# The 'Conservative Dynamical Core' priority project and other current dynamics developments in the COSMO model

**34th EWGLAM / 19th SRNWP meeting**
**08-11 Oct. 2012, Helsinki**

***Michael Baldauf*** (Deutscher Wetterdienst, Offenbach, Germany),
*Bogdan Rosa, Marcin Kurowski, Damian Wójcik, Michał Ziemiański*
(Institute of Meteorology and Water Management, Warsaw, Poland)

## COSMO-Priority Project 'Conservative dynamical core' (2008-2012)

*M. Ziemianski, M. Kurowski, B. Rosa, D. Wojcik,*
*Z. Piotrovski (IMGW), M. Baldauf (DWD), O. Fuhrer (MeteoCH)*

**Main goals**:

- develop a dynamical core with at least conservation of mass, possibly also of energy and momentum
- better performance and stability in steep terrain

**2 development branches**:

- assess aerodynamical implicit Finite-Volume solvers (*Jameson, 1991*)
- assess dynamical core of EULAG (e.g. *Grabowski, Smolarkiewicz, 2002*)

**EULAG**: anelastic approximated equations (Lipps, Hemler, 1982, MWR)
MPDATA for advection, GMRES for elliptic solver
non-oszillatory forward-in-time (NFT) integration scheme

## Exercise: how to implement an existing dynamical core into another model?

- ‚Fortran 90-style' (dynamic memory allocation, …) introduced into EULAG code
- domain decomposition: same
- Adaptation of EULAG data structures to COSMO:
  - `array`$_{EULAG}$`(1-halo:ie+halo, …, 1:ke+1)` → `array`$_{COSMO}$`(1:ie+2*halo, …, ke:1)`
  - A-grid → C-grid
- Rotated (lat-lon) coordinates in COSMO
- Adaptation of boundary conditions:
  EULAG elliptic solver needs globally non-divergent flow
  → adjust velocity at the boundaries
- Physical tendencies are integrated inside of the NFT-scheme (in 1st order)

# Realistic Alpine flow

• Simulations have been performed for domains covering the Alpine region

• Three computational meshes with different horizontal resolutions have been used
- standard domain with $496 \times 336 \times 61$ grid points and horizontal resolution of 2.2 km (similar to COSMO 2 of MeteoSwiss)
- the same as in COSMO 2 but with resolution 1.1 km in horizontal plane
- truncated COSMO 2 domain (south-eastern part) with 0.55 km in horizontal resolution

• Initial and boundary conditions and orography from COSMO model of MeteoSwiss. Simulation with the finest resolution has separately calculated unfiltered orography.

• TKE parameterization of sub-scale turbulence and friction (COSMO diffusion-turbulence model)

• Heat diffusion and fluxes turned on

• Moist processes switched on

• Radiation switched on (*Ritter and Geleyn MWR 1992*)

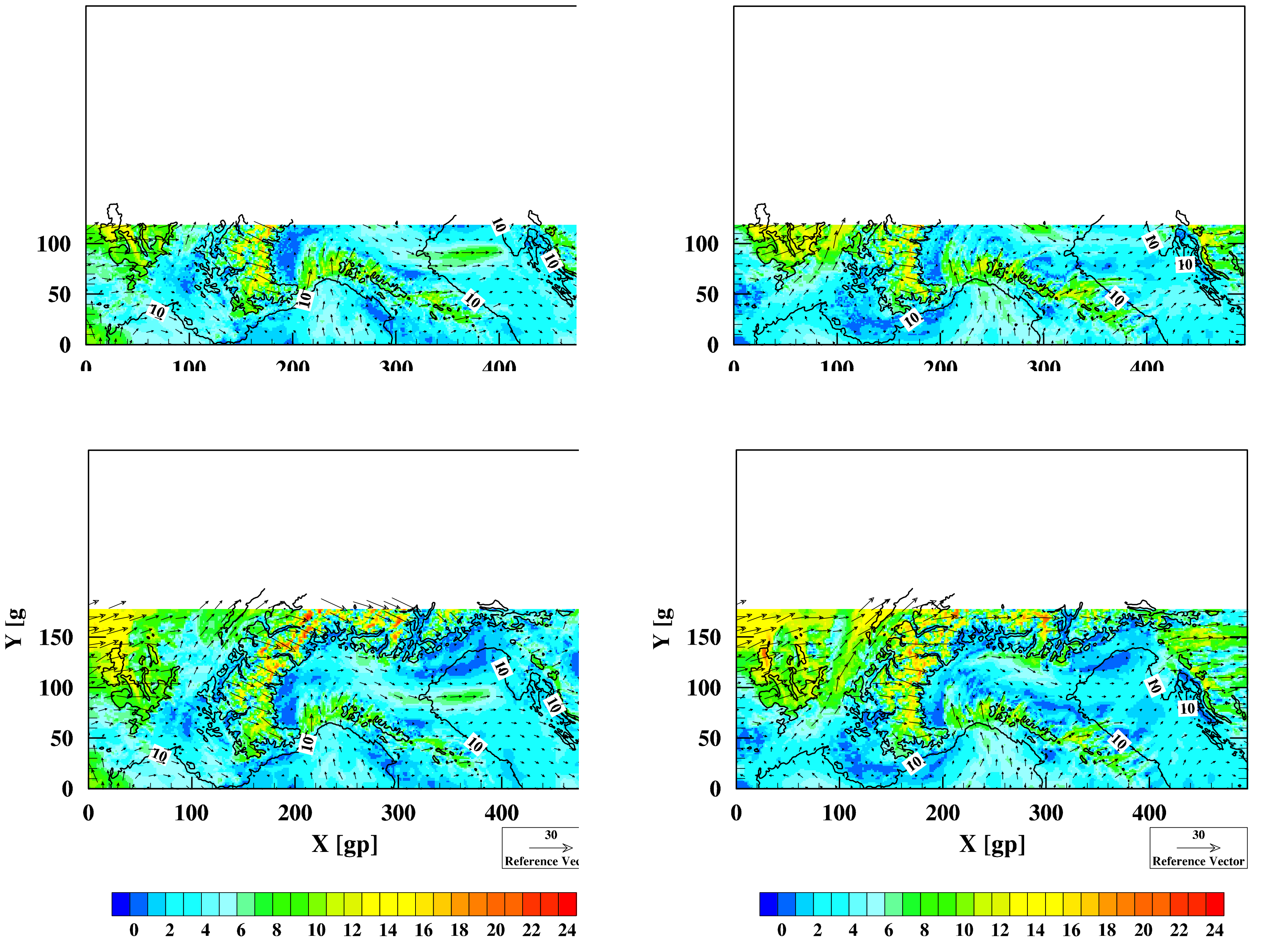
• Simulation start at 00:00 UTC (midnight), 12 November 2009

• Results are compared with Runge-Kutta dynamical core

# Horizontal velocity at 500 m

CE

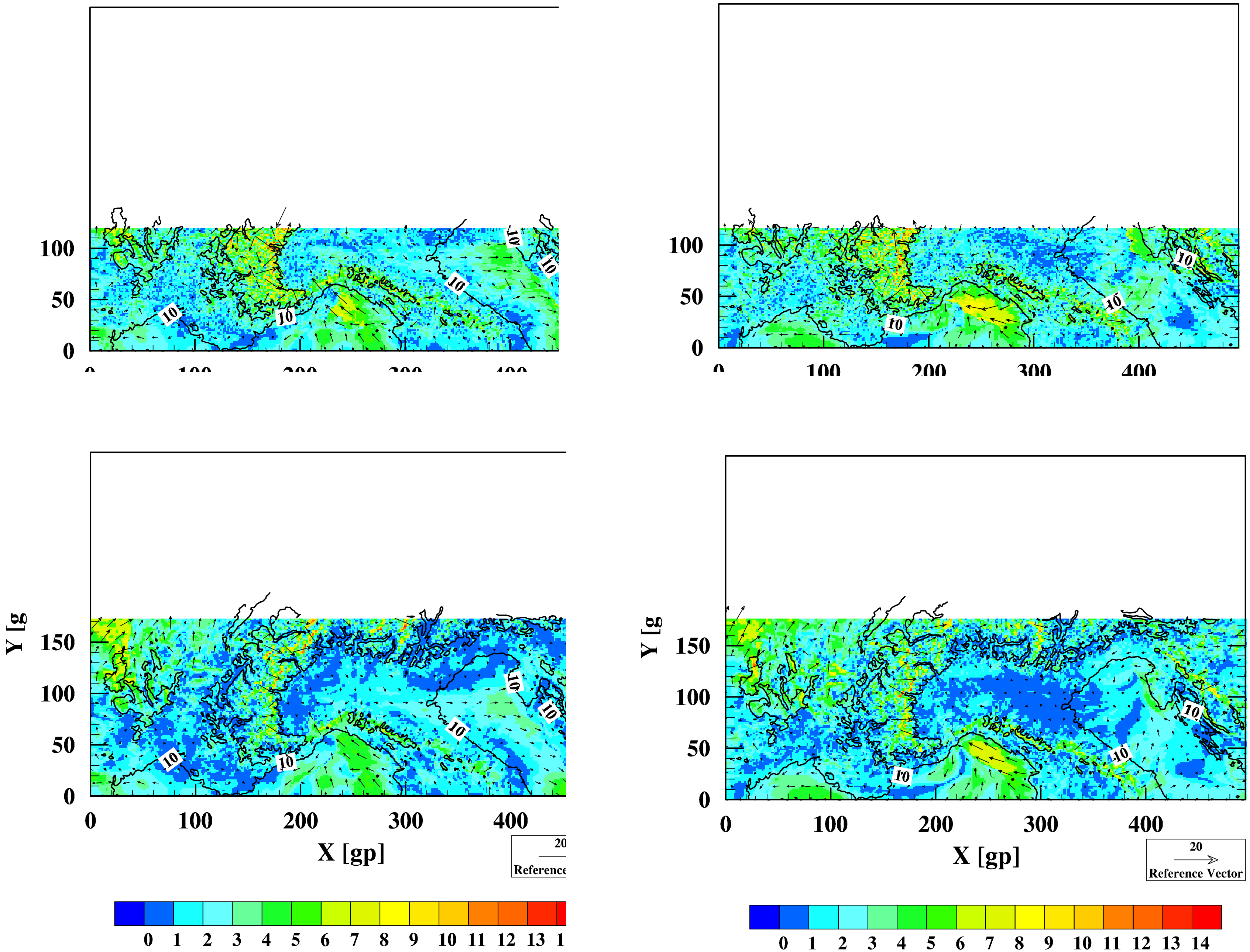
RK



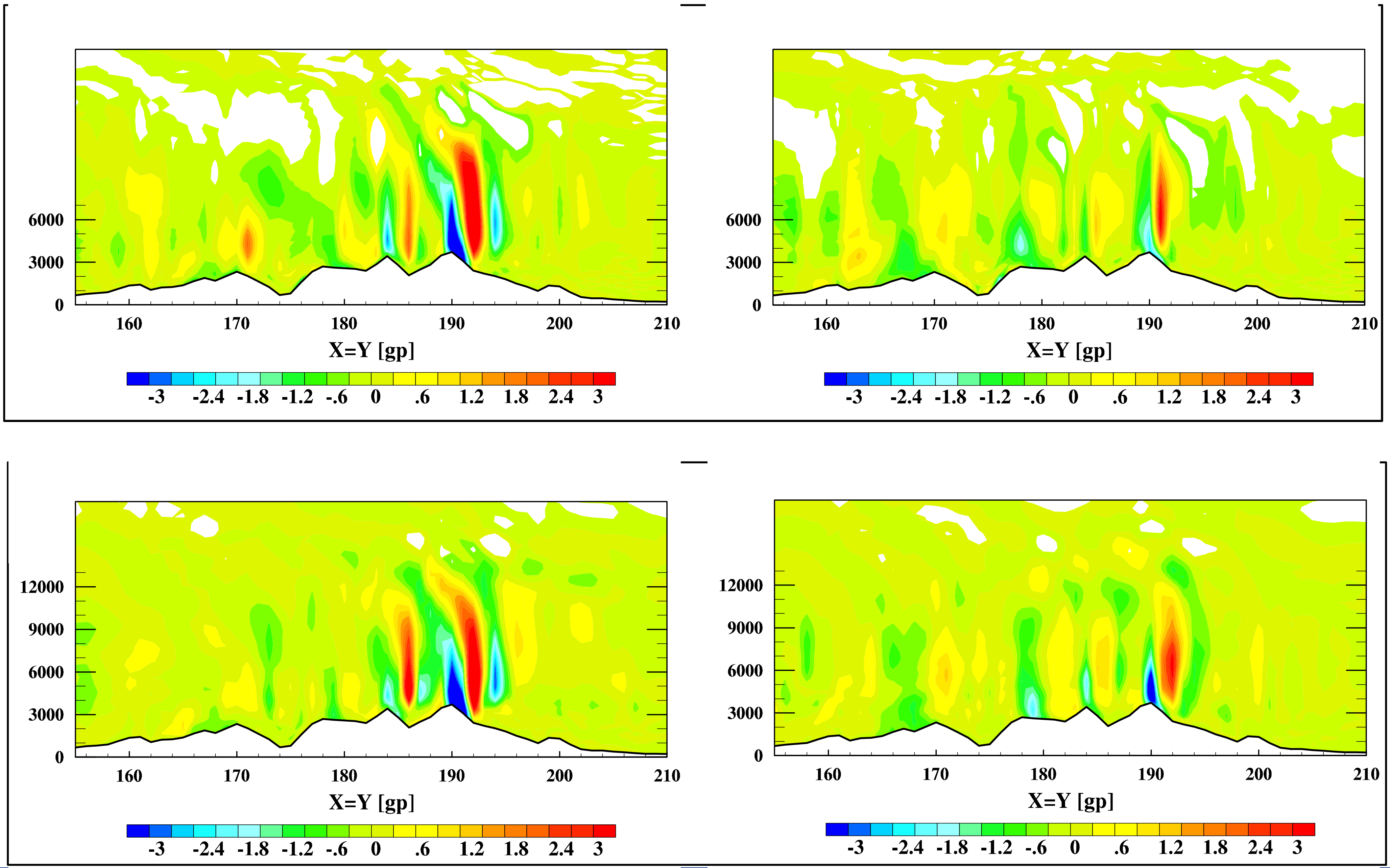
# Horizontal velocity at 10m

CE

RK



# Vertical velocity

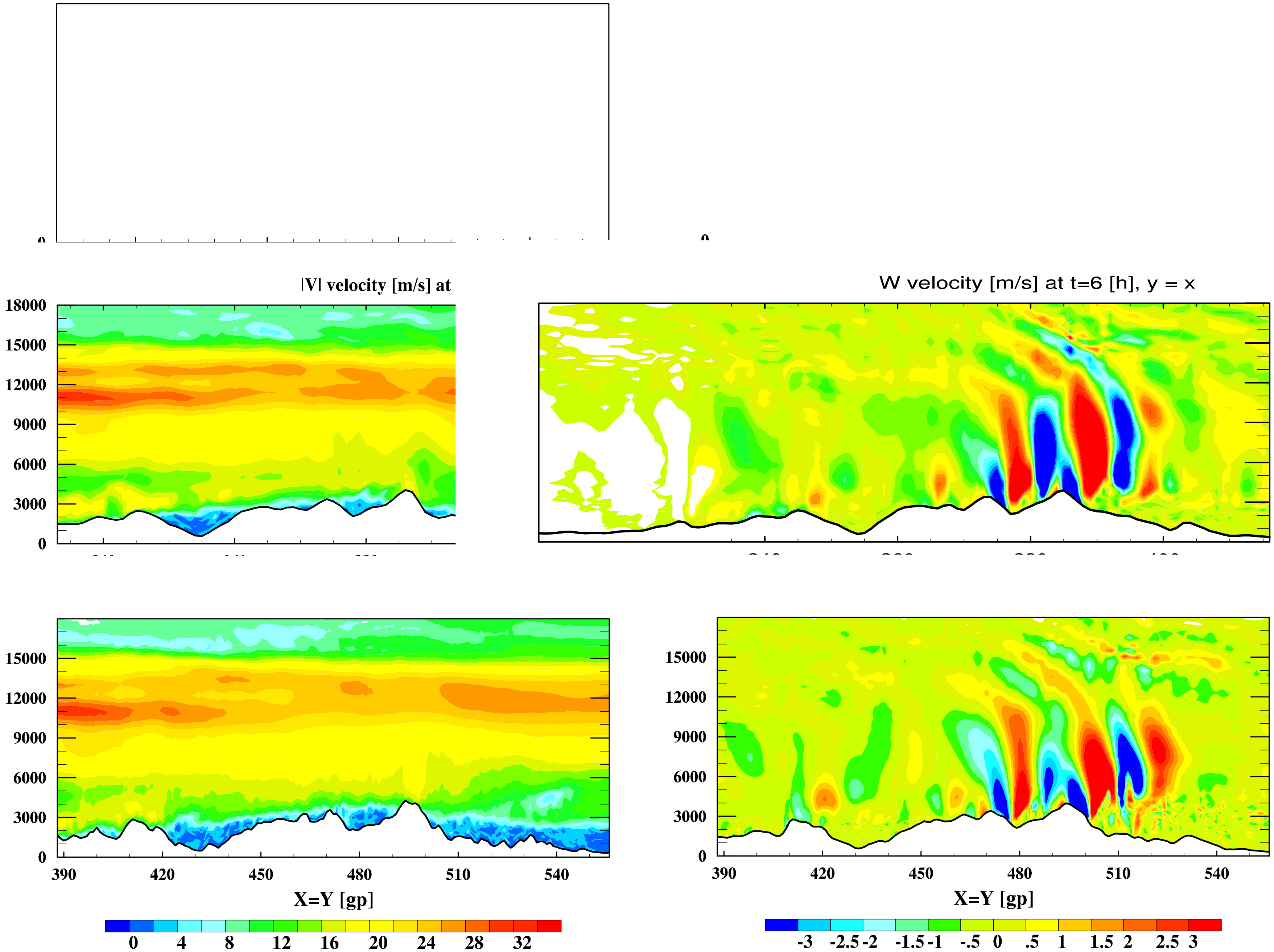


# CE - horizontal and vertical velocity over Mont Blanc

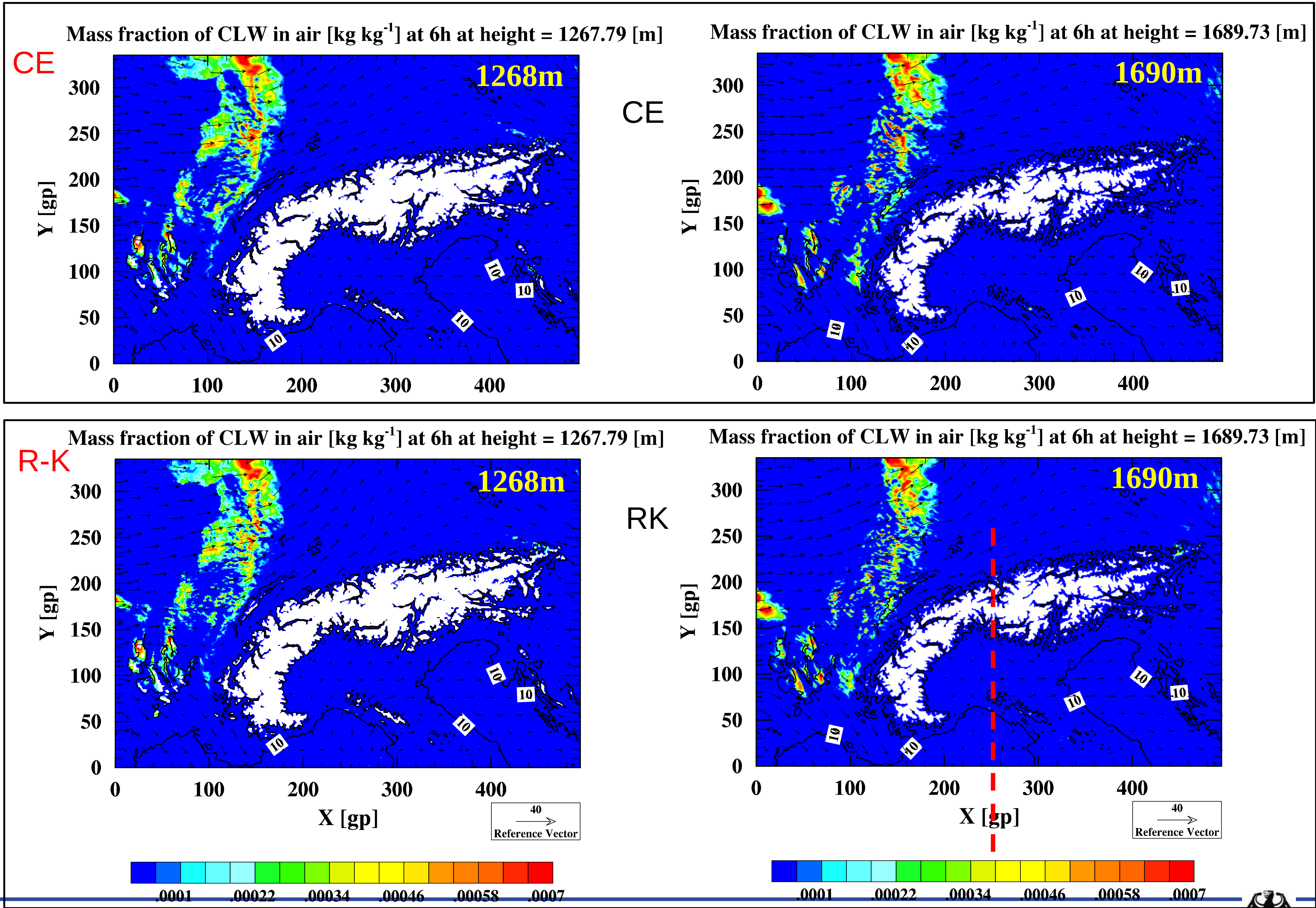
**2.2 km**

**1.1 km**

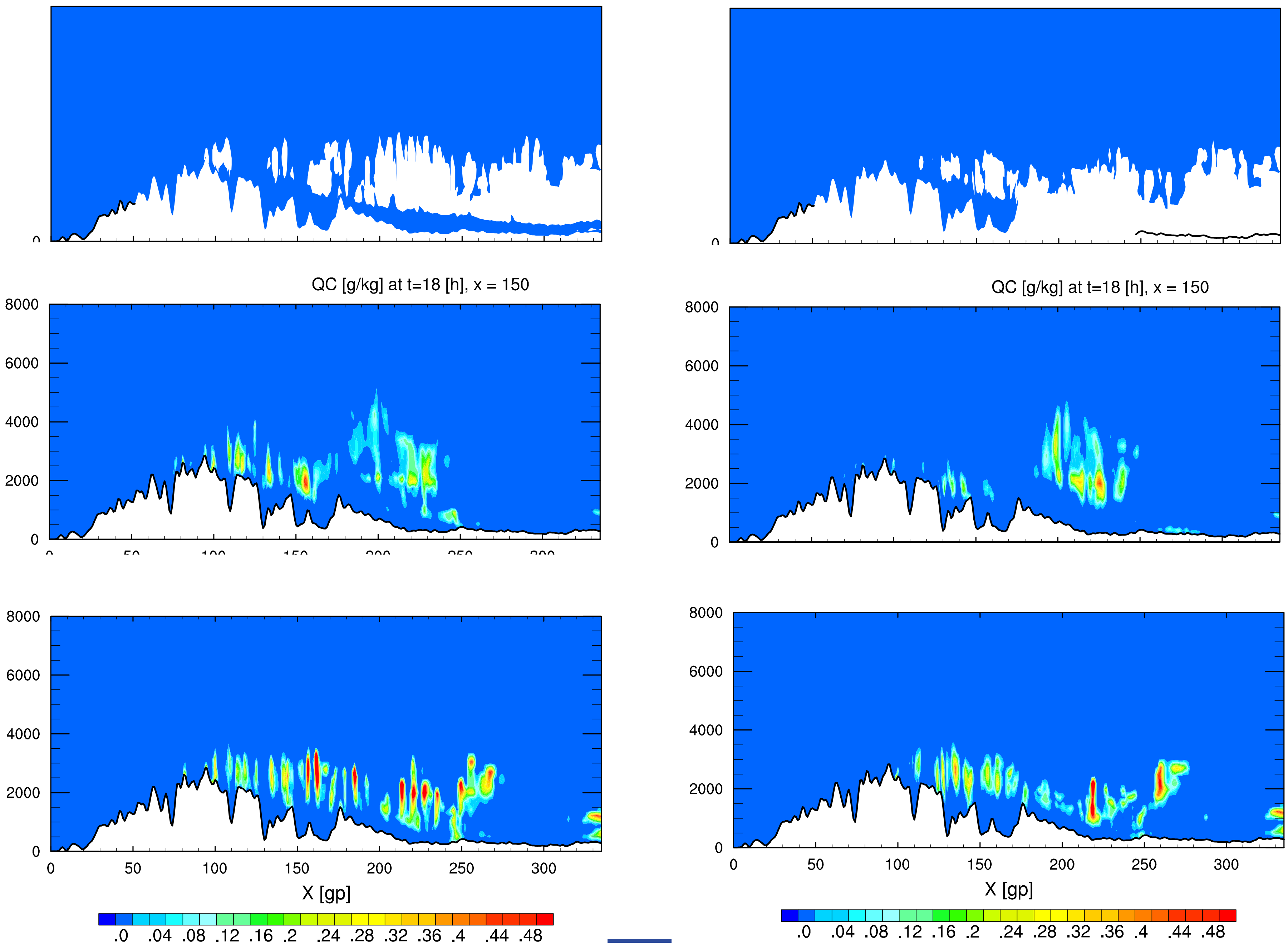
**0.55 km**



# Mass fraction of cloud liquid water – simulations with radiation



# Cloud water – simulations with radiation



## Summary

- a new dynamical core is available in COSMO as a **prototype**
  - split-explicit, HE-VI (Runge-Kutta, leapfrog): finite difference, compressible
  - semi-implicit: finite difference, compressible
  - **COSMO-EULAG**: finite volume, anelastic
    conservation of momentum, tracer mass
    flux form eq. for internal energy
    ability to handle steep slopes
- Realistic tests for Alpine flow with COSMO parameterization of friction, turbulence, radiation, surface fluxes.
- For the performed tests no artificial smoothing was required to achieve stable solutions
- The solutions are generally similar to Runge-Kutta results and introduce more spatial variability.
- In large number of tests (idealized, semi-realistic and realistic) we have not found a case in which an anelastic approximation would be a limitation for NWP.

## Outlook

• Follow-up project "COSMO-EULAG operationalization (CELO)"
project leader: Zbigniew Piotrowski (IMGW)

**Publications**

- *M. Z. Ziemiański, M. J. Kurowski, Z. P. Piotrowski, B. Rosa and O. Fuhrer*: Toward very high resolution NWP over Alps: Influence of the increasing model resolution on the flow pattern, **Acta Geophysica 59 (6)**, 2011, 1205-1235
- *B. Rosa, M. J. Kurowski, and M. Z. Ziemiański*: Testing the anelastic nonhydrostatic model EULAG as a prospective dynamical core of a numerical weather prediction model. Part I: Dry Benchmarks, **Acta Geophysica 59 (6)**, 2011, 1235-1266
- *M. J. Kurowski, B. Rosa and M. Z. Ziemiański*: Testing the anelastic nonhydrostatic model EULAG as a prospective dynamical core of numerical weather prediction model. Part II: Simulations of a supercell, **Acta Geophysica 59 (6)**, 2011, 1267-1293
- *M. Baldauf*: Non-hydrostatic modelling with the COSMO model, **Proceedings of 'ECMWF workshop on non-hydrostatic modelling'**, ECMWF, 2010, 161-169

# Development of a new fast waves solver for the Runge-Kutta scheme

*M. Baldauf (DWD)*

**Main changes towards the current solver:**

1. improvement of the vertical discretization:
   use of weighted averaging operators for all vertical operations

2. divergence in strong conservation form

3. optional: complete 3D (=isotropic) divergence damping

4. optional: Mahrer (1984) discretization of horizontal pressure gradients

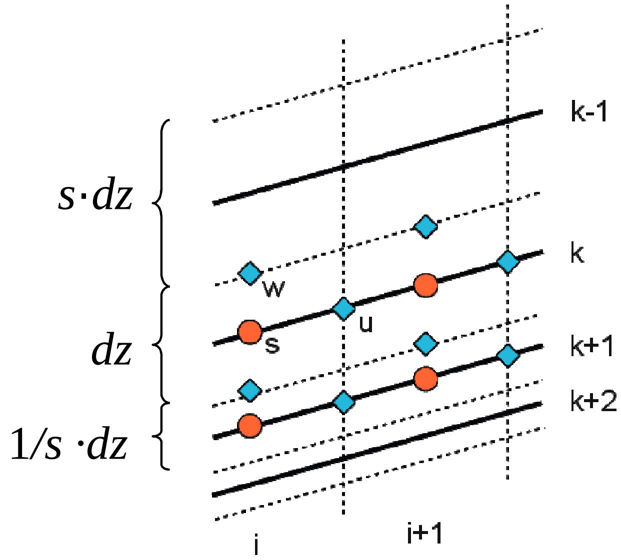
additionally some 'technical' improvements;
hopefully a certain increase in code readability

**overall goal: improve numerical stability of COSMO**

## Discretization error in stretched grids; Divergence

Divergence with <u>weighted average</u>
of $u$ (and $v$) to the half levels:

$$\mathrm{div}\,\mathbf{v} = \left.\frac{\partial u}{\partial x}\right|_z + \left.\frac{\partial w}{\partial z}\right|_x + \boxed{dz}\,\frac{1}{8}\frac{\partial h}{\partial x}\frac{\partial^2 u}{\partial z^2}\left(\frac{1}{s} - s\right) + O(dz^2, dx^2)$$

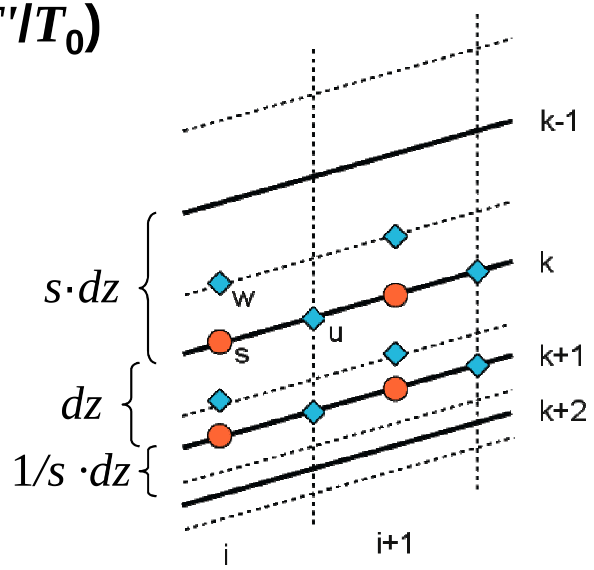



Divergence with <u>only arithmetic average</u> of $u$ (and $v$) to the half levels:

$$\begin{aligned}\mathrm{div}\,\mathbf{v} &= \left.\frac{\partial u}{\partial x}\right|_z + \boxed{\frac{\partial h}{\partial x}\frac{\partial u}{\partial z}\left(\frac{1}{2} - \frac{1}{4}\left(s + \frac{1}{s}\right)\right)} + \left.\frac{\partial w}{\partial z}\right|_x + \\ &+ dz\,\frac{1}{8}\frac{\partial h}{\partial x}\frac{\partial^2 u}{\partial z^2}\left(\left(\frac{1}{s} - s\right) + \frac{1}{2}\left(\frac{1}{s^2} - s^2\right)\right) + O(dz^2, dx^2)\end{aligned}$$

*not a consistent discretization if $s \neq 1$ !*

## Discretization error in stretched grids; Buoyancy ($T'/T_0$)




buoyancy term with weighted average of $T'$ ($T_0$ exact):

$$\frac{1}{T_0} A_\zeta^N T' \quad = \quad \frac{T'}{T_0} + \boxed{dz^2} \frac{1}{2} \frac{s}{(s+1)^2} \frac{1}{T_0} \frac{\partial^2 T'}{\partial z^2} + O(dz^3)$$

buoyancy term with arithmetic average of $T'$ ($T_0$ exact):

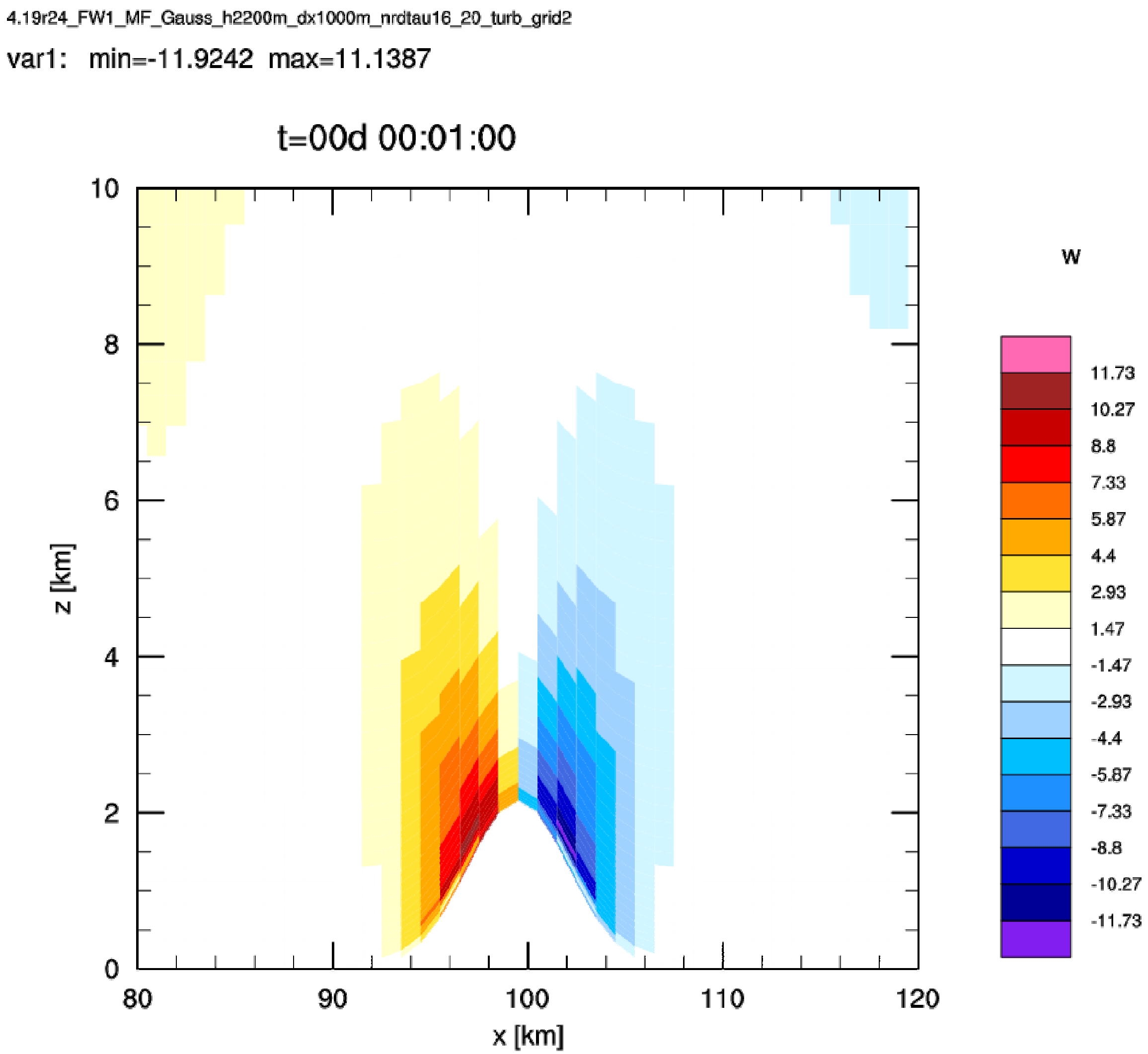
$$\frac{1}{T_0} A_\zeta T' \quad = \quad \frac{T'}{T_0} + \boxed{dz} \frac{1}{2} \frac{s-1}{s+1} \frac{1}{T_0} \frac{\partial T'}{\partial z} + O(dz^2)$$

buoyancy term with weighted average for $T'$ and $T_0$:

$$\frac{1}{A_\zeta^N T_0} A_\zeta^N T' \quad = \quad \frac{T'}{T_0} + dz^2 \frac{1}{2} \frac{s}{(s+1)^2} \left[ \frac{1}{T_0} \frac{\partial^2 T'}{\partial z^2} \boxed{- \frac{1}{T_0^2} \frac{\partial^2 T_0}{\partial z^2} T'} \right] + O(dz^3)$$

# Flow over a Gaussian mountain in a vertically stretched grid

current fast waves solver




$h_{max}$ = 2200 m
$a$ = 3000 m
$u_0$ = 20 m/s
$N$ = 0.01 1/s

$Fr_h$ = 0.9
$Fr_a$ = 0.67

max $\alpha$ = 27°
max $|h_i - h_{i+1}|$ = 500 m

grid ($z_{top}$= 25 km):
$\Delta z_{bottom} \approx$ 25 m
$\Delta z_{top} \approx$ 750 m

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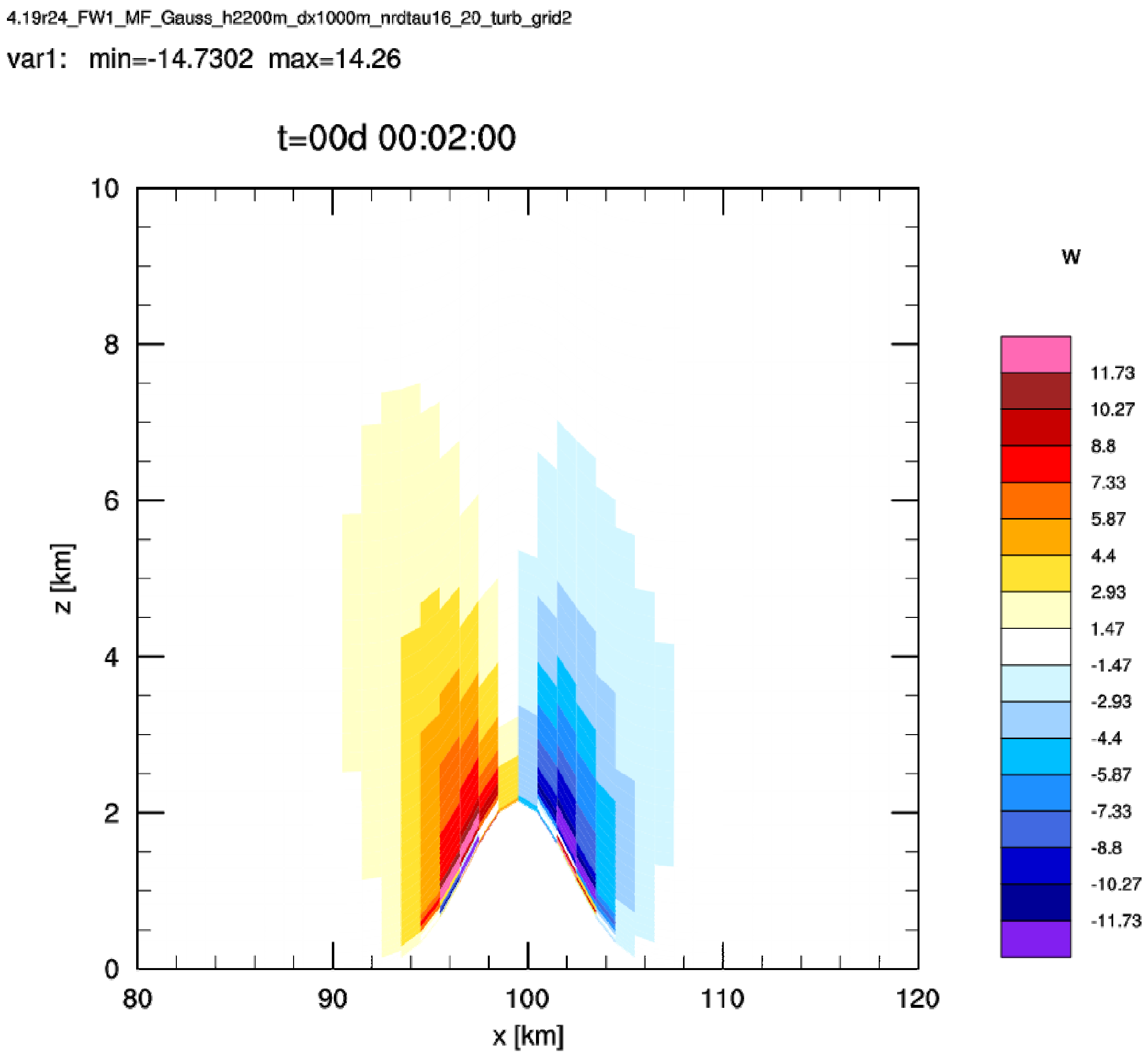


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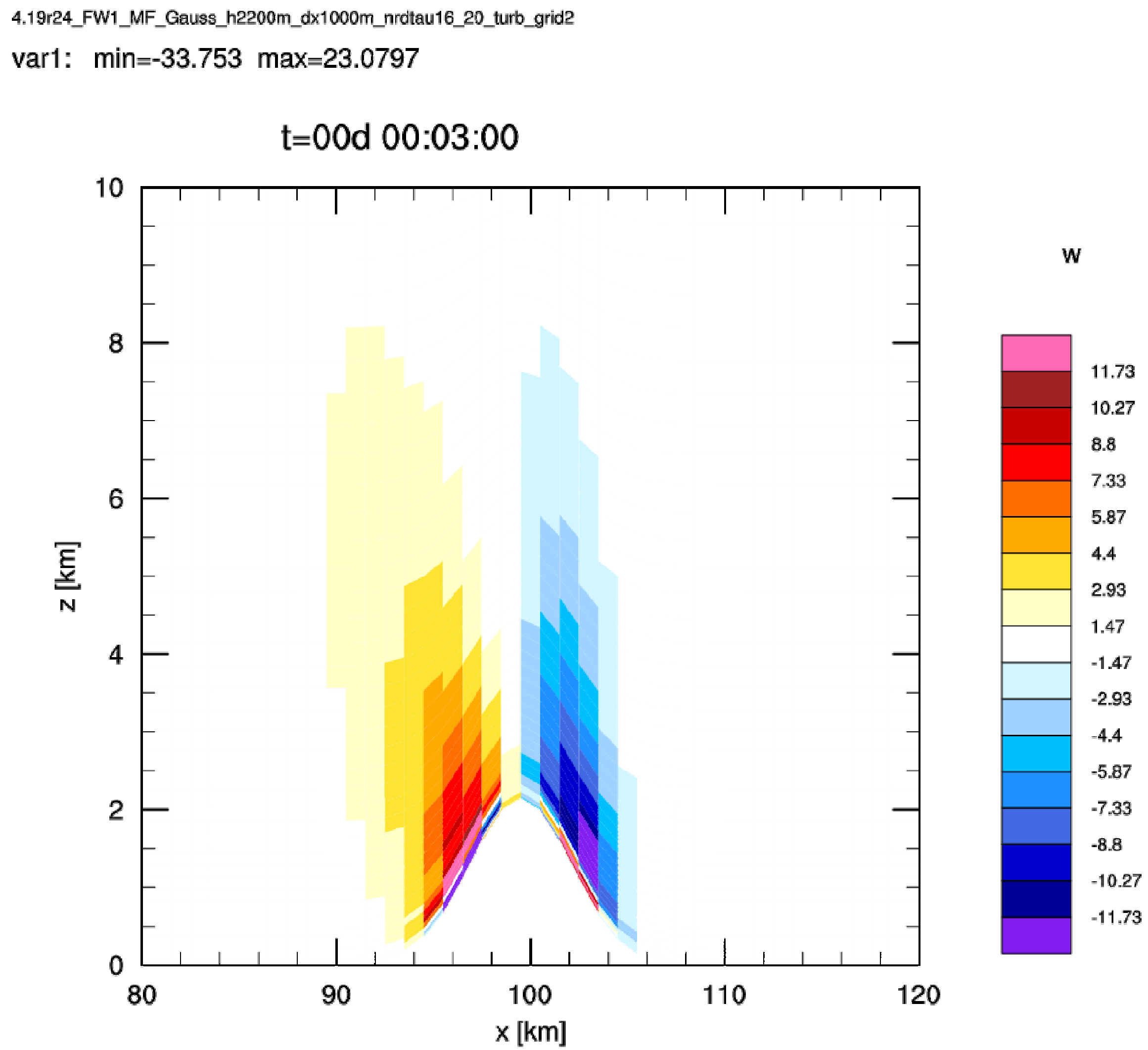


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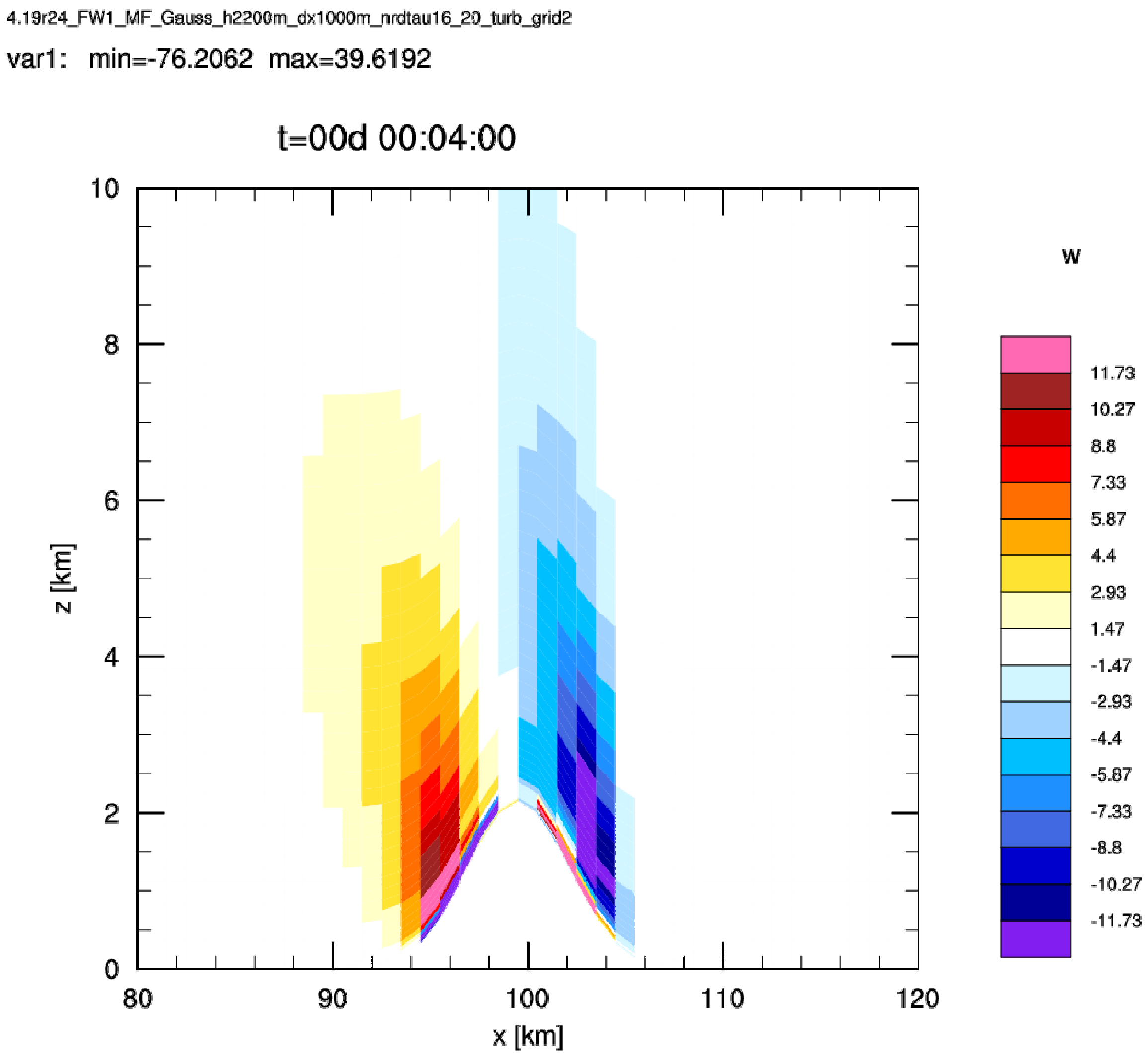
current fast waves solver




$h_{max}$ = 2200 m
$a$ = 3000 m
$u_0$ = 20 m/s
$N$ = 0.01 1/s

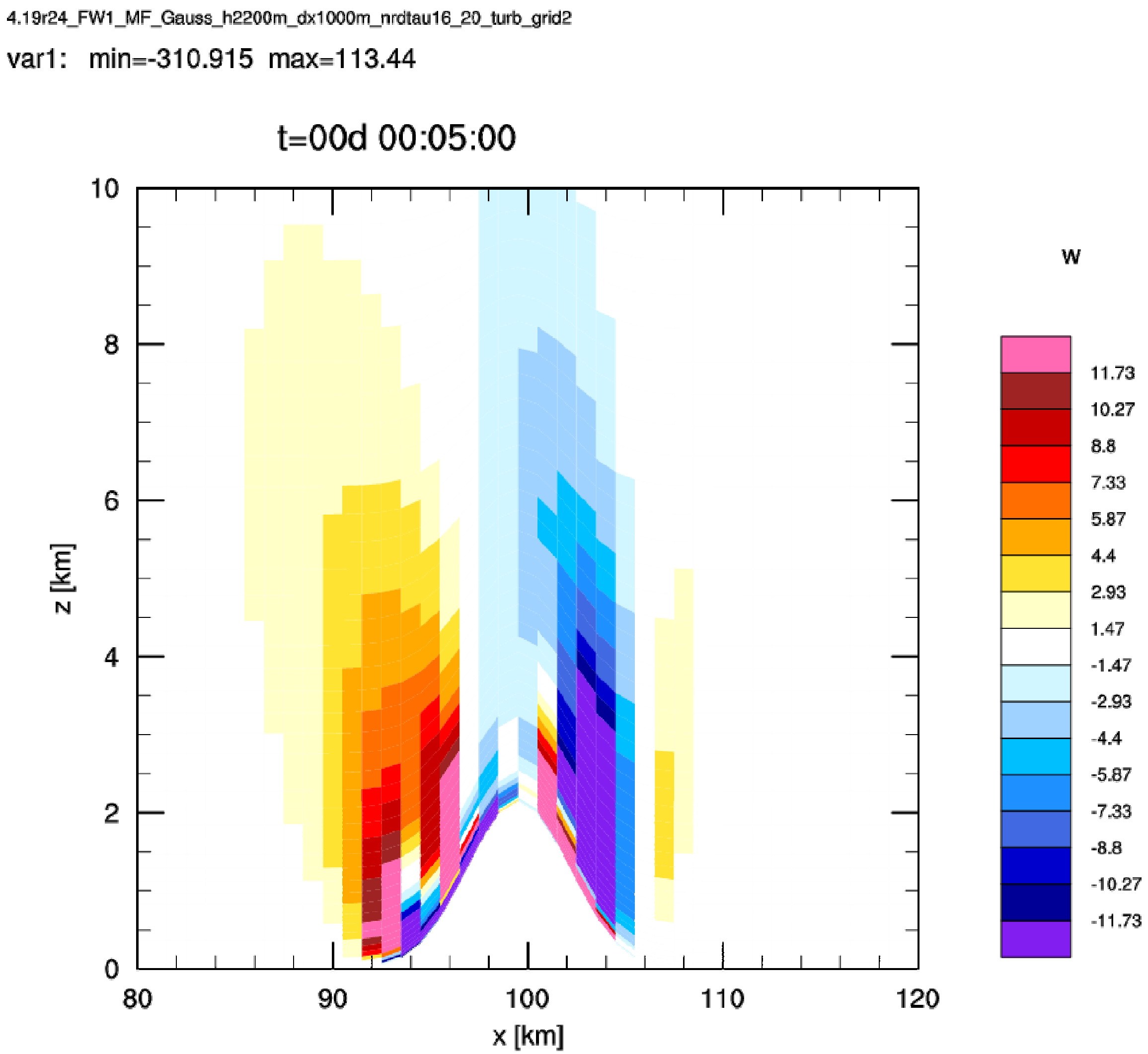
$Fr_h$ = 0.9
$Fr_a$ = 0.67

max $\alpha$ = 27°
max $|h_i - h_{i+1}|$ = 500 m

grid ($z_{top}$= 25 km):
$\Delta z_{bottom} \approx$ 25 m
$\Delta z_{top} \approx$ 750 m

# Flow over a Gaussian mountain in a vertically stretched grid

current fast waves solver




$h_{max}$ = 2200 m
$a$ = 3000 m
$u_0$ = 20 m/s
$N$ = 0.01 1/s

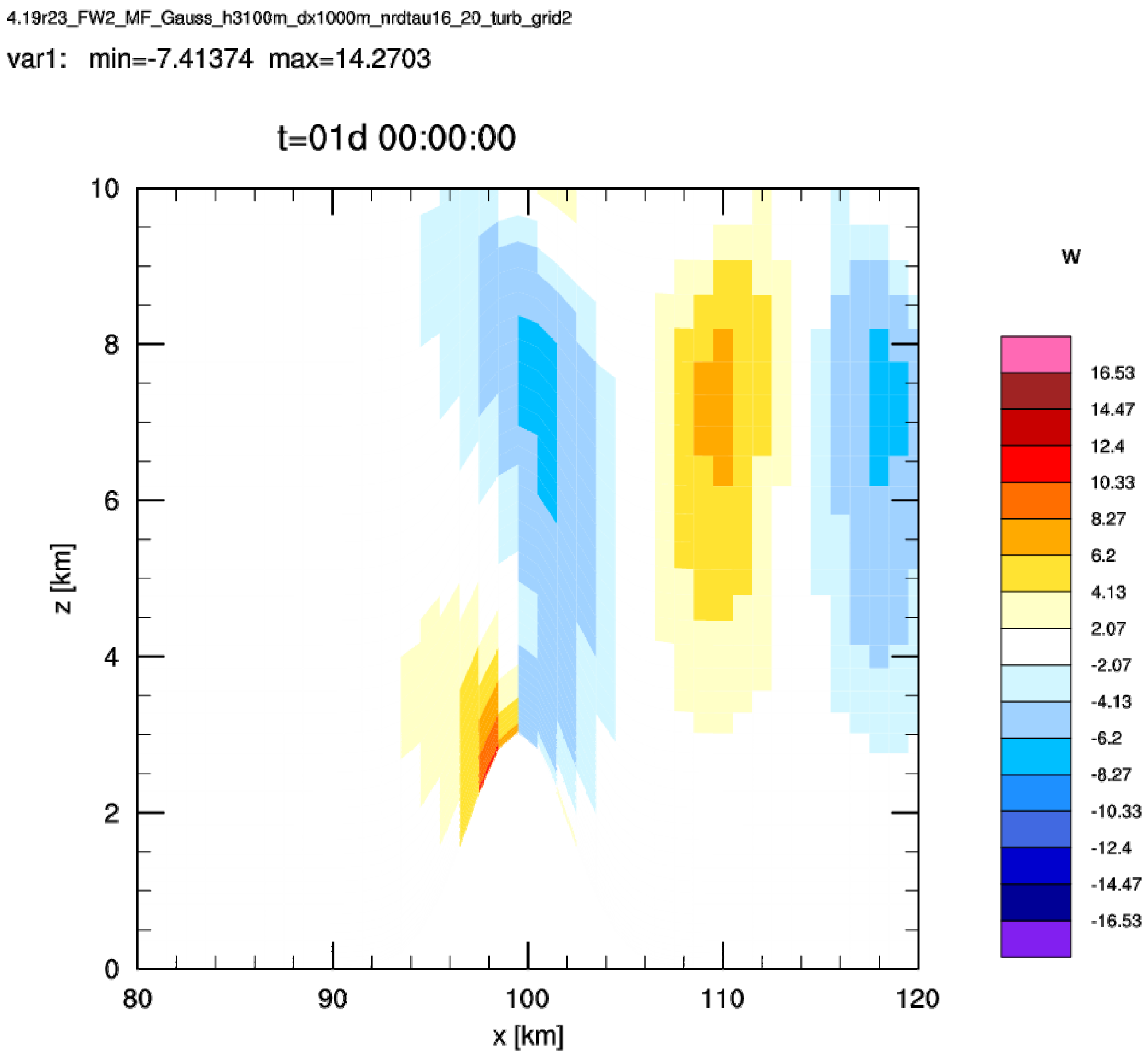
$Fr_h$ = 0.9
$Fr_a$ = 0.67

max $\alpha$ = 27°
max $|h_i - h_{i+1}|$ = 500 m

grid ($z_{top}$= 25 km):
$\Delta z_{bottom} \approx$ 25 m
$\Delta z_{top} \approx$ 750 m

# Flow over a Gaussian mountain in a vertically stretched grid

new fast waves solver




$h_{max}$ = 3100 m
$a$ = 3000 m
$u_0$ = 20 m/s
$N$ = 0.01 1/s

$Fr_h$ = 0.65
$Fr_a$ = 0.67

max $\alpha$ = 35°
max $|h_i - h_{i+1}|$ = 710 m

grid ($z_{top}$ = 25 km):
$\Delta z_{bottom} \approx$ 25 m
$\Delta z_{top} \approx$ 750 m

## Improved stability in real case applications

- *COSMO-DE 28.06.2011, 6 UTC runs* (shear instability case)
  must be cured by Smagorinsky diffusion
  operational deterministic and several COSMO-DE-EPS runs
  crashed after ~16 h
- *COSMO-DE 12.07.2011, 6 UTC run (‚explosion‘ of qr in Alps)*
  only stable with Bott2_Strang
- *COSMO-DE L65, 15.07.2011, 12 UTC run*
  model crash after 215 timesteps (~ 1.5 h)
- *COSMO-2, 16.06.2011, 0 UTC run* (reported by O. Fuhrer)
  model crash after 1190 timesteps (~6.6 h)
- *‚COSMO-1, 24.08.2011‘*, resolution 0.01°(~ 1.1km) 1700 * 1700 grid points
  (reported by A. Seifert) model crash after 10 time steps
- ...

- COSMO-DE L65 run stable for 2 months ('1.7.-31.8.2012')

one counterexample: COSMO-EU (7 km) crash ('09.09.2012') by horizontal shear instability
→ must be cured by Smagorinsky-diffusion

## Summary

- New fast waves solver cures crashes in several realistic test cases
- this is partly due to the fact that it allows steeper slopes
- dynamic bottom BC probably not necessary
- problems with geopotential bias are solved due to improved buoyancy formulation
- efficiency: the new fast waves solver needs about 30% more computation time than the current one on the NEC-SX9 → about 6% more time in total for COSMO-DE
- new `fast_waves_sc.f90` is **now available in COSMO 4.24**
  **(**if irefatm=1 is used → use int2lm 1.20 with lanalyt_calc_p0T0=.TRUE.)
- currently: new FW runs in Parallelroutine at DWD; is under consideration for COSMO-1 km runs at MeteoCH

## An analytic solution for linear gravity waves in a channel as a test case for solvers of the non-hydrostatic, compressible Euler equations

*M. Baldauf (DWD)*

For development of dynamical cores (or numerical methods in general) idealized test cases are an important evaluation tool

Existing analytic solutions:

- stationary flow over mountains
  linear: *Queney (1947, ...), Smith (1979, ...), Baldauf (2008)*
  non-linear: *Long (1955)* for Boussinesq-approx. atmosphere
- non-stationary, linear expansion of gravity waves in a channel
  ***Skamarock, Klemp (1994)* for Boussinesq-approx. atmosphere**

Most of the other idealized tests only possess 'known solutions' gained by other numerical models.

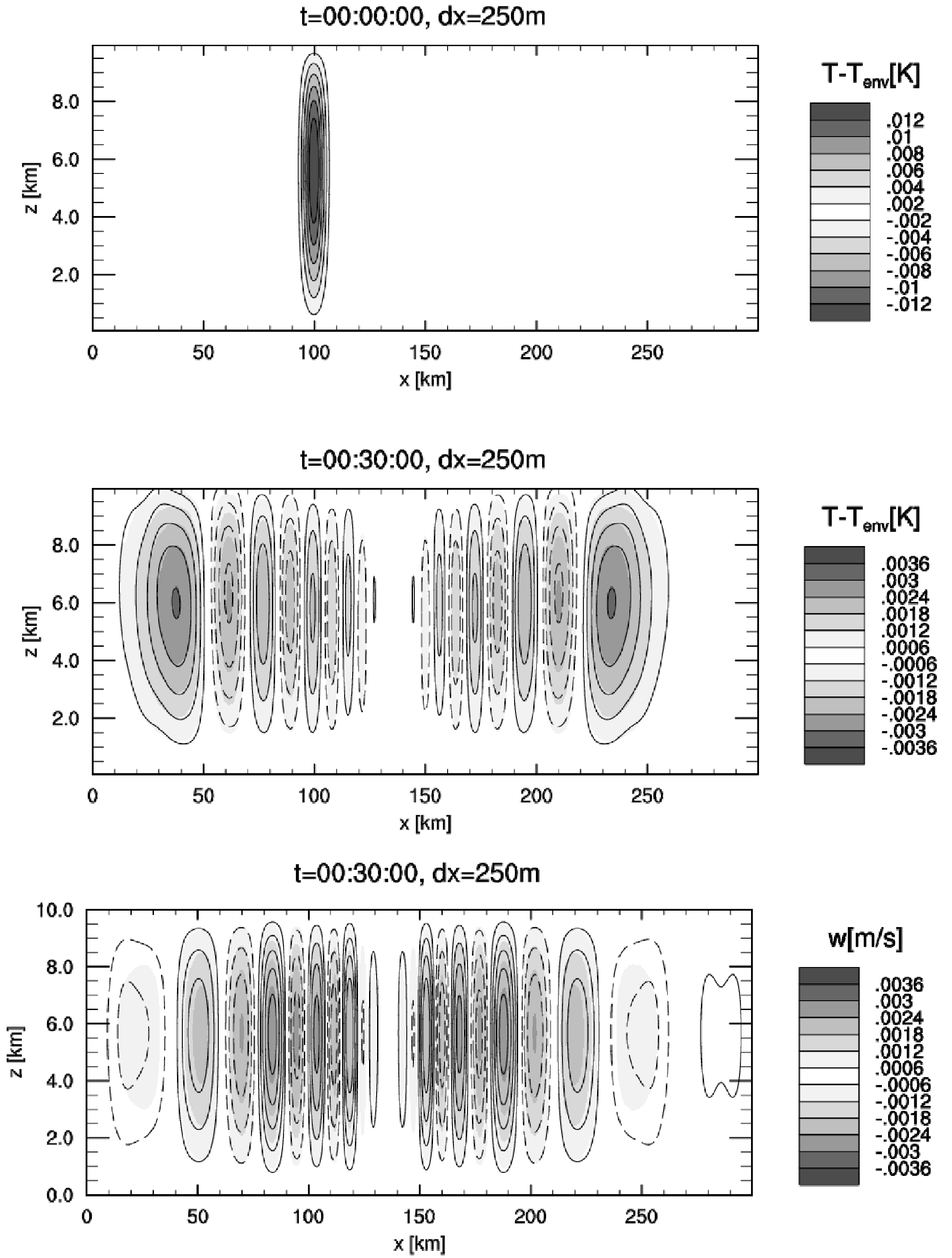
There exist even less analytic solutions which use <u>exactly the equations of the numerical model under consideration</u>, i.e. in a sense that a numerical model <u>converges to this solution</u>. One exception is presented here:

linear expansion of gravity/sound waves in a channel

**Small scale test**
with a basic flow $U_0$=20 m/s
f=0

Initialization similar to
*Skamarock, Klemp (1994)*

Black lines: analytic solution
Shaded: COSMO

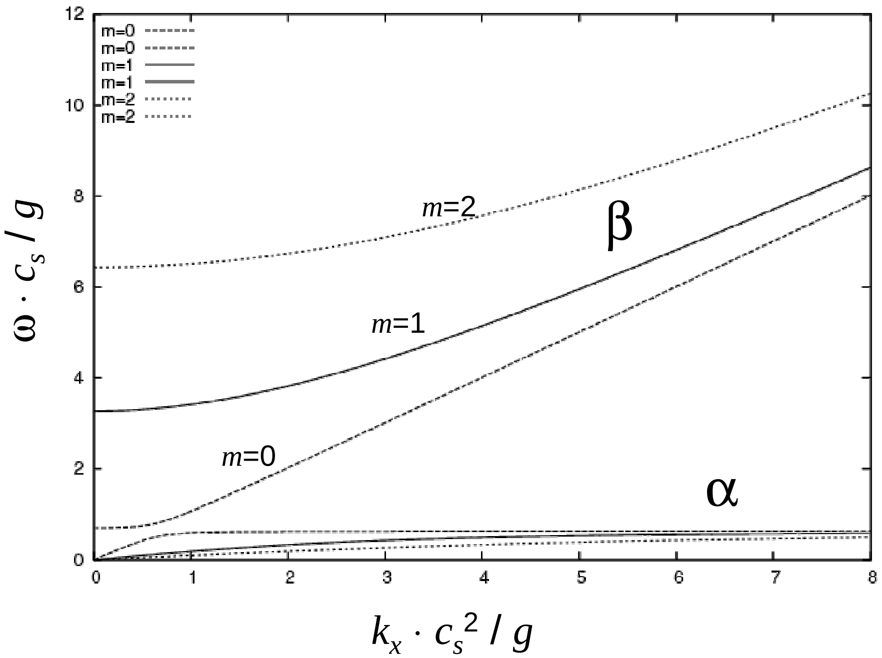


Analytic solution of the **fully compressible**, non-hydrostatic Euler equations for the Fourier transformed vertical velocity $w$

$$\hat{w}_b(k_x, k_z, t) = -\frac{1}{\beta^2 - \alpha^2}\left[-\alpha \sin \alpha t + \beta \sin \beta t + \left(f^2 + c_s^2 k_x^2\right)\left(\frac{1}{\alpha}\sin \alpha t - \frac{1}{\beta}\sin \beta t\right)\right] g \frac{\hat{\rho}_b(k_x, k_z, t=0)}{\rho_s}$$

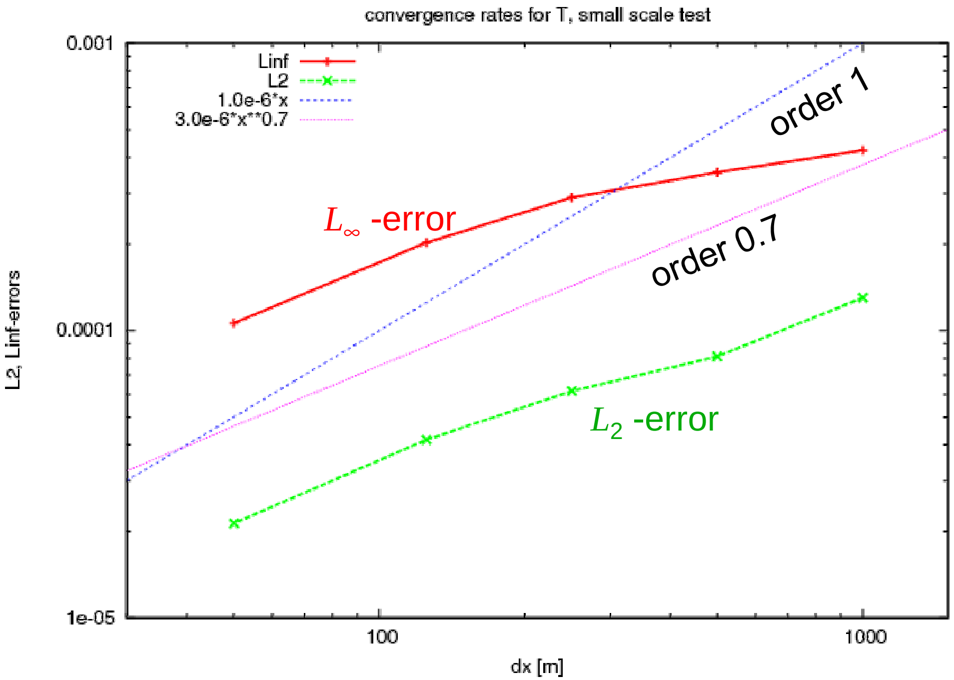
analogous expressions for $u_b(k_x, k_z, t)$, ...

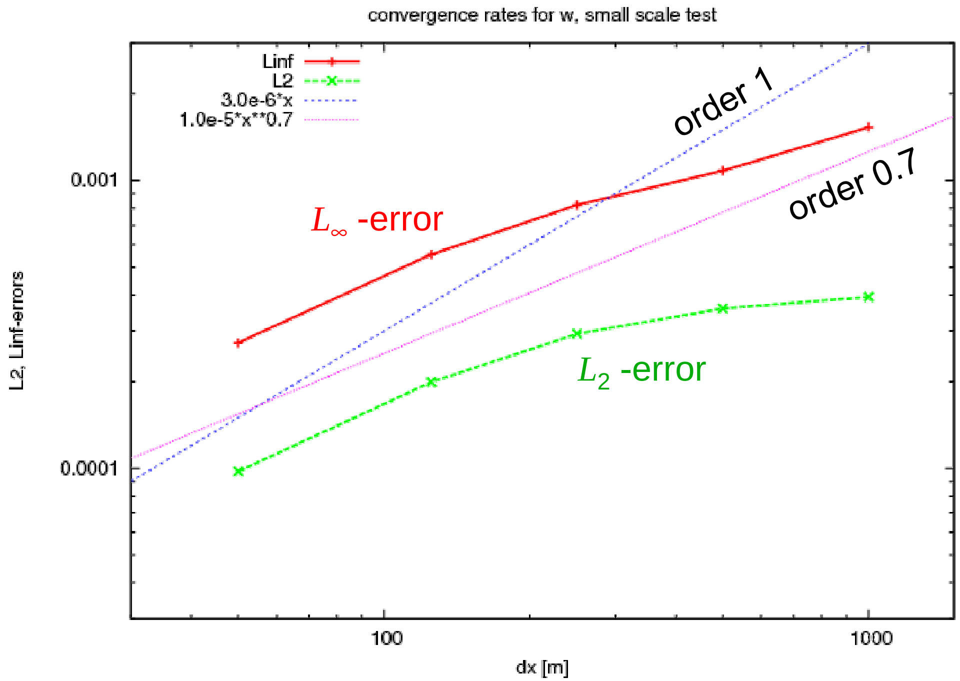
The frequencies α, β are the gravity wave and acoustic branch, respecticely, of the dispersion relation for compressible waves in a channel with height H;
kz = (π / H) · m



## Convergence properties of COSMO

- $L_2$, $L_\infty$ -errors are generally higher for $w$ than for $T'$
- COSMO has a spatial-temporal convergence rate of about $0.7$



## Summary

- An analytic solution of the compressible, non-hydrostatic Euler equations in a 2D channel was derived
- → a reliable solution for a well known test exists and can be used not only for qualitative comparisons but even as a reference solution for convergence tests
- For fine enough resolutions COSMO has a spatial-temporal convergence rate of about 0.7, no drawbacks visible.

*M. Baldauf, S. Brdar:* An Analytic solution for Linear Gravity Waves in a Channel as a Test for Numerical Models using the Non-hydrostatic, Compressible Euler Equations, submitted to *Quart. J. Roy. Met. Soc.*

**Contributors are requested to submit an abstract of not more than one page to**

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63067 Offenbach
Germany

Fax: +49 69 8062 3721

e-mail: **seminar.fe13@dwd.de**

**by 15 Feb 2013.**

**Please note your preference for poster or oral presentation.**
**Notification of acceptance will be by**

**15 March 2013.**

The first time, the workshop will take place in the Headquarter of DWD, Frankfurter Str. 135 in Offenbach/Main, Germany.

The aim of the workshop is to provide a forum of information concerning all questions related to fine-scale modeling.
Papers on all aspects of *high resolution modelling*, i.e. model resolutions covering about 0.2 to 5 km, in particular the *convective scale*, are welcome, e.g. on

- ***physical parameterizations***
- ***numerical algorithms and their performance***
- ***data assimilation using radar and satellite data***
- ***Predictability***
- ***experience in operational applications including verification issues.***

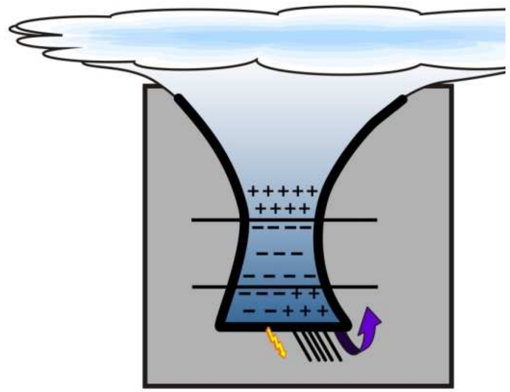
Presentations on other aspects of nonhydrostatic modelling, such as *global nonhydrostatic modelling* and applications are also welcome.
A special issue of this years meeting with an own session will be

**[[ Topic ]]**

Papers about this topic will be preferentially accepted for oral presentation.
The workshop will be open to *contributors* and *invited participants*.

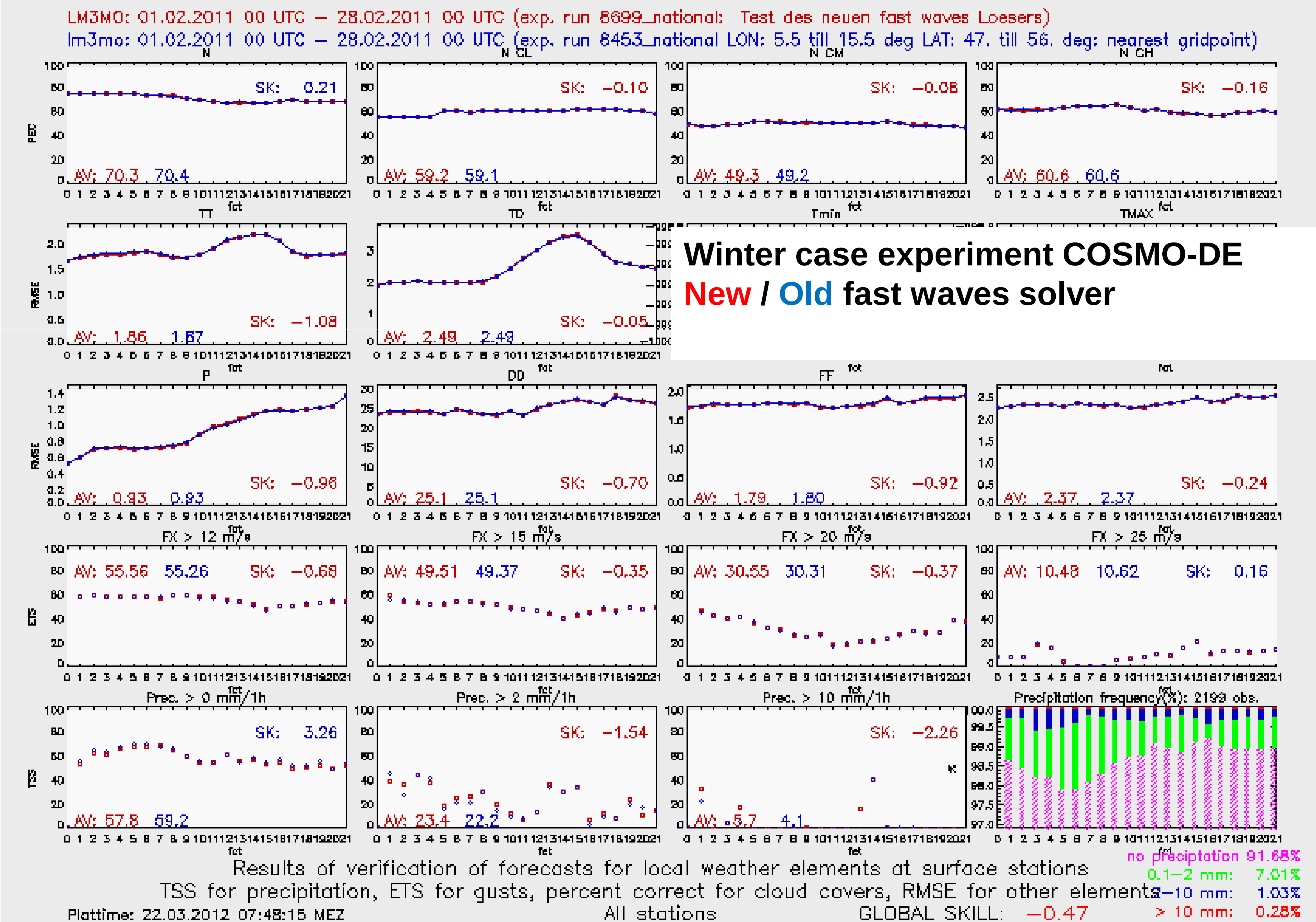
**Deutscher Wetterdienst**
***Wetter und Klima aus einer Hand***

# 10th International SRNWP-Workshop on Nonhydrostatic Modelling

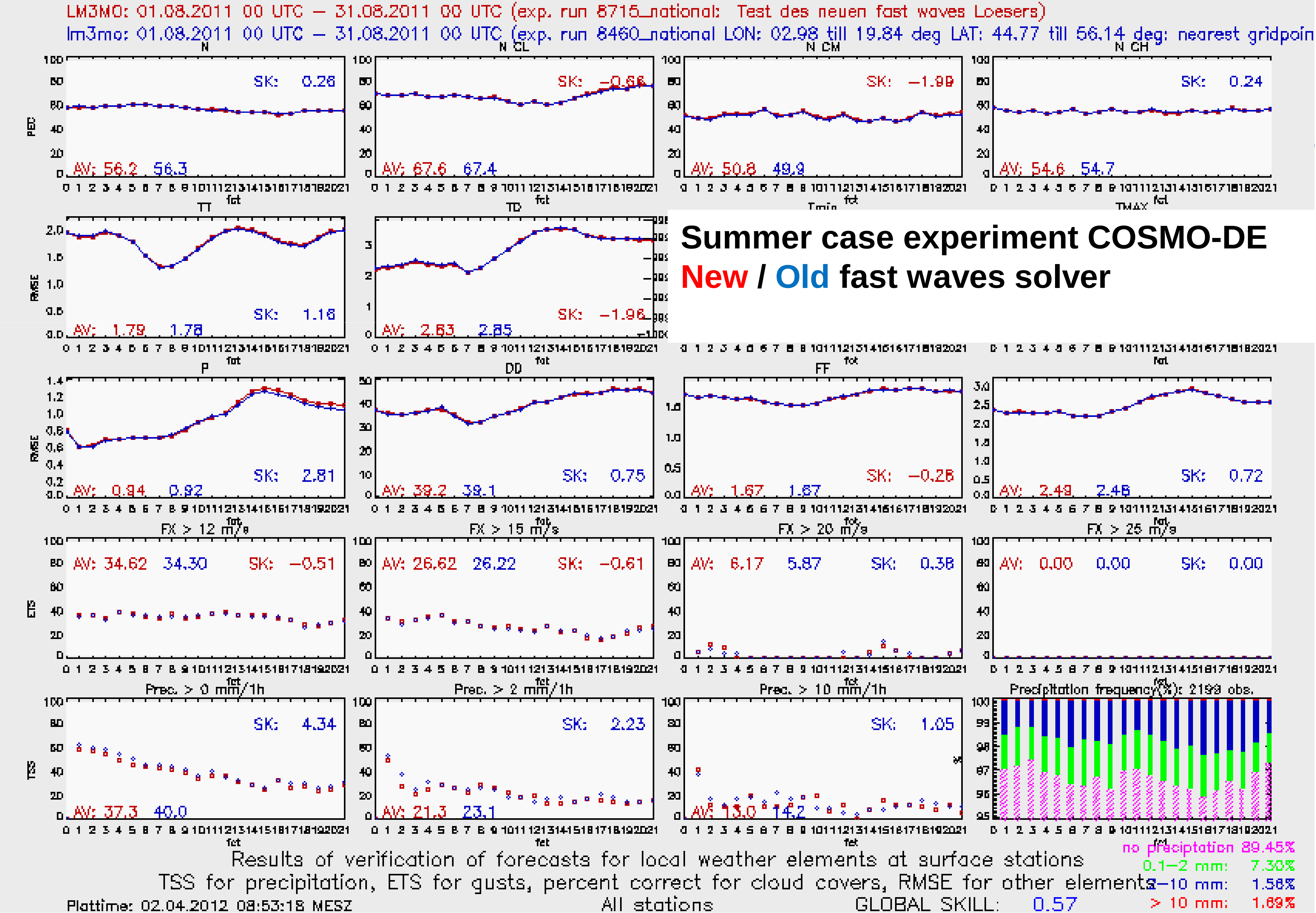


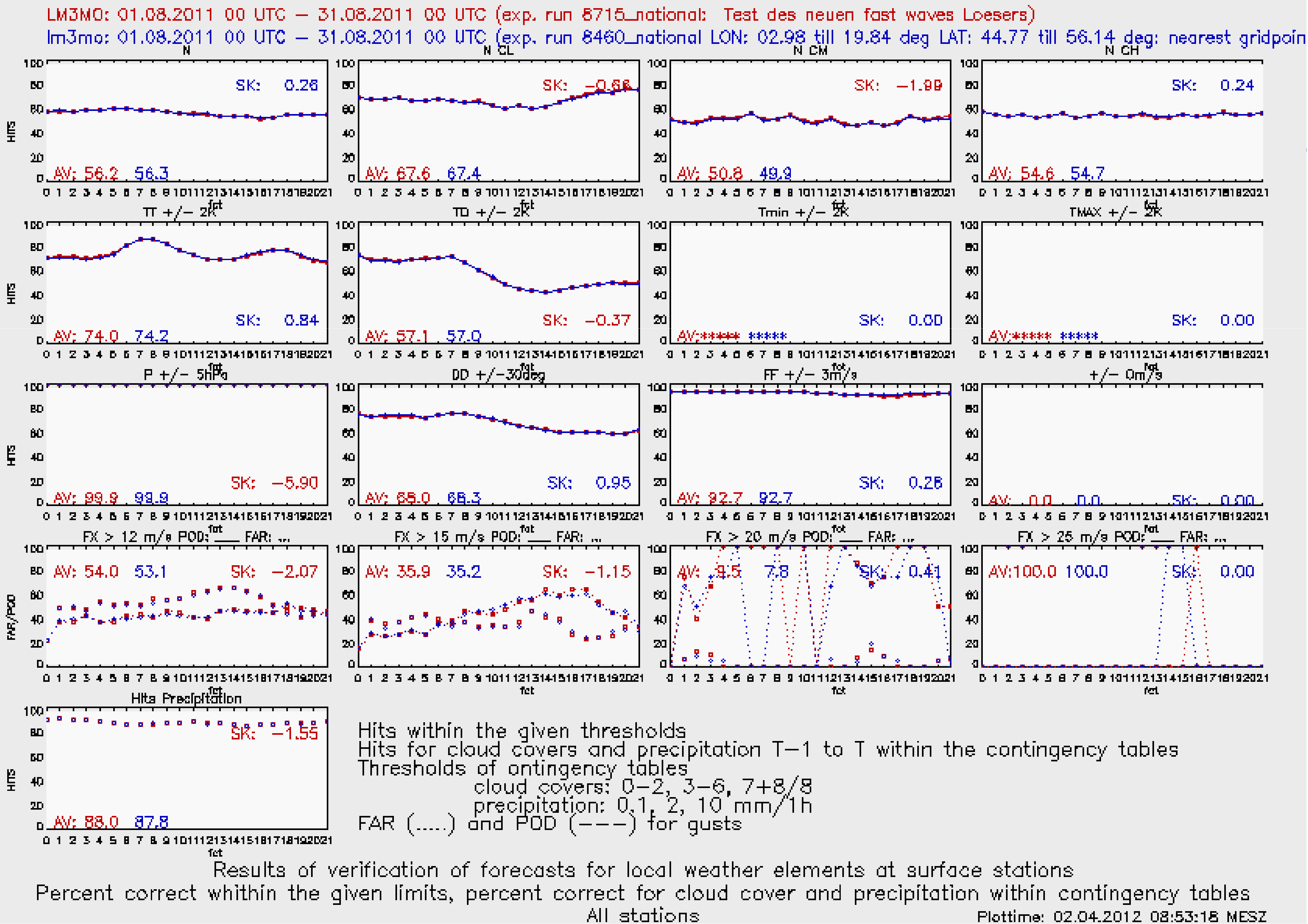
## 13.-15. May 2013

# Winter case experiment COSMO-DE
# New / Old fast waves solver



## Summer case experiment COSMO-DE
## New / Old fast waves solver




LM3MO: 01.08.2011 00 UTC – 31.08.2011 00 UTC (exp. run 8715_national: Test des neuen fast waves Loesers)
lm3mo: 01.08.2011 00 UTC – 31.08.2011 00 UTC (exp. run 8460_national LON: 02.98 till 19.84 deg LAT: 44.77 till 56.14 deg: nearest gridpoin
N
N CL
N CM
N CH
SK: 0.26
SK: -0.66
SK: -1.99
SK: 0.24
AV: 56.2 56.3
AV: 67.6 67.4
AV: 50.8 49.9
AV: 54.6 54.7
TT +/- 2K
TD +/- 2K
Tmin +/- 2K
TMAX +/- 2K
SK: 0.84
SK: -0.37
SK: 0.00
SK: 0.00
AV: 74.0 74.2
AV: 57.1 57.0
AV:***** *****
AV:***** *****
P +/- 5hPa
DD +/-30deg
FF +/- 3m/s
+/- 0m/s
SK: -5.90
SK: 0.95
SK: 0.26
AV: 99.9 99.9
AV: 65.0 65.3
AV: 92.7 92.7
AV: 0.0 0.0
SK: 0.00
FX > 12 m/s POD:___ FAR: ...
FX > 15 m/s POD:___ FAR: ...
FX > 20 m/s POD:___ FAR: ...
FX > 25 m/s POD:___ FAR: ...
AV: 54.0 53.1
SK: -2.07
AV: 35.9 35.2
SK: -1.15
AV: 9.5 7.8
SK: 0.41
AV:100.0 100.0
SK: 0.00
Hits Precipitation
SK: -1.55
AV: 88.0 87.8
HITS
FAR/POD
fct
Hits within the given thresholds
Hits for cloud covers and precipitation T-1 to T within the contingency tables
Thresholds of ontingency tables
cloud covers: 0-2, 3-6, 7+8/8
precipitation: 0.1, 2, 10 mm/1h
FAR (.....) and POD (---) for gusts
Results of verification of forecasts for local weather elements at surface stations
Percent correct whithin the given limits, percent correct for cloud cover and precipitation within contingency tables
All stations
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upper air verification of COSMO-DE L65 with new FW solver compared with Parallel-Routine COSMO-DE L50