Review about the current dynamical core and other numerics developments in the COSMO model

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Michael Baldauf (DWD), Zbigniew Piotrowski (IMGW), Andreas Will (Univ. Cottbus)

Outline

- Work finished in 2015:
    - Redesign of 3D diffusion
    - Other work/Bug fixes in the Runge-Kutta (RK) dynamical core
- Ongoing developments:
    - Higher Order Spatial Schemes for the COSMO Model (RK)
    - PP CELO: operationalisation of COSMO-EULAG
- Plans:
    - New PP CDIC: first steps in the transition to the ICON model

Consortium for Small Scale Modeling COSMO

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Increase of numerical stability in the diffusion scheme for 3D turbulence

M. Baldauf (DWD)

diffusion equation - scalar flux divergence:

terrain following coordinates

vertical

$$\rho \frac{\partial s}{\partial t} = -\frac{1}{r\cos\phi}\frac{\partial H^{*1}}{\partial \lambda} - \frac{J_\lambda}{\sqrt{G}}\frac{1}{r\cos\phi}\frac{\partial H^{*1}}{\partial \zeta} - \frac{1}{r}\frac{\partial H^{*2}}{\partial \phi} - \frac{J_\phi}{\sqrt{G}}\frac{1}{r}\frac{\partial H^{*2}}{\partial \zeta} + \frac{1}{\sqrt{G}}\frac{\partial H^{*3}}{\partial \zeta} - \frac{2}{r}H^{*3} + \frac{\tan\phi}{r}H^{*2}.$$

horizontal (cartesian)

earth curvature

diffusion flux vector for a scalar:

$$H^{*1} = -\rho K_s \frac{1}{r\cos\phi}\left(\frac{\partial s}{\partial \lambda} + \frac{J_\lambda}{\sqrt{G}}\frac{\partial s}{\partial \zeta}\right),$$

$$H^{*2} = -\rho K_s \frac{1}{r}\left(\frac{\partial s}{\partial \phi} + \frac{J_\phi}{\sqrt{G}}\frac{\partial s}{\partial \zeta}\right),$$

$$H^{*3} = +\rho K_s \frac{1}{\sqrt{G}}\frac{\partial s}{\partial \zeta},$$

analogous:
‚vectorial' diffusion of *u*, *v*, *w*

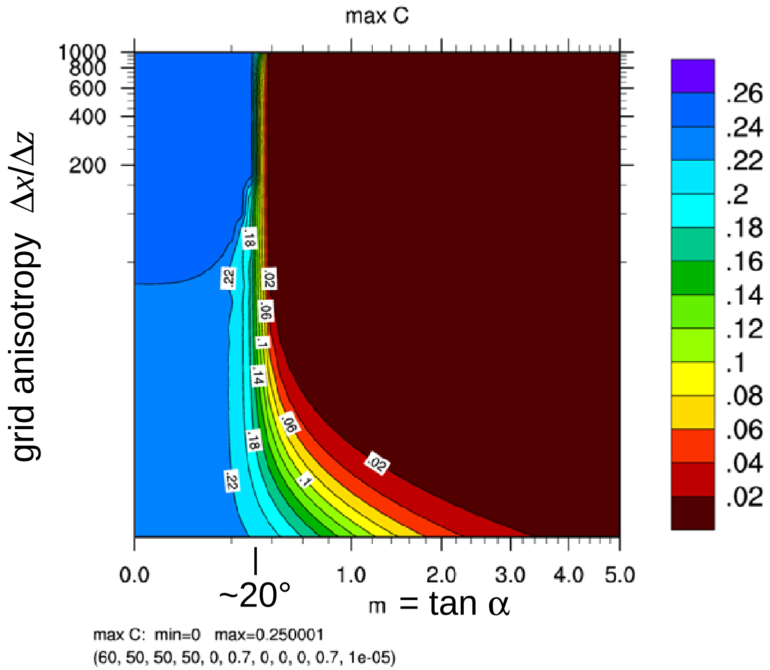
Baldauf (2005), COSMO-Newsl. No. 5

Increase of numerical stability in the diffusion scheme for 3D turbulence

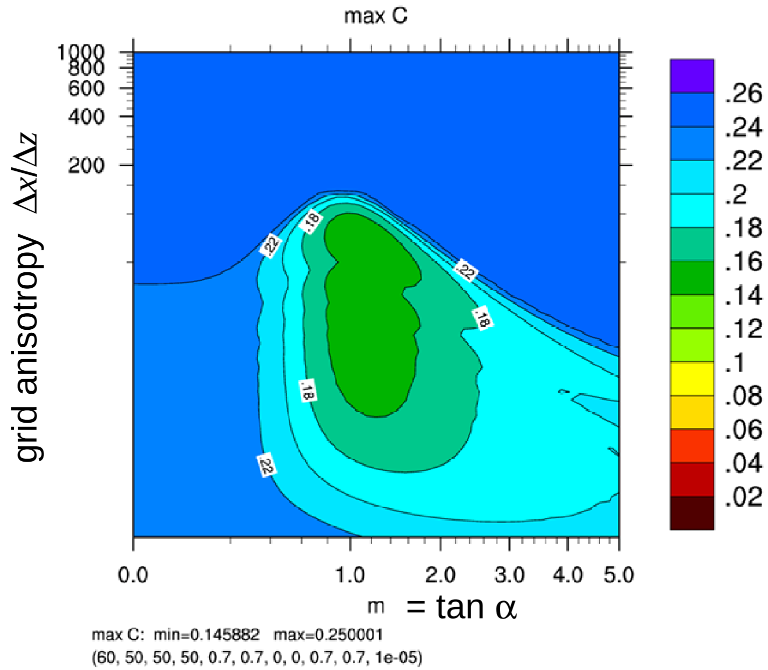
- The old implementation was not stable in steep terrain
- Stability analysis indicates that 3D diffusion in terrain following coordinates may be stable in *arbitrary steep* terrain if
  - use as many terms as possible in the tridiagonal solver
  - some off-centering
- → new implementation of the 3D diffusion was necessary.
- Testing by idealised tests with known analytic solution successfully carried out both for scalar diffusion (*Baldauf, 2005*) and vector diffusion (new!)
- New implementation runs stable in real case simulations
- Available in COSMO 5.3
- Remark: not used operationally, since 3D diffusion effects probably only relevant for $\Delta x < O(1\ \text{km})$
- Publication: *Baldauf, Brdar (in prep. for QJRMS)*

Stability analysis of 3D vector diffusion in tilted terrain: max C_{diff} ~Δt

vertically implicit, only ‚pure' z-deriv,
off-centering=0.7 (=old COSMO)

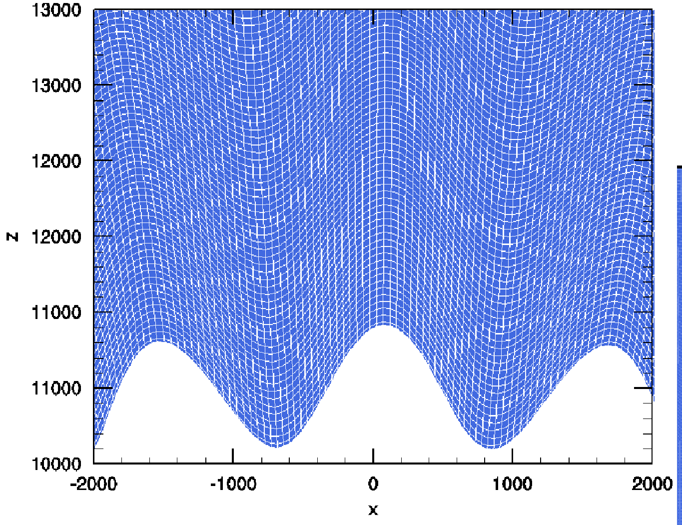


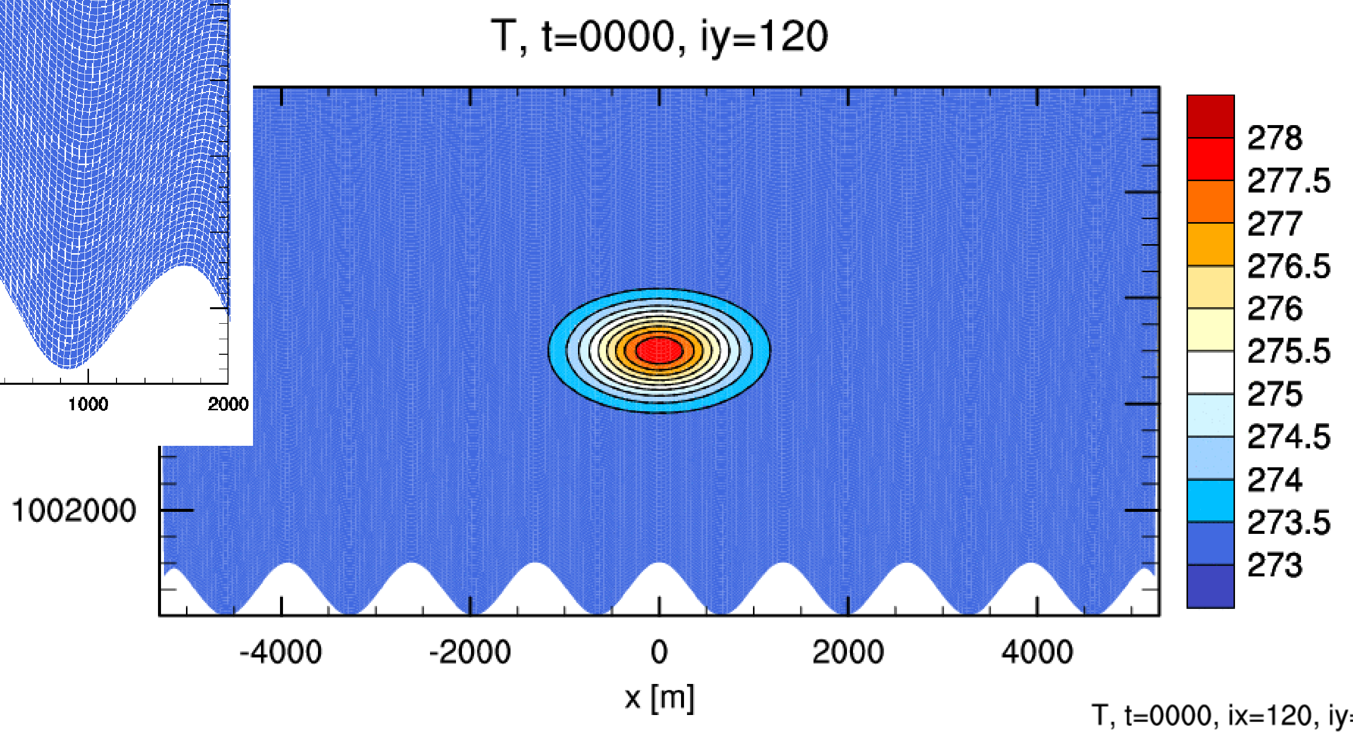
vertically implicit treatment of all
possible terms,
off-centering=0.7 (COSMO 5.3)



similar stability properties for scalar diffusion

Scalar diffusion test





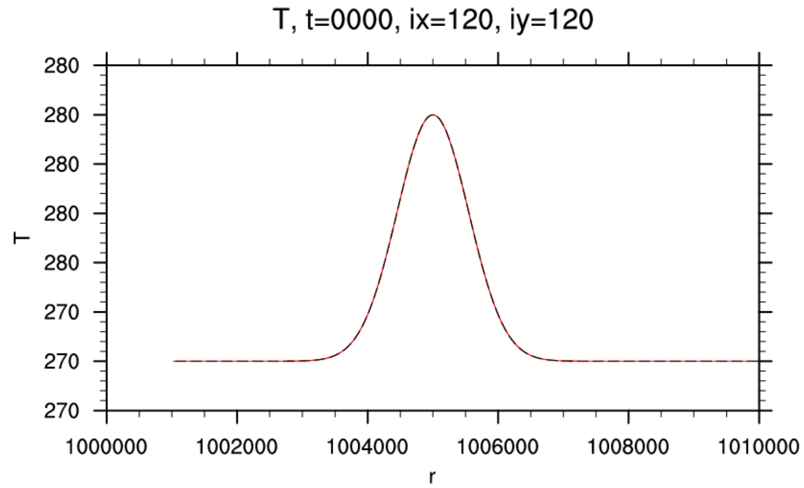
T,analy: min=273 max=277.997

T,simul: min=273 max=277.997

5.1r39_50_s_R1000km_h1000m_3dneu_3dturbT_3dmetrTi0.75_lmetrT

analytic solution: solid lines

COSMO solution: colors + dashed lines



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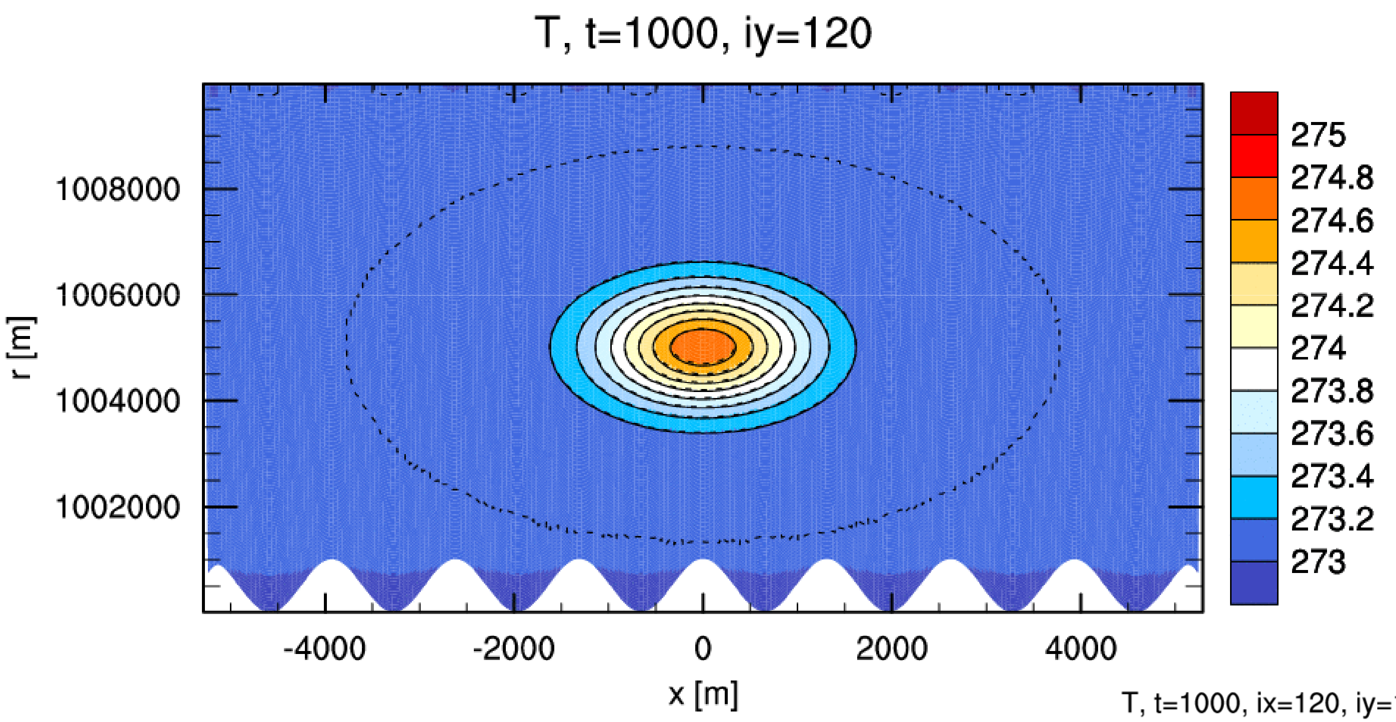

T,analy: min=273 max=274.767
T,simul: min=273 max=274.753

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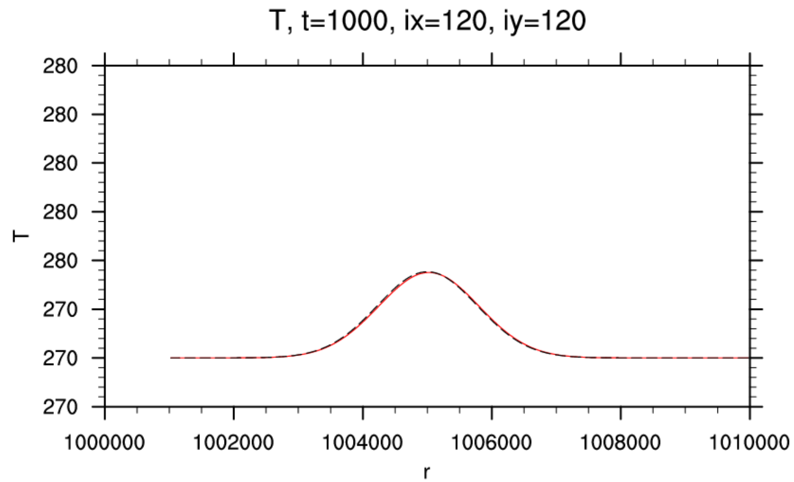

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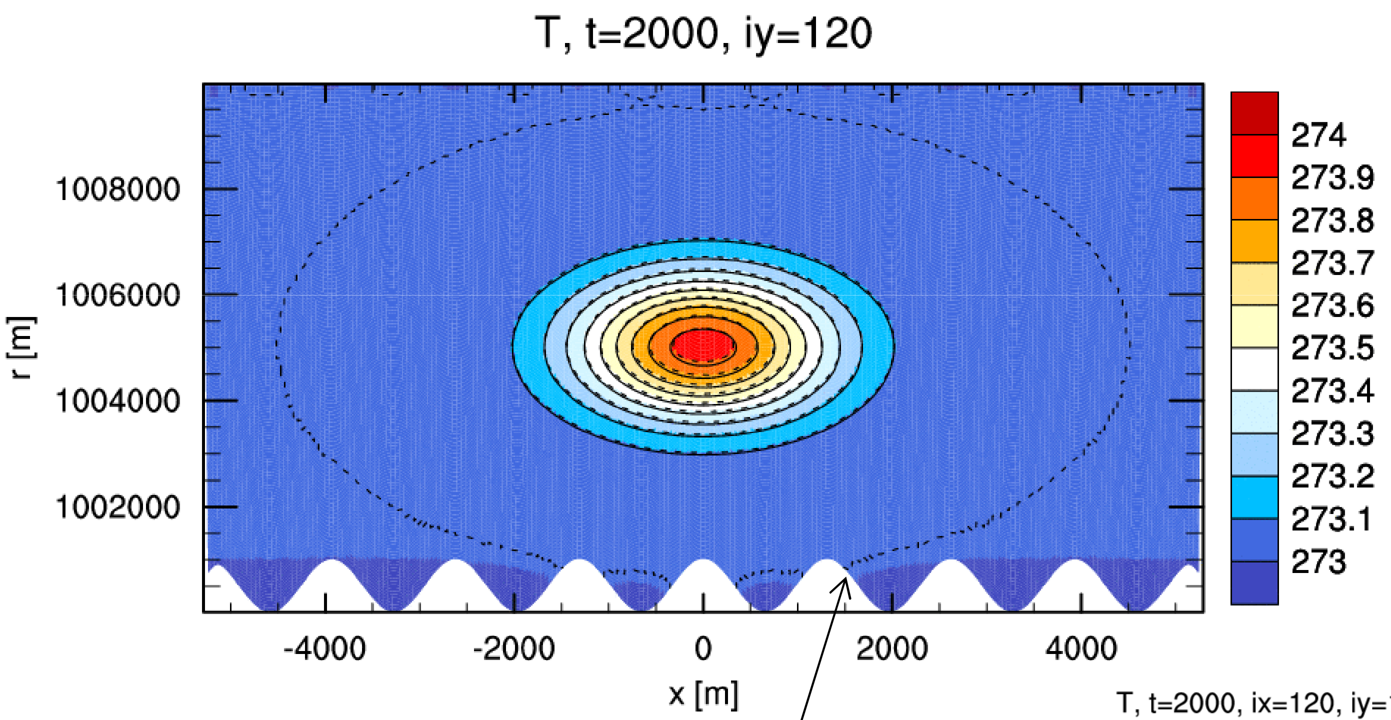


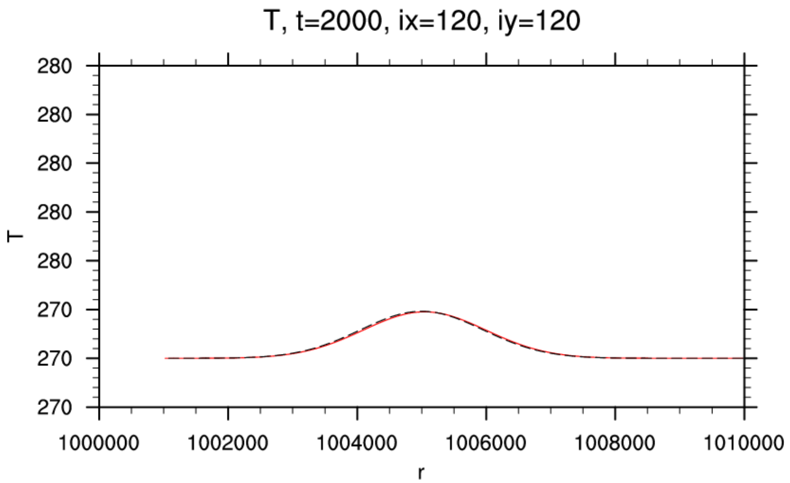
T,analy: min=273 max=273.962

T,simul: min=273 max=273.952

5.1r39_50_s_R1000km_h1000m_3dneu_3dturbT_3dmetrTi0.75_lmetrT

max slope ~ 2.3 ~ 67°

the run with only one vertical implicit term (=old COSMO version) became unstable!



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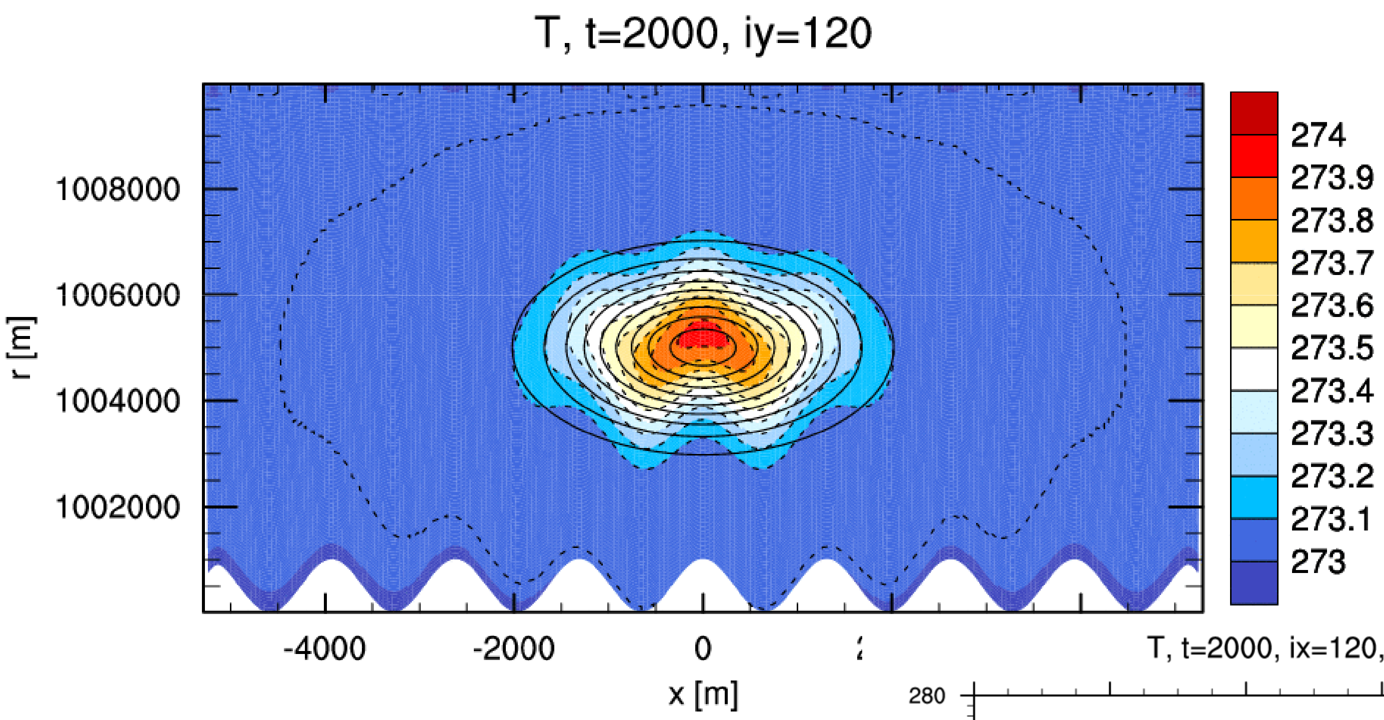
Scalar diffusion test



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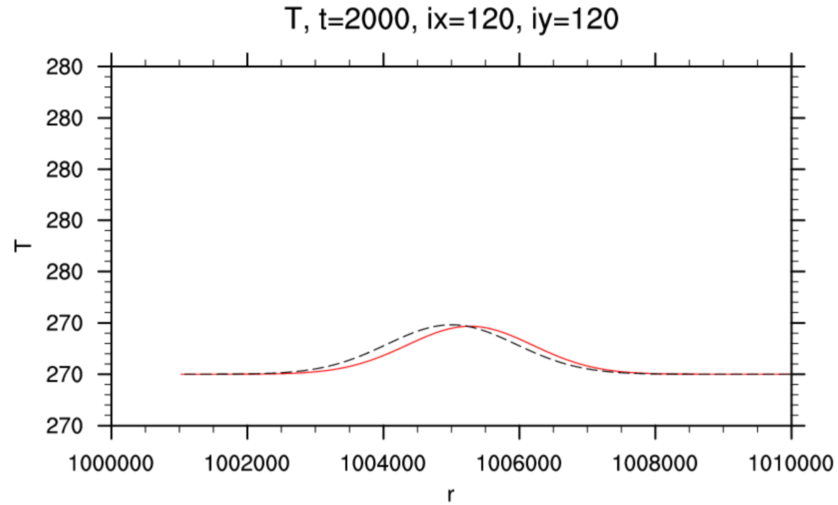
5.1r39_50_s_R1000km_h1000m_3dneu_3dturbT_3dmetrFi0.75_lmetrT



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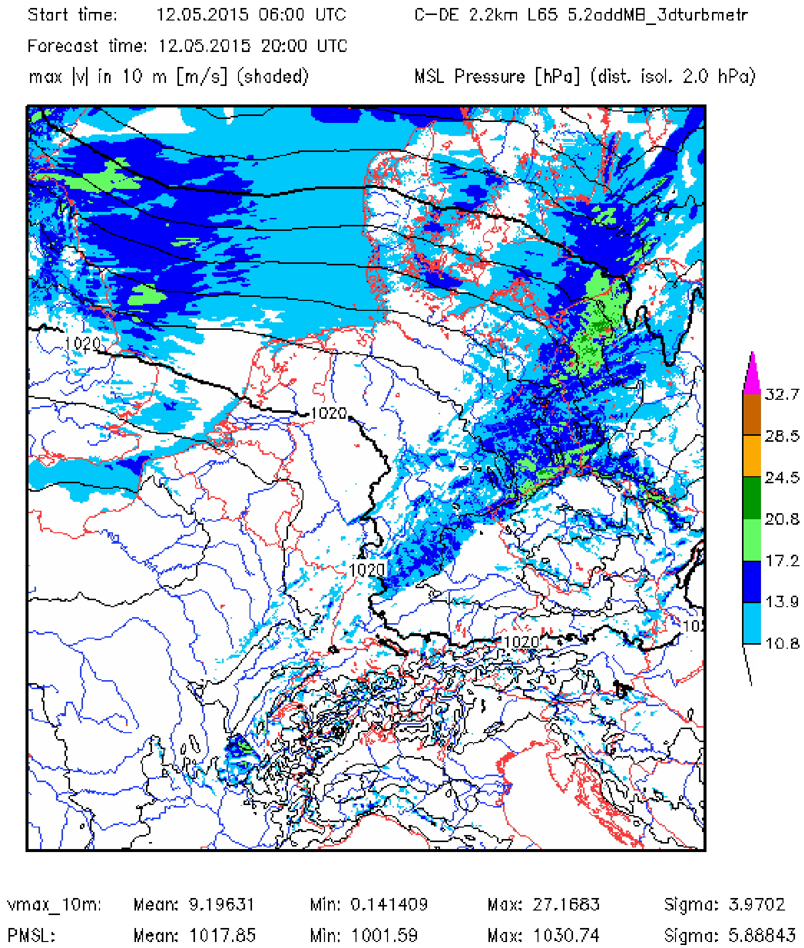
5.1r39_50_s_R1000km_h1000m_3dneu_3dturbT_3dmetrFi0.75_lmetrT

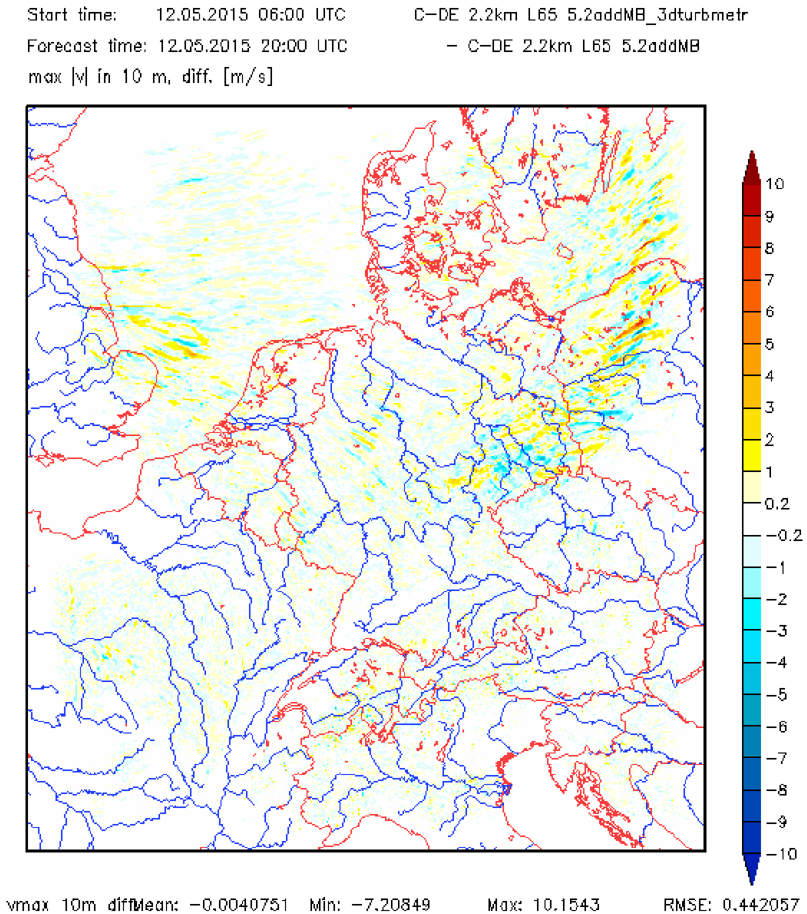
for comparison:
3D diffusion <u>without</u> metric terms

Real case: ‚12 May 2015, 06 UTC run‘, COSMO-D2, gusts

with 3D diffusion



difference to 1D diffusion



… further work done in/for WG2

- New **explicit sedimentation scheme** for the 2-moment cloud microphysics scheme, mitigating problems with rainrate spikes for longer time steps,
  Motivation: explicit sedimentation locally unstable for higher Courant numbers,
  semi-implicit scheme is (currently) not efficient enough,
  available in COSMO 5.3 (*U. Blahak, DWD*)
- **(again)** Reformulation of **divergence damping coeff**. in the new fast waves solver *(M. Baldauf (DWD), G. deMorsier (MeteoCH))*
- Bug fix in the ‚**targeted diffusion to avoid cold pools**‘ (*A. Arteaga, MeteoCH*)
  → roughly this halves the strength of the diffusion
  (retuning of diffusion coefficient necessary?)
- '**targeted diffusion …** ' now also avoids ‚hot pools‘ (*O. Fuhrer, MeteoCH*)
  → COSMO 5.1.1

Higher Order Spatial Schemes for the COSMO Model

A. Will, J. Ogaja (Univ. Cottbus)

Alternative Discretization of the Advection operator

Definitions:

centered averaging operators:

$$\overline{\phi_{i,j,k}}^{nx} := \frac{\phi_{i+\frac{n}{2},j,k} + \phi_{i-\frac{n}{2},j,k}}{2}$$

$$\overline{\phi_{i,j,k}}^{ny} := \frac{\phi_{i,j+\frac{n}{2},k} + \phi_{i,j-\frac{n}{2},k}}{2}$$

centered difference derivation operators:

$$\delta_x^{(n)}\phi_{i,j,k} := \frac{\phi_{i+\frac{n}{2},j,k} - \phi_{i-\frac{n}{2},j,k}}{n \cdot \Delta x}$$

$$\delta_y^{(n)}\phi_{i,j,k} := \frac{\phi_{i,j+\frac{n}{2},k} - \phi_{i,j-\frac{n}{2},k}}{n \cdot \Delta y}$$

4th order discretization for the velocity advection in a staggered grid:

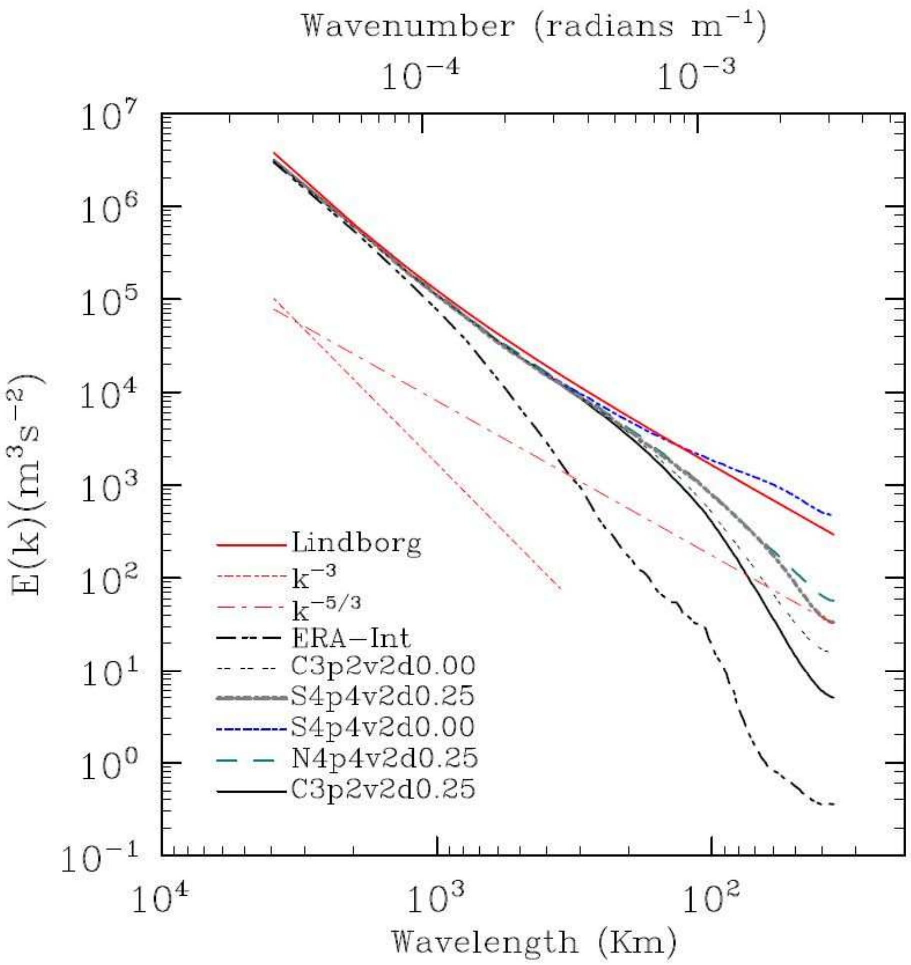
$$Diskret_{4.Ordn.}\left(v_j \frac{\partial v_i}{\partial x_j}\right) = \sum_j \left[\frac{9}{8} \overline{\left(\frac{9}{8}\overline{v_j}^{i} - \frac{1}{8}\overline{v_j}^{3i}\right) \cdot \delta_j^{(1)} v_i}^{j} - \frac{1}{8} \overline{\left(\frac{9}{8}\overline{v_j}^{i} - \frac{1}{8}\overline{v_j}^{3i}\right) \cdot \delta_j^{(3)} v_i}^{3j} \right]$$

Kinetic energy conserving discretization (*Morinishi et al. (1998)*)

Analogous: 4th order operators for horizontal pressure gradient and divergence

Morinishi et al. (1998) - spatial discretisation

A. Will, J. Ogaja (Univ. Cottbus)



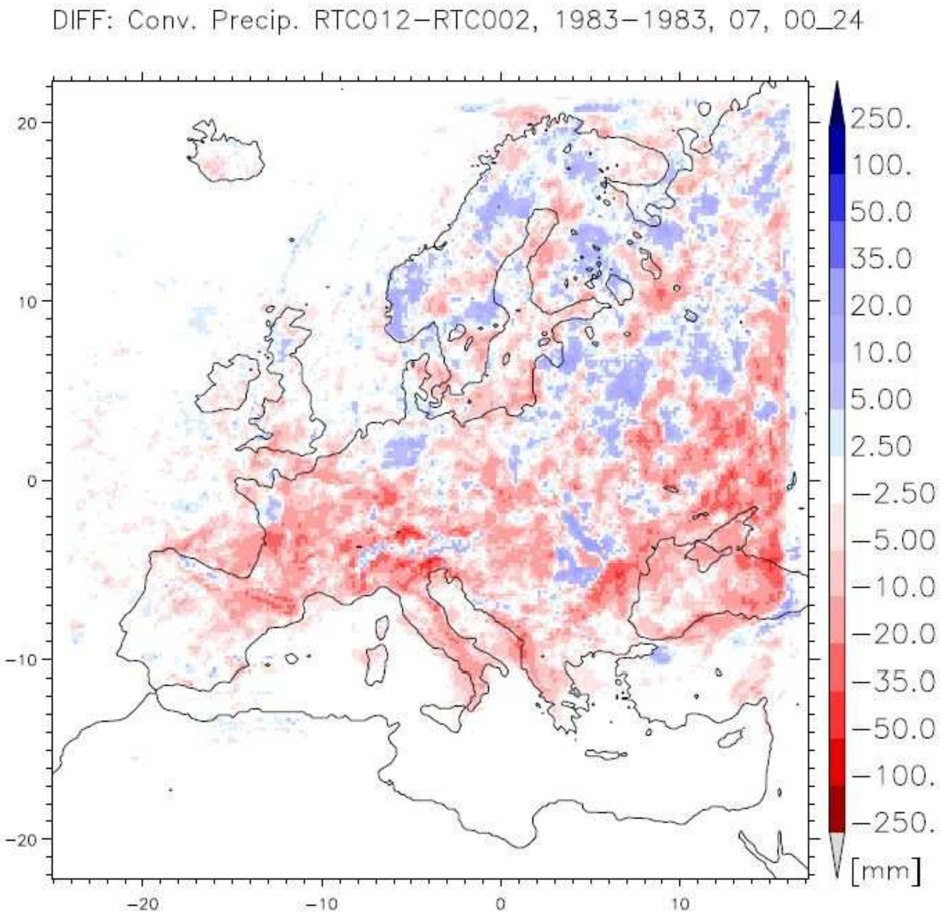
(from *Ogaja, Will, subm. to MetZ*)

main results:

- **power spectrum of kinetic energy** (here: annual (for 1979) and meridional mean for 3-6 km layer) → almost no reduction by the new scheme at small wavelengths!
- climate runs over several years stable without artificial horizontal diffusion!

Linear stability analysis of this new discretization does not show drawbacks!

however: strong reduction of the convective precipitation part



(c) PREC_CON

(from *Ogaja, Will, subm to MetZ*)

difference in convective precipitation part for month July during 1979-1983 between new scheme S4p4 and current RK dynamical core.

Conclusion:
Probably a readjustment of some parameterizations is necessary

Progress of CELO Priority Project

Zbigniew P. Piotrowski, Bogdan Rosa, Damian K. Wojcik

Institute of Meteorology and Water Management -
National Research Institute

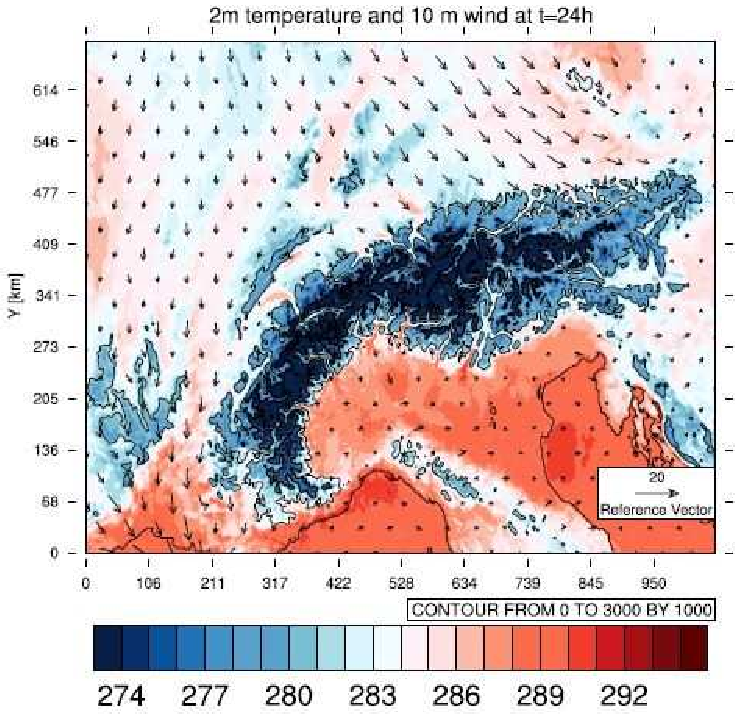
Project extension:
additionally to the anelastic equations (Lipps, Hemler, 1982)
and the dry pseudo-incompressible equations (Durran, 1989),
now the compressible, non-hydrostatic Euler equations will be available, too.

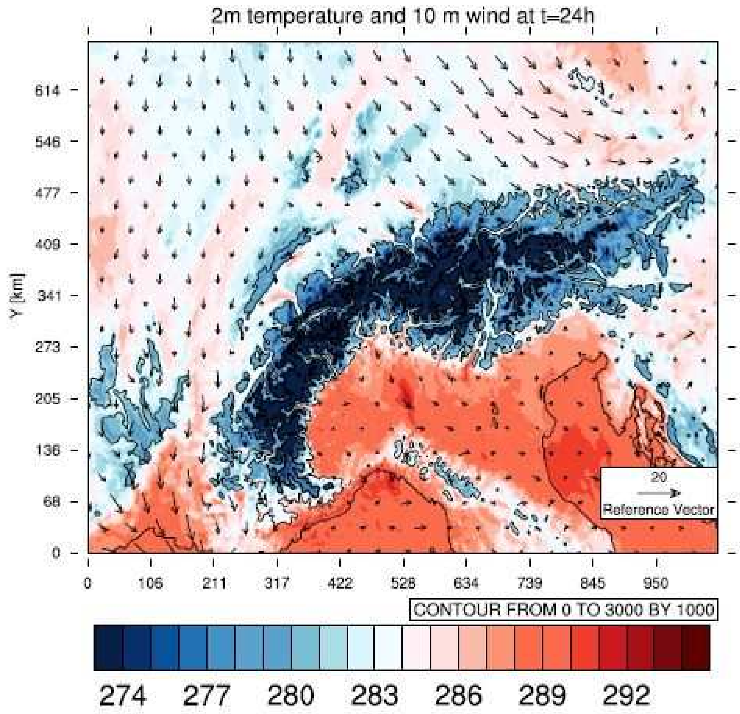
Preliminary integration of the implicit compressible EULAG dynamical core cont.

- Integration of the implicit compressible involved reorganization of the dynamical core, sourcing from the experiences of the evolution of EULAG model performed earlier.
- Anelastic and implicit compressible dynamical core share their main components (advection, implicit solver), so the increase of the source code complexity is only limited.
- All important stencils of COSMO-EULAG are now in the form that facilitates the adaptation to GPU. Special stencils for the boundary conditions of the iterative solver demands GridTools functionality for CUDA adaptation.

COSMO-EULAG implicit-compressible and Runge-Kutta 24h forecast for 01.06.2013.

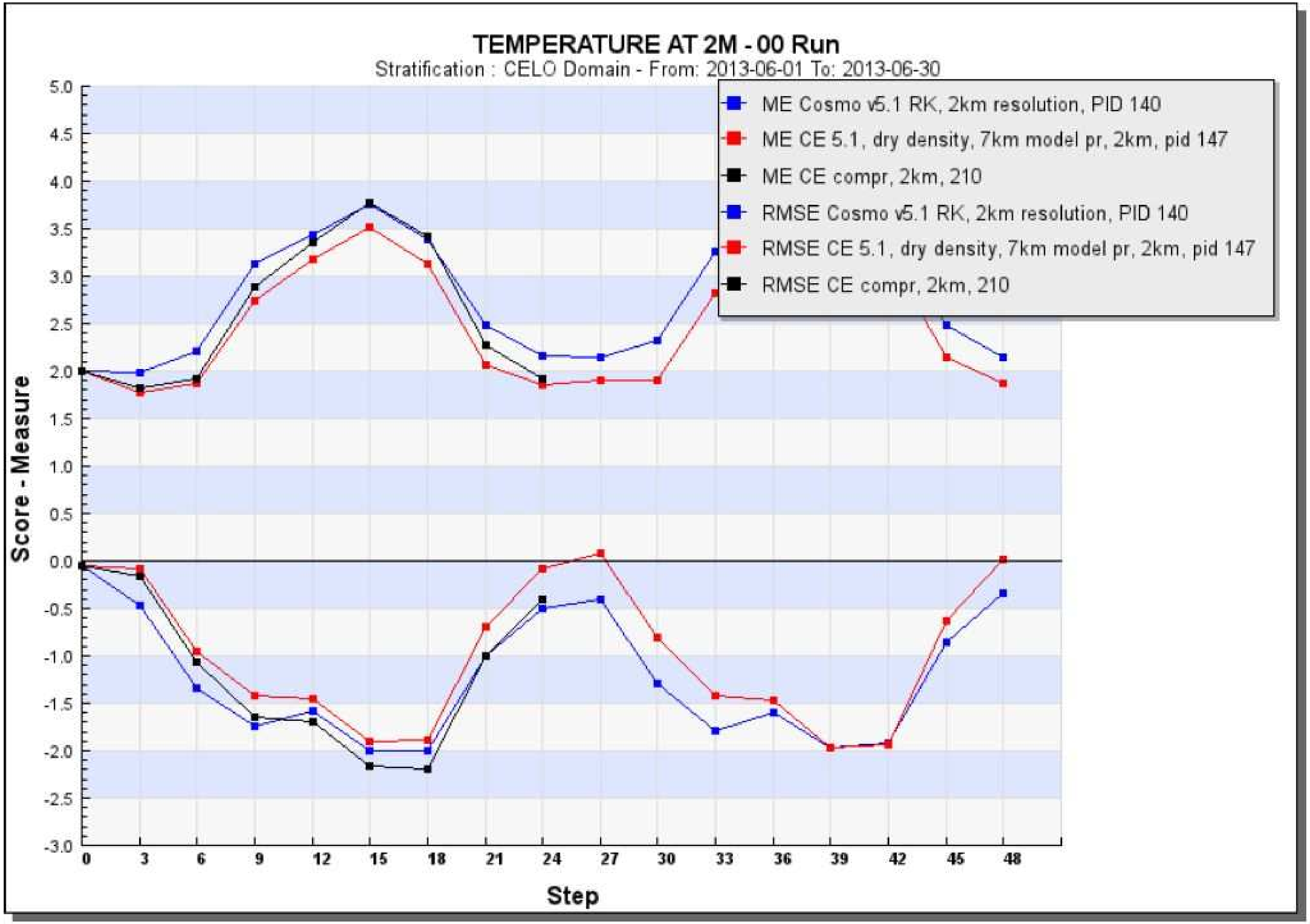
Horizontal crossection presenting 2 m temperature and vector wind field at 10 m level. Left panel presents COSMO-EULAG compressible results, whereas right panel presents COSMO-RK results.





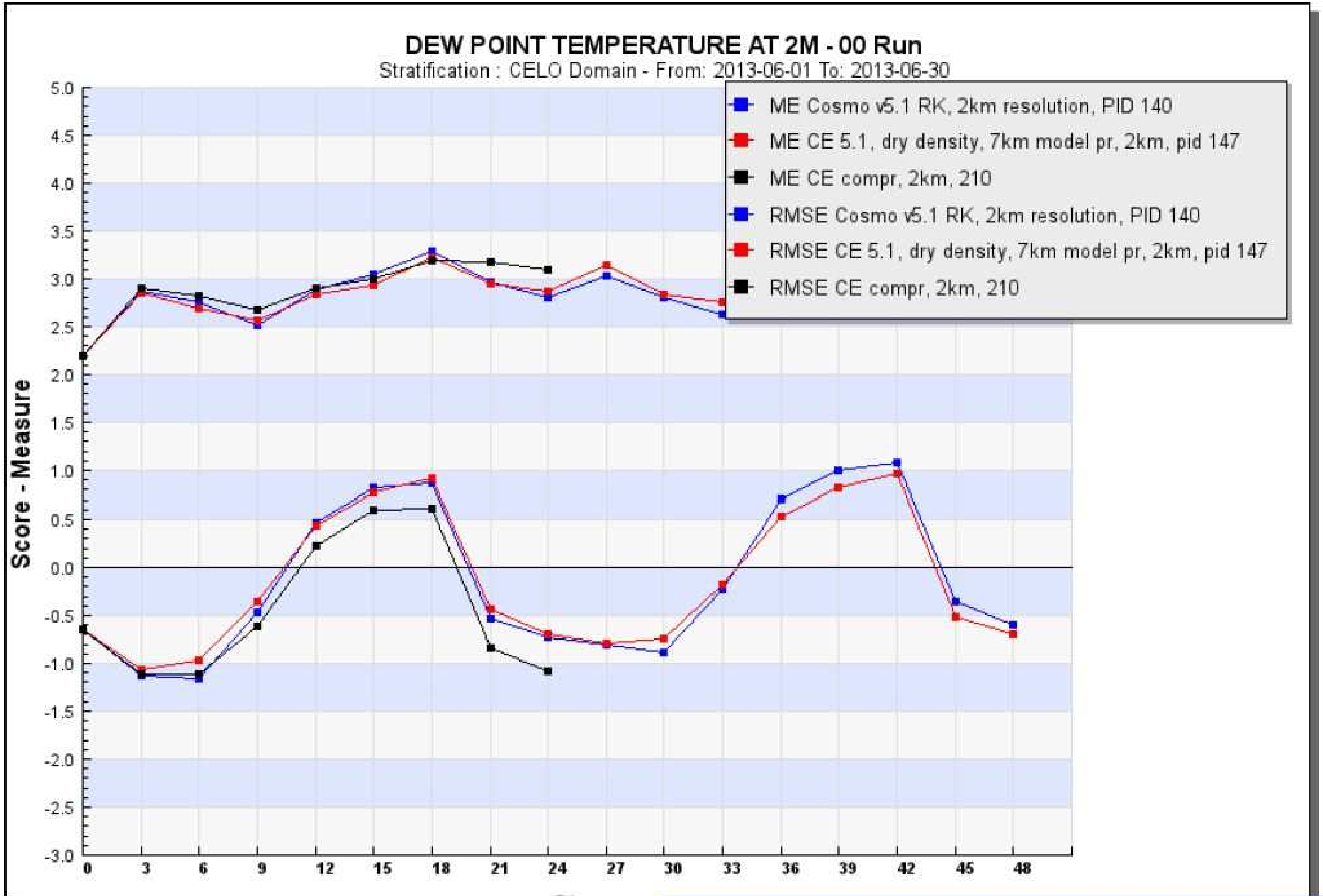
Verification study - temperature at 2 m

COSMO-EULAG anelastic score is the highest, whereas COSMO-EULAG compressible scores **black** are closer to the Runge-Kutta scores.

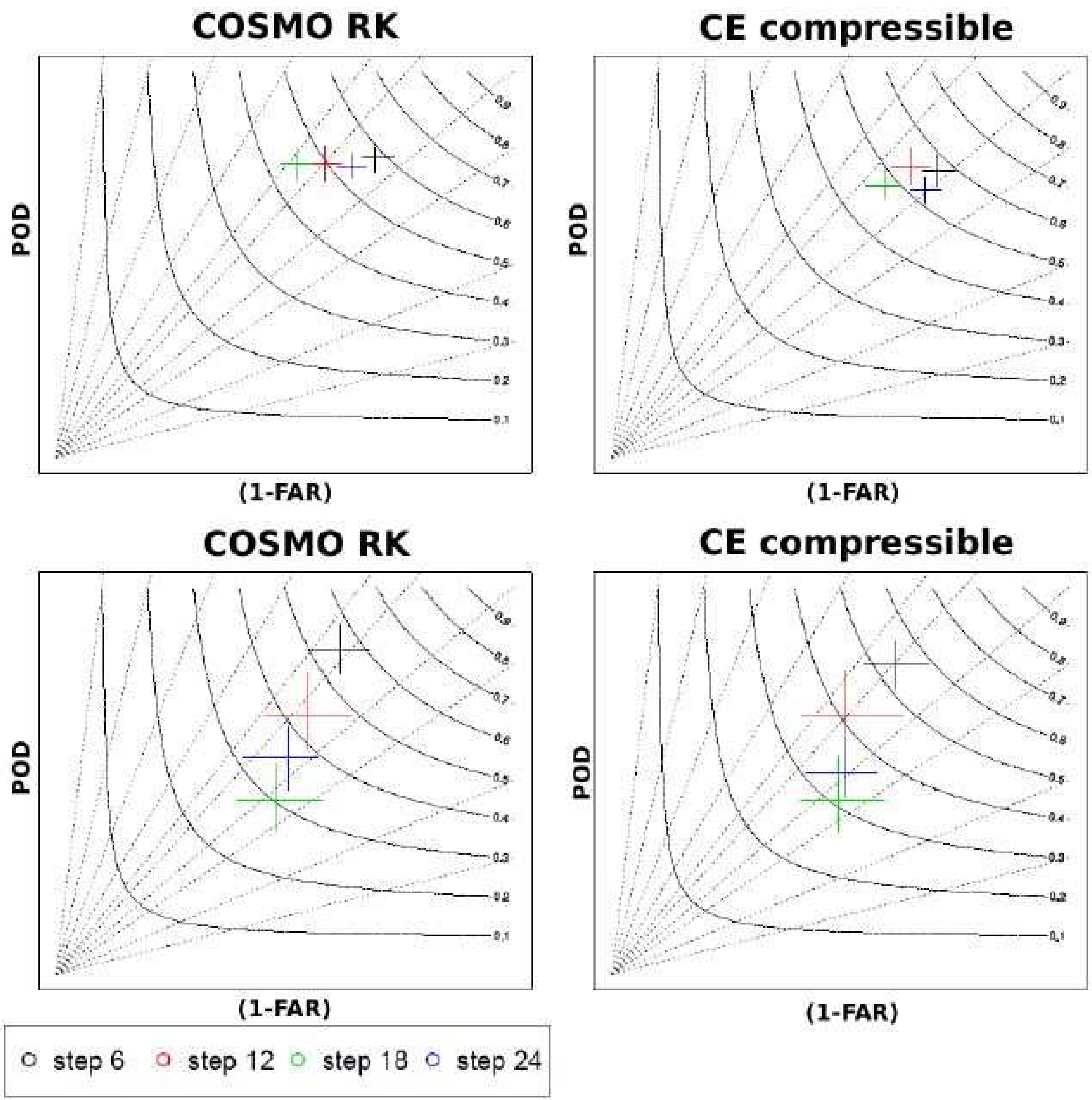


Verification study - dewpoint temperature at 2 m

For small rain ranges in June, COSMO-EULAG anelastic and Runge-Kutta scores are very similar, whereas COSMO-EULAG compressible scores are favourable in the afternoon but diverge in late evening.



Verification study - rain for +1. and +10.0 ranges



Rain verification scores between COSMO-EULAG and Runge-Kutta cores are similar, with COSMO-EULAG scores slightly higher at noon for +1.0 range, (upper plots), and slightly lower for + 10.0 range, (lower plots).

Conclusions

- COSMO-EULAG implicit compressible core is now preliminarily integrated and is able to produce forecasts.
- Implicit compressible forecasts seem to be closer to anelastic forecasts than to the Runge-Kutta forecasts.
- COSMO-EULAG verification scores are mostly comparable to Runge-Kutta
- Wind scores are the most similar, temperature, dew point temperature and total cloud cover sometimes slightly better in Runge-Kutta; this probably results from the tuning of the parameterizations as it depends on the time of the day.
- Rain verification scores for high ranges slightly better in COSMO-EULAG.

New priority project: ‚Comparison of the dynamical cores of ICON and COSMO' (CDIC)

Project Leader: Michael Baldauf (DWD)

- Task 1: Good performance on a standard set of idealized test cases
- Task 2: Ability to handle real-/semi-idealised cases reasonably well
- Task 3: Scalability/Performance suitable for operations as well as for future supercomputing platforms
- Task 4: Identification of differences in dynamical core formulations and their assessment
- Task 5: Suitability of ICON dynamical core for other applications than NWP (climate, chemistry, ...) compared to the COSMO model

Project duration: 2016-2017