A first comparison between the dynamical cores of COSMO and ICON

- Status of the COSMO priority project CDIC

COSMO user seminar
6-8 March 2017

Michael Baldauf (DWD), Rodica Dumitrache, Amalia Iriza (NMA)

with strong support from
Günther Zängl, Florian Prill, Daniel Reinert, Uli Schättler (DWD)

Aim of the COSMO priority project

‚Comparison of the dynamical cores of COSMO and ICON‘ (CDIC):

deliver an as objective as possible **comparison** of the **dynamical cores** of COSMO and ICON with the emphasis on **limited area modelling**.

- Task 1: idealised tests (main focus)
- Task 2: semi-realistic tests
- Task 3: scalability/performance on different platforms
- Task 4: Principal properties of the numerical formulation
- Task 5: Suitability for other applications (climate/chemistry)

Project Team (currently)
Michael Baldauf (DWD), project leader
Amalia Iriza (NMA)
Rodica Dumitrache (NMA)
Guy deMorsier (MeteoCH)
Damian Wojcik (IMGW)
Marina Shatunova (Roshydromet)
Denis Blinov (Roshydromet)

Task 1. Good performance on a standard set of idealized test cases

Defined test cases

1. Advection test with nonlinear dynamics *(Schär et al., 2002)*
2. Atmosphere at rest *(Zängl et. al (2004) MetZ)* 🛠
3. Cold bubble →unstationary density flow *(Straka et al., 1993)* 🛠
4. Mountain flow tests (stationary, orographic flows)
   - 4.1 *Schär et al. (2002), section 5b* ✓
   - 4.2 *Bonaventura (2000) JCP (selection)* ✓
   - 4.3 3D-case (dry) ✓
5. Linear Gravity waves *(Baldauf, Brdar, 2013)* ✓
6. Warm bubble *(Robert (1993), Giraldo (2008))* 🛠
7. Moist, warm bubble *(Weisman, Klemp, 1982)* 🛠
8. Advection tests for tracer schemes (solid body rotation, …) !

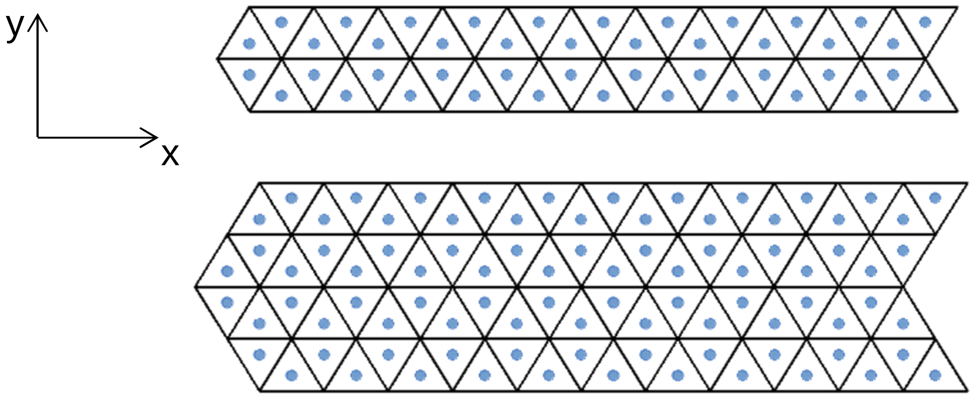
- All the tests use flat domains
- many of them are 2D slice (x-z) model tests
- and some of those use (double) periodic BCs → ***torus grid*** for ICON

Problems in ICON fixed:

- Interpolation to regular latlon-grid for output for a ‚torus-grid'
  (extension of subroutines `gc2cc`, `cc2gc`, thanks to *Florian Prill*)
- Choice of a torus grid (*L. Linardakis, MPI-M*)
  for 2D slice (x-z-) simulations:

first idea:

used now:



Test case 4.1: 2D linear flow over mountains

setup: *Schär et al. (2002)*

Orography: $$h(x) = h_0 \cdot e^{-x^2/b^2} \cdot \cos^2 \pi \frac{x}{\lambda}$$

h_0=25m, b=5km, λ=4km → Fr_h=40, Fr_a=0.1 … 0.5
u_0=10m/s, N=0.01 1/s, $T(z=0)$=288K

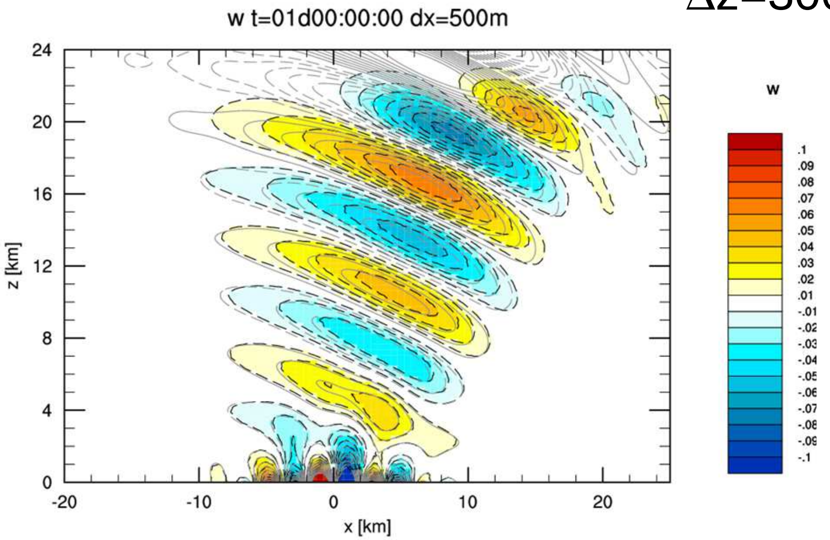
compare with analytic linear solution: *Baldauf, 2008, COSMO-NL*
(uses only a few further approximations, e.g. it is a fully compressible solution)

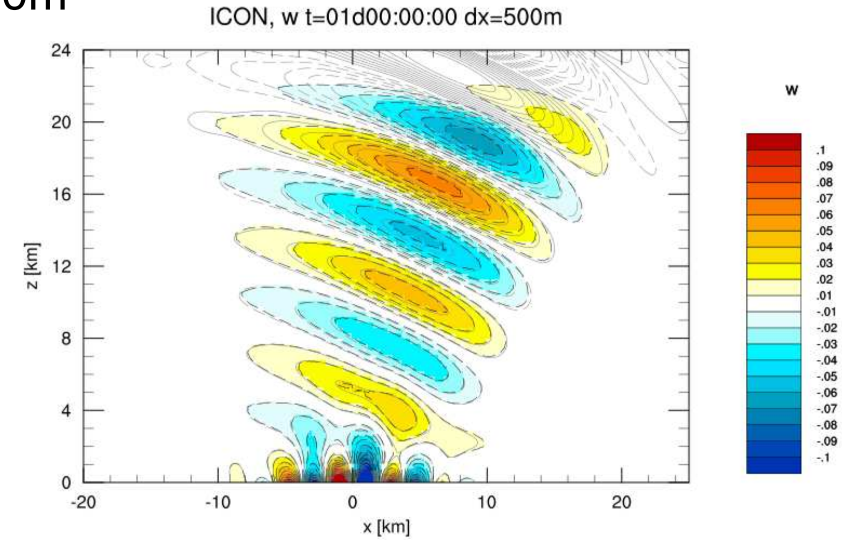
Test properties:

- test dry Euler equations without Coriolis terms
- stationary
- with orography → test also metric terms
- small amplitude → linear → comparison with analytic solution possible

Test case 4.1: 2D linear flow over mountains

COSMO | Δx=500m, Δz=300m | ICON





colors and black dotted lines: COSMO or ICON

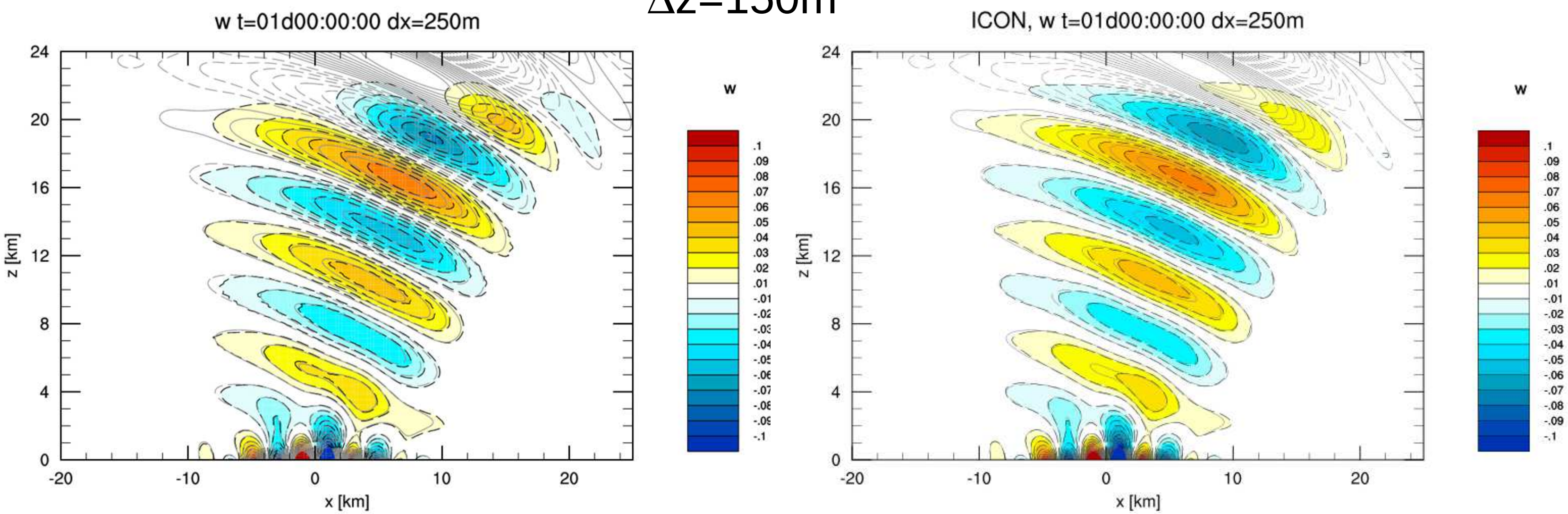
grey lines: analytic solution

vertically equidistant grid

Test case 4.1: 2D linear flow over mountains

COSMO Δx=250m ICON

Δz=150m



colors and black dotted lines: COSMO or ICON

grey lines: analytic solution

vertically equidistant grid

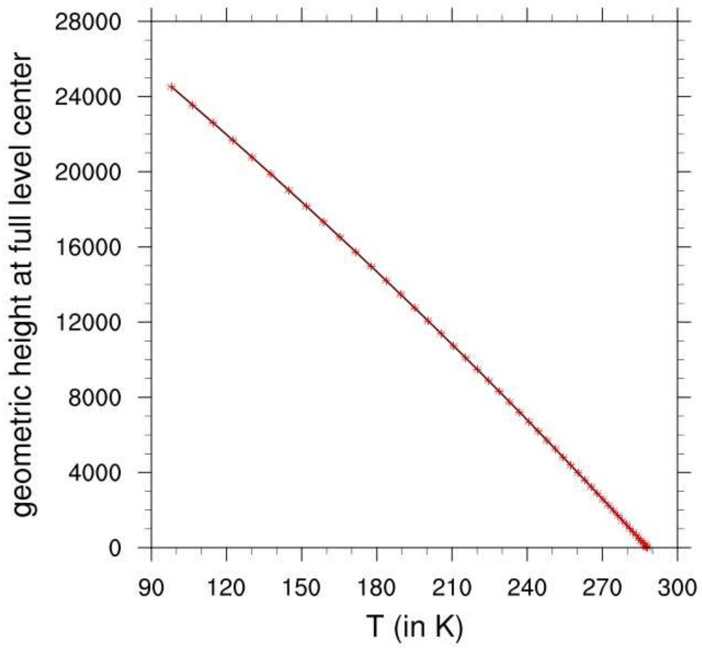
Test case 4.3a: 3D linear flow over mountains

$$h(x,y) = h_0 \; 2^{-\frac{x^2+y^2}{a^2}}$$

h_0=1 m, a=5000m
u_0=20 m/s
N=0.01 1/s
→ Fr_h =2000, Fr_a =0.4

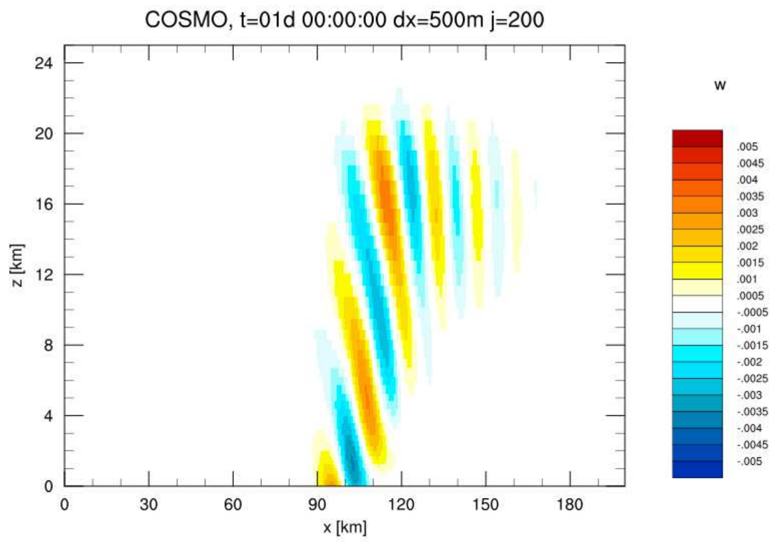
Δx=500m

vertically stretched grid:
Δz_{bottom} = 24.7m
Δz_{top} = 976 m

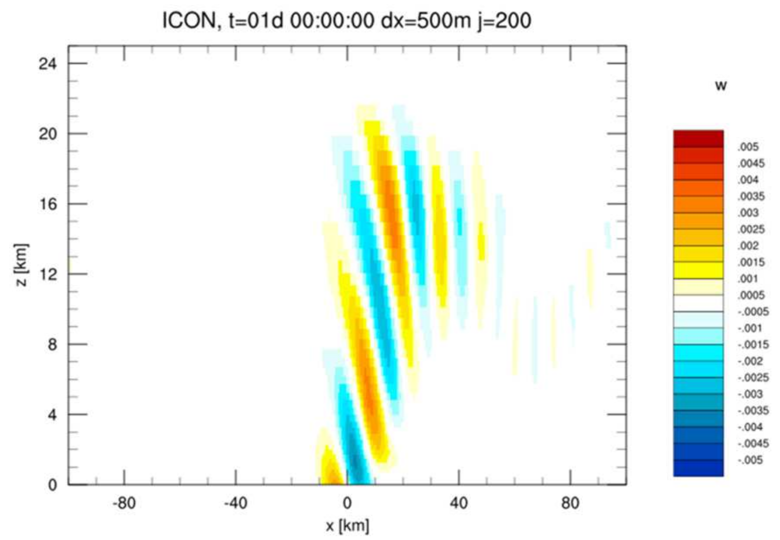


Test case 4.3a: 3D linear flow over mountains

comparable Rayleigh-damping (rdheight=14 km, 1-tanh fct.)
Htop=25 km, vcflat=13 km

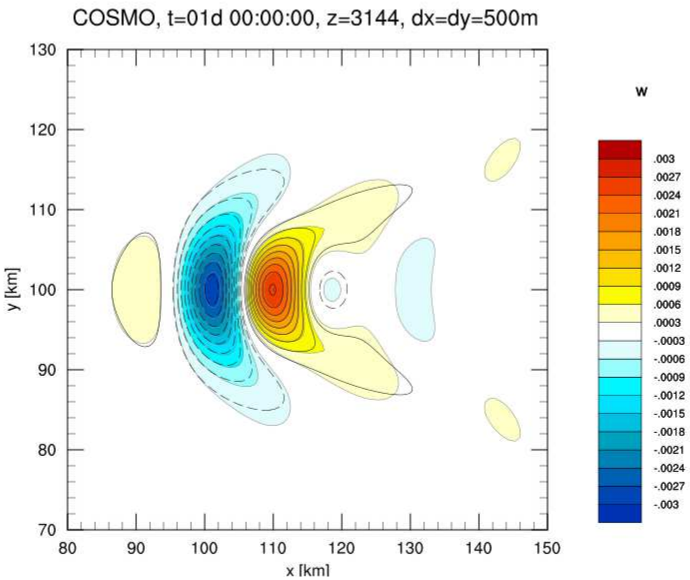


COSMO

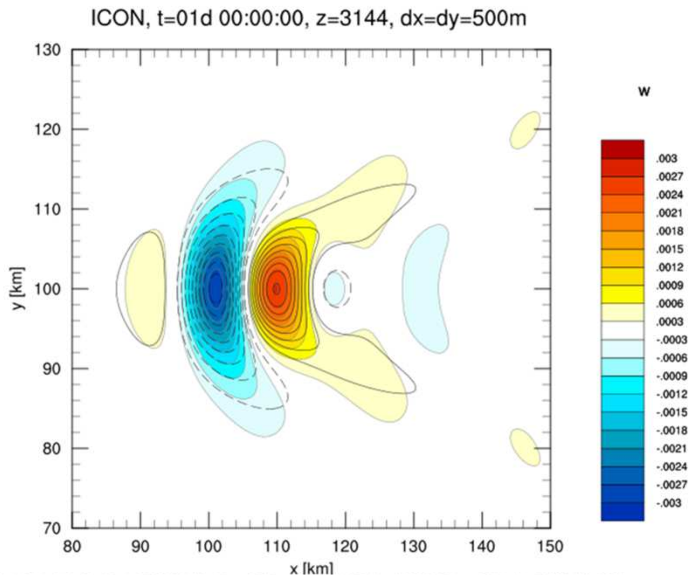


ICON

Test case 4.3a: 3D linear flow over mountains



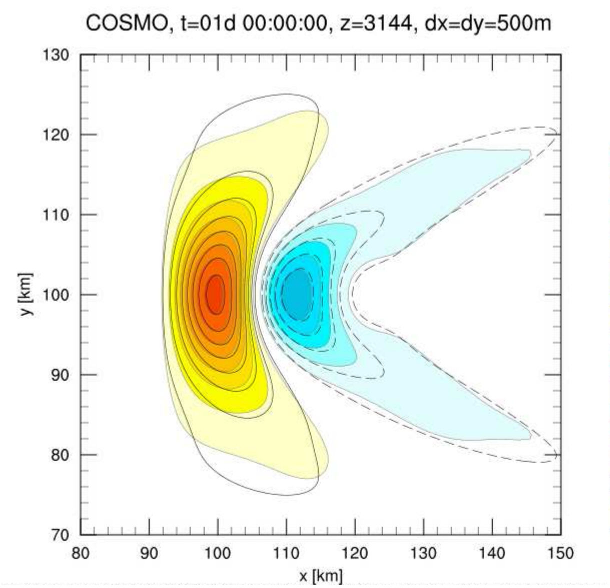
COSMO

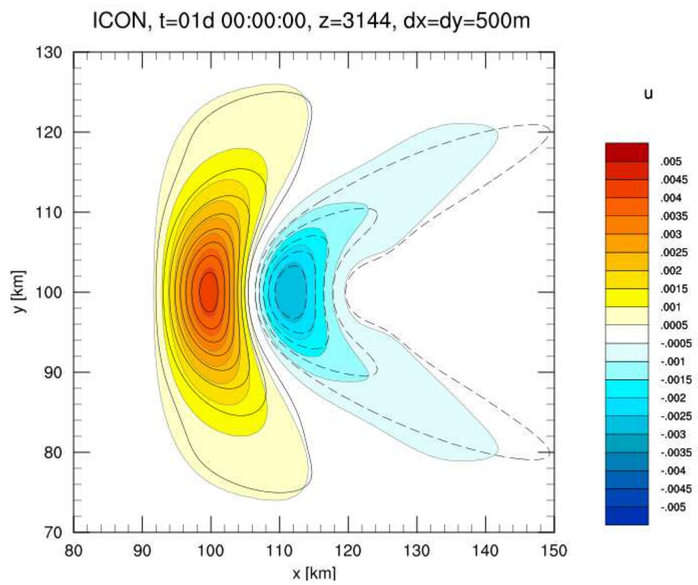


ICON

colors and grey lines : COSMO or ICON simulation
black lines: analytic solution

Test case 4.3a: 3D linear flow over mountains





COSMO ICON

colors and grey lines : COSMO or ICON simulation
black lines: analytic solution

Test case 4.3b: 3D nonlinear flow over mountains

$$h(x,y) = h_0 \; 2^{-\frac{x^2+y^2}{a^2}}$$

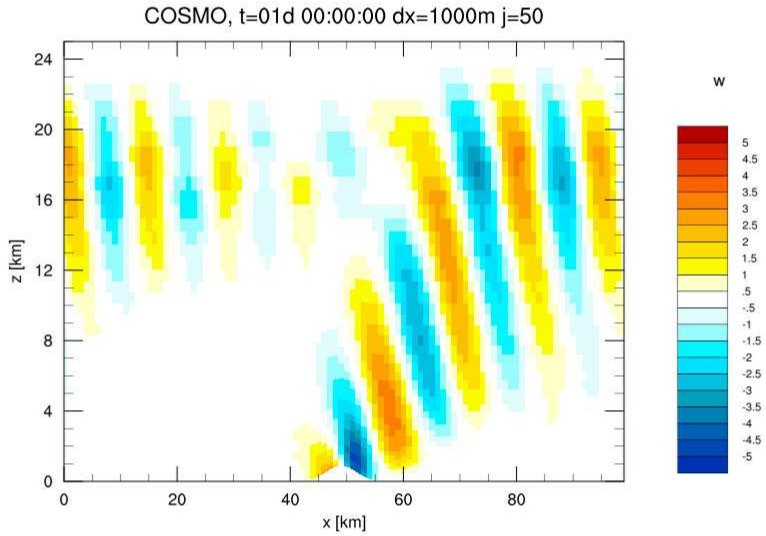
a=3000m
u_0=20 m/s, N=0.01 1/s
→ Fr_a =0.667

Δx=1000m

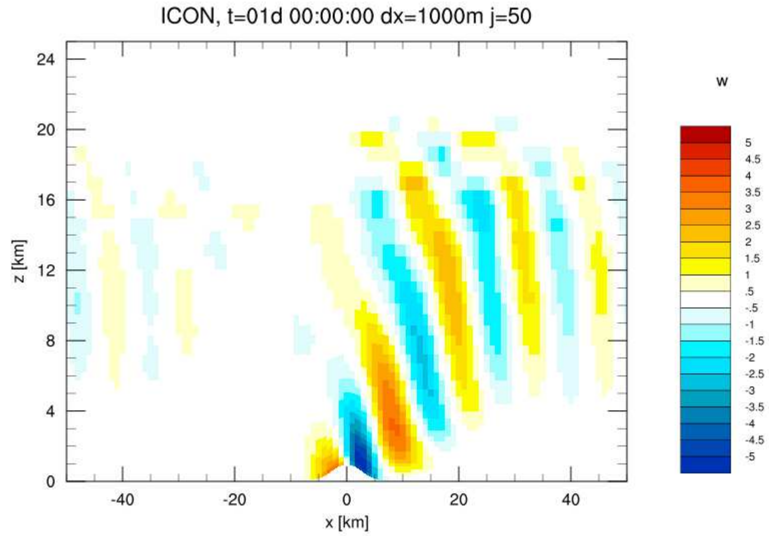
vertically stretched grid:
Δz_{bottom} = 24.7m
Δz_{top} = 976 m
(same as for linear 3D test)

Test case 4.3b: 3D nonlinear flow over mountains

COSMO



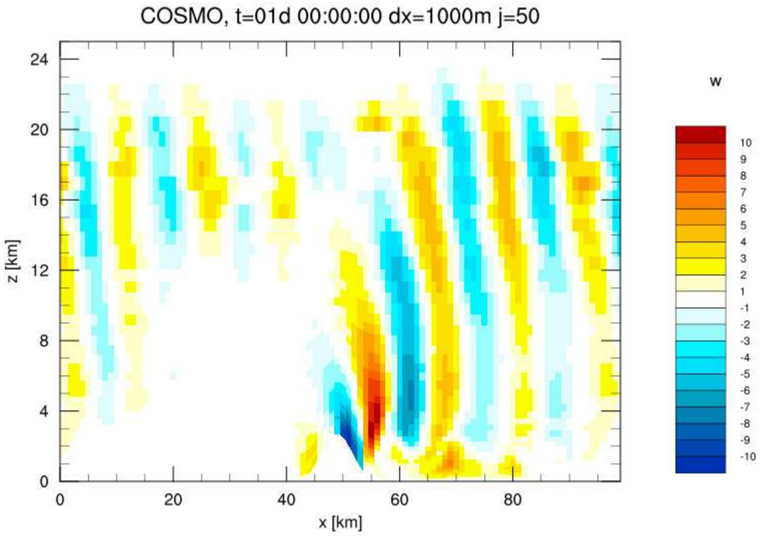
ICON



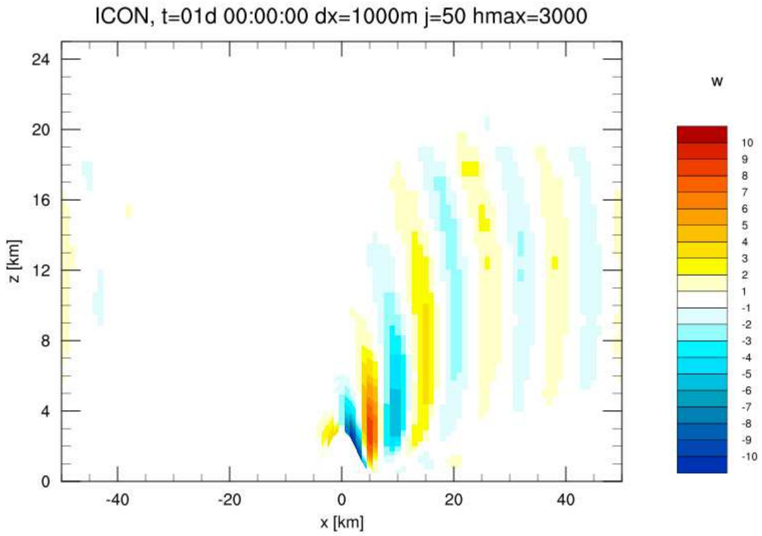
h_0=1000m → max Δh = 234.9m → max α = 13.2°

Test case 4.3b: 3D nonlinear flow over mountains

COSMO



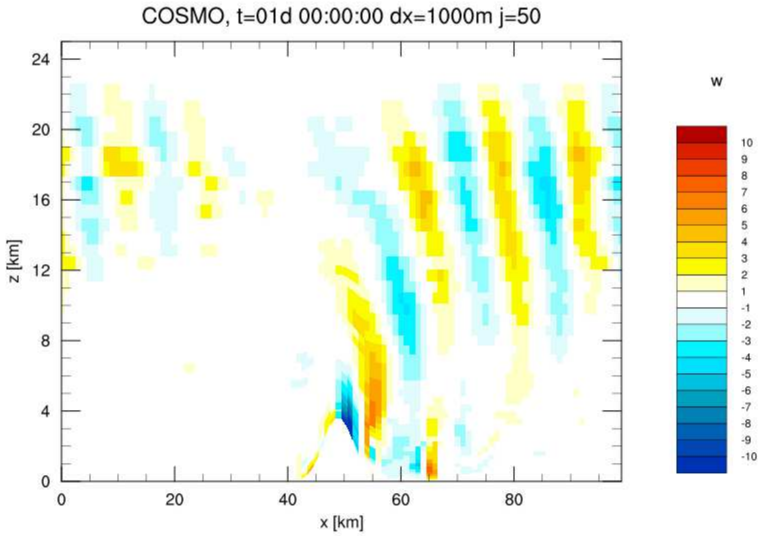
ICON



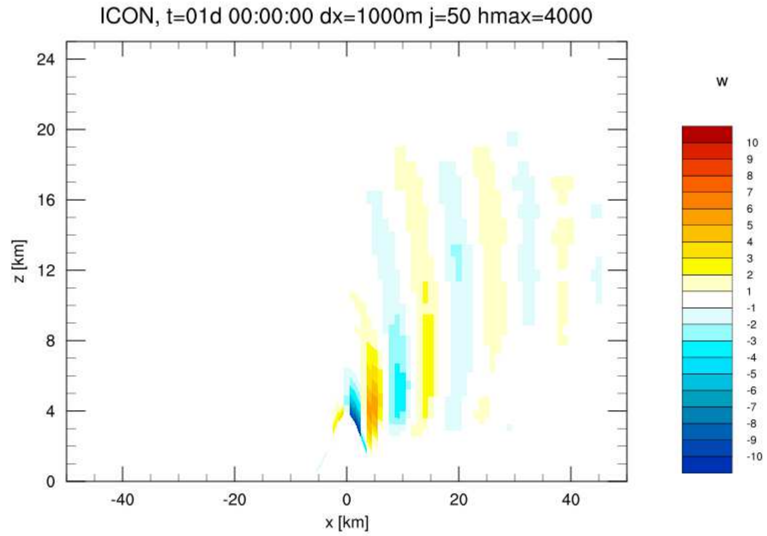
h_0=3000m → max Δh = 704.7m → max α = 35.2°

Test case 4.3b: 3D nonlinear flow over mountains

COSMO



ICON



stable only with Mahrer-discretization

h_0=4000m → max Δh = 939.6m → max α = 43.2°

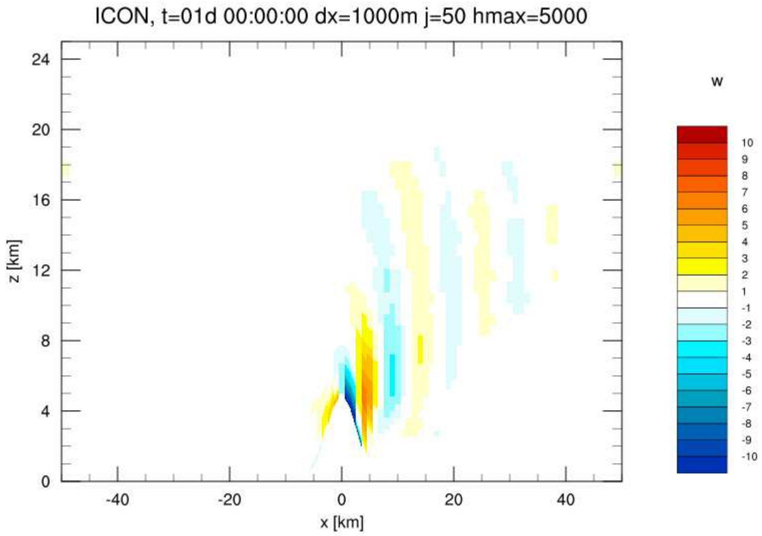
Test case 4.3b: 3D nonlinear flow over mountains

COSMO

ICON

COSMO: unstable

stable until h_0=4600m
max Δh = 1080m → max α = 47.2°



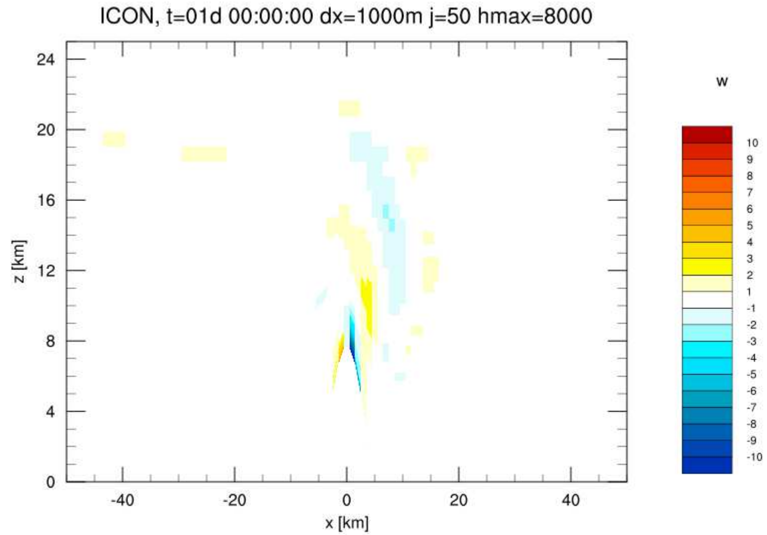
h_0=5000m → max Δh = 1174m → max α = 49.6°

Test case 4.3b: 3D nonlinear flow over mountains

COSMO

COSMO: unstable

ICON



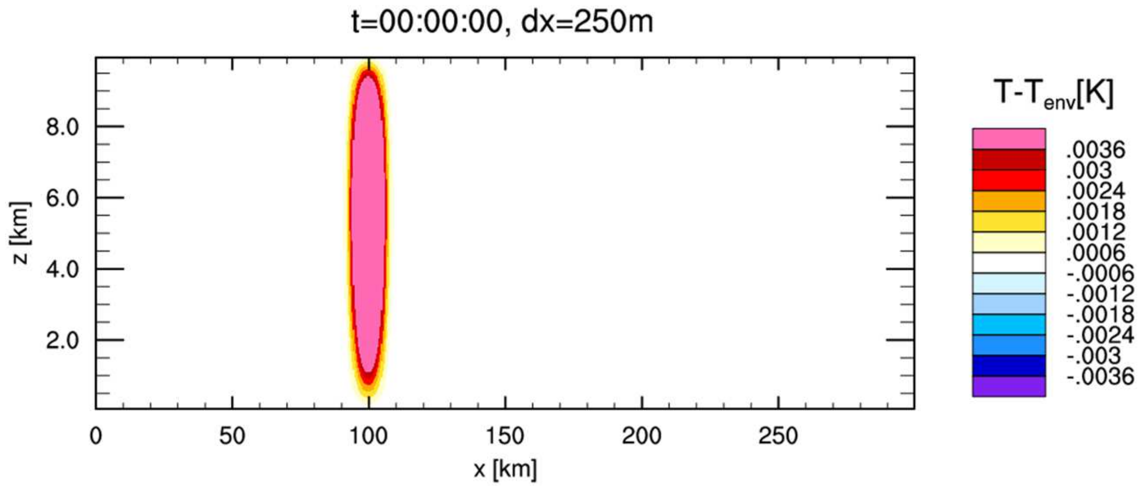
h_0=8000m → max Δh = 1879m → max α = 62.0°

Summary for flow over mountains test

- In the Schär et al. 2D linear mountain flow test both models COSMO and ICON behave quite similar; with slight advantages for ICON.
- Also in the 3D linear test the analytic solution is very well simulated
  → metric terms are correctly implemented in both models
  (no clear winner)
- ICON tolerates much steeper slopes than COSMO
  (*Zängl (2012) MWR*)
- The high mountain tests should be repeated with ‚non-periodic BCs‘ to prevent from increasing blocking effects

Test case 5: Linear gravity waves

setup similar to *Skamarock, Klemp (1994) MWR*



An analytic solution for the **compressible non-hydrostatic** Euler equations is given in *Baldauf, Brdar (2013) QJRMS*

Test properties:

- test dry Euler equations
- unstationary
  → inspect time integr.
- no orography
- small amplitude
  → linear → comparison with analytic solution

Initialization similar to
Skamarock, Klemp (1994)

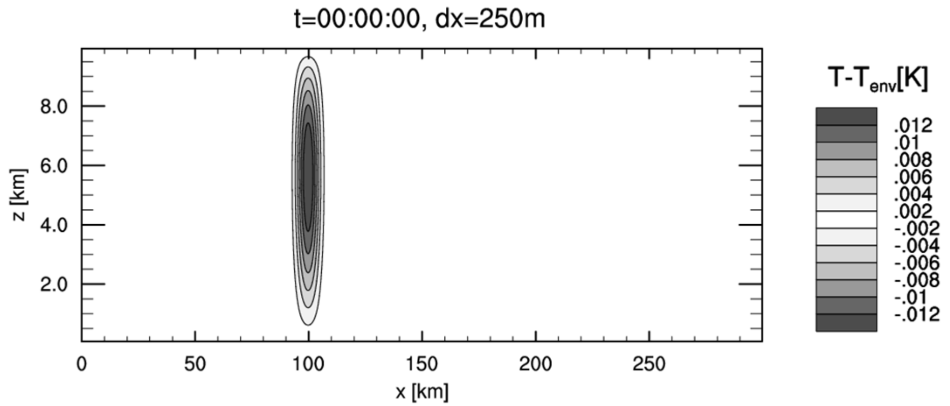
$$T'(x,z,t=0) = \Delta T \cdot e^{\frac{1}{2}\delta z} \cdot e^{-\frac{(x-x_c)^2}{d^2}} \cdot \sin \pi \frac{z}{H}$$

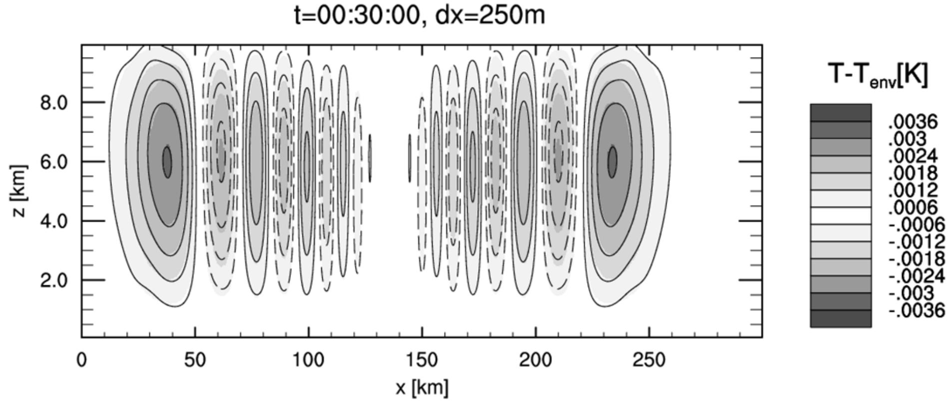
$$p'(x,z,t=0) = 0$$

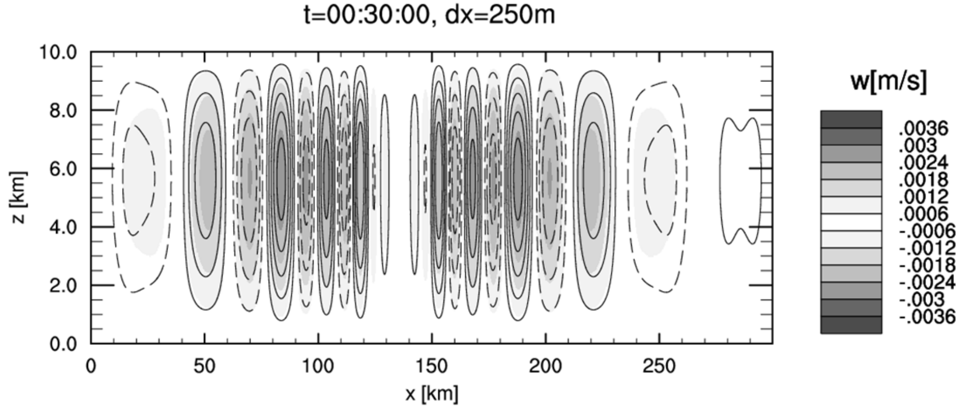
Small scale test
with a basic flow U_0=20 m/s, f=0

Black lines: analytic solution
(Baldauf, Brdar (2013) QJRMS)

Shaded: COSMO







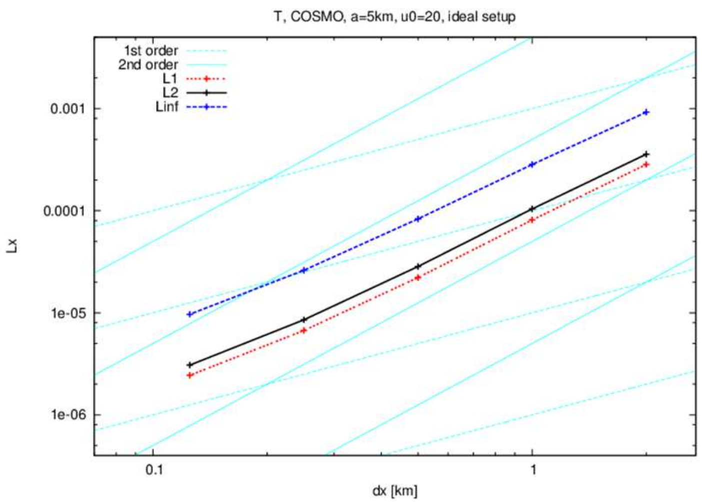
Convergence behaviour

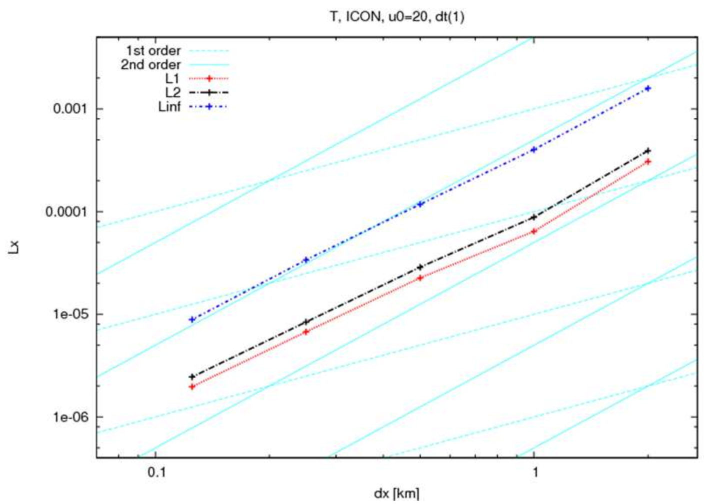
Deutscher Wetterdienst
Wetter und Klima aus einer Hand

COSMO

ICON

T‘

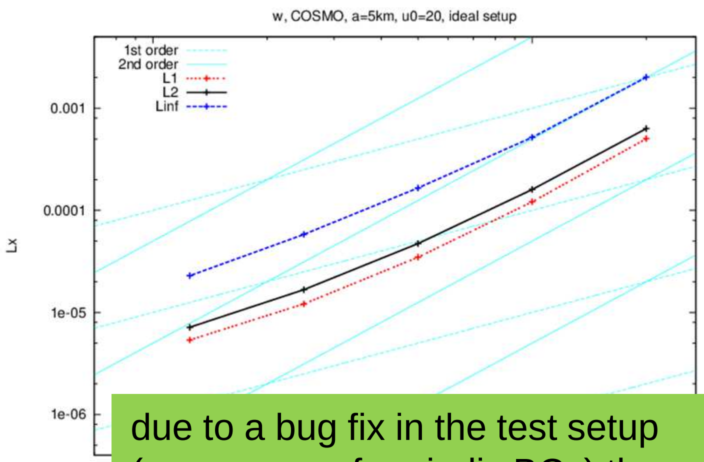


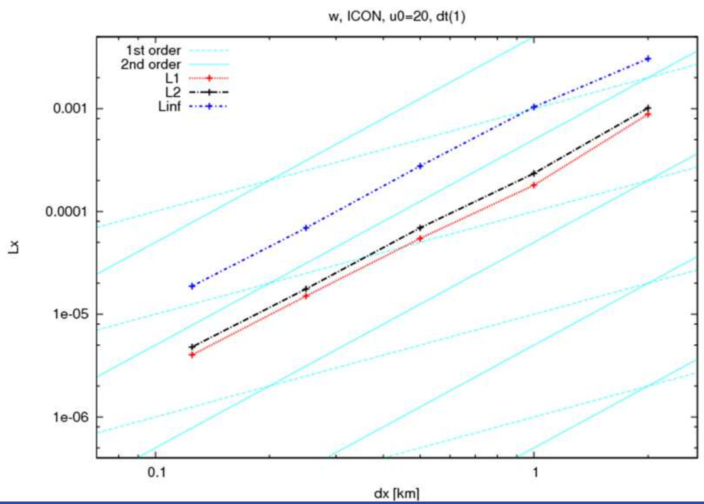


2nd order

1st order

w



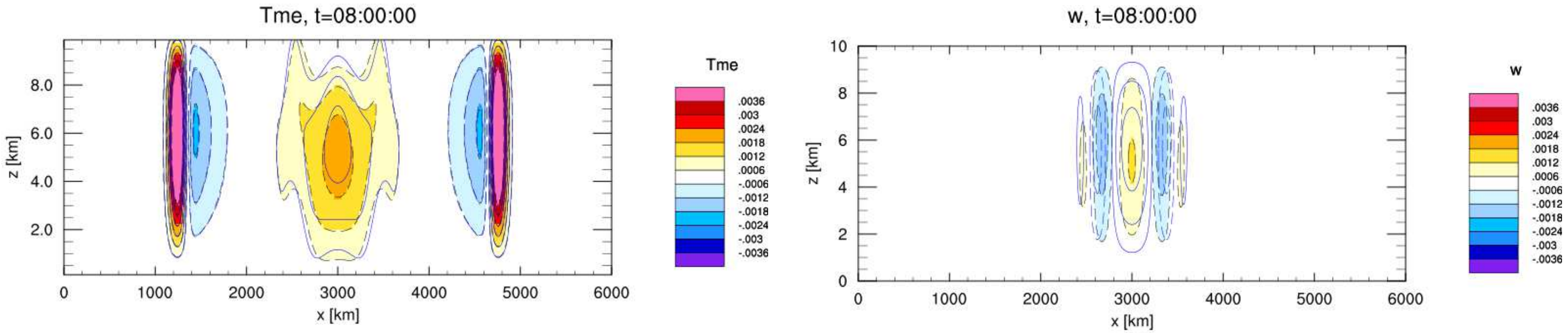


due to a bug fix in the test setup (proper use of periodic BCs) the COSMO result is now better than that described in *BB2013*

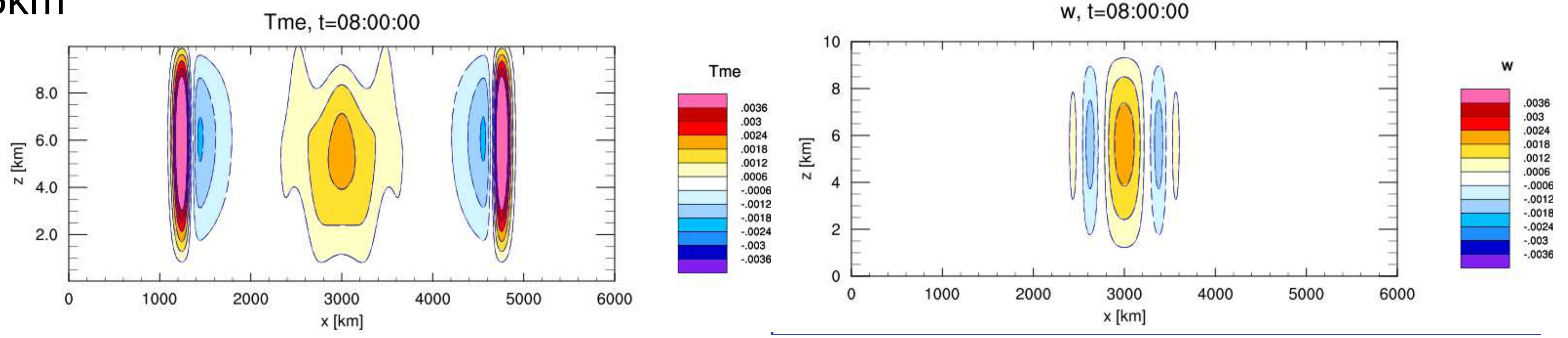
Large scale test without advection but with Coriolis force

colors and black dotted lines: ICON, blue lines: analytic solution

dx=10km



dx=2.5km

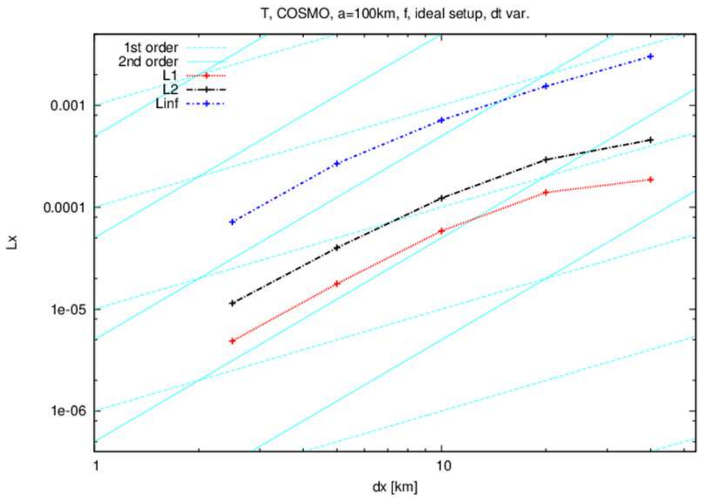


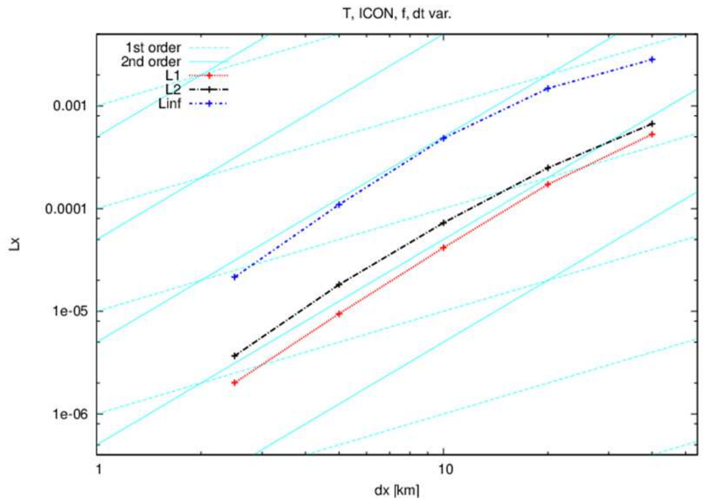
Convergence behaviour

COSMO

ICON

T'

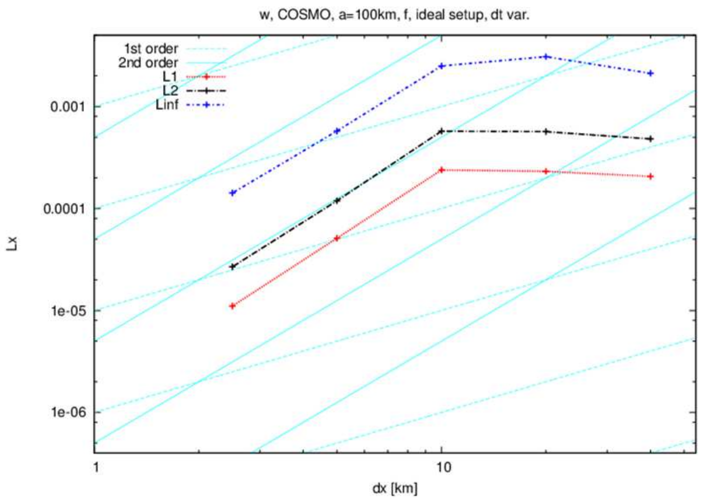


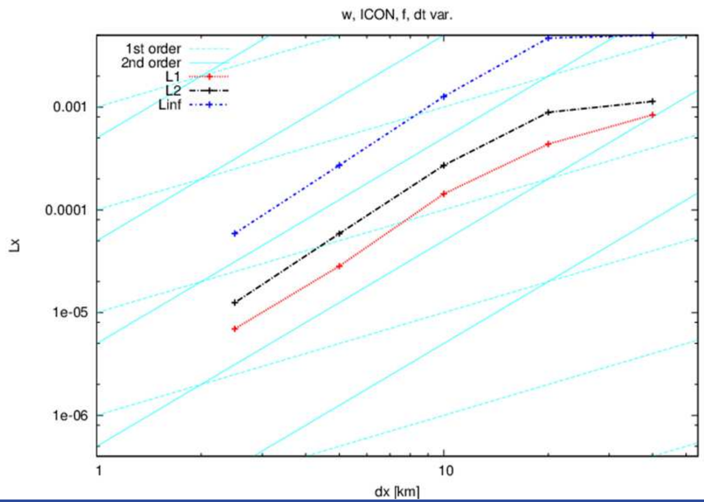


2nd order

1st order

w





Summary for the linear wave test

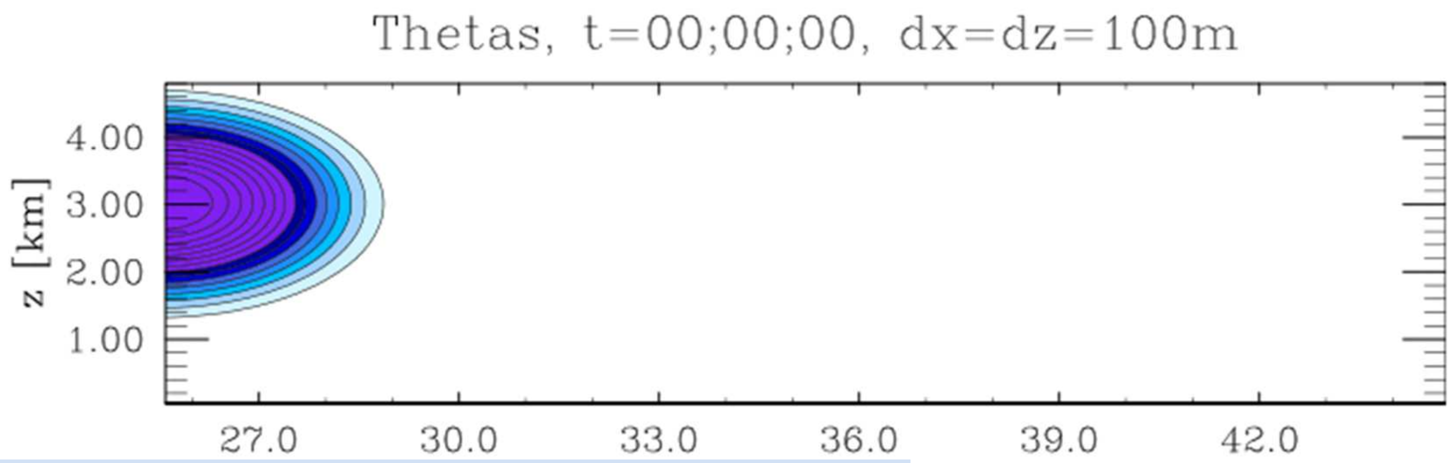
- Test 1 (only fast waves):
  ICON shows nearly 2nd order convergence
  COSMO shows nearly 2nd order only in T, but less in w
  → w error is smaller in ICON for fine resolutions
- Test 2 (FW + advection):
  ICON behaviour is similar to test 1.
  COSMO convergence order is slightly reduced
  for coarse resolutions ICON errors are a bit larger than in COSMO,
  for fine resolutions a bit smaller
- Test 3 (FW + Coriolis):
  both models show 2nd order convergence;
  but the errors are smaller in ICON

Remark: to get 2nd order, one needs to switch off any vertical off-centering

Test case 3: cold bubble

R. Dumitrache, A. Iriza (NMA)

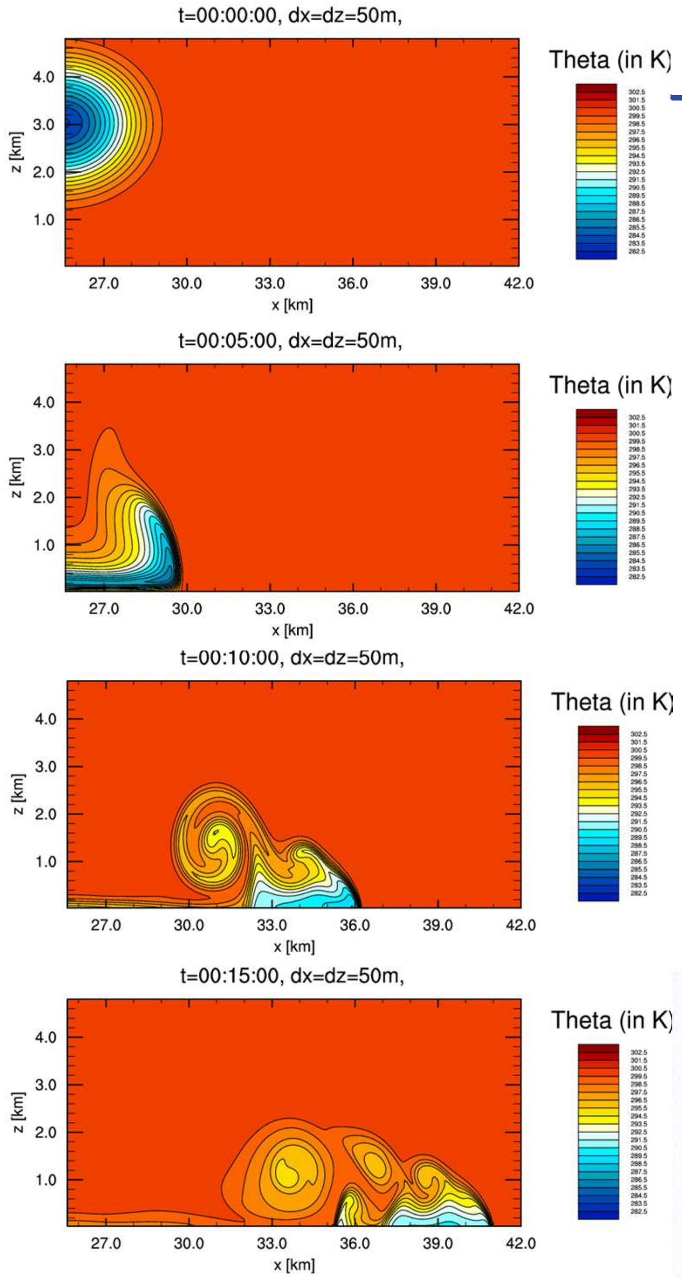
Testsetup by *Straka et al (1993)*



Test properties:

- test of dry Euler equations (without Coriolis force)
- unstationary
- strongly nonlinear
- comparison with reference solution from paper

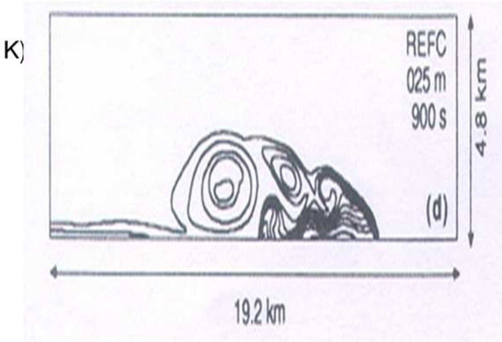
COSMO

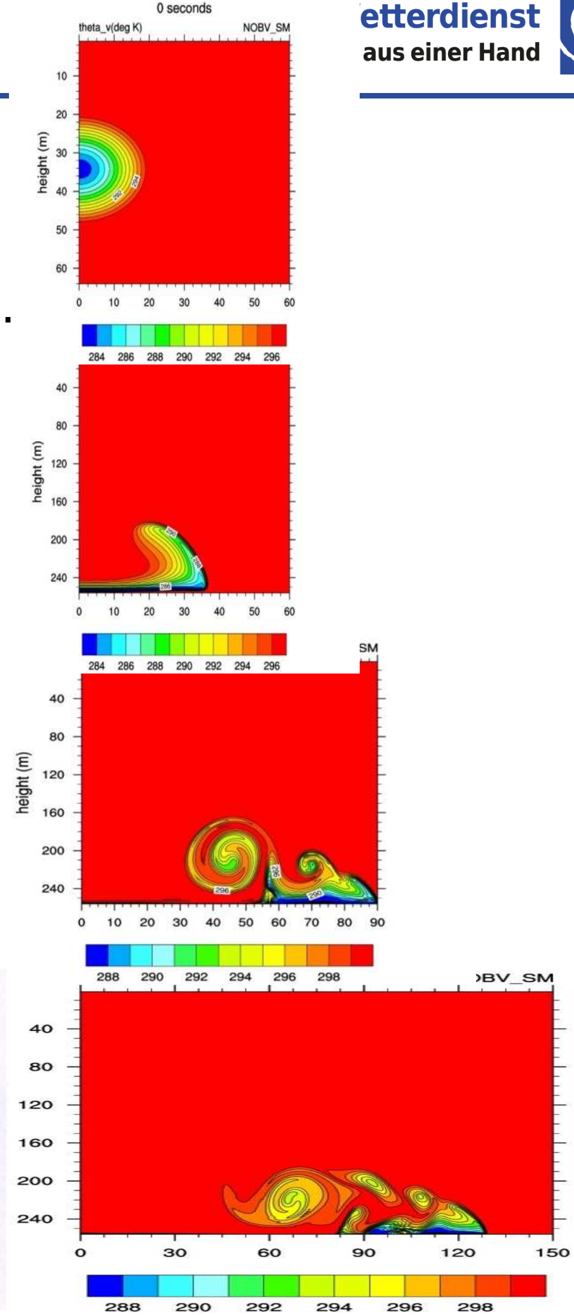


ICON

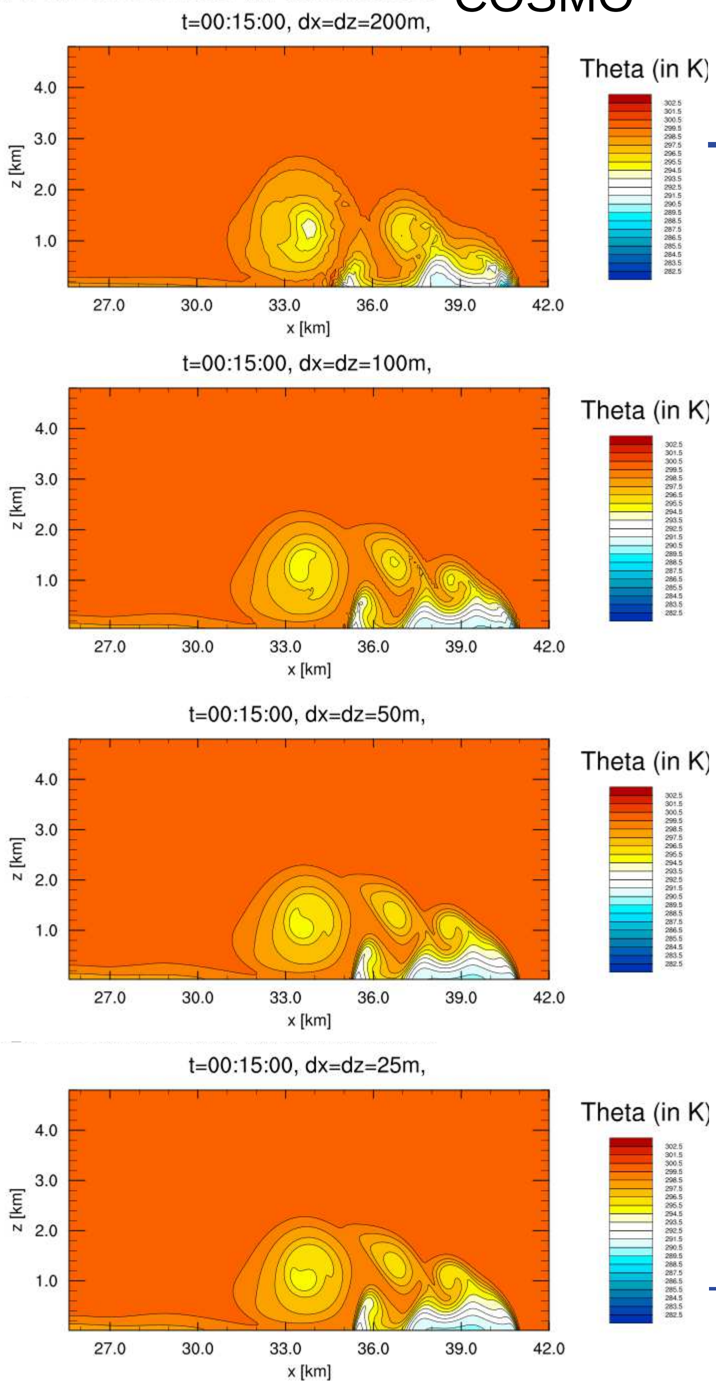
θ at t=0, 5, 10, 15 min.

Reference solution from Straka et al.:



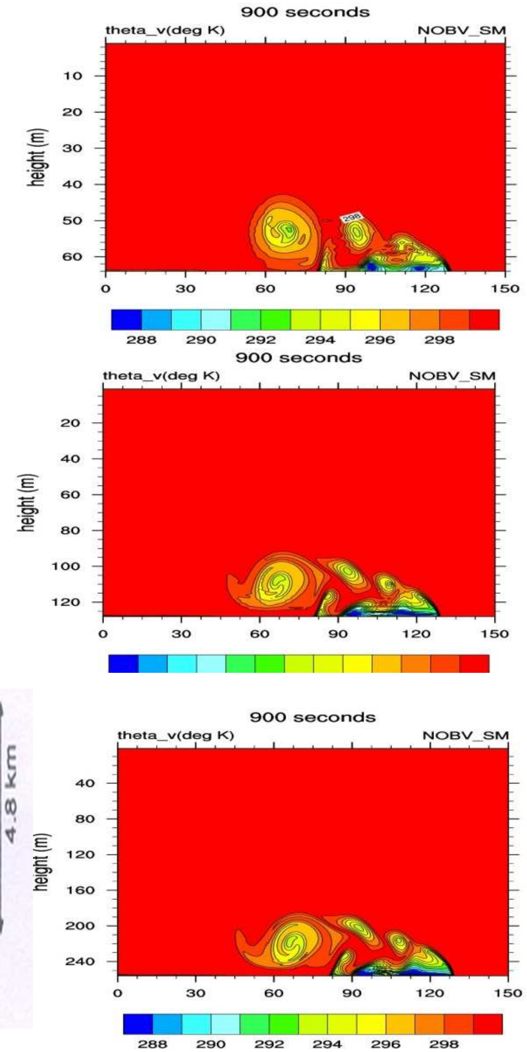


COSMO

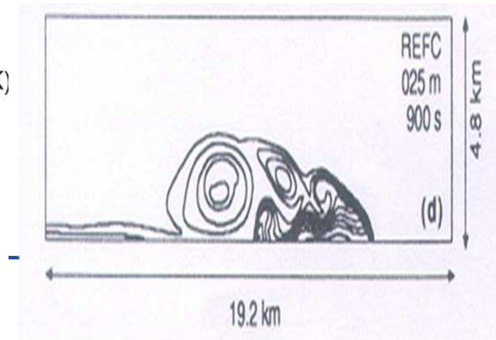


θ at t=15 min.
for Δx= 200, 100, 50, 25m

ICON



Reference solution from Straka et al.:



Summary for the cold bubble test

- COSMO agrees almost perfect with the reference solution of *Straka et al. (1993)*
- In ICON there still might be a problem with the correct diffusion setup (K=const. is necessary for this test) ToDo!

Overall conclusions

- Most of the planned idealised tests have been inspected,
  several of these tests have been finished
- In general no detrimental effects of ICON visible so far (in the contrary!)
- However, the question remains
  „what is a fair comparison"?
  E.g. quadrilateral vs. triangle grid, ...: what is the ‚right' resolution?
  Probably the best is to compare
  „error as fct. of model run time" (on the same computer)
  (but this needs some extra considerations for 2D slice tests)

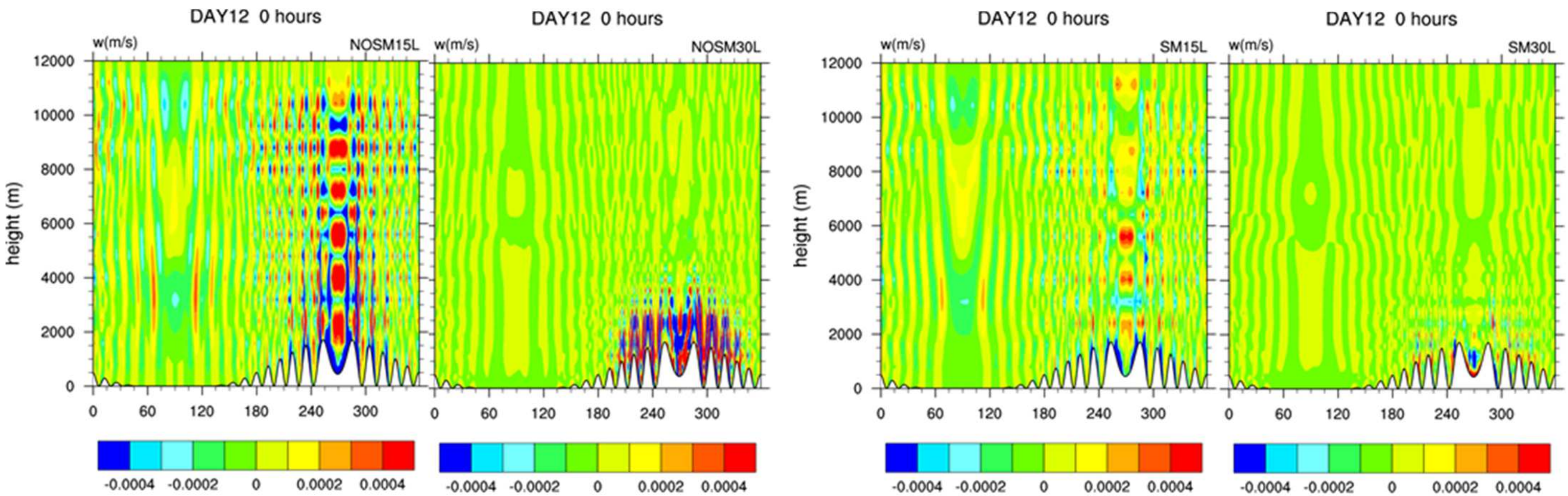
<u>Test case 2: atmosphere at rest</u>

R. Dumitrache, A. Iriza (NMA)

global model ICON with dx ~80 km, mountains at equator.
w after 12 days for 15 or 30 vertical levels (equidistant) and with or without Smagorinski-diffusion

Test properties:

- dry Euler equations
- test of well-balancing
- reference solution trivial



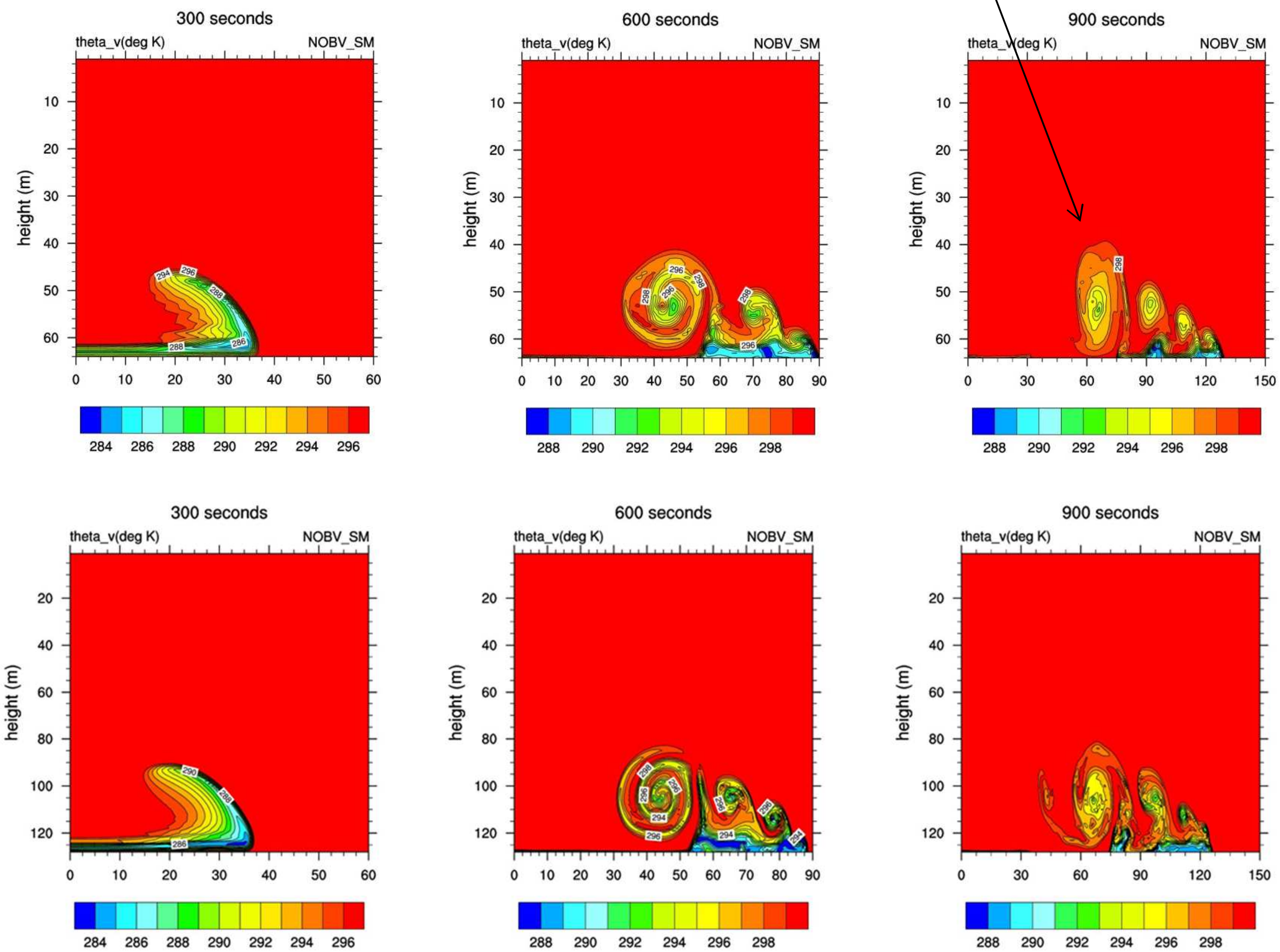
Test setup 2:
small scale test with advection (U_0=20 m/s) and without Coriolis force

In COSMO: divergence damping is necessary

Inspect resolutions:	2km,	1km,	500m,	250m,	125m
dt (COSMO)	10s,	5s,	2.5s,	1.25s,	0.625s
dt (ICON)	6s,	3s,	1.5s,	0.75s,	0.375s

In the following convergence study compare:
COSMO: dx=grid mesh size, dt_small = dt/6
ICON: dx=length of triangle edge, dt_small = dt/5
for an equilateral triangle √A=dx * 0.658…

physical 3D diffusion is still missing!



dx=100m
dt=0.5

dx=50m
dt=0.25

Task 1. Good performance on a standard set of idealized test cases

Defined test cases

1.	Advection test with nonlinear dynamics *(Schär et al., 2002)*	NN	
2.	Atmosphere at rest *(Zängl et. al (2004) MetZ)*	Barbu/Dumitrache/Iriza	🛠
3.	Cold bubble →unstationary density flow *(Straka et al. (1993))*	Barbu/Dumitrache/Iriza	🛠
4.	Mountain flow tests (stationary, orographic flows)		
4.1	*Schär et al. (2002), section 5b*	Baldauf	✓
4.2	*Bonaventura (2000) JCP*	“	✓
4.3	3D-case (dry)	“	✓
5.	Linear Gravity waves *(Baldauf, Brdar, 2013)*	Baldauf	✓
6.	Warm bubble *(Robert (1993), Giraldo (2008))*	Wojcik	!
7.	Moist, warm bubble: *(Weisman, Klemp, 1982)*	Wojcik	🛠
8.	Advection tests for tracer schemes (solid body rotation, …)	Will (without FTE)	!