Review about the current dynamical core developments in the COSMO model/consortium

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COSMO Priority Project:
Comparison of the dynamical cores of ICON and COSMO (CDIC)

Time range: Sept. 2015 - Sept. 2017
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

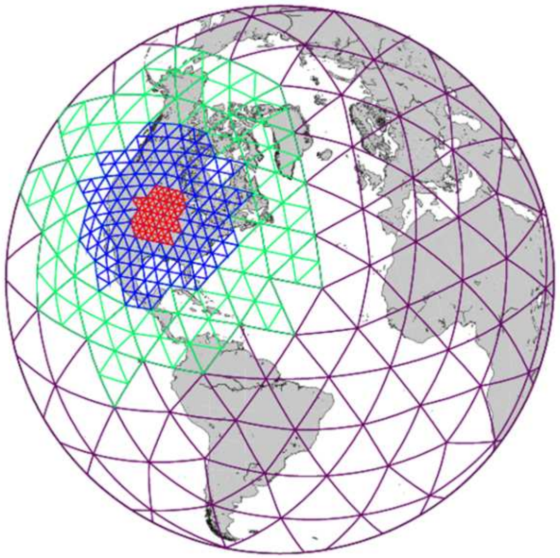
Max-Planck-Institut für Meteorologie

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

DWD

The ICOsahedral Nonhydrostatic (ICON) modelling framework

- ➔ Joint development project of **DWD** and **Max-Planck-Institute for Meteorology** for the next-generation global NWP and climate modeling system
- ➔ **Nonhydrostatic**, **compressible** dynamical core on an **icosahedral-triangular C-grid**; coupled with full set of physics parameterizations for NWP
- ➔ Better **conservation** properties (air mass, mass of trace gases and moisture, consistent transport of tracers)
- ➔ **Two-way nesting** with capability for multiple nests per nesting level; vertical nesting, one-way nesting mode and **limited-area mode** are also available (to replace both the former global model GME and the regional model setup COSMO-EU (7km) at DWD)
- ➔ **Scalability** and efficiency on massively parallel computers
- ➔ in operational use at DWD since Jan. 2015



Properties of the dynamical cores:

	COSMO	ICON
horizontal grid	rectangular (lat-lon) C-staggering	triangle (Icosaeder) C-staggering
prognostic variables	u, v, w, p', T'	$v_n, w, \rho, \rho\Theta_v$ or Π
time integration	2 TLs, HE-VI, split-explicit Runge-Kutta stage 3	2 TLs, HE-VI, Predictor-Corrector (not split-explicit)
spatial discr. fast waves	centered differences 2nd order	finite volume / centered differences, 2nd order
advection of dynamic variables	5th order	2nd/ 3rd order
advection of tracers	Bott FV scheme SL 3rd order (optional)	horiz.: Miura-2nd order vert.: PPM
artificial damping	divergence damping, 4th order hyperdiffus. for velocity	4th order divergence damping

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

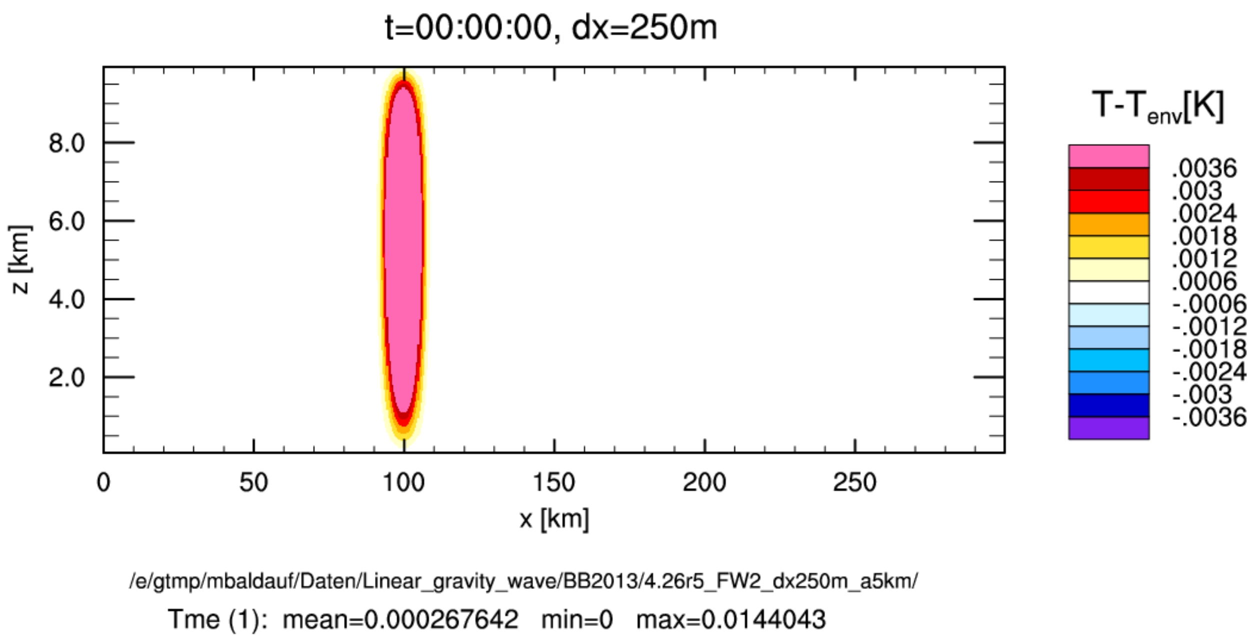
1.	Advection test with nonlinear dynamics (Schär et al. (2002))	NN
2.	Atmosphere at rest (Zängl et. al (2004) MetZ)	Barbu/Dumitrache/Iriza
3.	Cold bubble (Straka et al. (1993)) (unstationary density flow)	Barbu/Dumitrache/Iriza
4.	Mountain flow tests (stationary, orographic flows)	
4.1	Schaer et al.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

Overall assessment:
test cases are a bit behind schedule ← to get familiar with ICON is more difficult compared to COSMO mainly due to the unstructured grid (both code complexity and use of external grid files)

Test case 5: Linear gravity waves

test defined in *Baldauf, Brdar (2013) QJRMS*

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



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

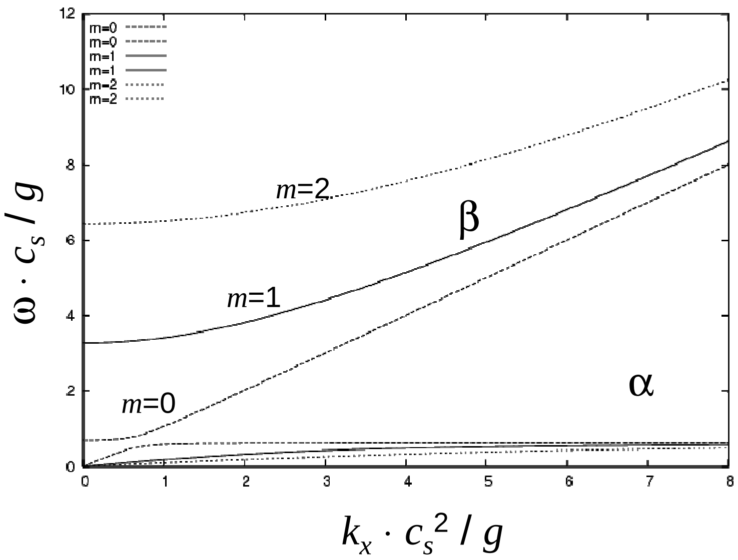
Derivation of an analytic solution for the non-hydrostatic, compressible 2D Euler equations in a flat channel on an f-plane

Bretherton-, Fourier- and Laplace-Transformation →
Analytic solution 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, respectively, of the dispersion relation for compressible waves in a channel with height H;
$k_z = (\pi / H) \cdot m$



Baldauf, Brdar (2013) QJRMS

Initialization similar to
Skamarock, Klemp (1994)

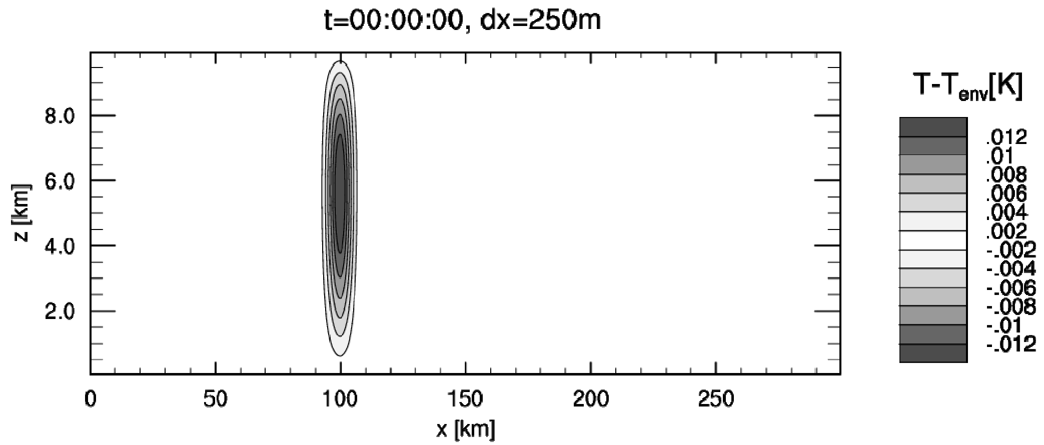
$$T'(x,z,t=0) = \Delta T \cdot e^{\frac{1}{2}\delta z} \cdot e^{-\frac{(x-x_c)^2}{d^2}} \cdot \sin \pi \frac{z}{H}$$

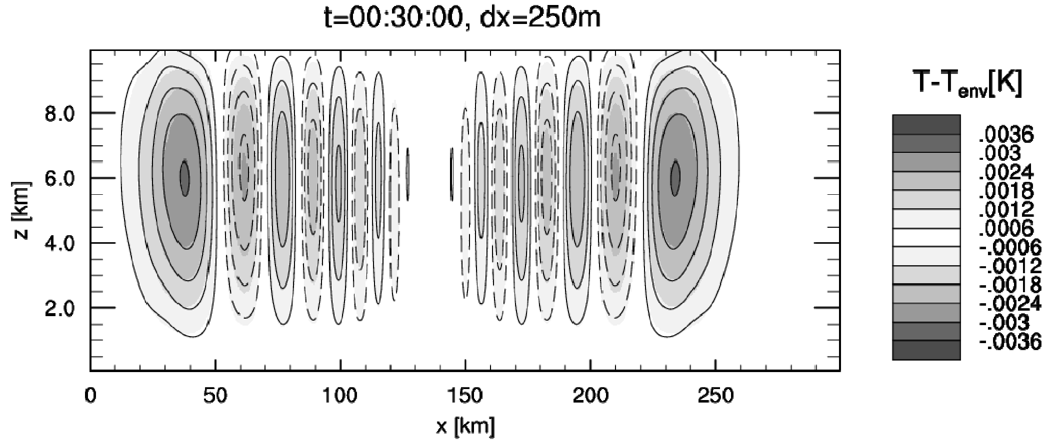
$$p'(x,z,t=0) = 0$$

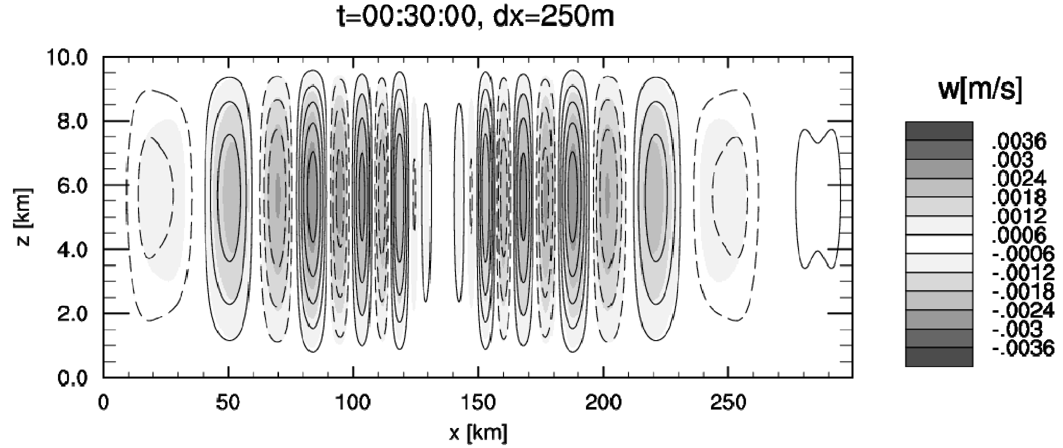
Small scale test
with a basic flow U_0=20 m/s
f=0

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

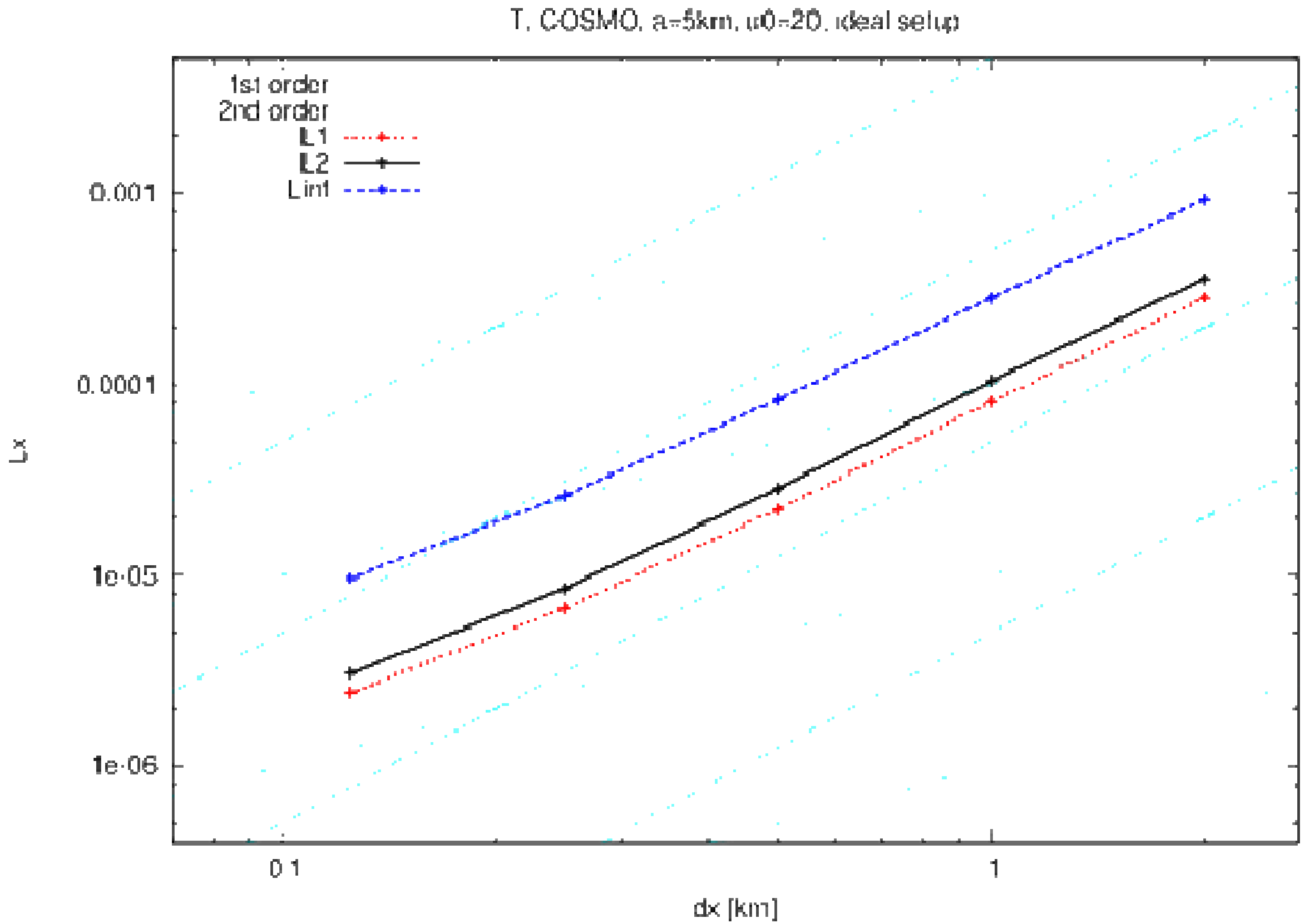
Shaded: COSMO



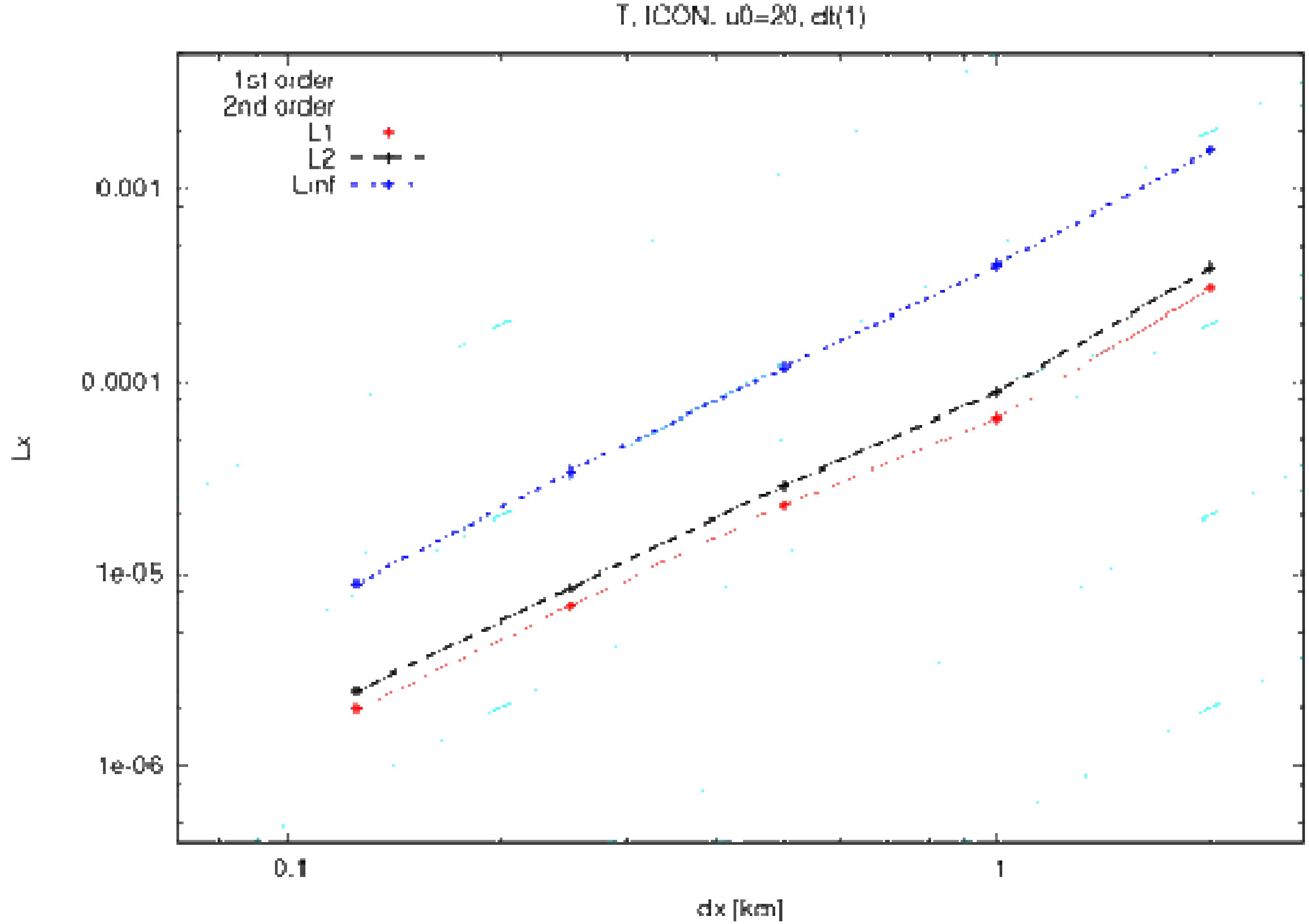




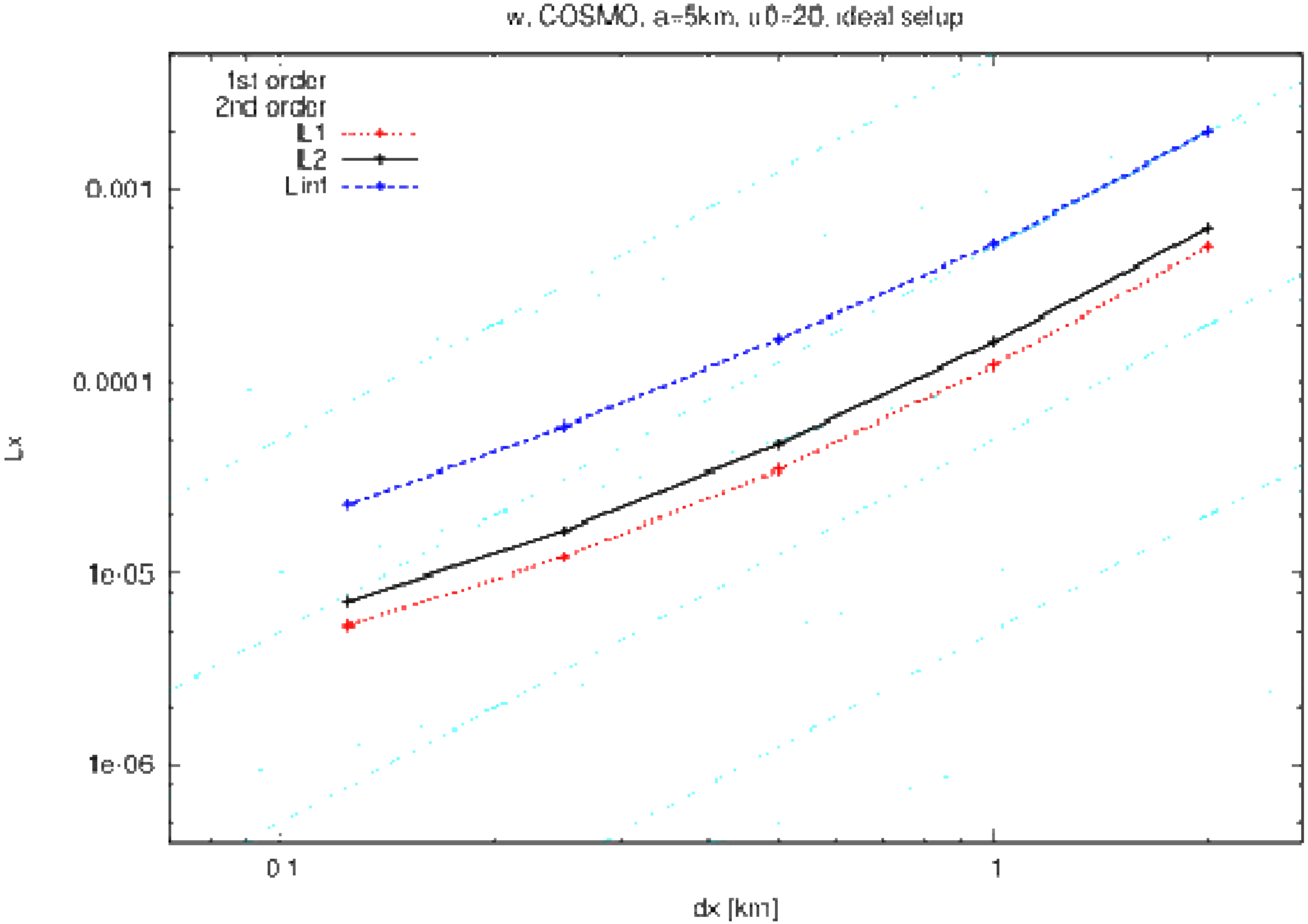
small scale test; convergence measures for T; COSMO



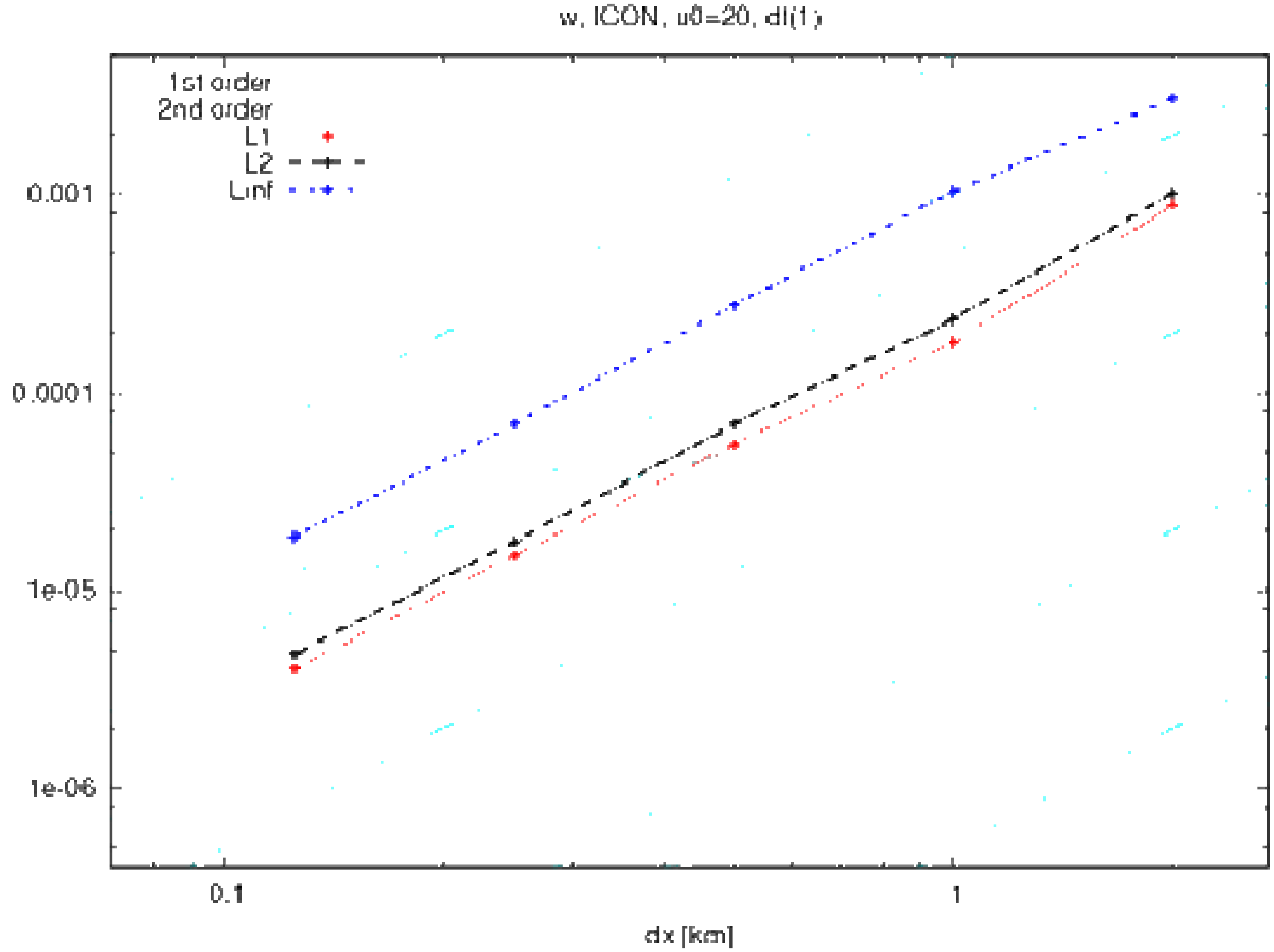
small scale test; convergence measures for T; ICON



small scale test; convergence measures for w; COSMO



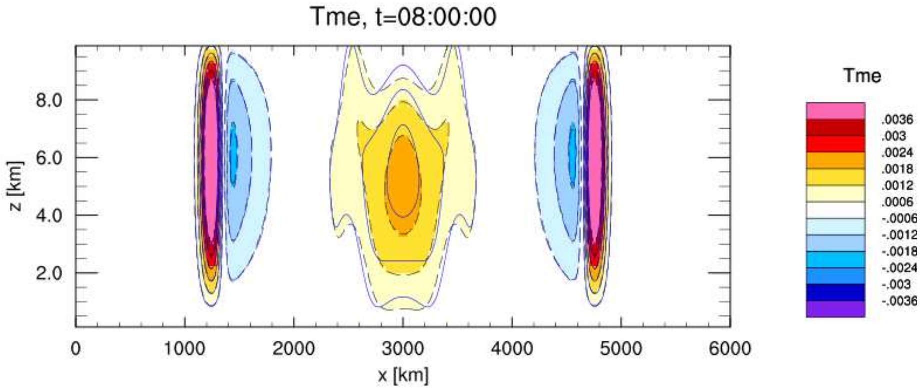
small scale test; convergence measures for w; ICON

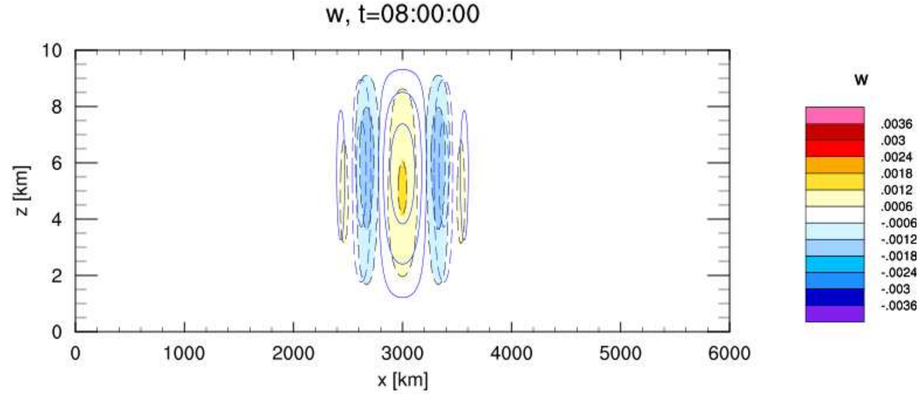


Large scale test without advection but with Coriolis force

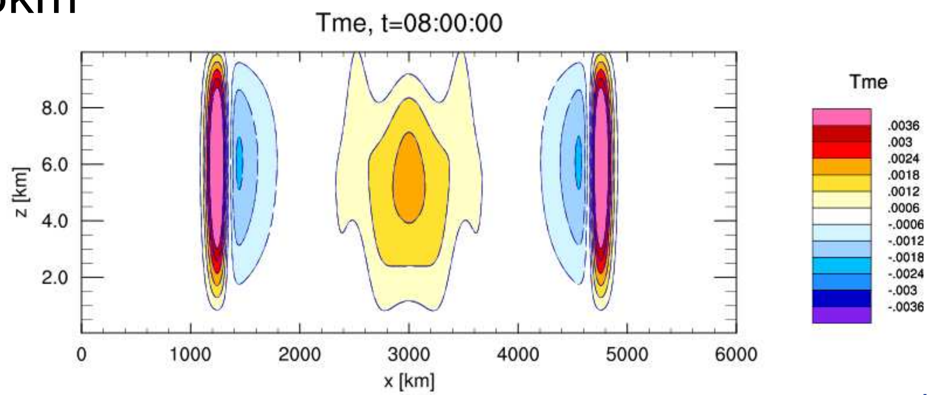
ICON results: (colors and black dotted lines: ICON, blue lines: analytic sol.)

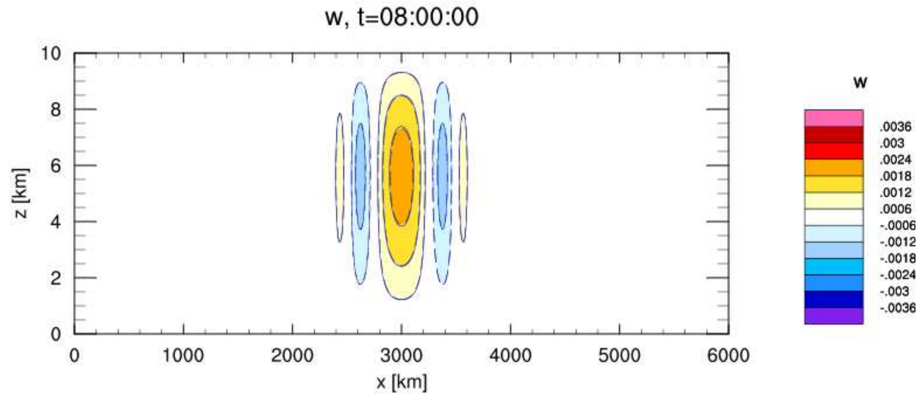
dx=10km



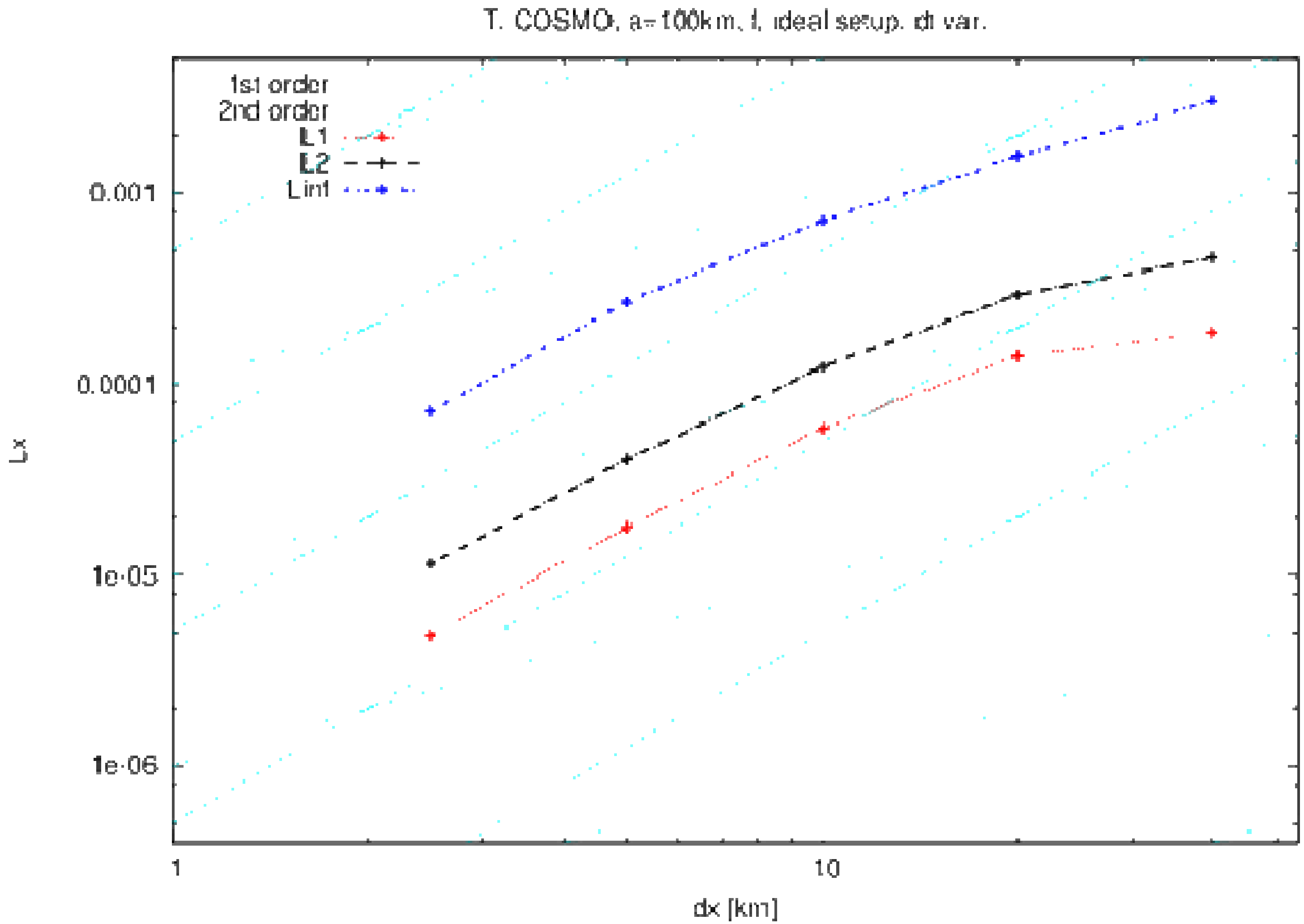


dx=2.5km

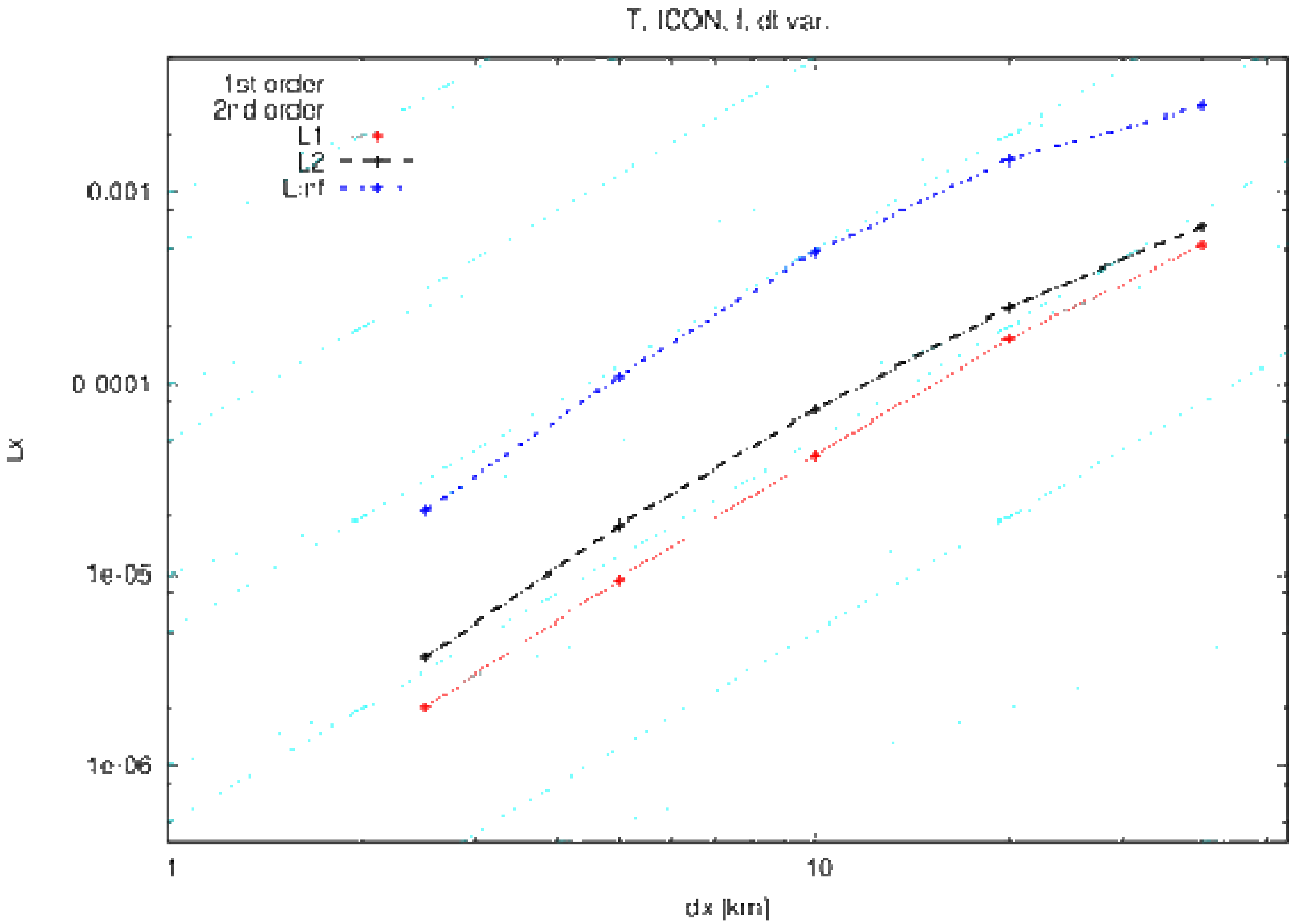




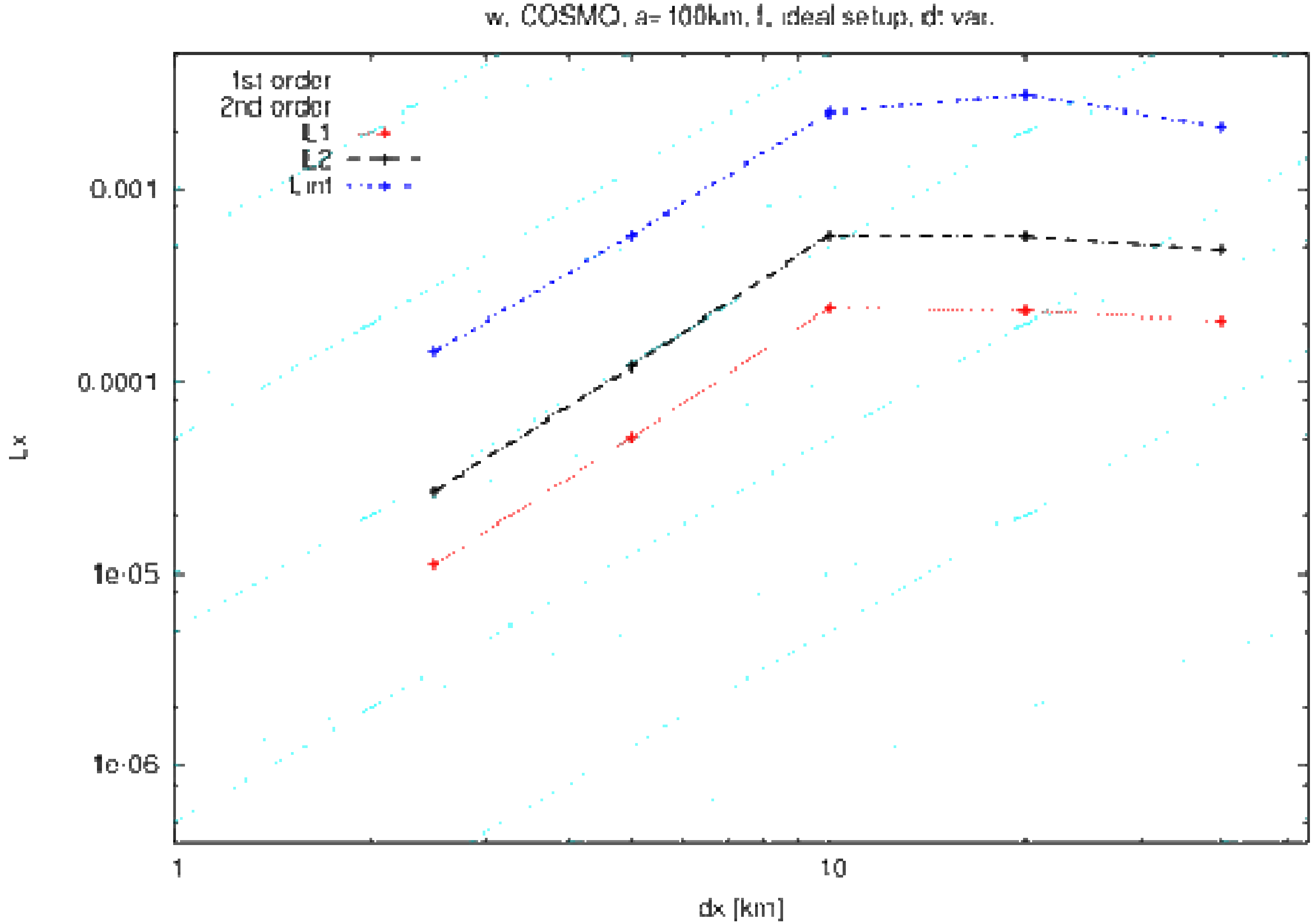
large scale test; convergence measures for T; COSMO



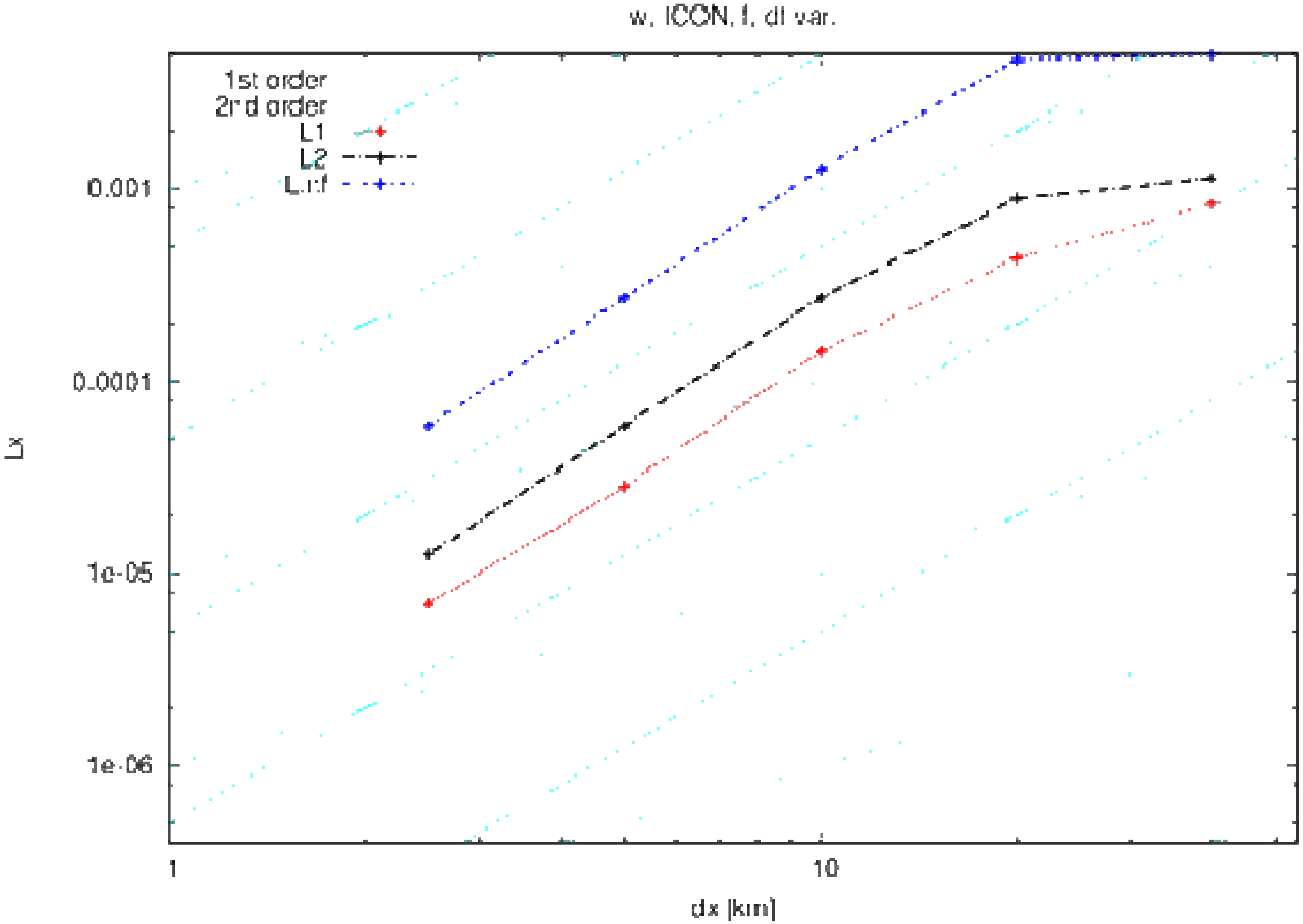
large scale test; convergence measures for T; ICON



large scale test; convergence measures for w; COSMO



large scale test; convergence measures for w; ICON



Summary for the linear wave test

from convergence results against the analytic solution of *(Baldauf, Brdar, 2013)*

- small scale test (fast waves + advection):
  ICON shows nearly 2nd order convergence.
  COSMO shows nearly 2nd order only in T, but less in w
  for coarse resolutions ICON errors are a bit larger than in COSMO
  w error is smaller in ICON for fine resolutions
- large scale test (fast waves + Coriolis force):
  both models show 2nd order convergence;
  but the errors are smaller in ICON

→ This task is almost finished

Test case 4c: 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
u_0=10m/s, N=0.01 1/s, $T(z=0)$=288K

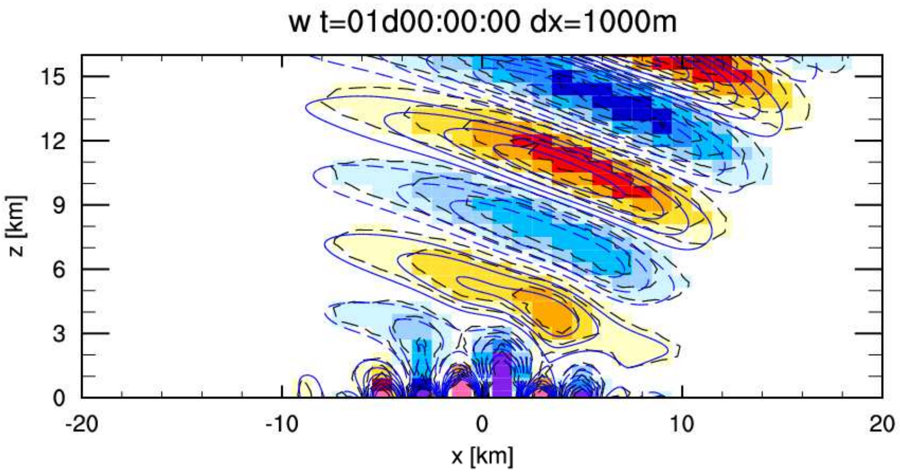
analytic linear solution: *Baldauf, 2008, COSMO-NL*
(uses almost no further simplifications, e.g. it is a fully compressible solution)

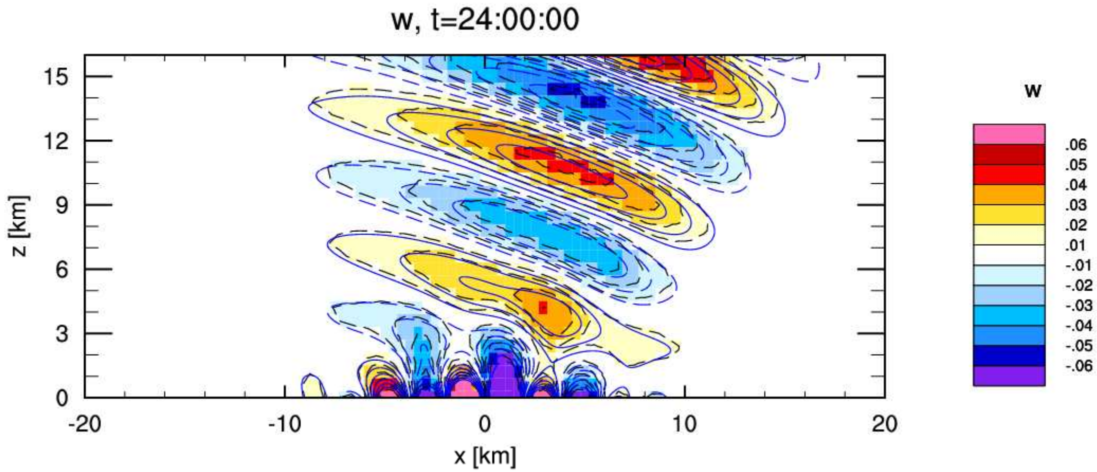
Test properties:

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

COSMO ICON

dx=1000m

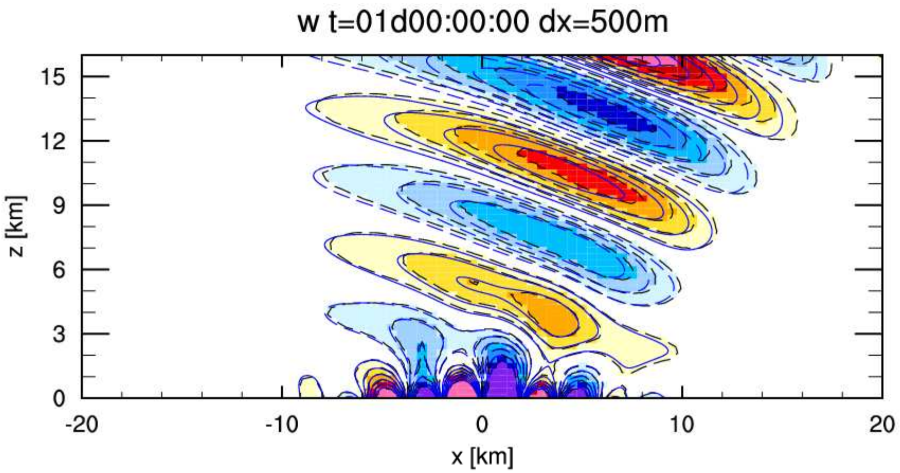


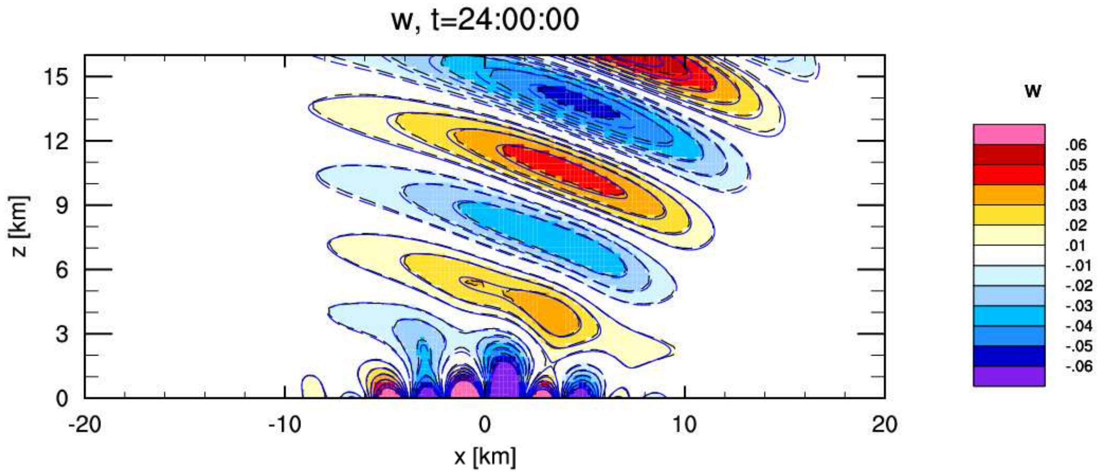


colors and black dotted lines: COSMO or ICON
blue lines: analytic solution

COSMO ICON

dx=500m

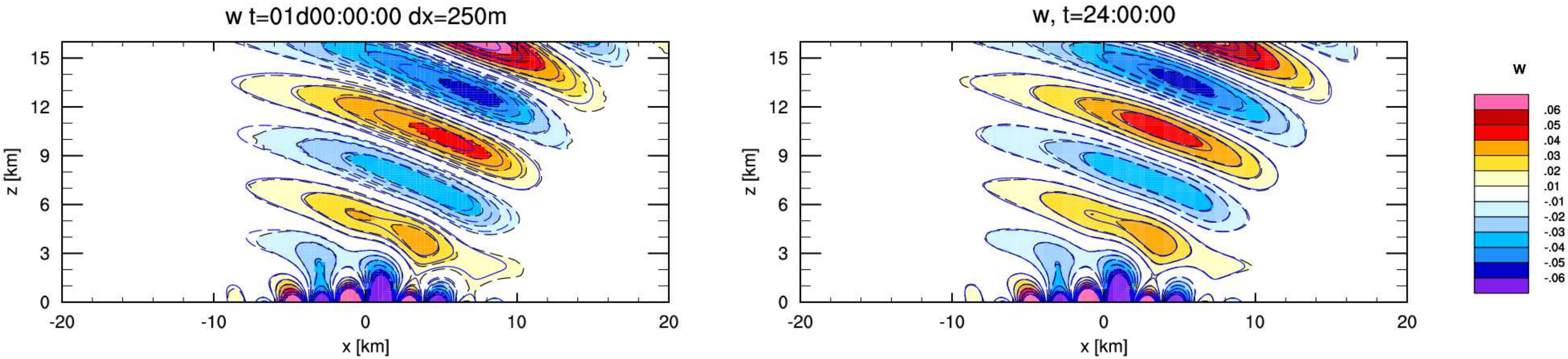




colors and black dotted lines: COSMO or ICON
blue lines: analytic solution

COSMO ICON

dx=250m



colors and black dotted lines: COSMO or ICON
blue lines: analytic solution

Summary for linear flow over mountains (Schär et al.) test

- In this low mountain test both models COSMO and ICON behave quite similar; with slight advantages for ICON.
- The overall agreement with the analytic solution is very good in both models
  → metric terms are correctly implemented

Next steps

- agreement with analytic solution in the 3D case
- comparison of stability limits for very high/steep mountains

COSMO priority project:
COSMO-EULAG operationalisation (CELO)

Time range: Sept. 2012 – March 2018
Projekt leader: Zbigniew Piotrowski, Bogdan Rosa (IMGW, Poland)

Task 1: Integration of (anelastic) EULAG DC with COSMO framework

Task 2: Consolidation and optimization of the EULAG DC formulation

Task 3: EULAG DC code restructuring and engineering

Task 4: Optimization and testing of COSMO with EULAG DC

Task 5: Integration and consolidation of the EULAG compressible DC with COSMO framework

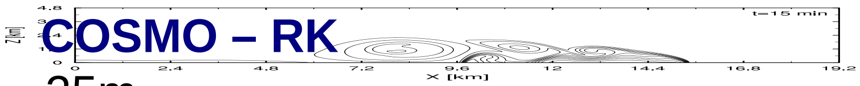
- **Integration of the consistent formulation of EULAG within CE**
- **Evaluation of idealized tests with compressible CE (CE-C)**
    - Cold density current (Straka et al., 1993)
    - Linear gravity waves (Skamarock et al., 1994)
    - Dry orographic flows (Klemp et al. (1977), Bonaventura (2000))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

Cold density current : a reassessment

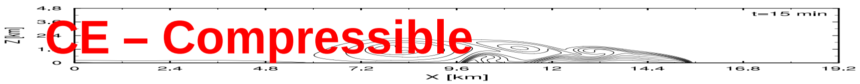
Straka, J. M., Wilhelmson, Robert B., Wicker, Louis J., Anderson, John R., Droegemeier, Kelvin K., Numerical solutions of a non-linear density current: A benchmark solution and comparison *International Journal for Numerical Methods in Fluids*, (**17**), 1993

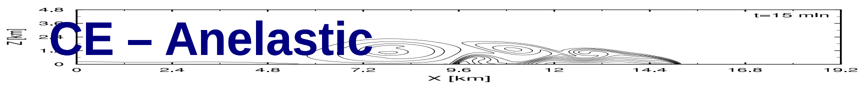
Experiment configuration:

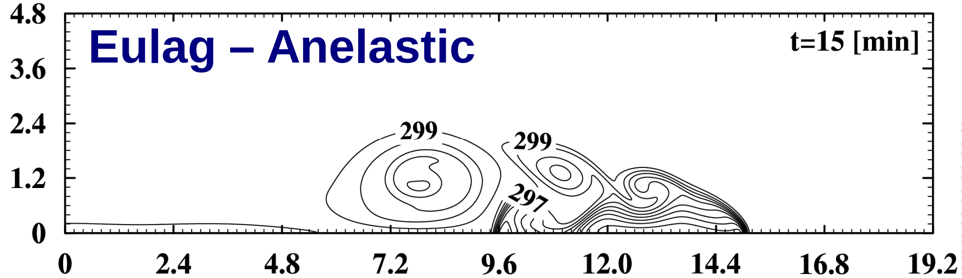
- isentropic atmosphere, $\theta(z)$=const (300K)
- open lateral boundaries
- free-slip bottom b.c.
- **constant subgrid mixing, $K=75m^2/s$**
- domain size 51.2km x 6.4km
- bubble min. temperature -15K
- bubble size 8km × 4km
- no initial flow
- integration time 15 min
- isotropic grid



25m







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

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}

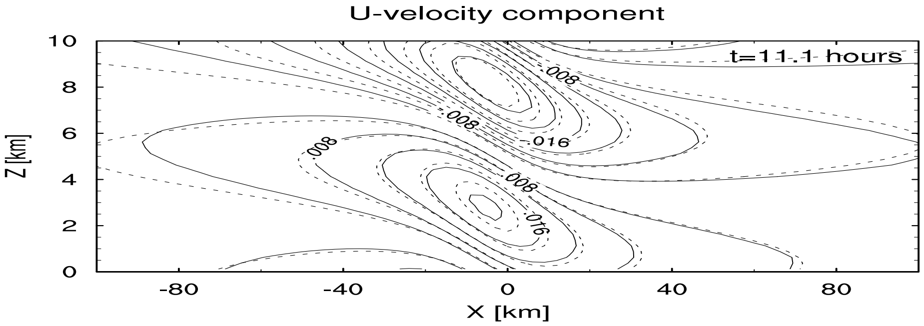
Klemp, J. B. and D. K. Lilly : Numerical Simulation of Hydrostatic Mountain Waves, *JAS*, vol. 35, 1977.

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.

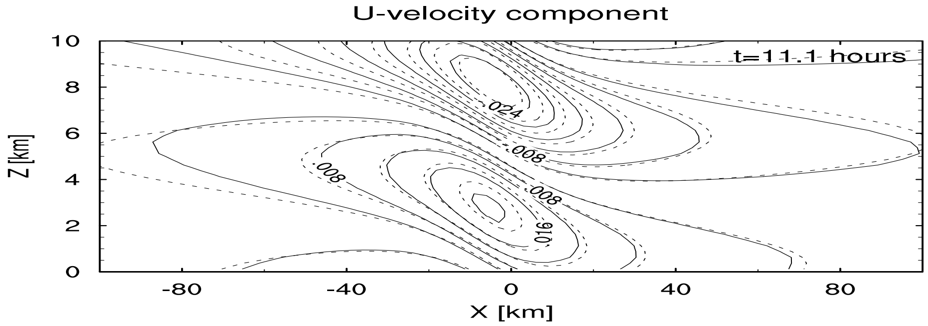
Pinty, J.P., R. Benoit, E. Richard, and R. Laprise : Simple tests of a semi-implicit semi-Lagrangian model on 2D mountain wave problems, MWR, vol. 123, 1995.

Linear hydrostatic flow: U after 11.1 h.

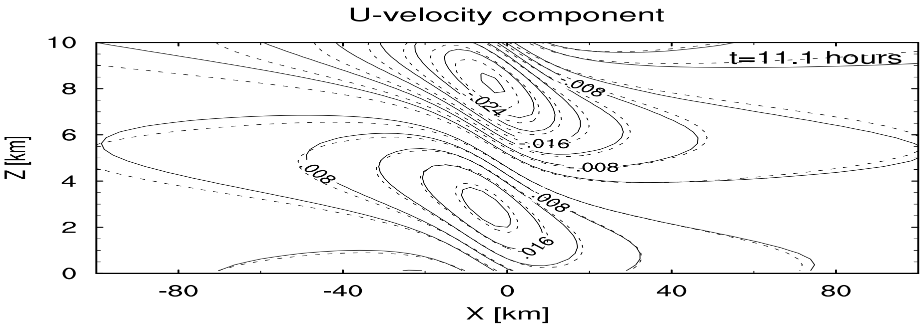
CE-C-Implicit



CE-C-Explicit



RK

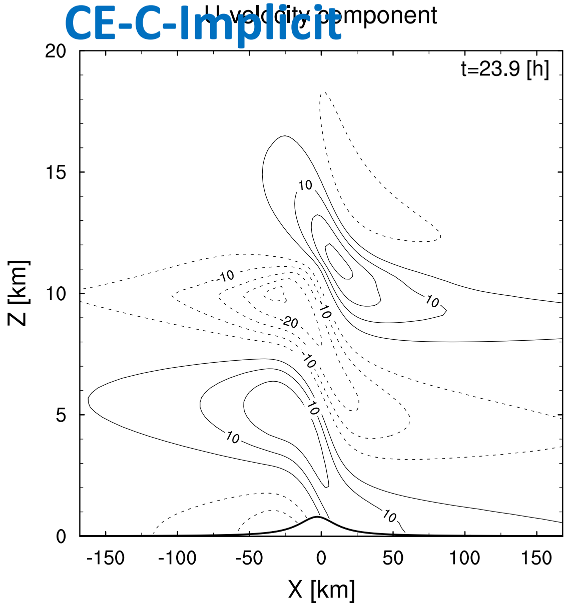


Solid lines - U component of velocity computed using different numerical models/approaches.

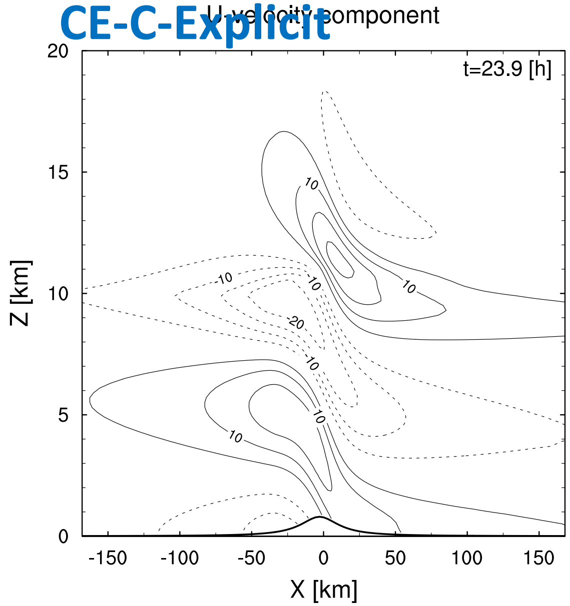
The plots confirm consistency between numerical solutions and the analytical formula (dashed lines).

Nonlinear hydrost. flow : U after 23.9 h.

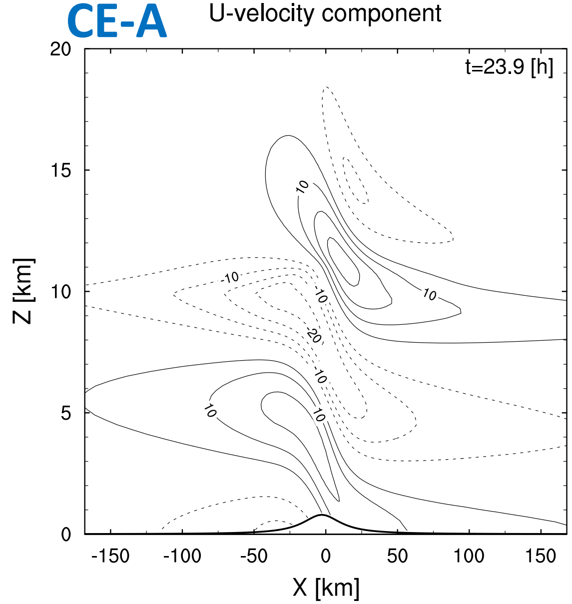
CE-C-Implicit



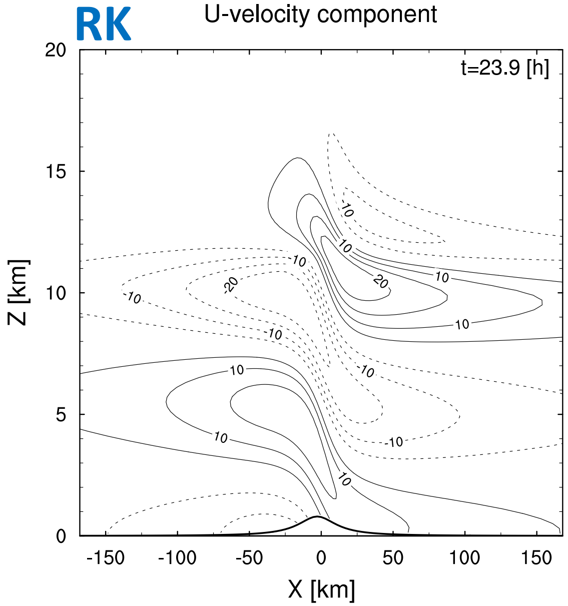
CE-C-Explicit



CE-A



RK



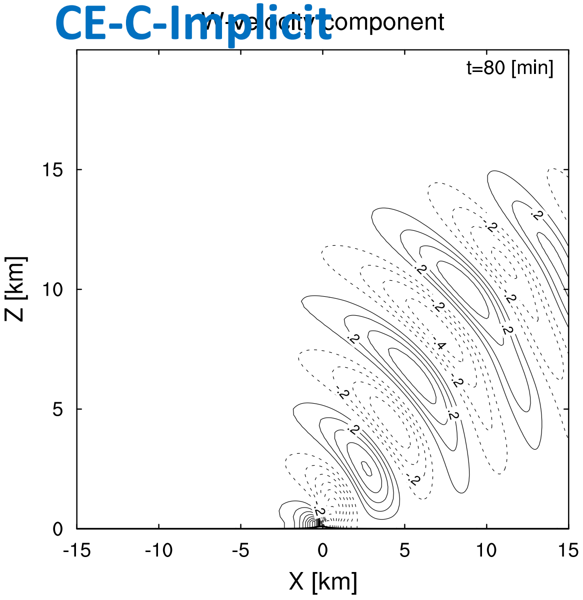
The series of figures present U component of velocity. The simulations have been performed using different numerical approaches and different codes.

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

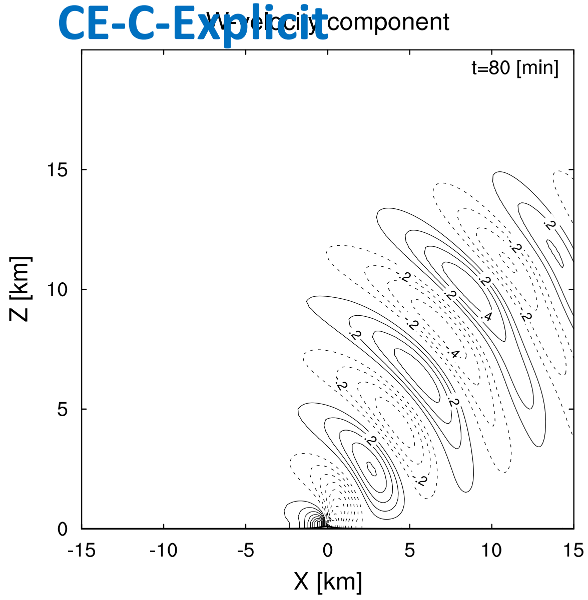
The differences in the stratosphere may result from different configuration of the sponge layer.

Linear nonh. flow : W after 80 min.

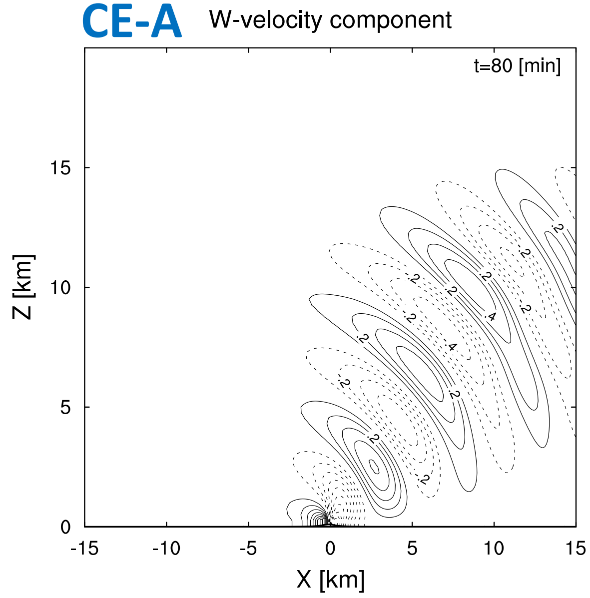
CE-C-Implicit



CE-C-Explicit



CE-A



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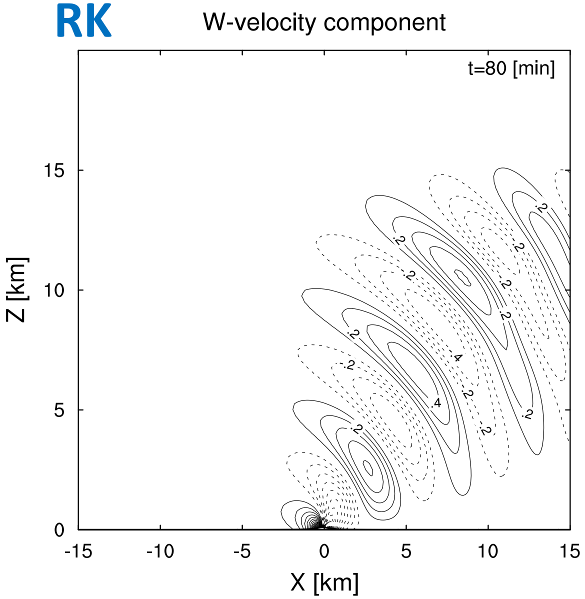
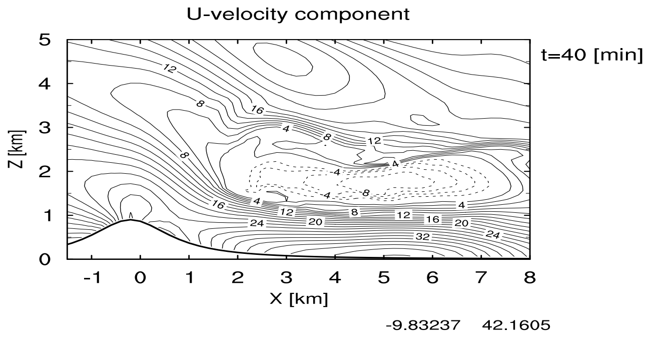


Spatial distribution of the vertical velocity perturbation.

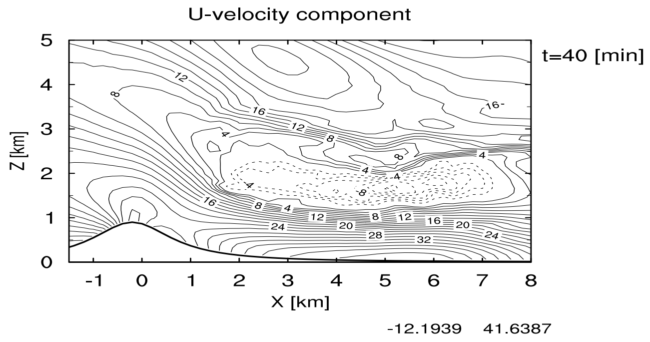
The results confirm high consistency of the numerical results (W) computed with different models.

Nonlinear nonh. flow : U after 40 min.

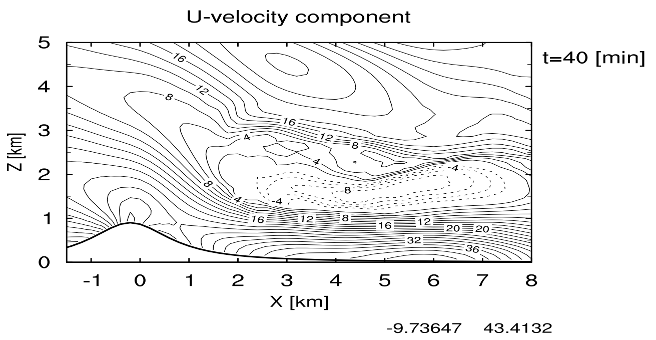
CE-C-Implicit



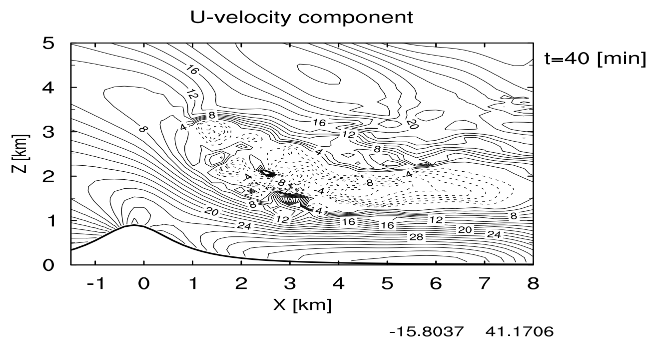
CE-C-Explicit



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.

Further numerics developments in COSMO last year

- Improvement / Bugfix in the slope dependency of the diffusion coefficient for the divergence damping
- higher order (=4th order) discretization in the horizontal direction with a symmetric version of 4th order advection (*A Will, J. Ogaja, Univ. Cottbus*)

Conclusions from the comparison of different dynamical cores for regional models

- our todays (nearly) 2nd order dynamical cores behave quite similar concerning accuracy and are in good agreement with known (partly analytic) solutions.
- In particular we know how to deal with
  - metric terms (terrain-following coordinates),
  - vertically stretched grids,
  - time-integration schemes.
- Differences can occur in the treatment of
  - strong non-linearities (where physical diffusion is necessary)
  - local conservation (FV based methods!)
  - steep slopes.

(additional slides)

Nonhydrostatic equation system (dry adiabatic limit)

$$\frac{\partial v_n}{\partial t} + (\zeta + f)v_t + \frac{\partial K}{\partial n} + w\frac{\partial v_n}{\partial z} = -c_{pd}\theta_v \frac{\partial \pi}{\partial n}$$

$$\frac{\partial w}{\partial t} + \vec{v}_h \cdot \nabla w + w\frac{\partial w}{\partial z} = -c_{pd}\theta_v \frac{\partial \pi}{\partial z} - g$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\vec{v}\rho) = 0$$

$$\frac{\partial \rho\theta_v}{\partial t} + \nabla \cdot (\vec{v}\rho\theta_v) = 0$$

v_n,w: normal/vertical velocity component

ρ: density

θ_v: Virtual potential temperature

K: horizontal kinetic energy

ζ: vertical vorticity component

π: Exner function

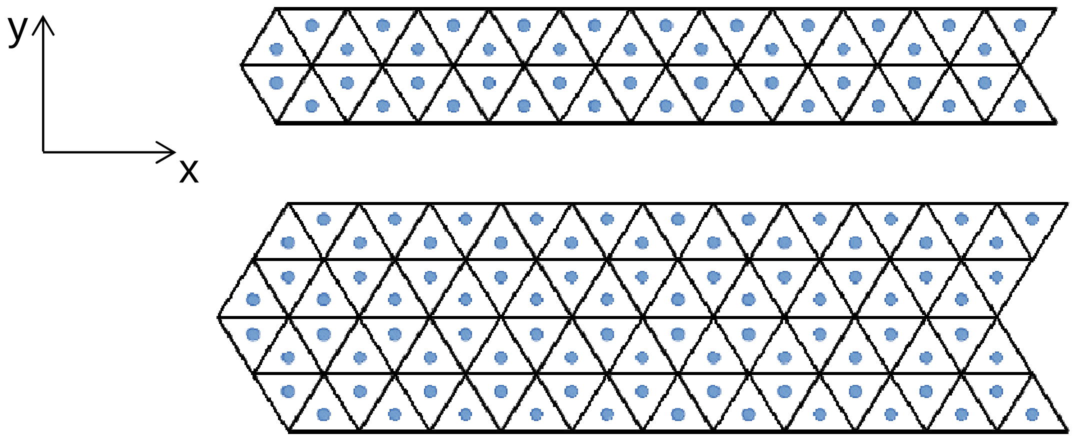
blue: independent prognostic variables

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

Problems in ICON fixed:

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

used now:



Derivation of an analytic solution for the non-hydrostatic, compressible, 2D Euler equations in a flat channel (shallow atmosphere) on an f-plane

$$\frac{\partial u}{\partial t} + \mathbf{v} \cdot \nabla u = -\frac{1}{\rho}\frac{\partial p}{\partial x} + f v,$$

$$\frac{\partial v}{\partial t} + \mathbf{v} \cdot \nabla v = -f u,$$

$$\frac{\partial w}{\partial t} + \mathbf{v} \cdot \nabla w = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g,$$

$$\frac{\partial \rho}{\partial t} + \mathbf{v} \cdot \nabla \rho = -\rho \left(\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} \right),$$

$$\frac{\partial p}{\partial t} + \mathbf{v} \cdot \nabla p = c_s'^2 \left(\frac{\partial \rho}{\partial t} + \mathbf{v} \cdot \nabla \rho \right),$$

$$T = \frac{p}{R\rho},$$

$$c_s' = \sqrt{\frac{c_p}{c_v} R T},$$

most LAMs using the compressible equations should be able to exactly use these equations in the dynamical core

For analytic solution only one further approximation is needed: linearisation (= *controlled* approximation) around an **isothermal, steady, hydrostatic** atmosphere at rest (f≠0 possible) or with a constant basic flow U_0 (and f=0)

Test setup 2:
small scale test with advection (U0=20 m/s) and without Coriolis force

In COSMO: now 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

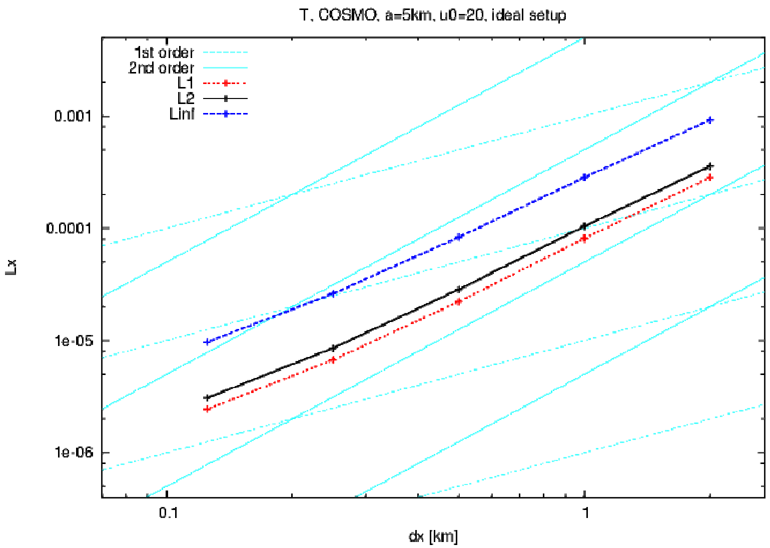
In the following convergence study compare:
COSMO: dx=grid mesh size, dt_small = dt/6
ICON: dx=length of triangle edge, dt_small = dt/5
for an equilateral triangle $\sqrt{A}=dx * 0.658\ldots$

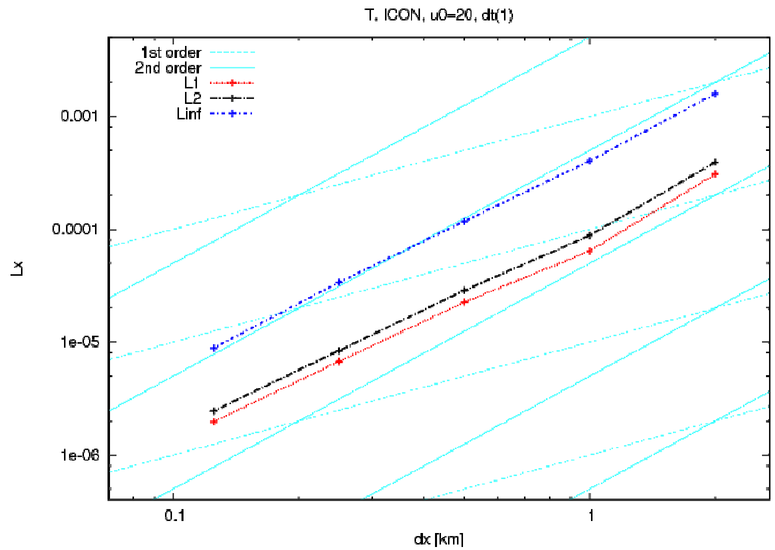
Convergence behaviour

COSMO

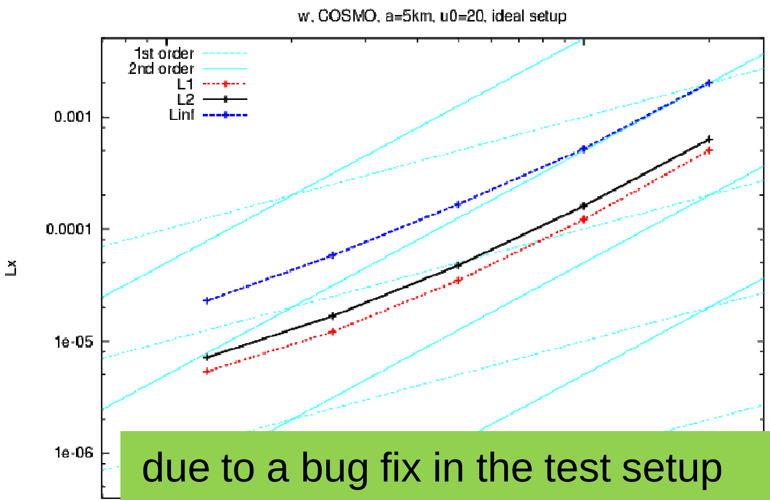
ICON

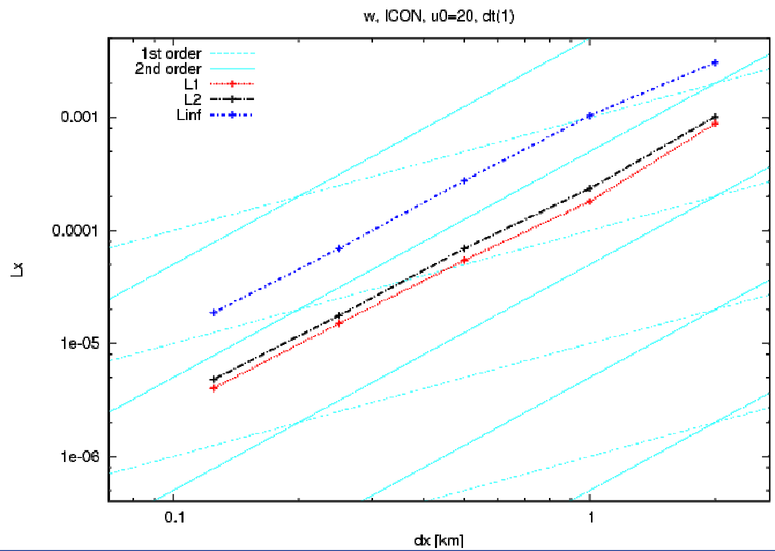
T‘





W





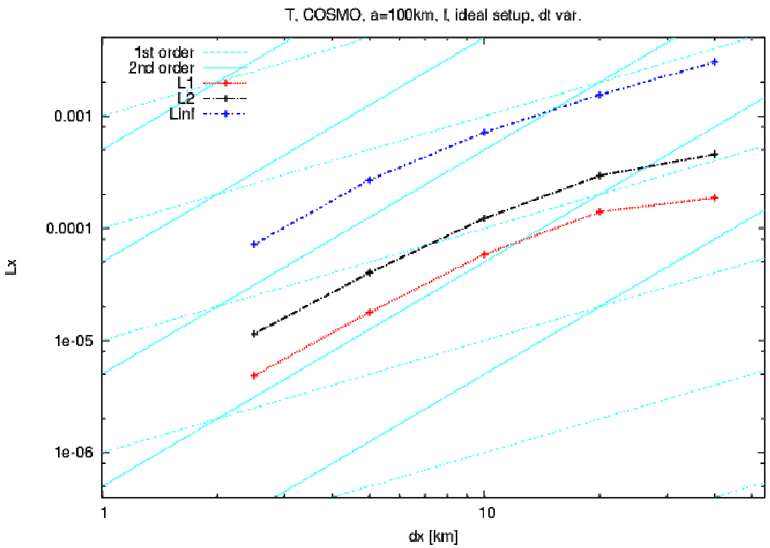
due to a bug fix in the test setup (proper use of periodic BCs) the COSMO result is now better than that described in BB2013

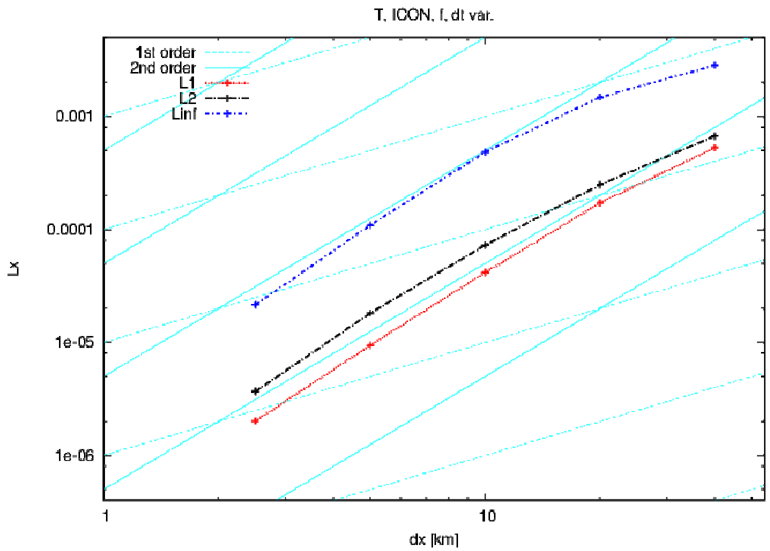
Convergence behaviour

COSMO

ICON

T'





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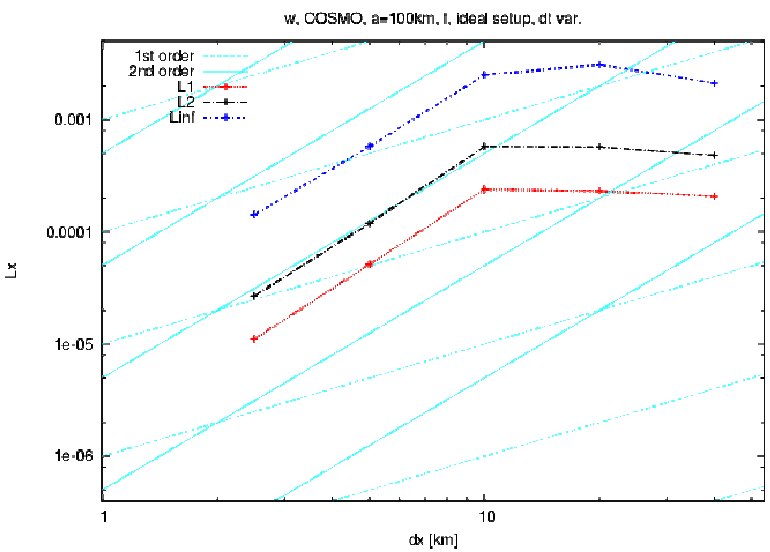
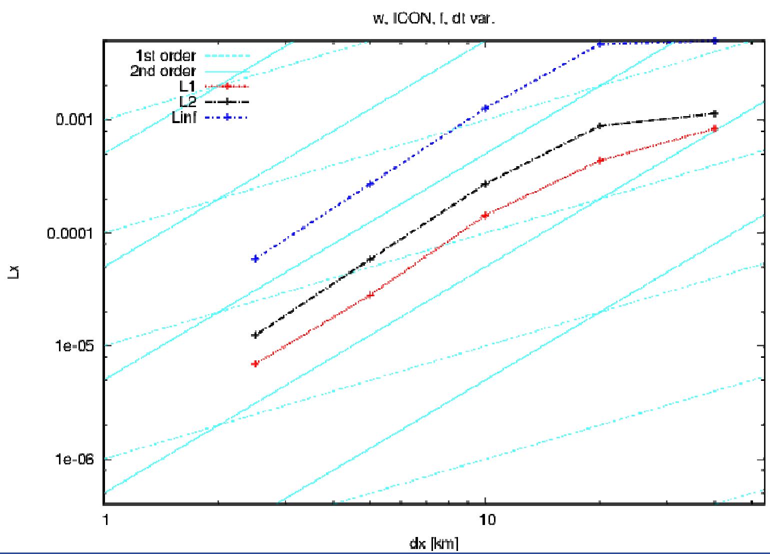
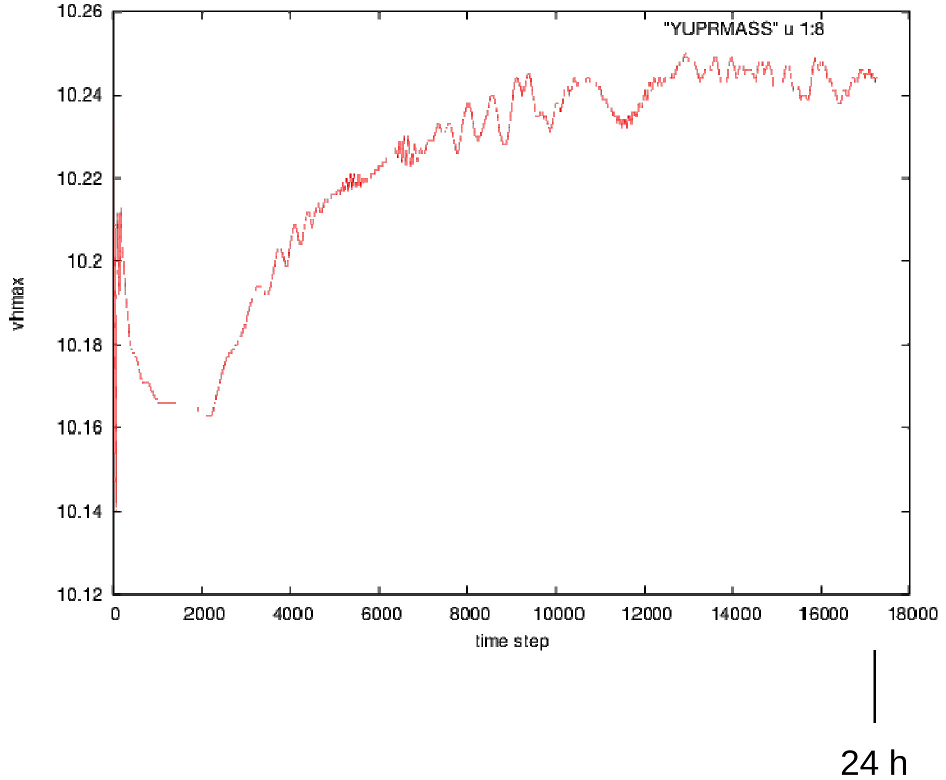




- Lessons learned:
  - for comparison with exact analytic solutions, in particular for convergence tests
    → the model run must use double precision
  - but also the model output must use double precision
    (not possible in COSMO → at least write e.g. T' instead of T);
    otherwise you will see Moiré-patterns in a plot ‚Φ_{model} - Φ_{analytic}'.
  - For time-dependent tests:
    check **every** prognostic field ($T, p, \rho, u, w, \ldots$) at t=0

How long should we integrate to get a stationary solution?

look e.g. to the time series of max v_{hor} :

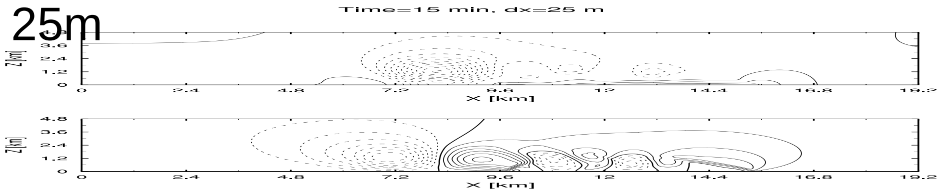


← roughly stationary

Cold density current : P’ and W

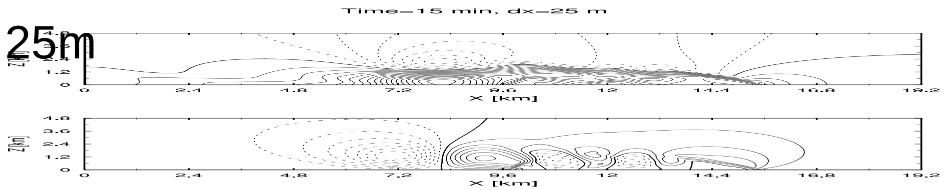
Cosmo – RK P’

25m

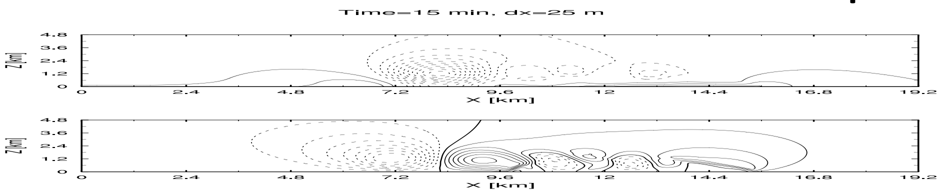


Cosmo – RK W

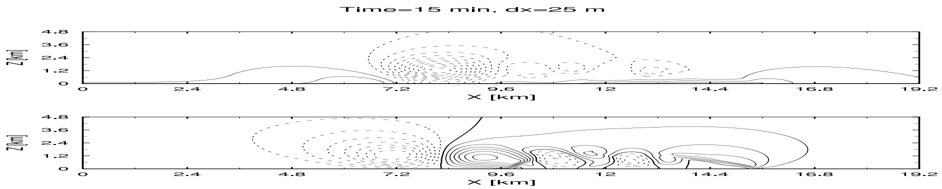
25m



CE – C P’



CE – C W

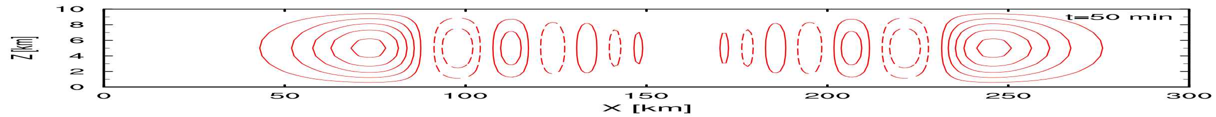


Parameter	RK		CE-C	
	Δx = 25 m	Δx = 100 m	Δx = 25 m	Δx = 100 m
P'_{max} [hPa]	2.0	1.7	1.9	1.6
P'_{min} [hPa]	-5.6	-5.5	-5.8	-5.6
W_{max} [m/s]	12.7	13.6	13.1	12.9
W_{min} [m/s]	-15.8	-15.9	-15.9	-15.5

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 :

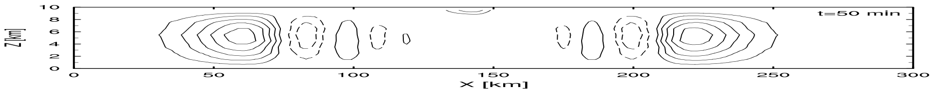
- Dry flow
- 2-D domain (XZ)
- Periodic b.c. in X
- Domain size 300 km x 10 km
- Free-slip upper and bottom b.c.
- $N_{B\text{-}V} = 0.01\ s^{-1}$
- Ambient flow U= 20 m/s
- The inertia-gravity waves are excited by an initial Θ perturbation (warm bubble) of small amplitude $\Delta\Theta_0 = 10^{-2}$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

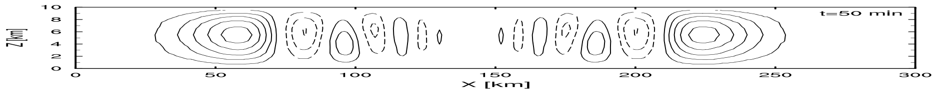
Analytical solution - potential temperature perturbation at t=50 min

Linear gravity wave: short channel

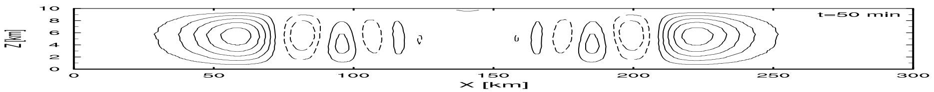
CE-C

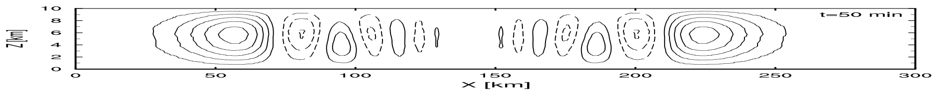
RK



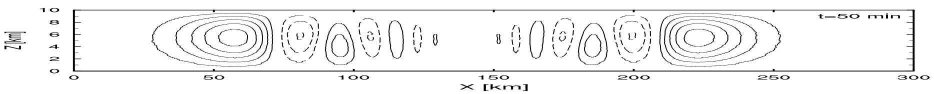


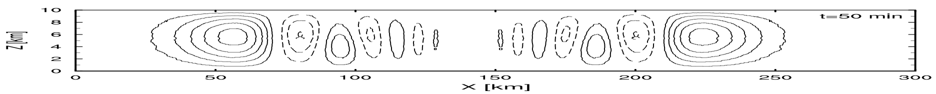
Δx=Δz=1km





Δx=Δz=0.5km



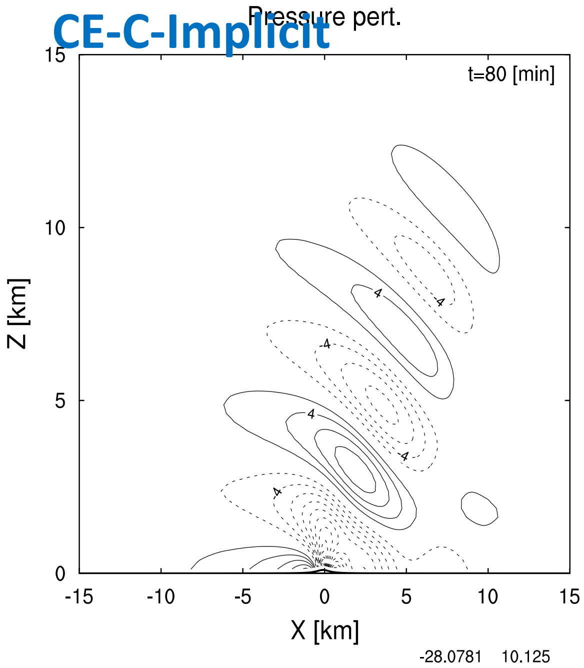


Δx=Δz=0.25km

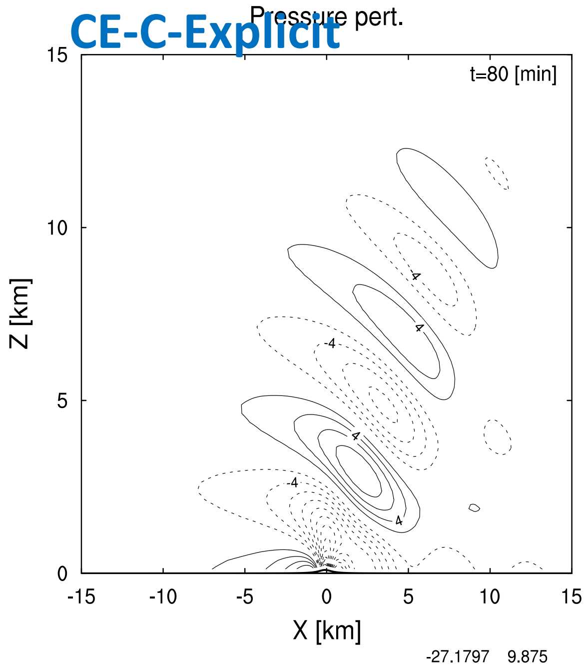
The figures show spatial distribution of the potential temperature perturbation.

Linear nonh. flow : P’ after 80 min.

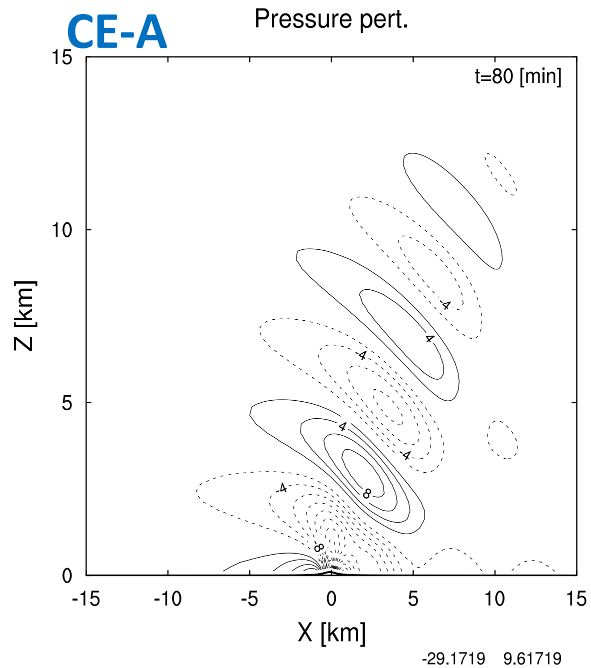
CE-C-Implicit



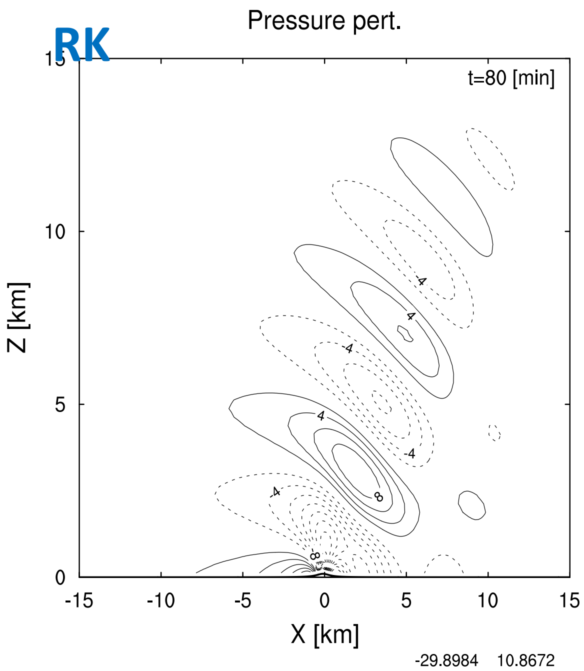
CE-C-Explicit



CE-A



RK



	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.