Status of "COSMO-EULAG operationalization (CELO)" Priority Project

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CELO priority project tasks – an overview

Task 1: Integration of EULAG DC with COSMO framework
(coupling to parametrizations and surface model,
global model data management)

Task 2: Consolidation and optimization of the EULAG DC formulation
(flexible vertical coordinate, full pressure retrival,
boundary conditions optimization, pressure solver effeciency)

Task 3: Integration of EULAG DC with COSMO framework
(code optimization and restructuring, restart, consolidation
of MPI parallelism, stencil library)

Task 4: Optimization and testing of COSMO with EULAG DC
(after completion of Task 1-3)

Task 1 activities

Highlights:

- **Review of the moist physics coupling, testing stable and convective scenarios over the Alps (COSMO framework with EULAG dynamical core for 2.2 km, 1.1 km, 0.55 km and 0.28 km, compared to RK dynamical core with 2.2 km and 1.1 km), optionally with MPDATA implemented for moist variables;**

- **Idealized testing of physics - dynamics coupling (work in progress);**

- **Consolidation of global model data management (not shown).**

Setup of realistic simulations

Domain :

- (ie_tot x je_tot) = (520 x 350) / (1040 x 700) / (806 x 806)
  (2.2km) / (1.1km) / (0.55km & 0.28km)
- Gal-Chen coord. system : vcflat = 23588.50, standard level distribution
- rlwidth = 40 km (2.2km, 1.1km and 0.55km) or 20km (0.28km)
- rd_height = 15km top sponge

Dynamics :

- lcond =TRUE (condensation is switch on)
- lhoridiff=F
- MPDATA advection of the moisture quantities

Microphysics :

lgsp=T, itype_gscp=4 (ice, rain, snow, graupel) grid scale precipitation

Radiation :

- lrad=T Radiation switched on
- hincrad=0.25 for 2.2km, 0.1 for higher resolutions

Others :

- Soil model : lsoil=T, lforest=T
- Turbulence : ltur=T, itype_turb=3, imode_turb=1
- Surface layer fluxes : itype_tran=2, imode_tran=1
- Convection parametrisation : lconv=F switched off
- Sgs orography : lsso=F, ltkesso=F, lradtopo=F

Setup of realistic simulations

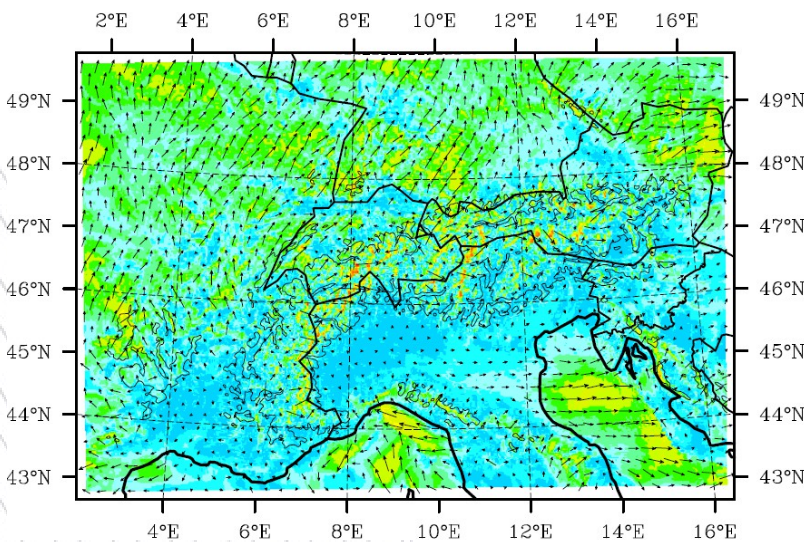
Initial and boundary data:

Data for all resolutions are interpolated from COSMO-7 of MeteoSwiss.
For presented results standard orography filtering was applied:
lfilter_oro=T
    ilow_pass_oro=4
    numfilt_oro=1
    ilow_pass_xso=5
    numfilt_xso=1
    rxso_mask=750.0

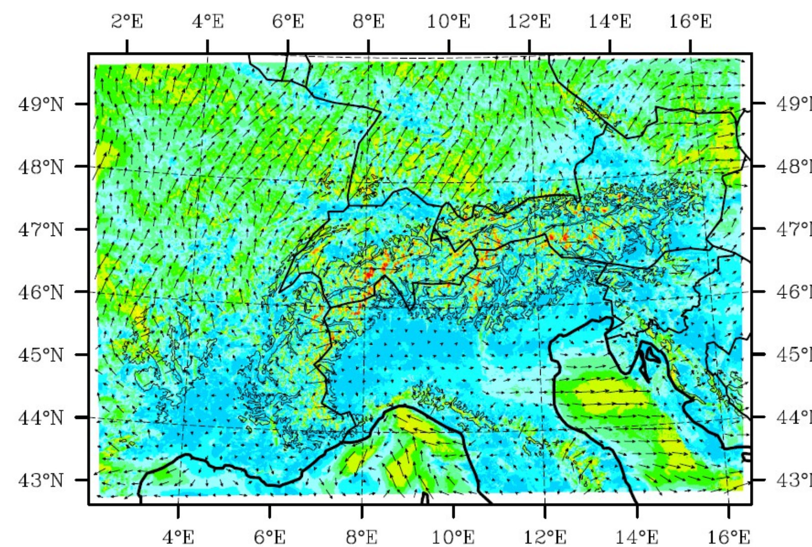
Maximum slopes :
2.2km → 20°
1.1km → 31°
0.55km → 55°
0.28km → 65 °

Stable autumn scenario

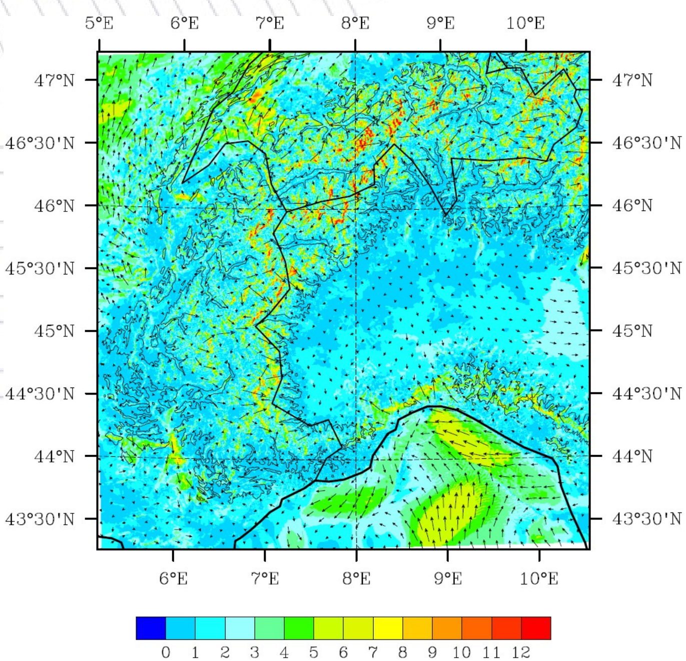
Flow : 10 m above ground level, 12 UTC



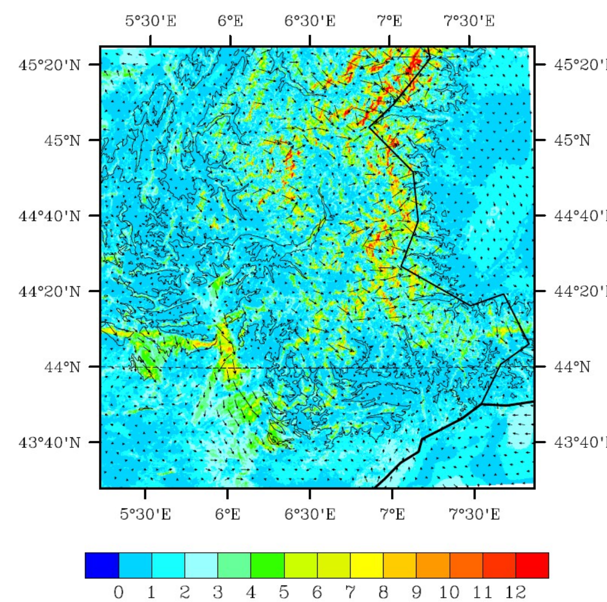
2.2 km



1.1 km

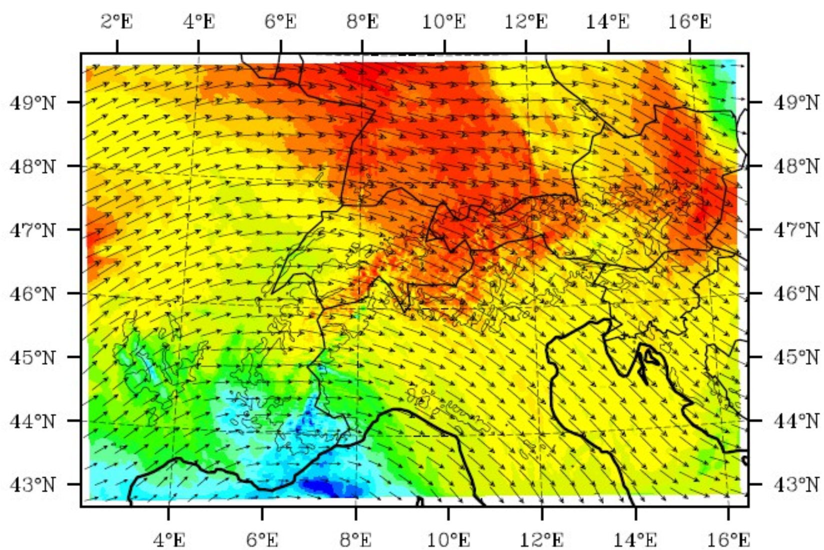


0.55 km

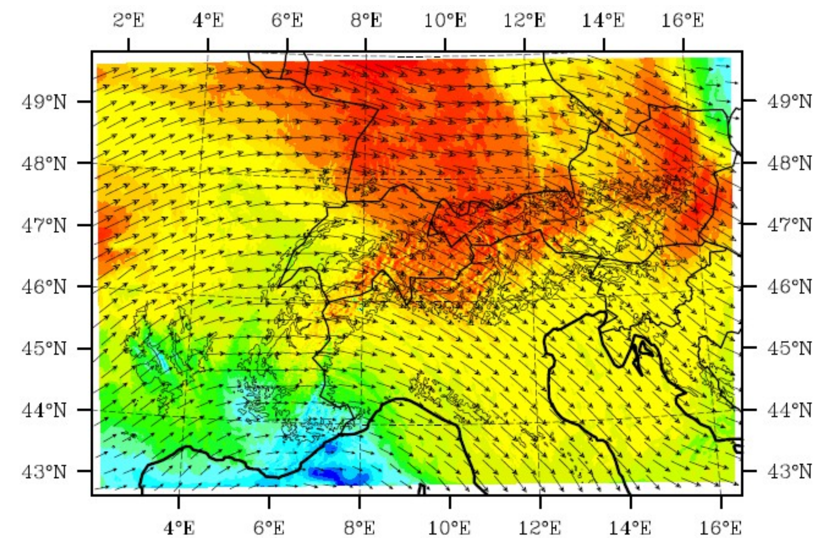


0.28 km

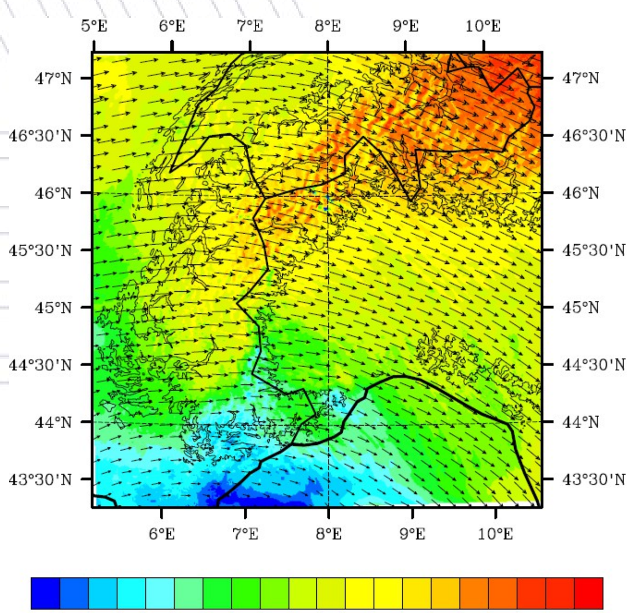
Flow : 4500 m above ground level, 12 UTC



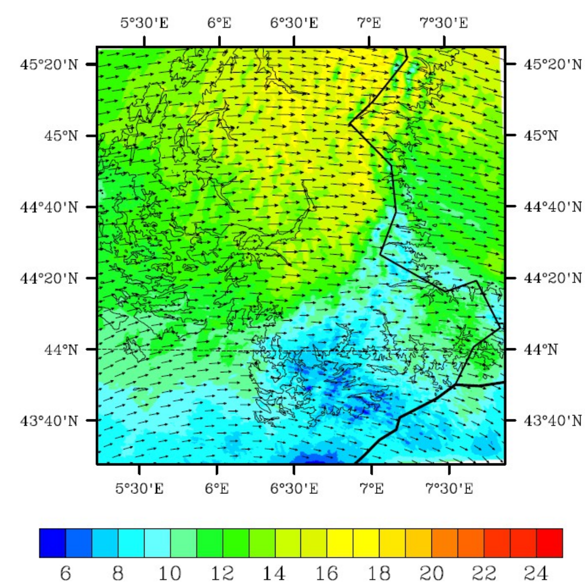
2.2 km



1.1 km

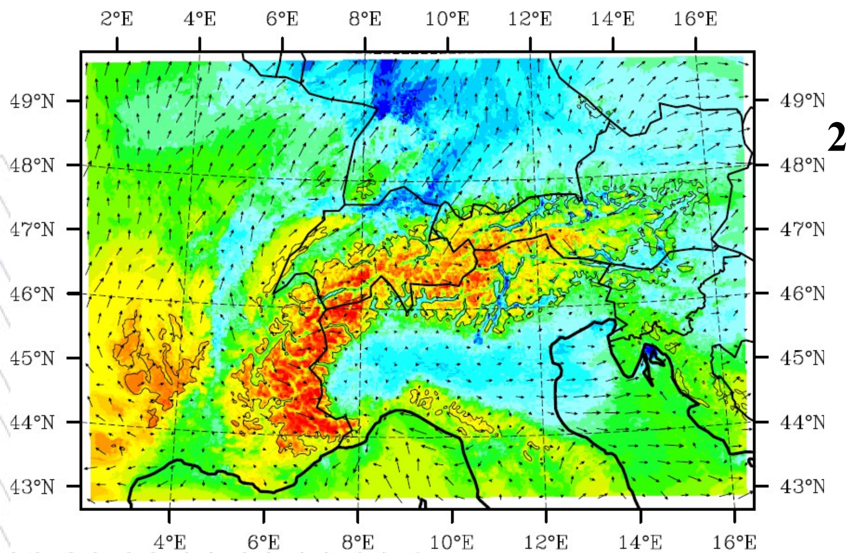


0.55 km

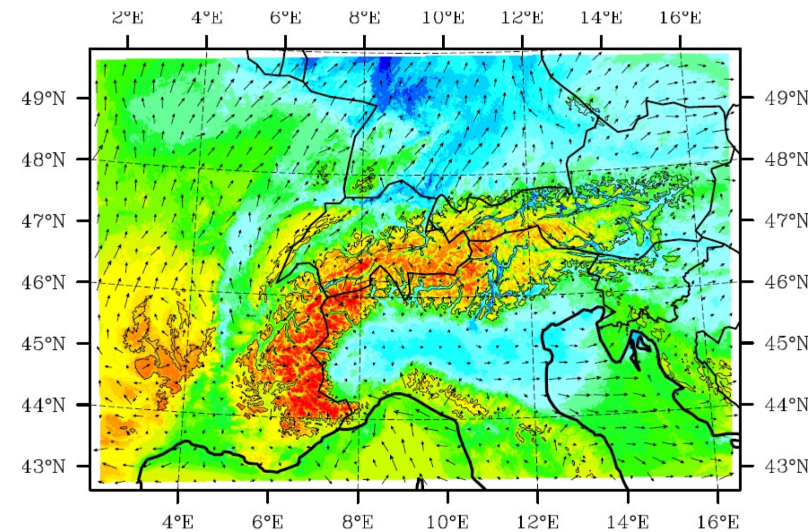


0.28 km

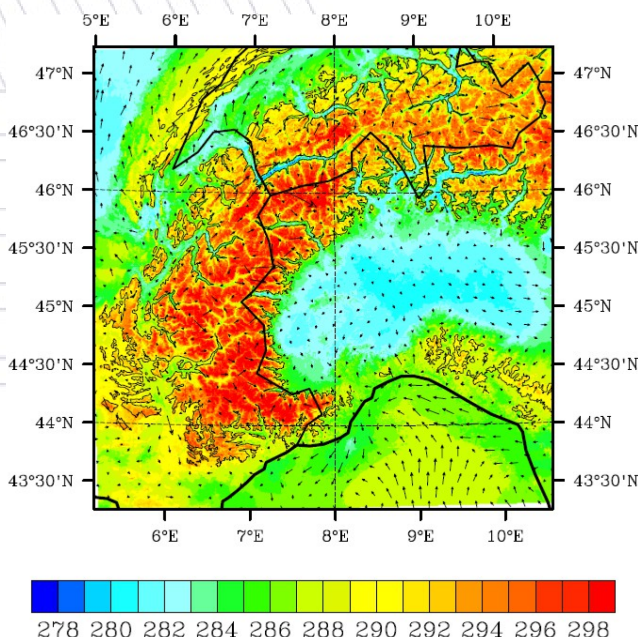
Theta : 10 m above ground level, 12 UTC



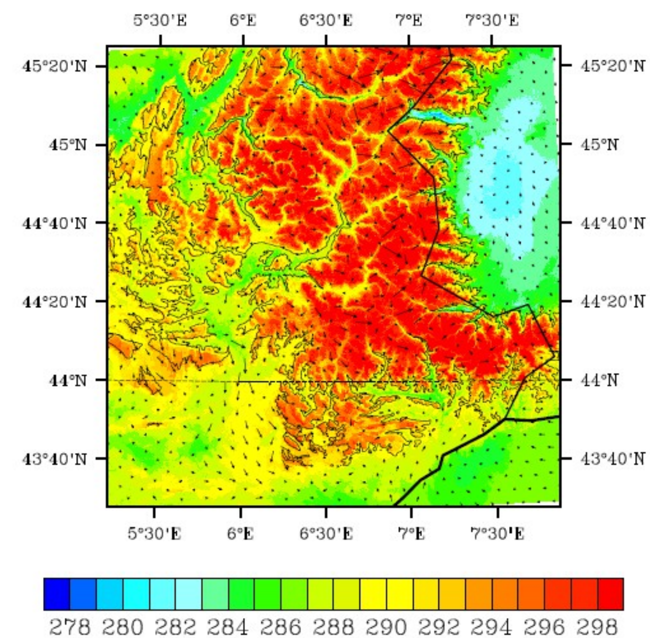
2.2 km



1.1 km



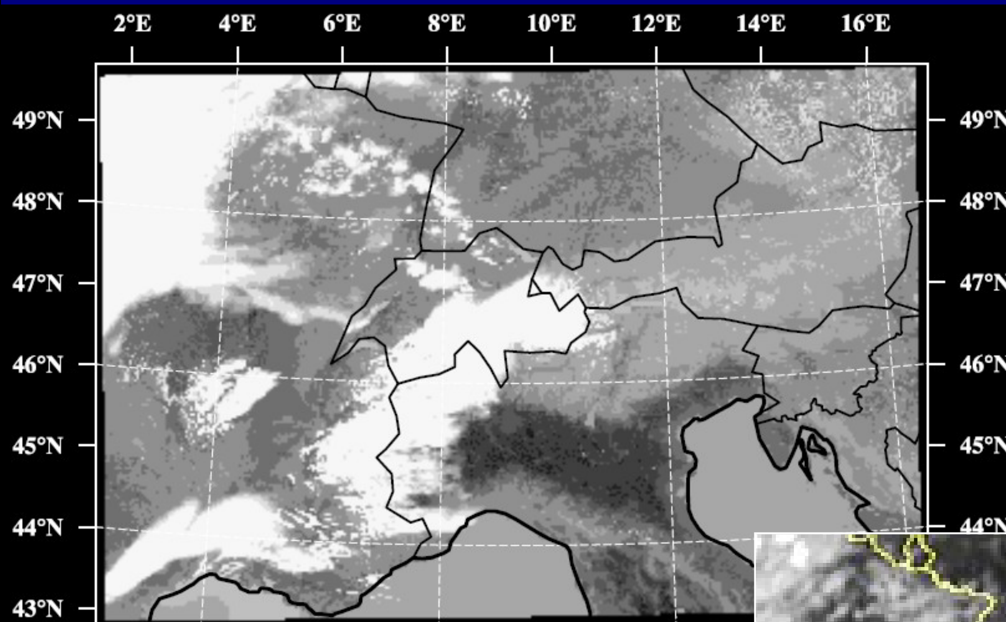
0.55 km



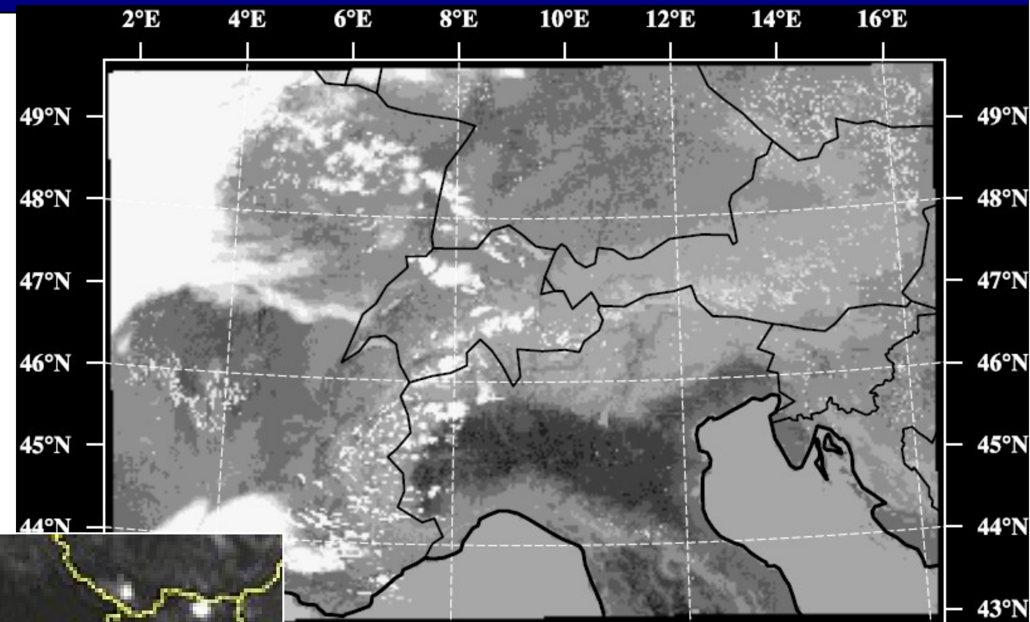
0.28 km

Convective summer scenario

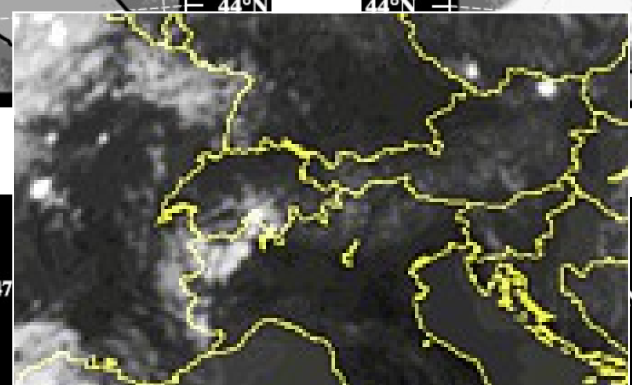
Cloud radiance (high res.) 14:00 UTC (COSMO 4.17)



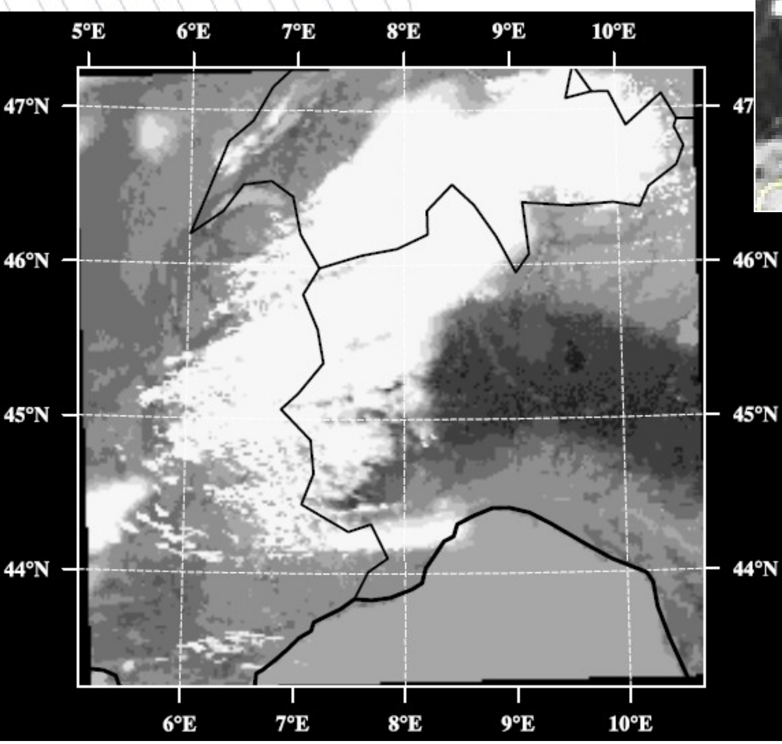
CE 1.1km SCP on

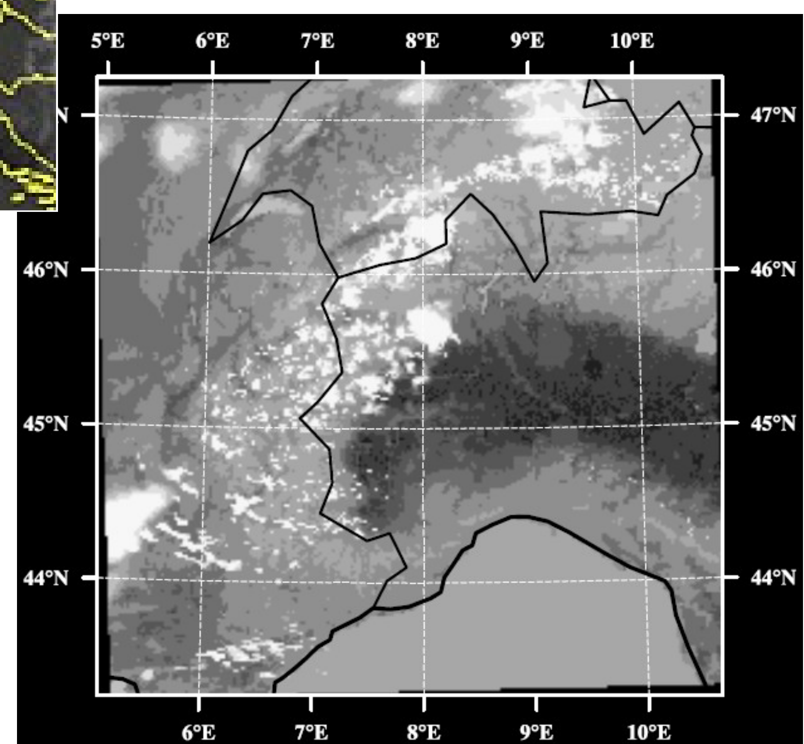


CE 1.1km SCP off



MSG infrared band

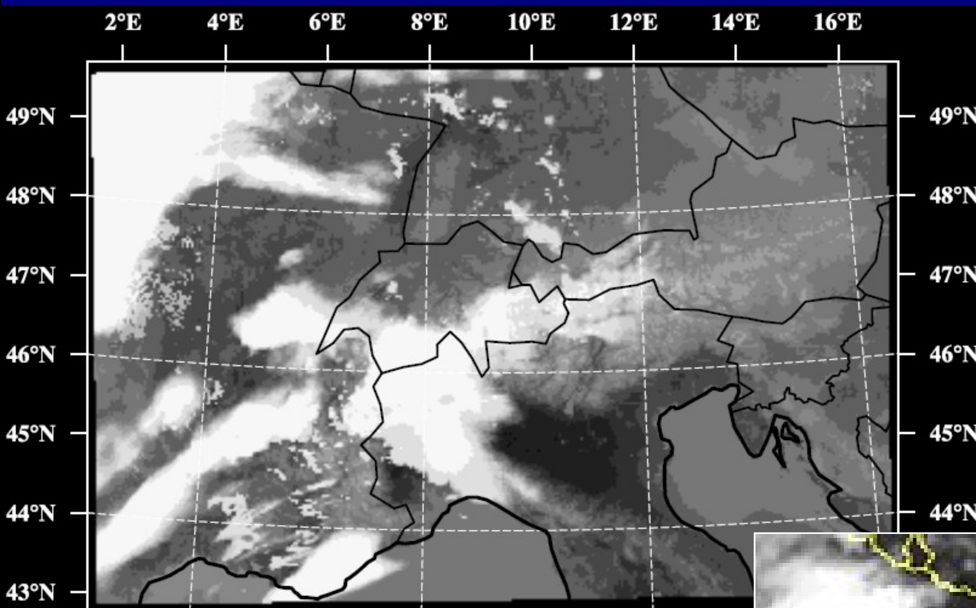




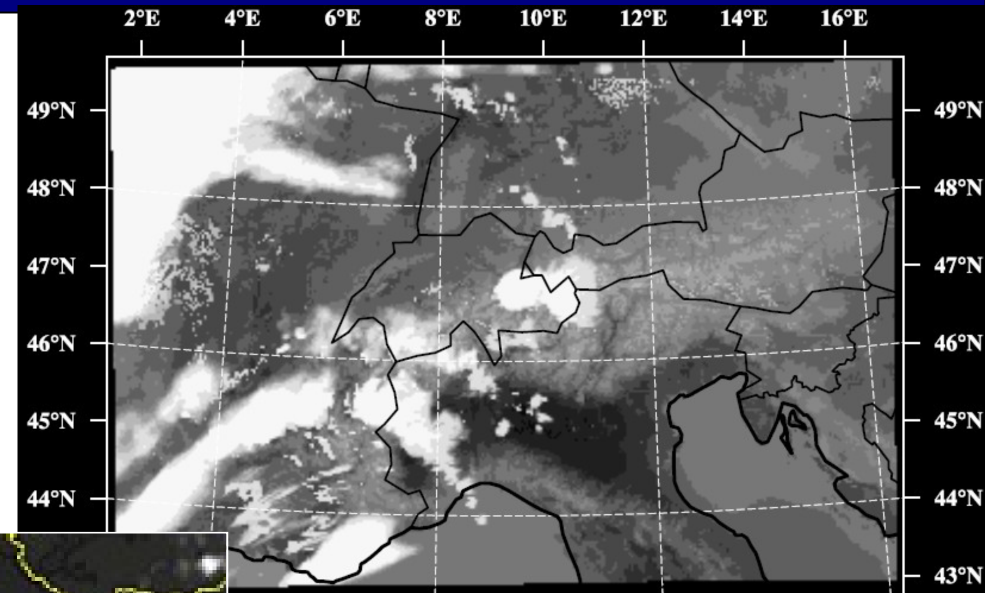
CE 0.5km SCP off

CE 0.5km SCP on

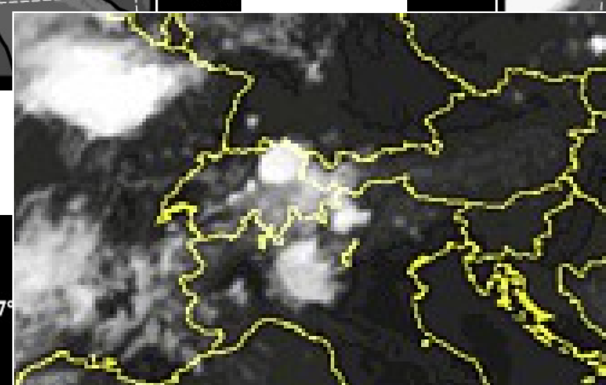
Cloud radiance (high res.) 18:00 UTC



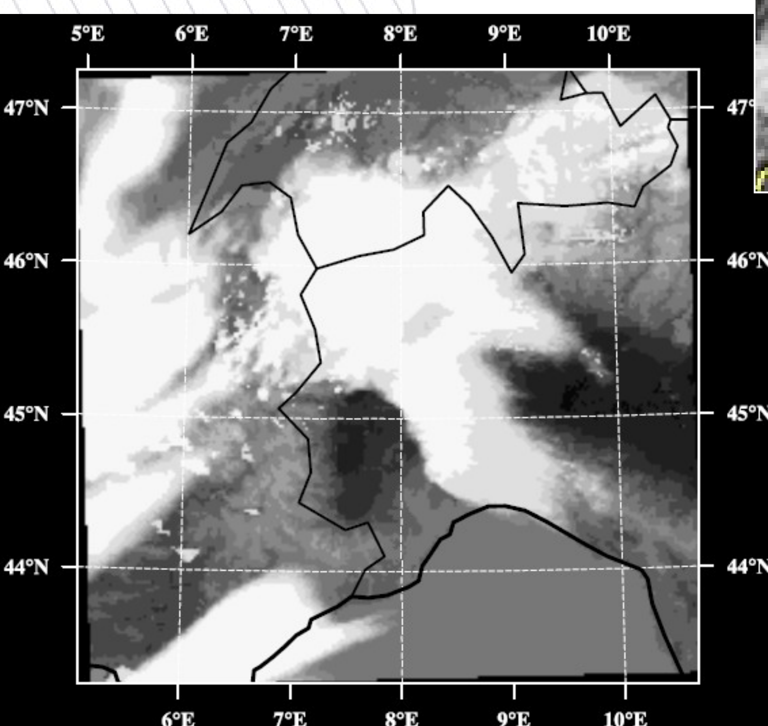
CE 1.1km SCP on

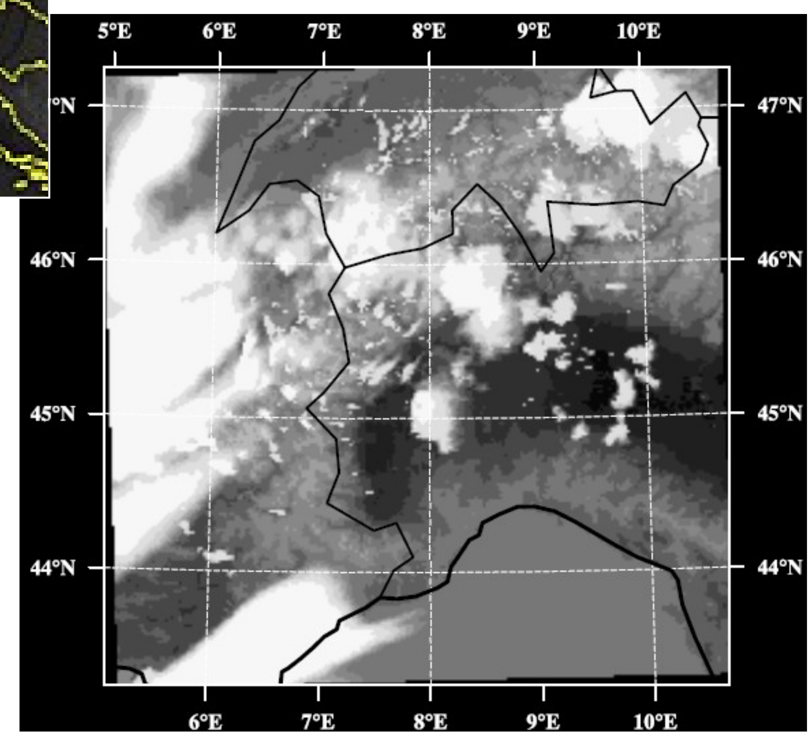


CE 1.1,km SCP off



MSG infrared band





CE 0.5km SCP off

CE 0.5km SCP on

Idealized experiments evaluating dynamics – physics coupling

To examine in detail EULAG DC coupling to physics and facilitate future tuning of parameterizations, relevant idealized tests are implemented.

Comparision between EULAG and RK DC and verification against reference results is planned

Idealized experiments evaluating dynamics – physics coupling

Splitting storm experiment (Weisman Klemp 1982)

Discussed later in the presentation

Modeling of daytime convection development (Grabowski et al. 2006))

The goal of the experiment is to investigate convective development over land and shallow to deep convection transition.

- The case is based on general features of convective development observed over Amazonia.
- The initial sounding, the evolution of surface latent- and sensible-heat fluxes, and the evolution of the temperature tendency due to radiative processes are all based on observations and simulations of the 23 February 1999 TRMM-LBA case.
- No large-scale advective tendencies of temperature or moisture are imposed.
- The case features the development of a well-mixed convective boundary layer from the early morning sounding, subsequent formation of shallow convection as the boundary layer deepens, and eventual transition from shallow to deep convection.

Task 2 activities

Highlights:

- **Implementation of the generalized metric terms for arbitrary vertical coordinate provided by COSMO**

- **Power spectra for COSMO-EULAG and COSMO-RK**

- **Role of anelastic pressure perturbation in moist processes – idealized study**

Computation of the inverse metric coefficients

Equations are derived based on the assumption that 16 differential identities:

$$\delta^r_s \equiv \frac{\partial \overline{x}^r}{\partial x^q}\frac{\partial x^q}{\partial \overline{x}^s}$$

x,y,z – physical coordinates, here in lat-lon-z for EULAG DC

are satisfied. For the transformation at hand:

$$(\overline{t},\overline{x},\overline{y},\overline{z}) \equiv (t, E(t,x,y), D(t,x,y), C(x,y,z,t))$$

computational space (ordered like Cartesian grid)

we are left with 9 non-trivial equations:

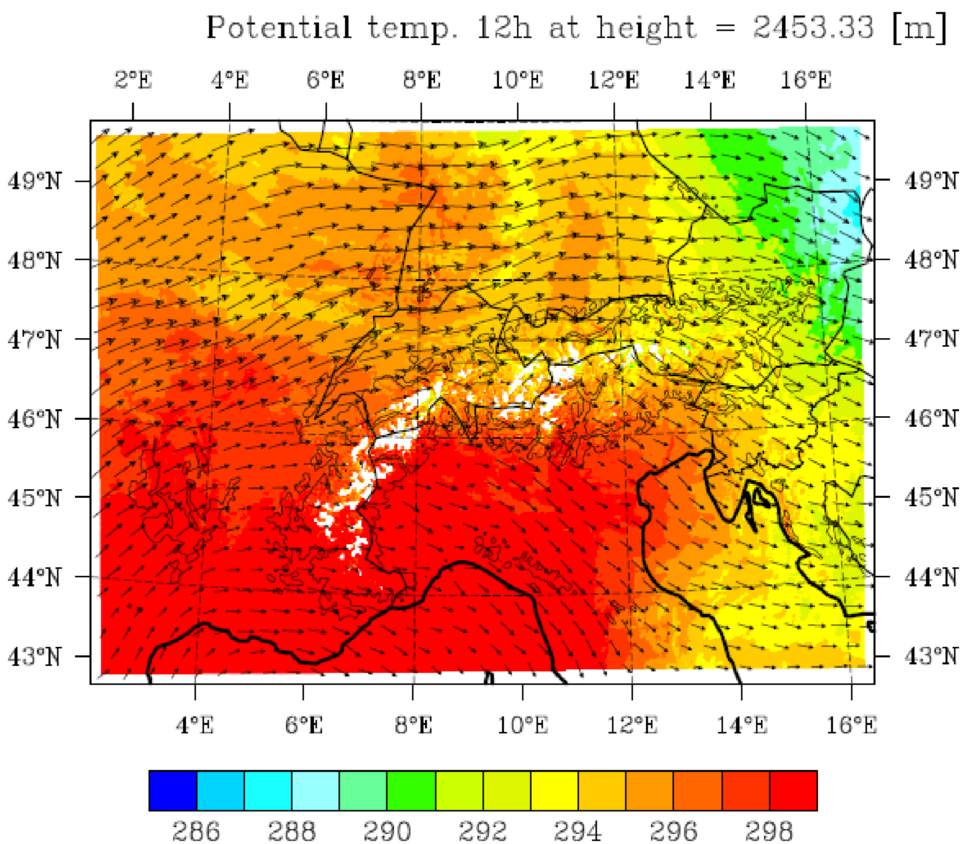
$$\begin{bmatrix} \frac{\partial x}{\partial E} & \frac{\partial y}{\partial E} & 0 \\ \frac{\partial x}{\partial D} & \frac{\partial y}{\partial D} & 0 \\ \frac{\partial x}{\partial \overline{t}} & \frac{\partial y}{\partial \overline{t}} & 1 \end{bmatrix} \begin{bmatrix} \frac{\partial E}{\partial x} \\ \frac{\partial E}{\partial y} \\ \frac{\partial E}{\partial t} \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} \frac{\partial x}{\partial E} & \frac{\partial y}{\partial E} & 0 \\ \frac{\partial x}{\partial D} & \frac{\partial y}{\partial D} & 0 \\ \frac{\partial x}{\partial \overline{t}} & \frac{\partial y}{\partial \overline{t}} & 1 \end{bmatrix} \begin{bmatrix} \frac{\partial D}{\partial x} \\ \frac{\partial D}{\partial y} \\ \frac{\partial D}{\partial t} \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$$

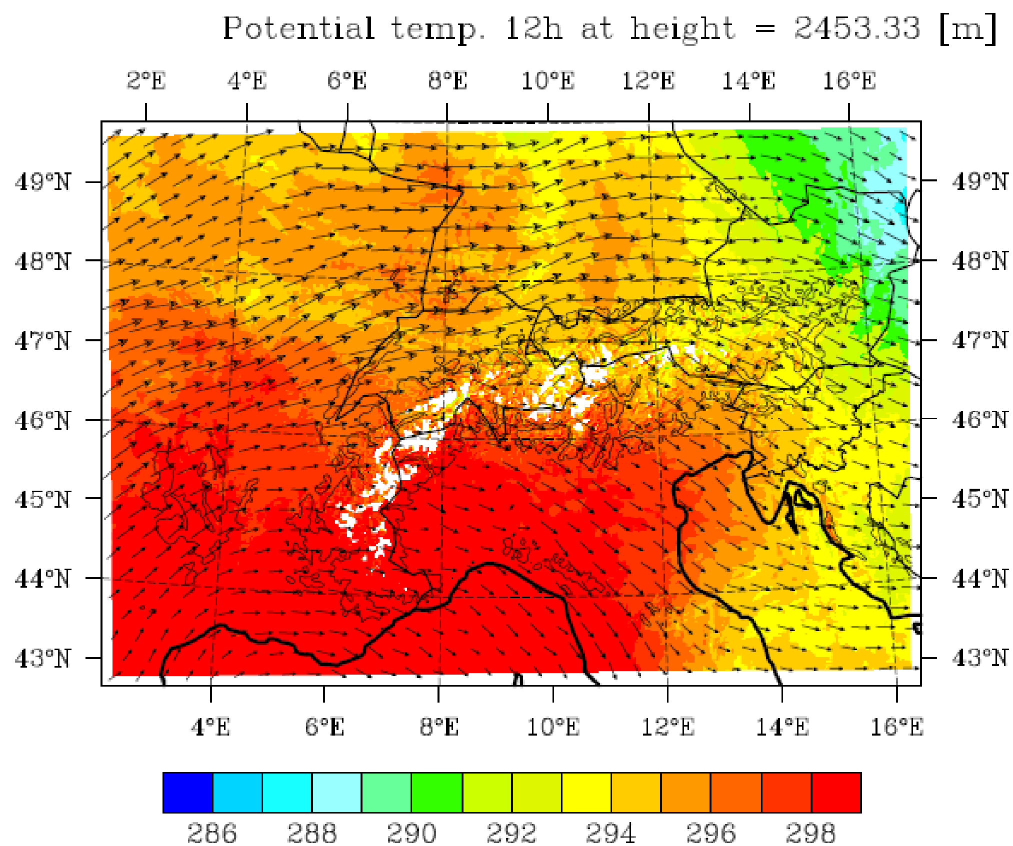
that are solved analytically for the metric terms.

$$\begin{bmatrix} \frac{\partial x}{\partial E} & \frac{\partial y}{\partial E} & 0 \\ \frac{\partial x}{\partial D} & \frac{\partial y}{\partial D} & 0 \\ \frac{\partial x}{\partial \overline{t}} & \frac{\partial y}{\partial \overline{t}} & 1 \end{bmatrix} \begin{bmatrix} \frac{\partial C}{\partial x} \\ \frac{\partial C}{\partial y} \\ \frac{\partial C}{\partial t} \end{bmatrix} = \begin{bmatrix} -\frac{\partial z}{\partial E} / \frac{\partial z}{\partial C} \\ -\frac{\partial z}{\partial D} / \frac{\partial z}{\partial C} \\ -\frac{\partial z}{\partial \overline{t}} / \frac{\partial z}{\partial C} \end{bmatrix}$$

Example of flow realization in Gal-Chen and SLEVE coordinate



Gal-Chen



SLEVE

Realization of the flow after 12 h is comparable, resulting potential temperature distribution generally differs by about 1 K.

Remarks on atmosphere at rest tests

COSMO-EULAG, in addition to reference states, employs '*environmental*' states (functions of x,y,z,t) such that:

$$0 = -\widetilde{\mathbf{G}}(\overline{\nabla}(\pi_e - \pi_0)) - \mathbf{g}\frac{\theta_e - \theta_0}{\theta_0} - \mathbf{f} \times \mathbf{v}_e + \mathbf{M}_e$$

where '0' subscript denotes anelastic reference state.

If environmental states are chosen such that the temperature perturbation is zero, then in any atmosphere-at-rest experiment atmosphere will remain **exactly at rest** regardless of the coordinate transform, slope shape, height or steepness and initial and reference temperature profiles.

Atmosphere at rest tests performed within CDC Priority Project shown no significant production of spurious circulations for typical magnitudes of potential temperature perturbation.

Kinetic energy spectra

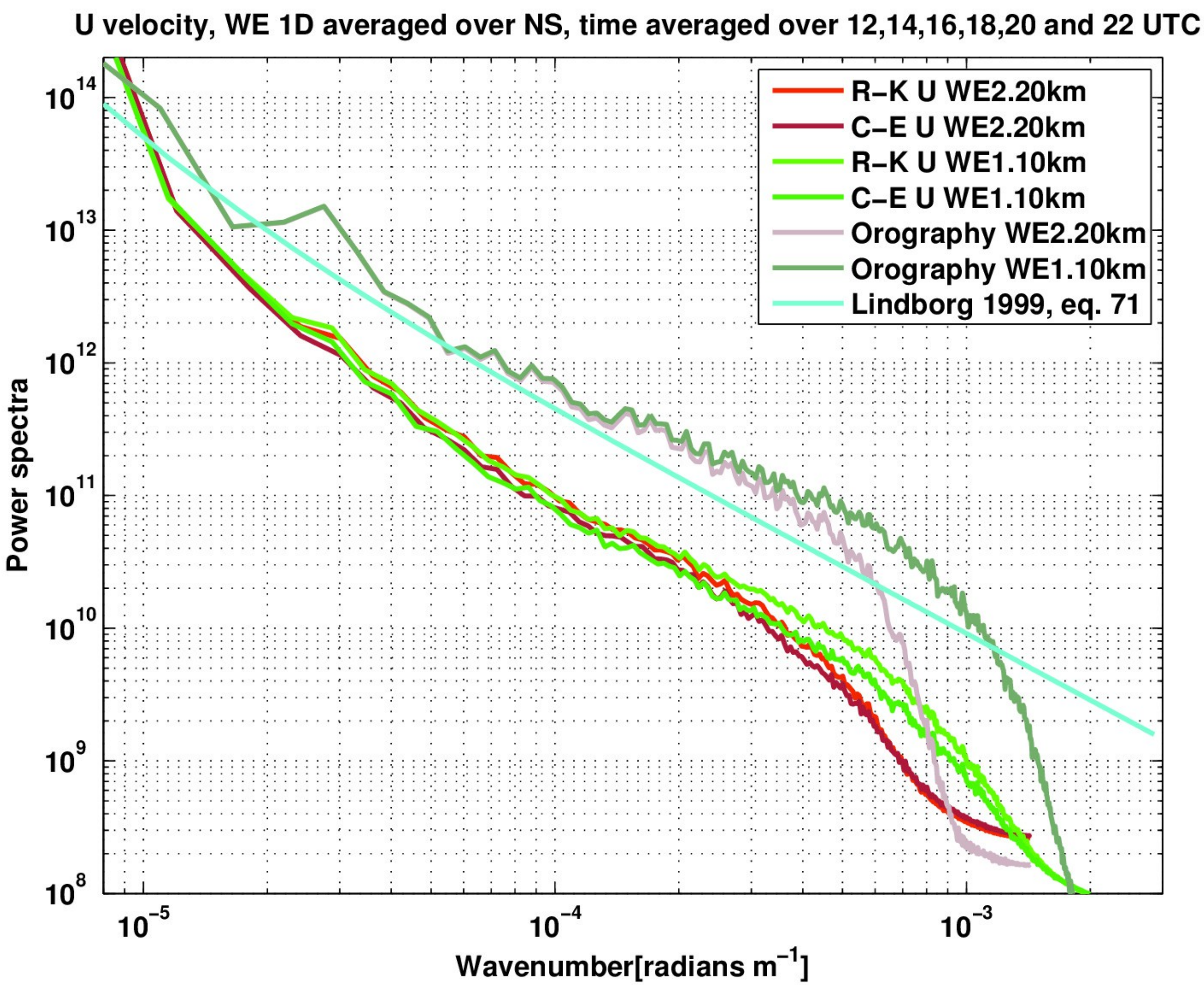
We evaluate power spectra for COSMO-EULAG and COSMO-RK at 2.2 km and 1.1 km. In addition, we examine power spectra for 0.55 km and 0.28 km COSMO-EULAG simulations on a limited domain.

Methodology follows Skamarock 2004 „Evaluating Mesoscale NWP Models Using Kinetic Energy Spectra" paper.

For the 2.2 km and 1.1 km both dynamical cores exhibit similar response to the increasing resolution.

Spectral response of the model seem to be connected to the spectral properties of the topography.

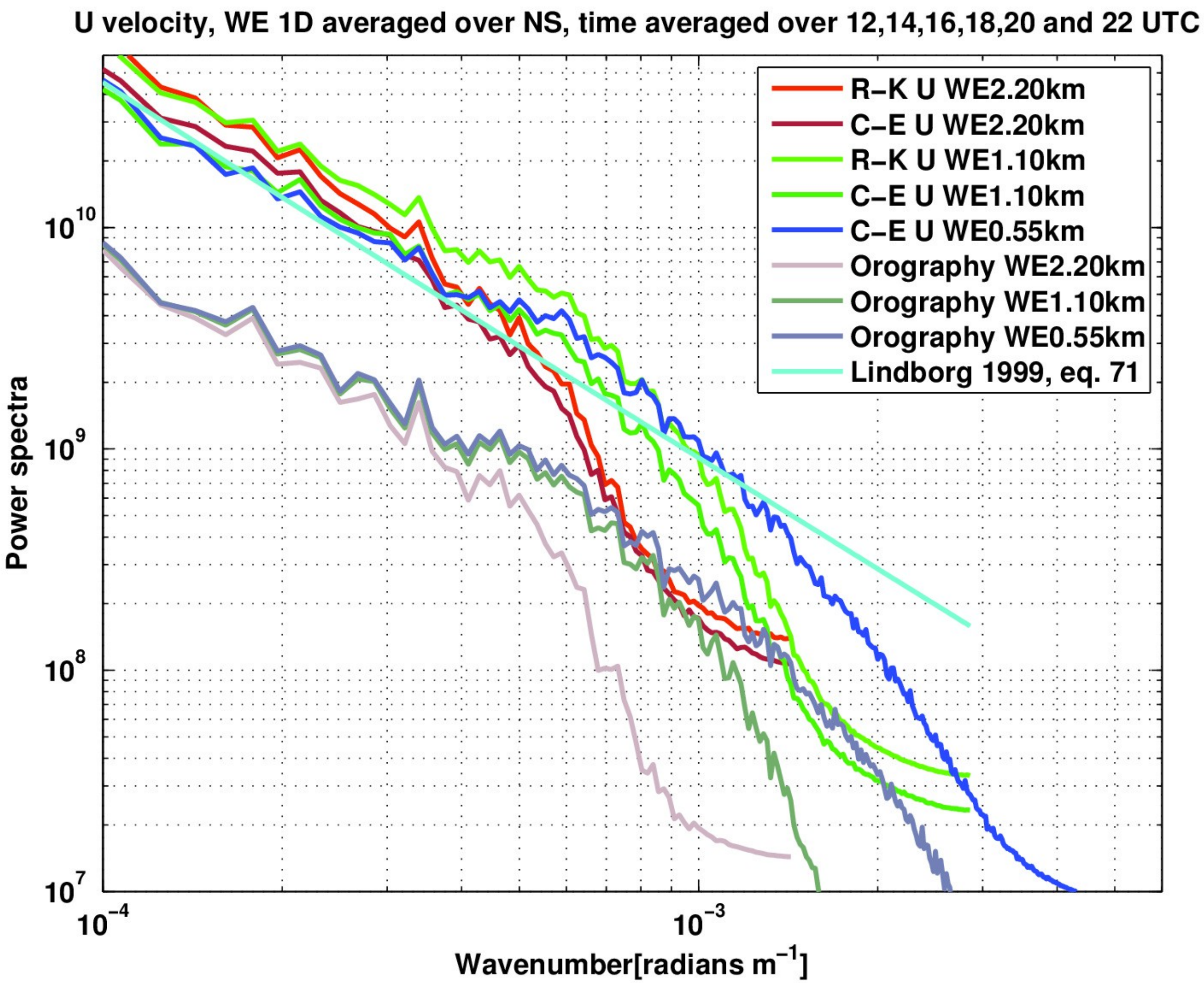
Kinetic energy spectra 2.2 km and 1.1 km



Comparision of kinetic energy spectra for CE and RK simulations of stable scenario for 26th - 36th model level above the ground.

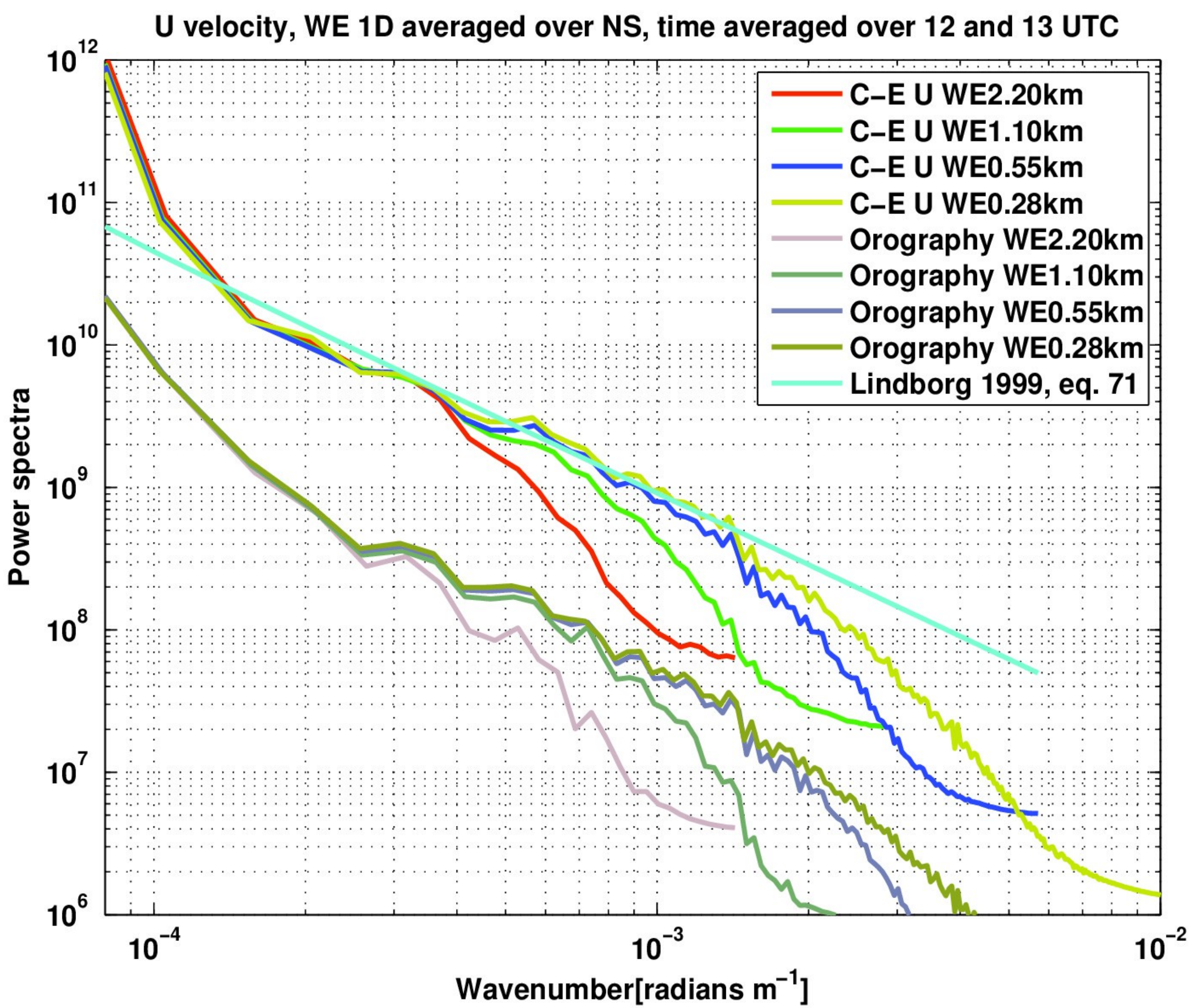
Note that spectra pairs (2.2 km red and 1.1 km green) for CE and RK compare similarly to the reference slope (blue).

Kinetic energy spectra 2.2 km, 1.1 km and 0.55 km on limited domain



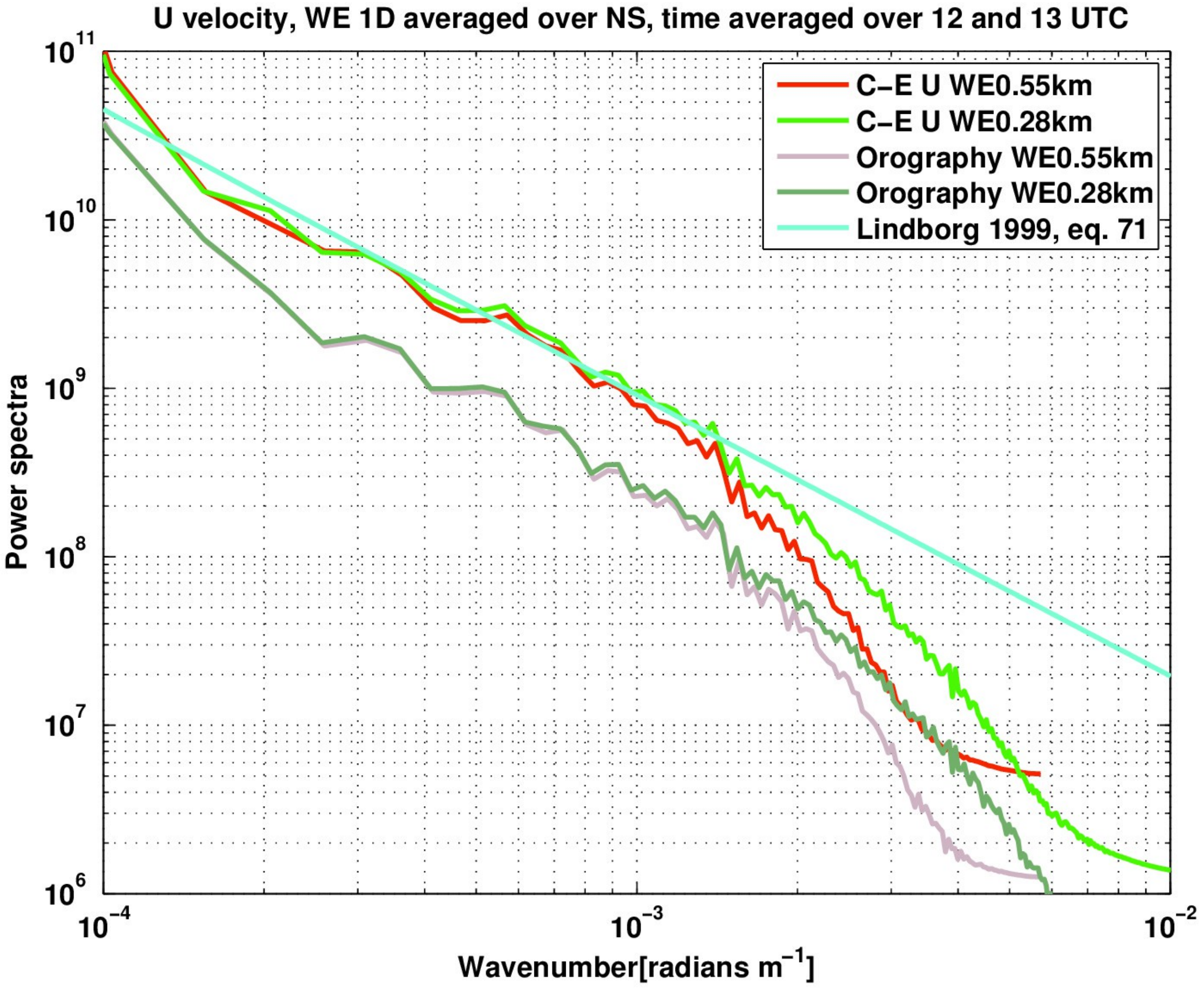
Comparision of kinetic energy spectra for CE and RK simulations of stable scenario for 26th - 36th model level above the ground (only tail of the spectrum is shown)

Kinetic energy spectra 2.2 km, 1.1 km, 0.55 km and 0.28 km on limited domain



Comparision of kinetic energy spectra for CE simulations of stable scenario for 26th - 36th model level above the ground

Kinetic energy spectra 0.55 km and 0.28 km on limited domain



Comparision of kinetic energy spectra for CE and RK simulations of stable scenario for 26th - 36th model level above the ground (only tail of the spectrum is shown)

Anelastic vs Compressible pressure – study by dr Marcin Kurowski et al. at NCAR

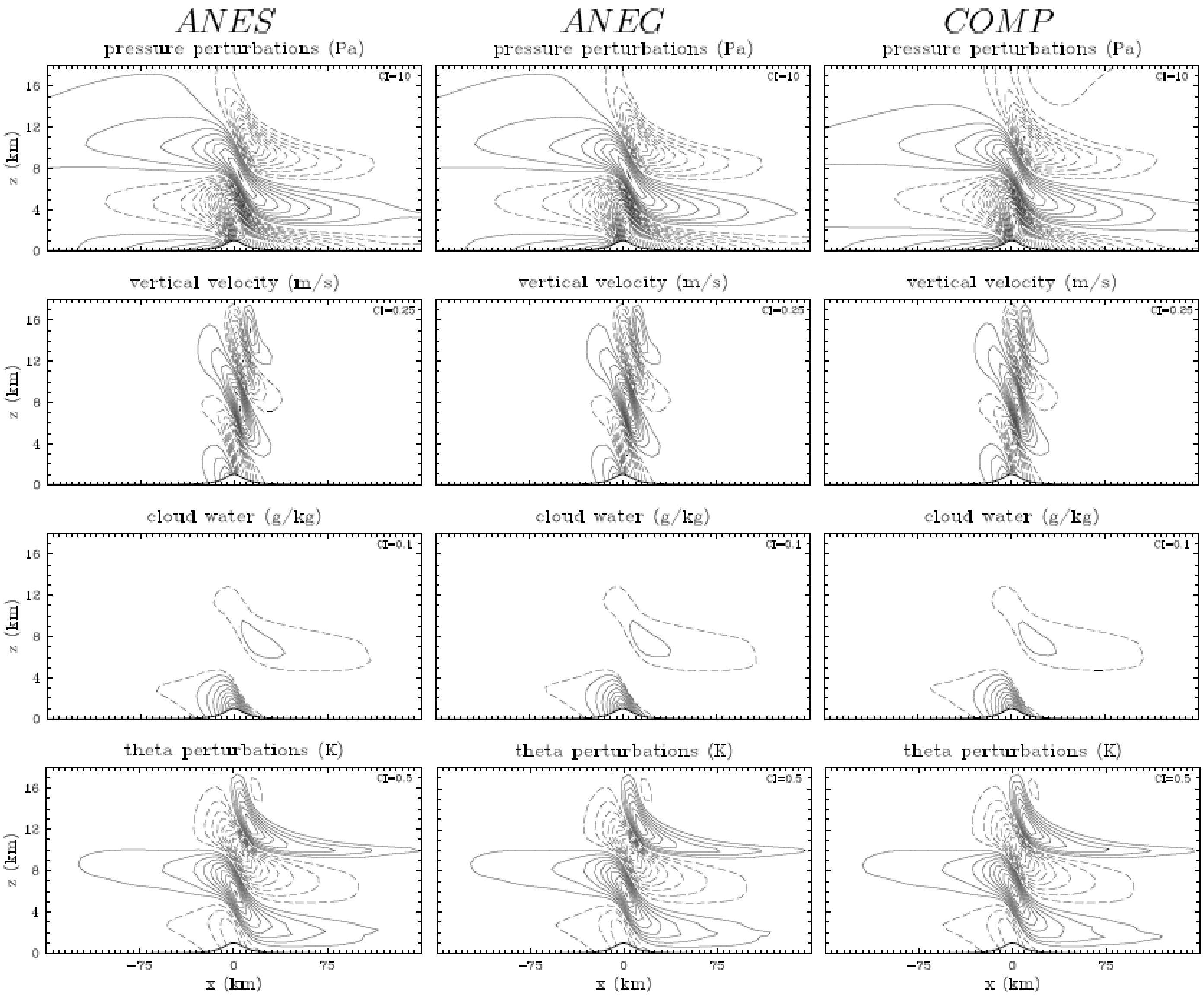
Moist orographic flow experiment

(Grabowski and Smolarkiewicz 1996)

Legend:

ANES – standard anelastic
ANEG –generalized anelastic (with p' included in moist thermo-dynamics)
COMP – fully compressible

Anelastic vs Compressible pressure – study by dr Marcin Kurowski et al. at NCAR



Pressure perturbation (1st row),

vertical velocity (2nd row),

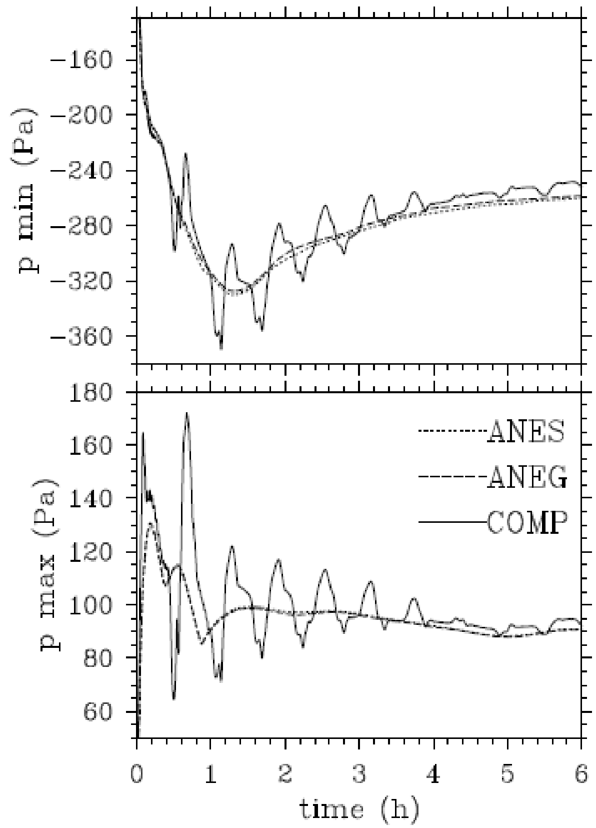
cloud water mixing ratio (3rd row) and

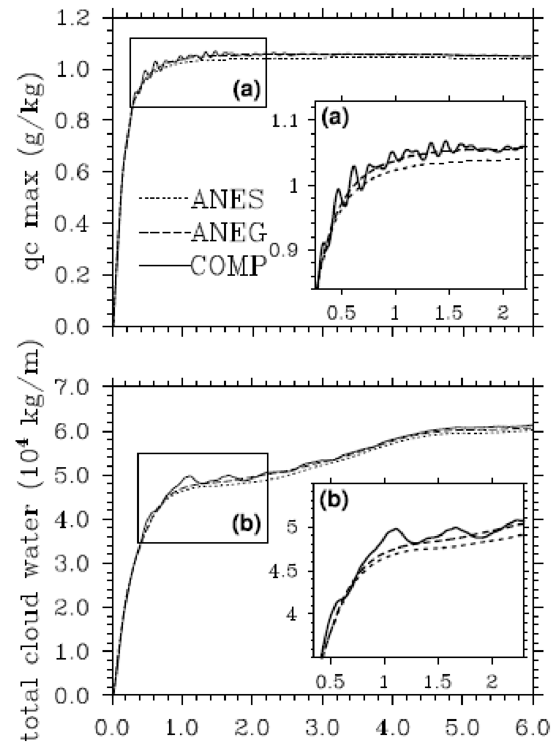
potential temperature (4th row) after 6h of the moist flow over mesoscale topography.

Contour intervals (CI) are shown in the right upper corner of each plot.

The dashed line in the cloud water panels represents isoline of 0.01 g kg^{-1}.

Anelastic vs Compressible pressure – study by dr Marcin Kurowski et al. at NCAR





	p' [Pa]		w [m s^{-1}]		q_c [g kg^{-1}]		θ' [K]	
	min	max	min	max	min	max	min	max
ANES	-259.8	91.2	-2.54	2.83	0	1.037	-5.14	5.09
ANEG	-258.1	91.1	-2.53	2.81	0	1.049	-5.10	5.03
COMP	-252.4	92.0	-2.62	2.86	0	1.049	-5.17	5.25
ANES-COMP	-21.2	11.8	-0.15	0.13	-0.07	0.02	-0.32	0.32
ANEG-COMP	-23.2	12.4	-0.16	0.13	-0.07	0.02	-0.31	0.36

Highlights of Task 3 activities

- **New COSMO version**

- **Introduction of fully flexible computational domain decomposition (not shown)**

- **Code optimizations and simplifications,**

- **Cooperation with Technical University of Czestochowa and Poznan Supercomputing Centre on porting EULAG to modern architectures**

Technical advancements

- Transition of COSMO-EULAG core to COSMO 4.26
- Introduction of flexible parallelization subdomains – loop ranges and boundary conditions are modified to allow for flexible subdomain size. Restriction that the number of cores must divide number of grid points is now waived
- Consolidation of halo management in COSMO-EULAG
- Code optimizations and simplifications, e.g. optimized and simplified halo update subroutines, vector global communication in iterative pressure solver (GCR)

Current computational performance of COSMO-EULAG

	Mesh	MPI grid	dt	Execution time
RK 1km	1040x700	30x50	10s	1 H 55’
CE 1km	1040x700	30x50	10 s	3 H 6’
CE 0.5km	806x806	40x40	5s	6H 8’
CE 0.28km	806x806	40x40	2.8s	11H 56’

Porting of EULAG to GPU - highlights

Partners of IMGW are in process of porting MPDATA and pressure solver to GPU and multi-GPU clusters.

Double speedup of pressure solver (intensive global communication) resulting from mapping task to cluster topology is reported by colleagues from Poznan.

Use of OpenMP to mitigate communication cost of pressure solver was investigated and led to ~10 % improvement.

MPDATA GPU implementation on 392x256x64 mesh, 1000 timesteps

CPU* time [s]	GPU time [s]	Speedup
609	42	14.5

Development of code documentation in accordance with COSMO coding standards was started.

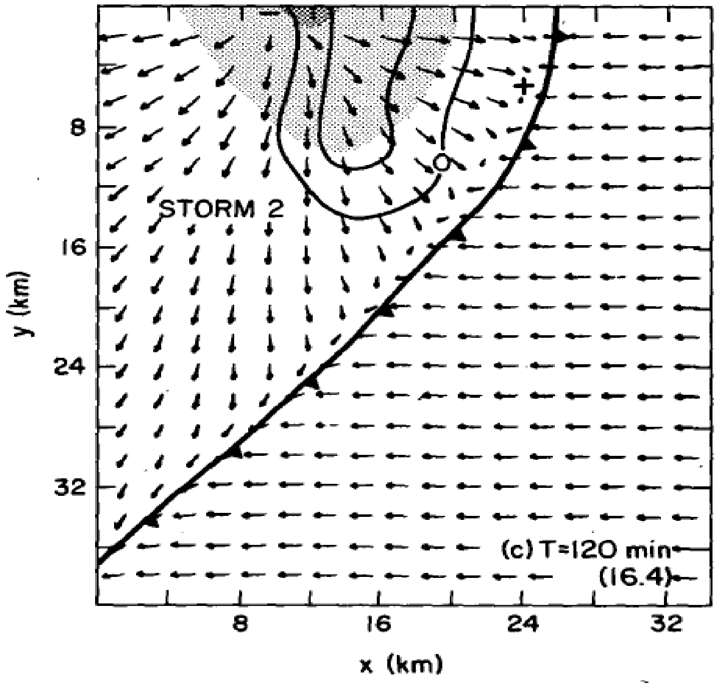
Stencil library outlook

Main stencil operations of EULAG dynamical core were recoded to expose stencil computations and identify special boundary conditions that need to be coded (this development is not merged with main COSMO-EULAG yet).

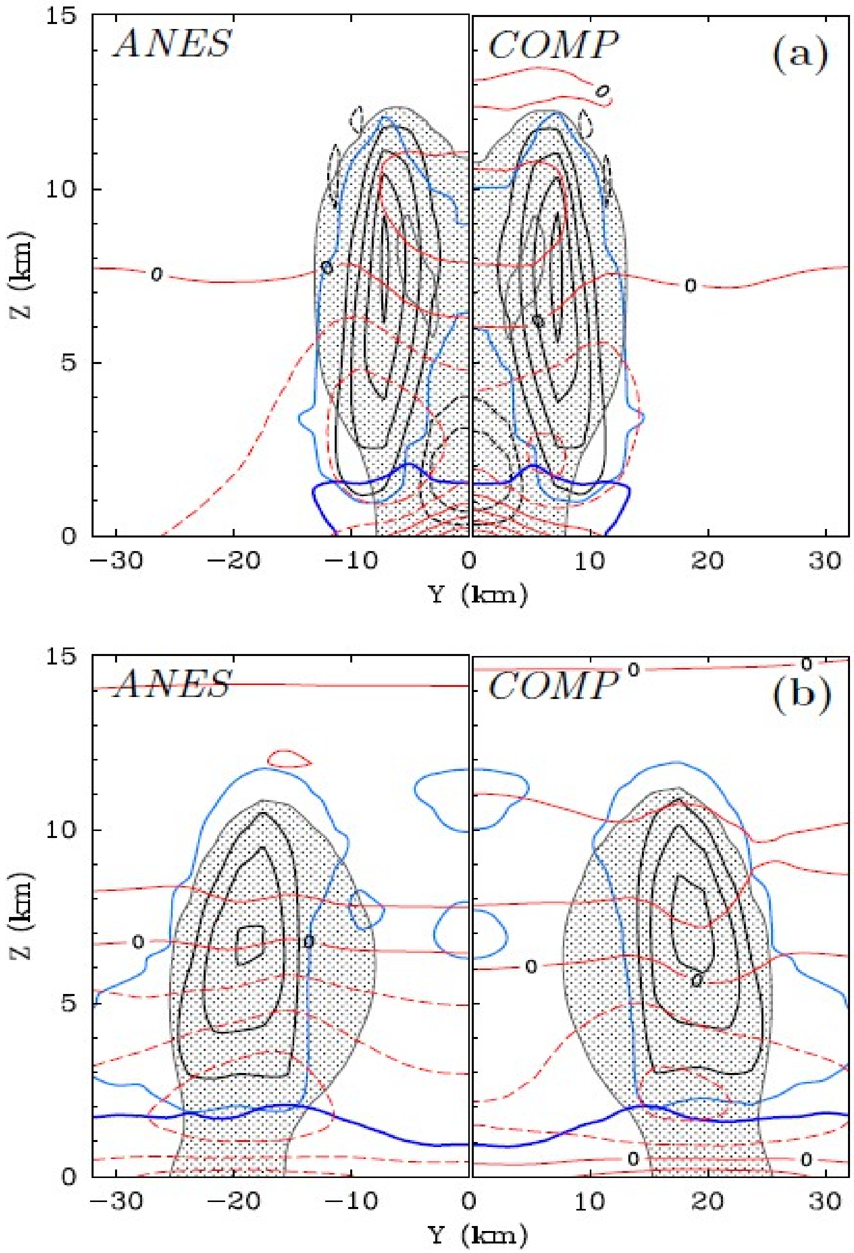
No major difficulties with porting of COSMO-EULAG to stencil library are expected so far (more details during POMPA session)

Anelastic vs Compressible deep convection study by dr Marcin Kurowski et al. at NCAR

Splitting storm experiment (evolution of a storm under wind shear) Weisman and Klemp 1982



Anelastic vs Compressible deep convection – study by dr Marcin Kurowski et al.



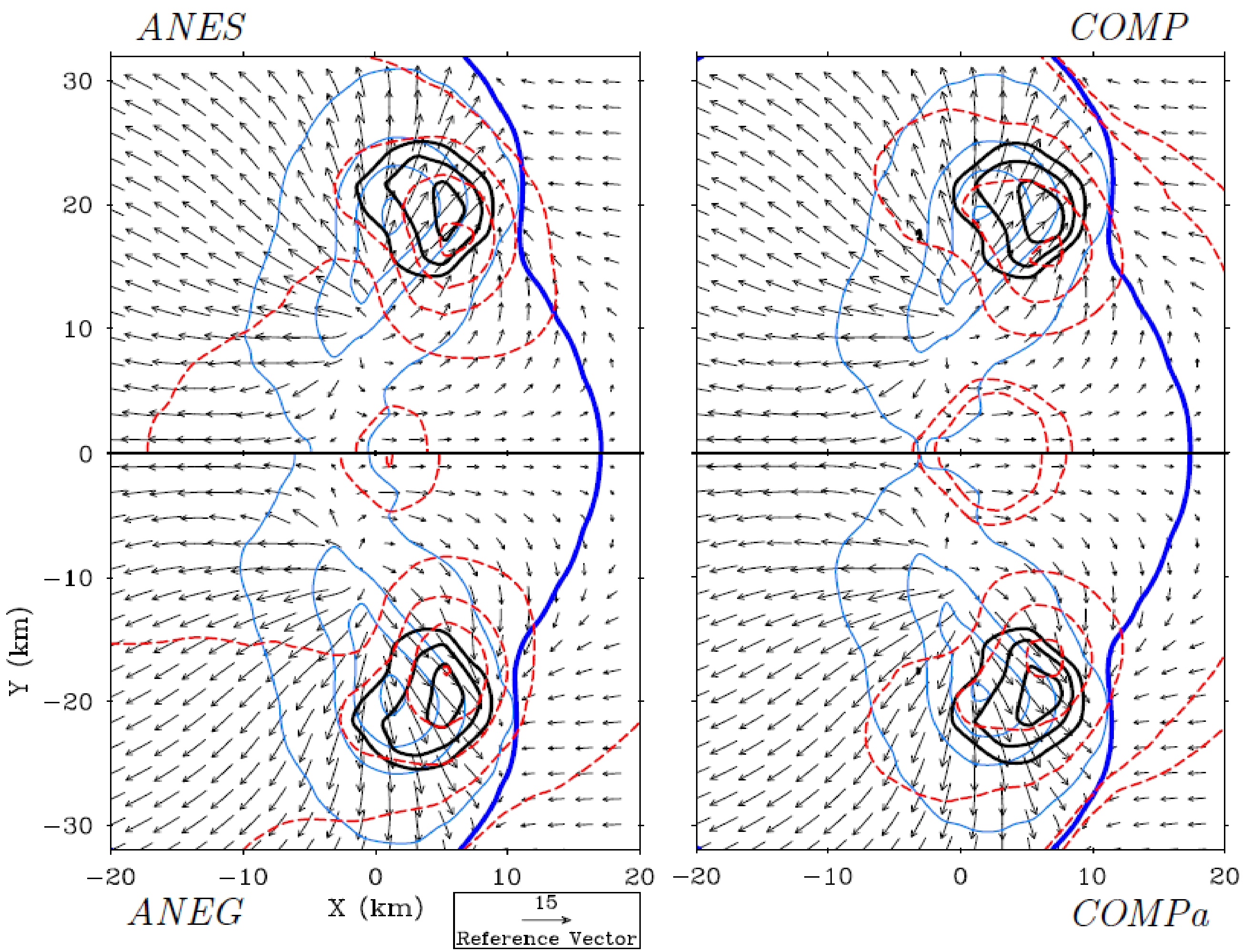
Vertical cross sections (y − z) through the convective cores for anelastic (ANES) and fully compressible (COMP) solutions at 60 min (a) and 120 min (b).

Black contours **vertical velocity** 5 m/s, shaded regions show presence of rain water with qr > 1 g/kg,

light blue isolines: **cloud edge** qc > 0.1 g/kg

dark blue thick line indicates location of the **near-ground cold pool** (theta ′ = −0.5 K) and

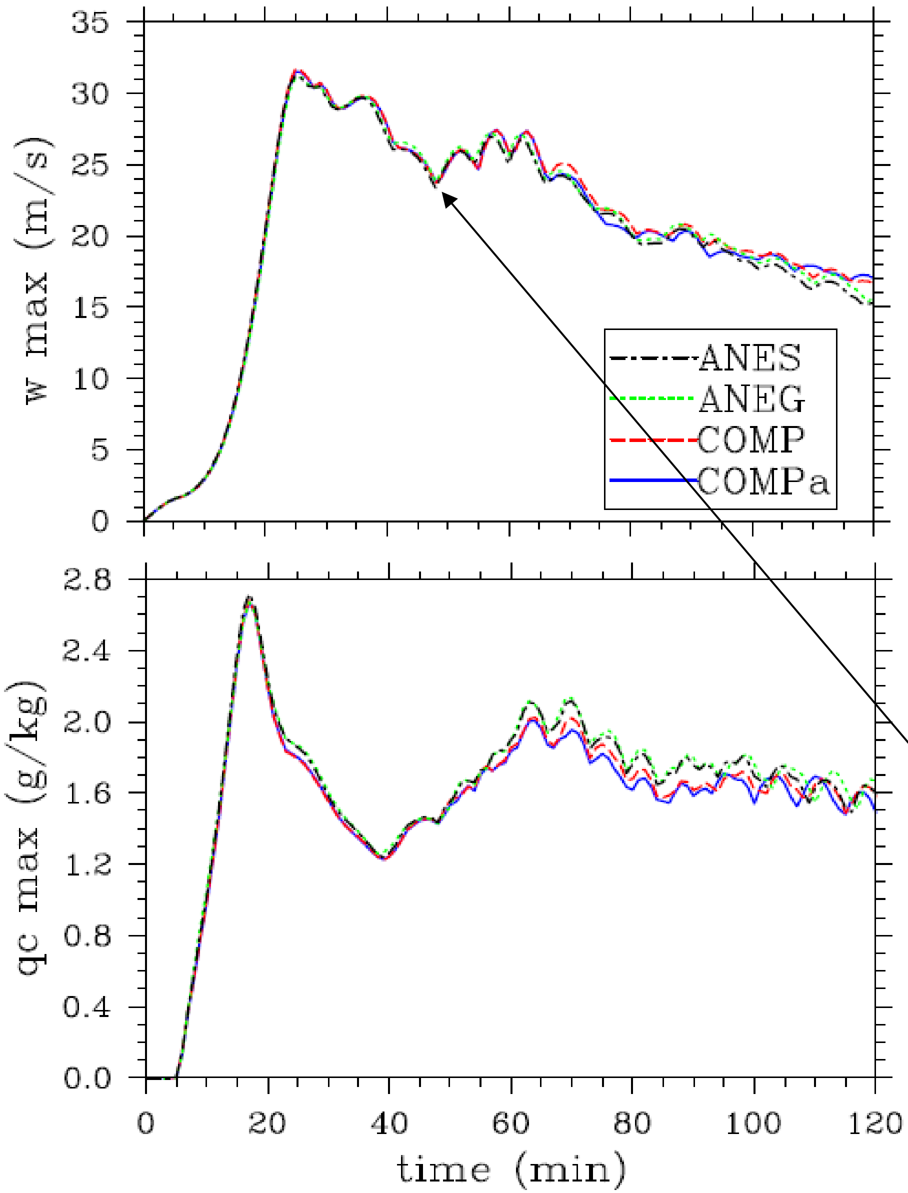
red lines are **pressure perturbations** contoured with 70 Pa interval and negative values dashed.
Only half of the solution is shown for each model.



Comparison of four different EULAG solution (ANES, ANEG, COMP, COMPa) after 120 min from the WK82 storm splitting experiment for Us=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 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**.

Anelastic vs Compressible deep convection –
study by dr Marcin Kurowski et al.



Evolutions of the maximum vertical velocity (w) and maximum cloud water mixing ratio (qc) for Us=15 m/s ANES, ANEG, COMP and COMPa simulations.

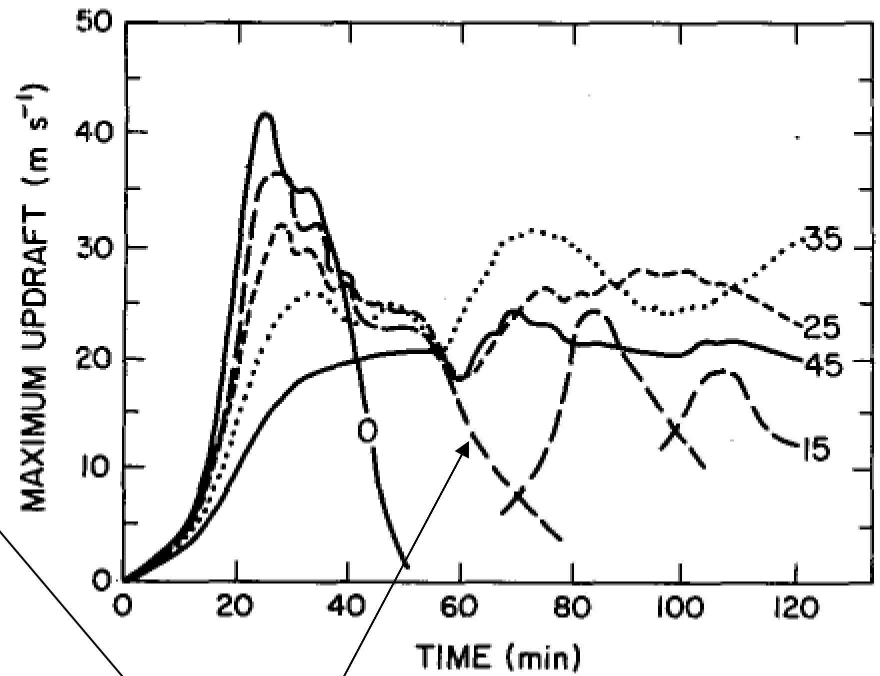


FIG. 3. Time series of maximum vertical velocities for the U_S = 0, 15, 25, 35 and 45 m s^{-1} wind shear experiments. q_{v0} = 14 g kg^{-1}.

Note that difference EULAG - WK82 is much larger than EULAG compressible - anelastic

Outlook of CELO activities for the next 6 months

Evaluation of the optimal dynamical treatment of moist processes for COSMO-EULAG with idealized experiments, investigation into proper surface model coupling

Investigation of variable computational domain geometry in response to pressure system changes, consolidation of the absorber profiles

Contribution to preparation of prototype implementation of EULAG dynamical core on GPU in cooperation with partners from Czestochowa and Poznan; COSMO-EULAG coding and performance improvements

Preliminary COSMO-EULAG verification

Improvements in preconditioning for pressure solver and very high resolution Alpine flow tests (student projects)

Conclusions

➔ **EULAG DC was successfully tested within COSMO framework for a autumn stable and summer convective scenario with 2.2 km, 1.1 km, 0.55 km and 0.28 km**

➔**EULAG and RK dynamical cores produce similar spectral kinetic energy response at 2.2 km and 1.1 km for the scenario at hand, effective resolution further improves at 0.55 km and 0.28 km as expected**

➔**Dynamics – physics coupling is being reviewed and evaluated in idealized tests**

Conclusions

- ➔ **New formulation of metric coefficients allows for arbitrary vertical coordinate in EULAG DC**

- ➔ **Boundary conditions, global model data management and parallelization were consolidated between RK and EULAG DC**

- ➔ **Porting of EULAG to emerging supercomputer architectures is in progress, possible performance improvements are successfully investigated**

- ➔ **New experiments confirm very good agreement between compressible and anelastic simulation of deep convection**