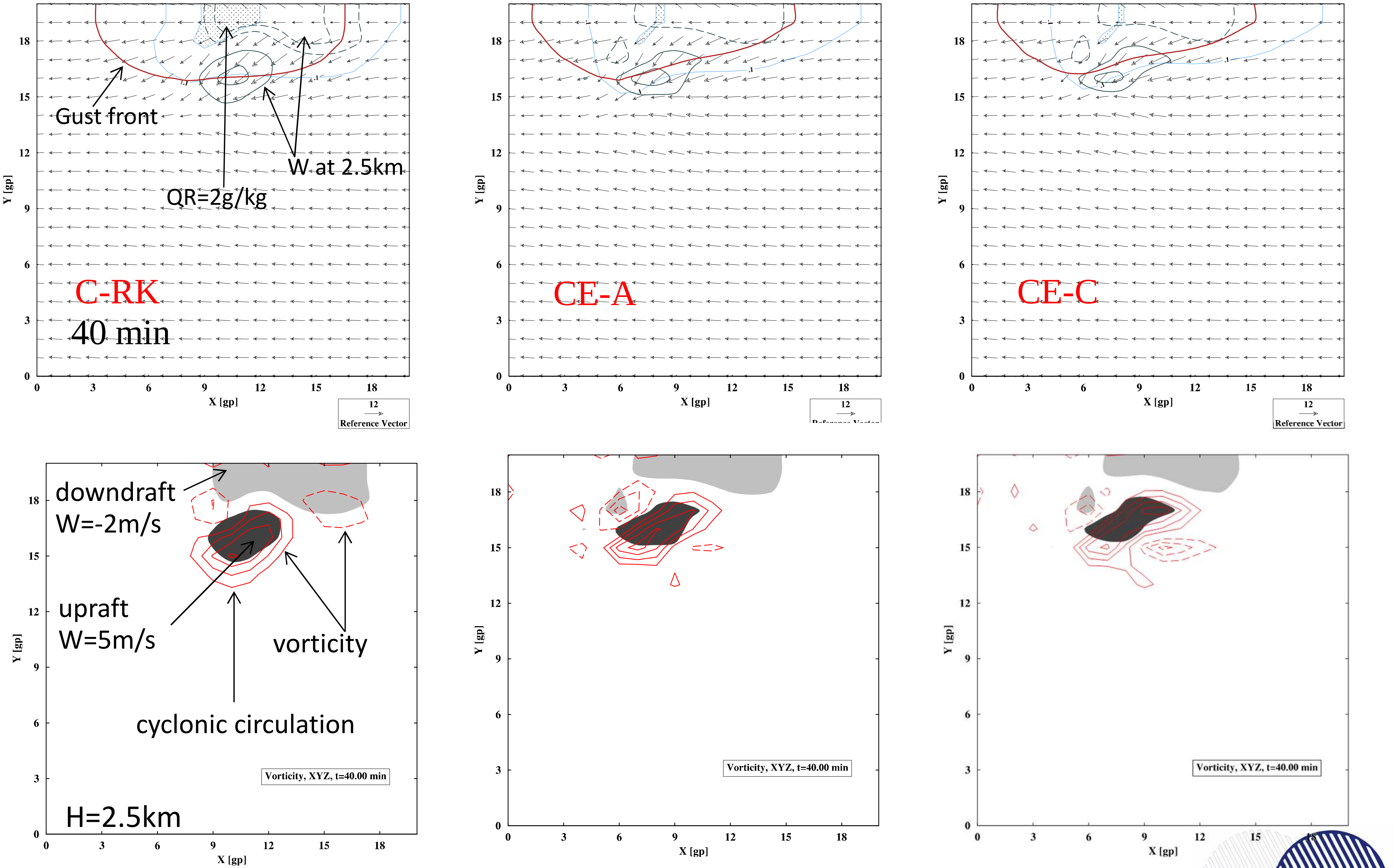
Wind profile (horizontal component):

$$U(z) = U_S \tanh(z / z_s)$$

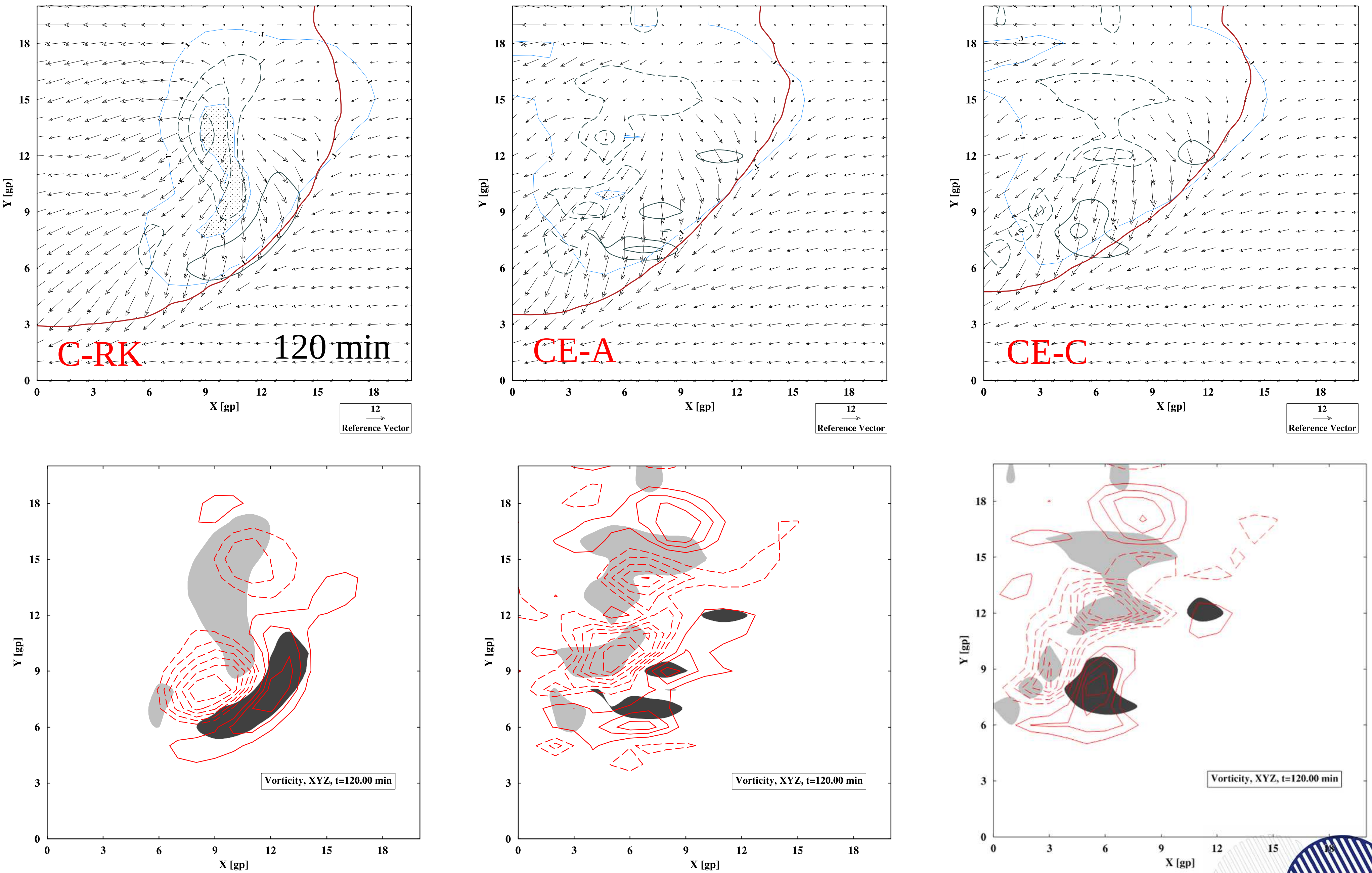
$$z_s = 3km$$

U_s is varied from 0 through 45 m/s

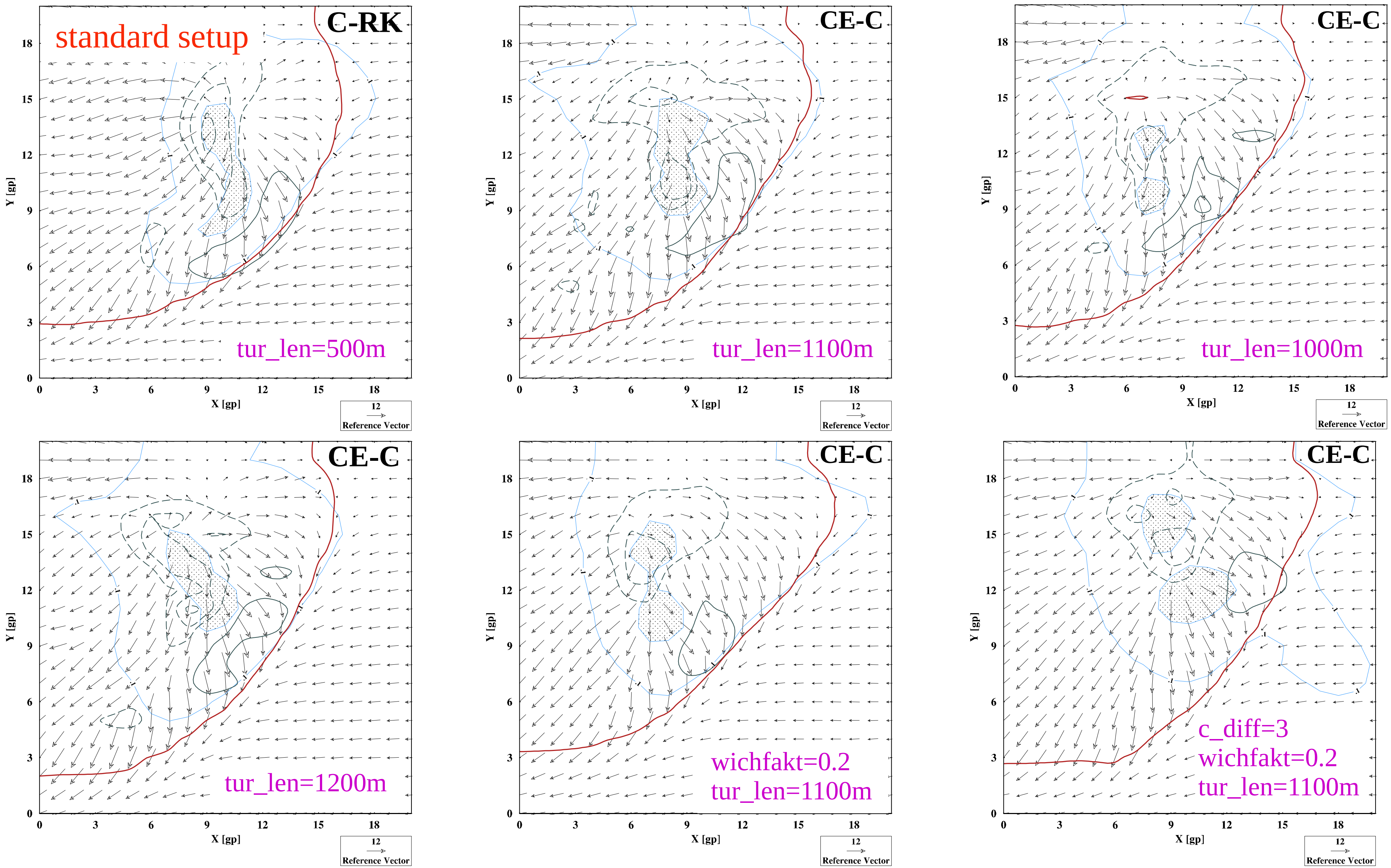
Moist benchmark test - Weisman and Klemp (*MWR*, 110, 1982)



Moist benchmark test - Weisman and Klemp (*MWR*, 110, 1982)



Moist benchmark test - Weisman and Klemp (*MWR*, 110, 1982)



tur_len - maximal turbulent length scale (m) [0, 10000] (default 500m)

wichfakt - vertical smoothing factor for explicit vertical diffusion coefficients (0, 0.5]. (default 0)

c_diff - Factor for turbulent diffusion of TKE (0, 10) (default 0.2)

Modeling of daytime convective development using CE-C/A

1. Computational grid depends on simulation
- horizontal (**100 m - 1800 x 180 grid points**; **2km - 300 x 300**)
- vertical as in COSMO 2.2km (**60 levels**)

2. Initial soundings from Grabowski et al 2006 linearly interpolated to the COSMO grid.

3. Periodic lateral boundary conditions.

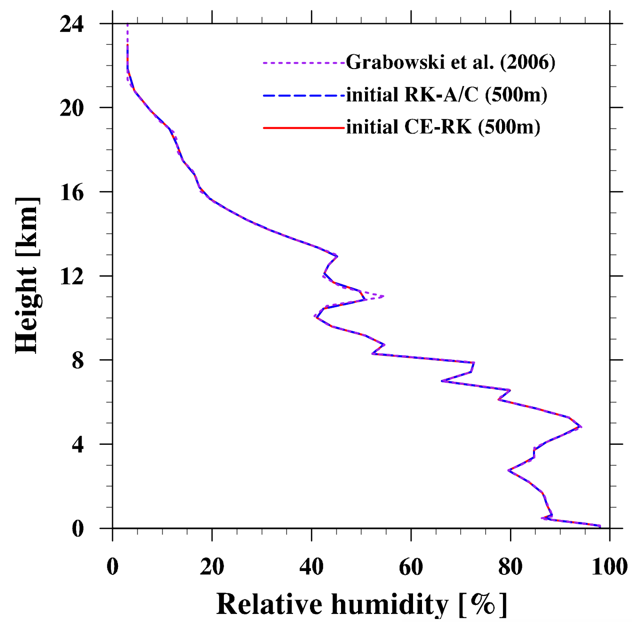
4. Surface latent and sensible heat fluxes applied as analytical functions of time plus 10% random noise.

5. Temperature and moisture random perturbation added below 1 km height with the amplitude of **0.1K** and **0.1g/kg** every 15 min.

6. No **radiative cooling.**

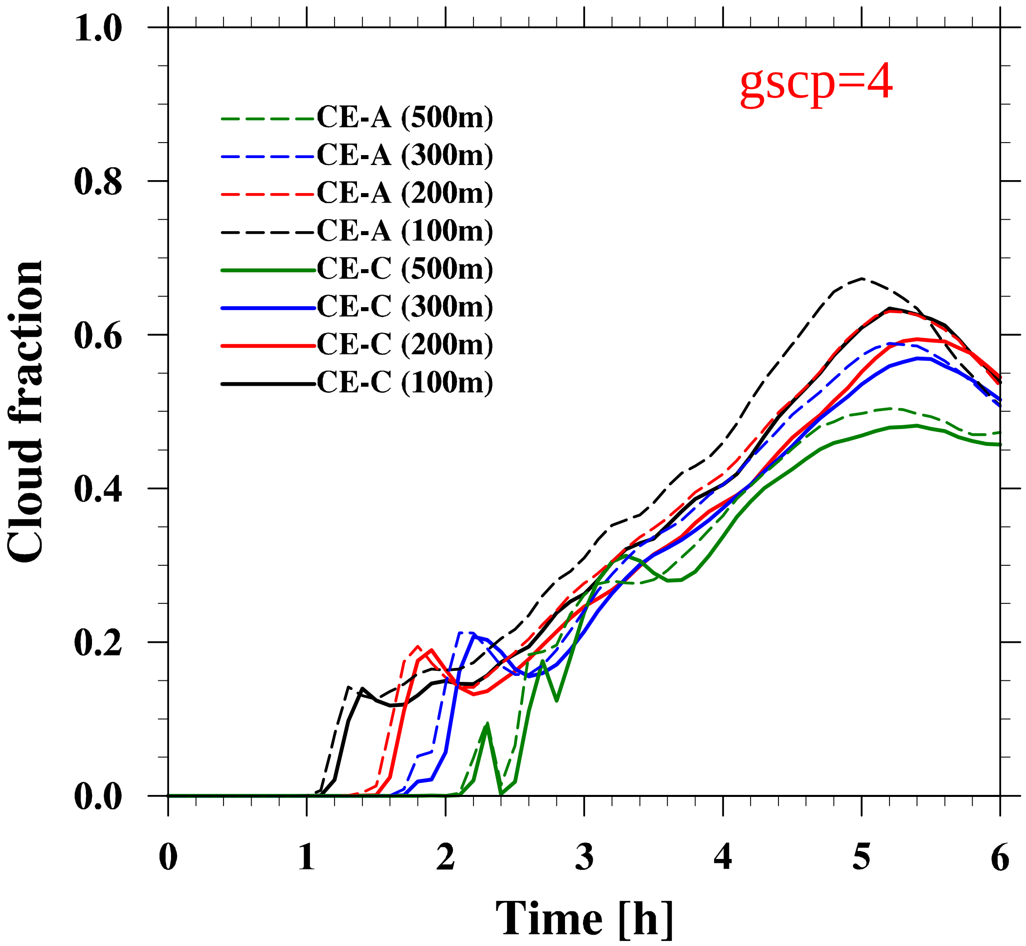
7. **Shallow convection parameterization switched off.**

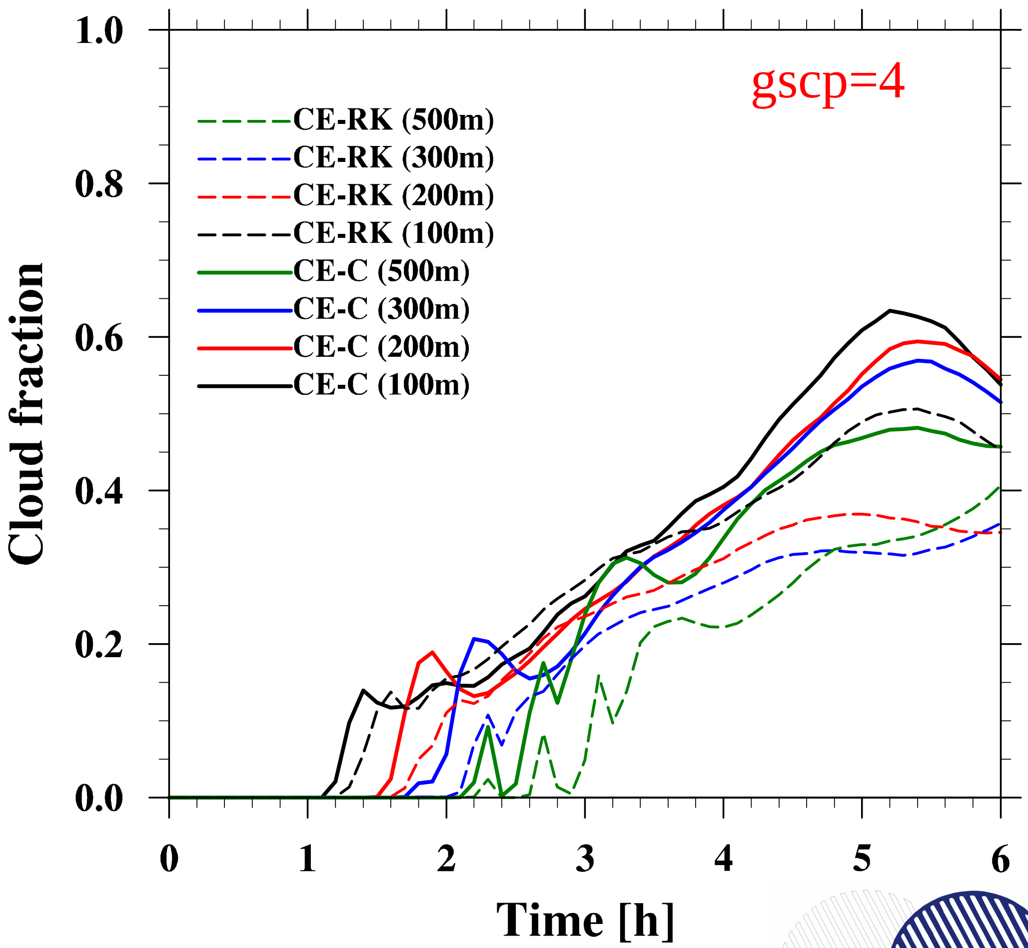
8. **Subgrid-scale turbulence** based on 1-D TKE and 3D closure



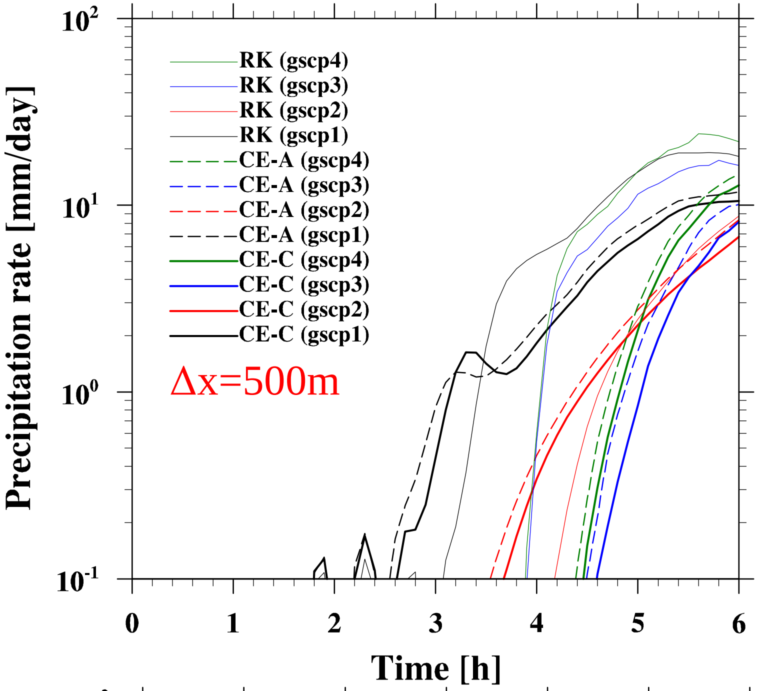
Cloud fraction

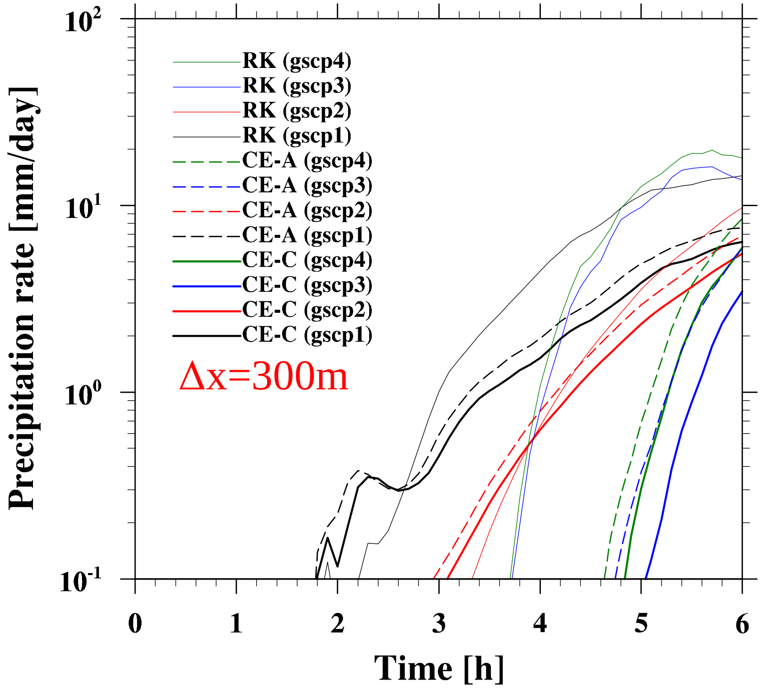
The cloud fraction is defined as a fraction of grid boxes at a given level with the cloud condensate mixing ratio (water plus ice) larger than the threshold value, selected as 10^{-5} [kg/kg].

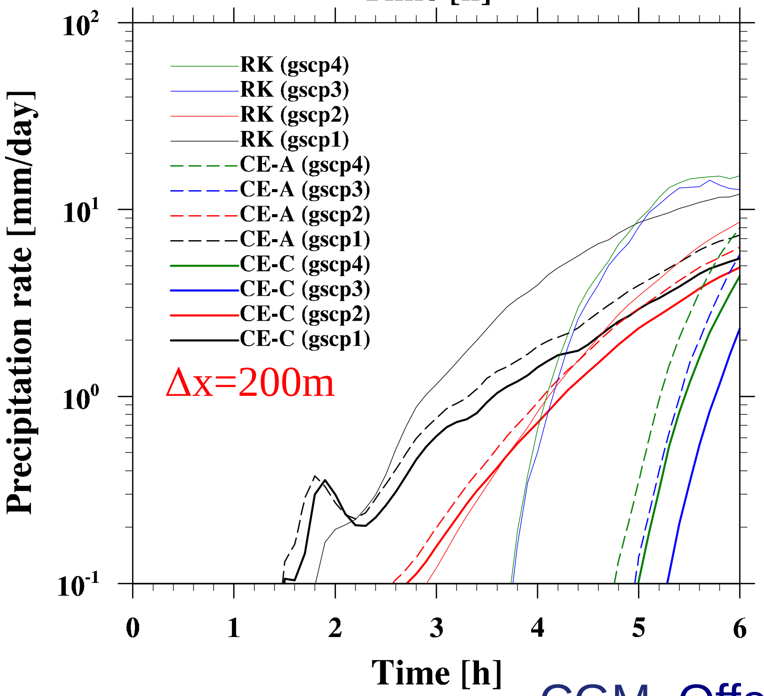




Precipitation rate [mm/day]







1. Results from high resolution simulations with the three dynamical cores are in qualitative agreement with the reference solution from Grabowski et al. 2006.
2. Formation of precipitation in simulations with CE-A/C is slightly faster than in C-RK (depends on the mesh resolution).
3. Amount, temporal structure and onset of precipitation strongly depend on microphysics parameterization scheme.

Future work

- Further tuning and optimization
- Development of a single precision version and restart subroutine
- Implementation of full ICON physics

External resources (Z. Piotrowski) :

- Optimization of numerical and physical formulation of COSMO-EULAG at and near the surface
- Adaptation of EnKF capabilities (KENDA, KENDA-O) to the EULAG numerical formulation
- Implementation of EULAG dycore into the STELLA / GridTools library