A Semi-Implicit Semi-Lagrangian Dynamical Core for High Resolution NWP over Complex Terrain

Davide Cesari — Servizio Idro Meteo, ARPA-SIM — Bologna

Luca Bonaventura — MOX — Politecnico di Milano

Max-Planck-Institut für Meteorologie
Max Planck Institute for Meteorology — Hamburg

General description

- Dynamical core based on [Bonaventura, JCP. 2000]
- Implemented within Lokal Modell code structure
- Vertical geometrical (Z) coordinate
- Semi-implicit 2 time level discretization
- Semi-Lagrangian advection

Discretization approach

- Divergence computed by finite volume discretization
- 3-d solver for weakly nonlinear system $Ax + f(x) = b$: fixed point iterations with Conjugate Gradient as linear kernel
- Block tridiagonal preconditioning with linear operator of vertical discretization
- Coriolis term computed with operator-splitting approach
- Semi-Lagrangian advection with cut cell/RBF approach

Discretization approach: new features

- Bug fixes $\Rightarrow$ improvement in solver speed
- Introduction of RBF interpolator for semi-Lagrangian advection
- Full 3-dimensional semi-Lagrangian advection
- Partial implementation of a domain decomposition preconditioner to speedup solver in parallel runs

Radial Basis Function interpolator

Joint work with Giorgio Rosatti (University of Trento).

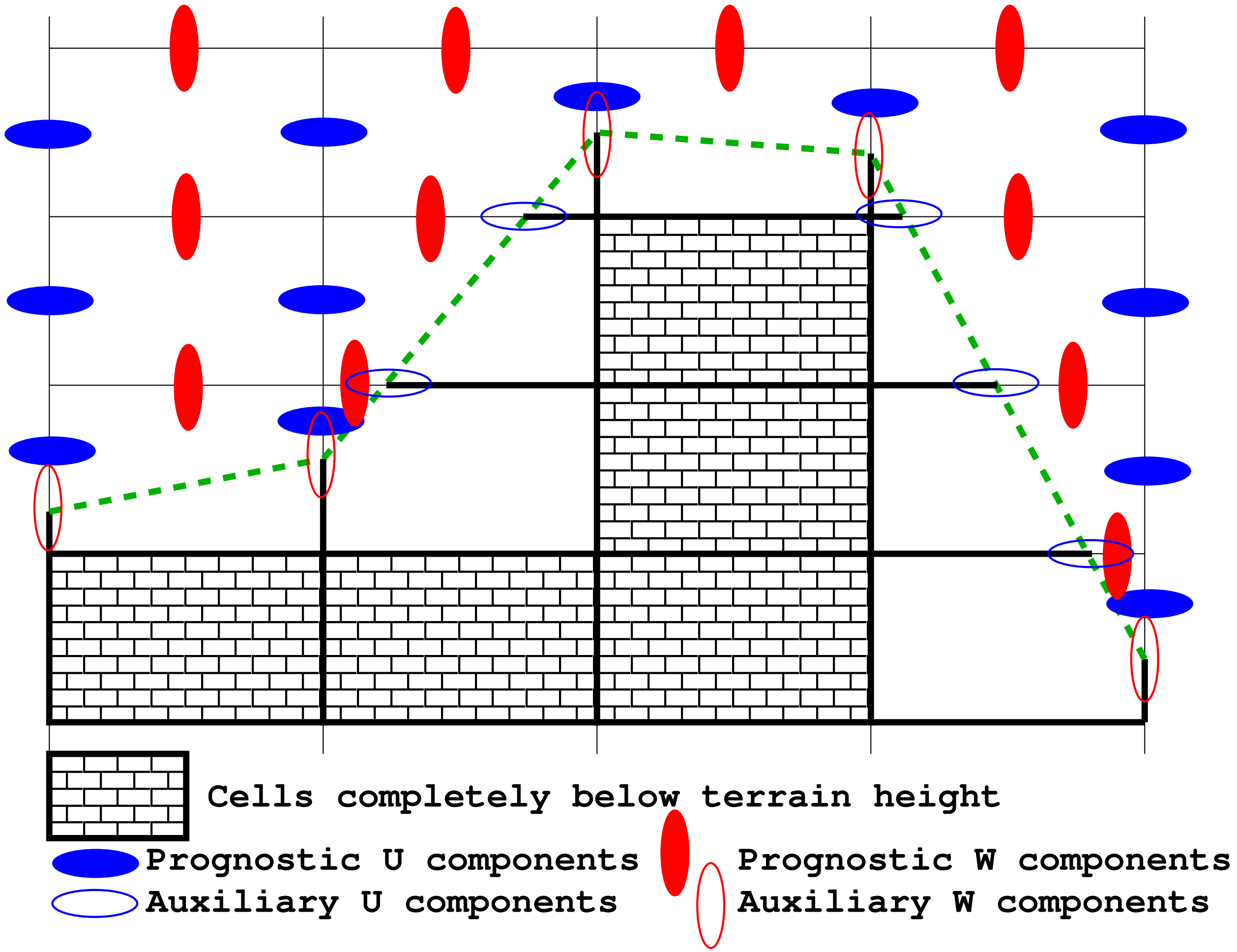
RBF technique provides an interpolator which can smoothly and accurately reconstruct a field (and optionally its derivatives) sampled on an irregularly distributed set of points.

- The radial basis function used here is $\phi(x) = \sqrt{1+(x/\Delta x)^2}$ where Δx is a proper spatial scale
- The algorithm requires to solve a $(n+n_1)\times(n+n_1)$ linear system where n is the number of points used for interpolation and $n_1 = 0 \div 4$
- It is straightforward to adjust the stencil used for interpolation to achieve the desired accuracy
- The algorithm is computationally expensive but can be optimized at the expense of more memory occupation

Semi Lagrangian advection: computation of trajectories

- Trajectories are computed with Runge-Kutta substepping method
- Number of substeps depends on the local Courant number (computed taking into account that cut cells are smaller)
- Velocity interpolation in trajectory substeps: bilinear within the domain, RBF ($2 \times 2 \times 2$ stencil) close to the boundary
- Auxiliary velocity components, computed according to cut-cell free-slip lower boundary condition, are added in RBF interpolation in order to help keeping the trajectories within computational domain

Computational grid for advection: auxiliary points



Semi Lagrangian advection: interpolation

- Interpolation at trajectory departure point: bicubic away from the boundaries, RBF ($4\times4\times4$ stencil) close to the boundary
- No lower boundary condition required with RBF interpolator
- If the departure point falls slightly outside the computational domain, the accuracy of the interpolation is not compromised

Results obtained applying RBF interpolator show a further improvement in the representation of flow over orography. The results will be part of a paper to appear in Journal of Computational Physics.

2d flow over an obstacle: Gallus-Klemp test case

$\Delta x = 2000\,m$

$\Delta z = 150\,m$

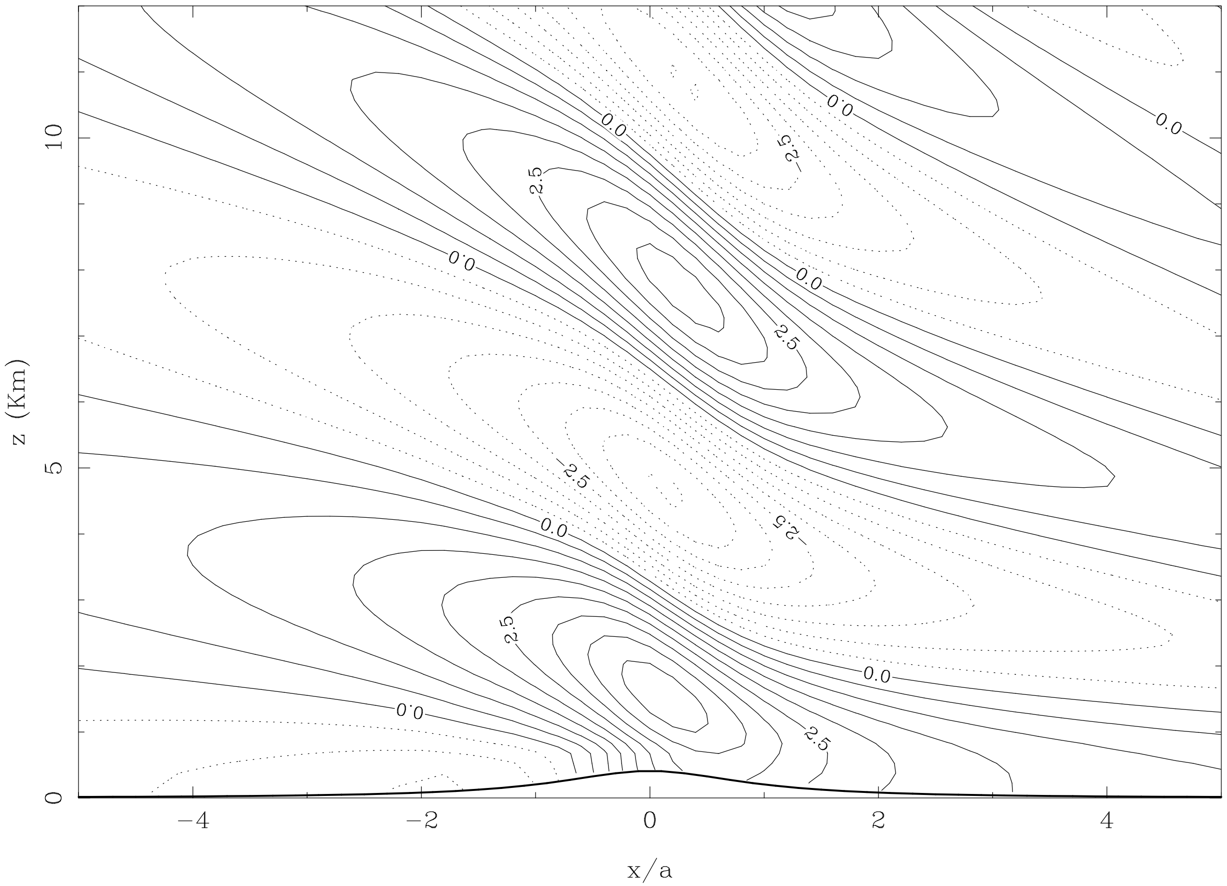
$\Delta t = 10\,s$

$H = 400\,m$

$a = 10\,Km$

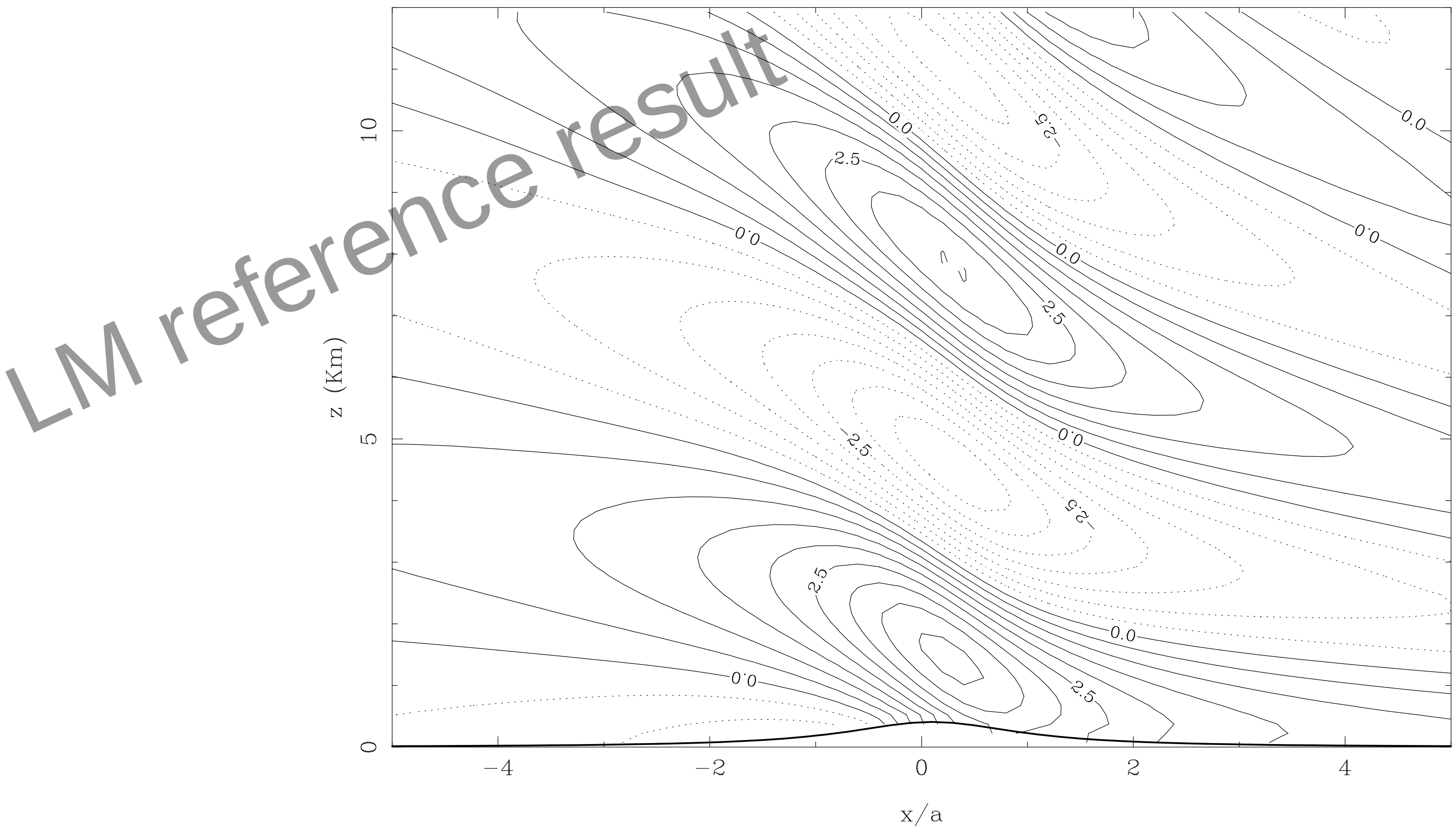
$U = 10\,m/s$

Hydrostatic regime



Horizontal velocity perturbation, contour interval $0.5\,m/s$

2d flow over an obstacle: Gallus-Klemp test case



Horizontal velocity perturbation, contour interval $0.5\,m/s$

2d flow over an obstacle: Gallus-Klemp test case

$\Delta x = 2000\,m$

$\Delta z = 150\,m$

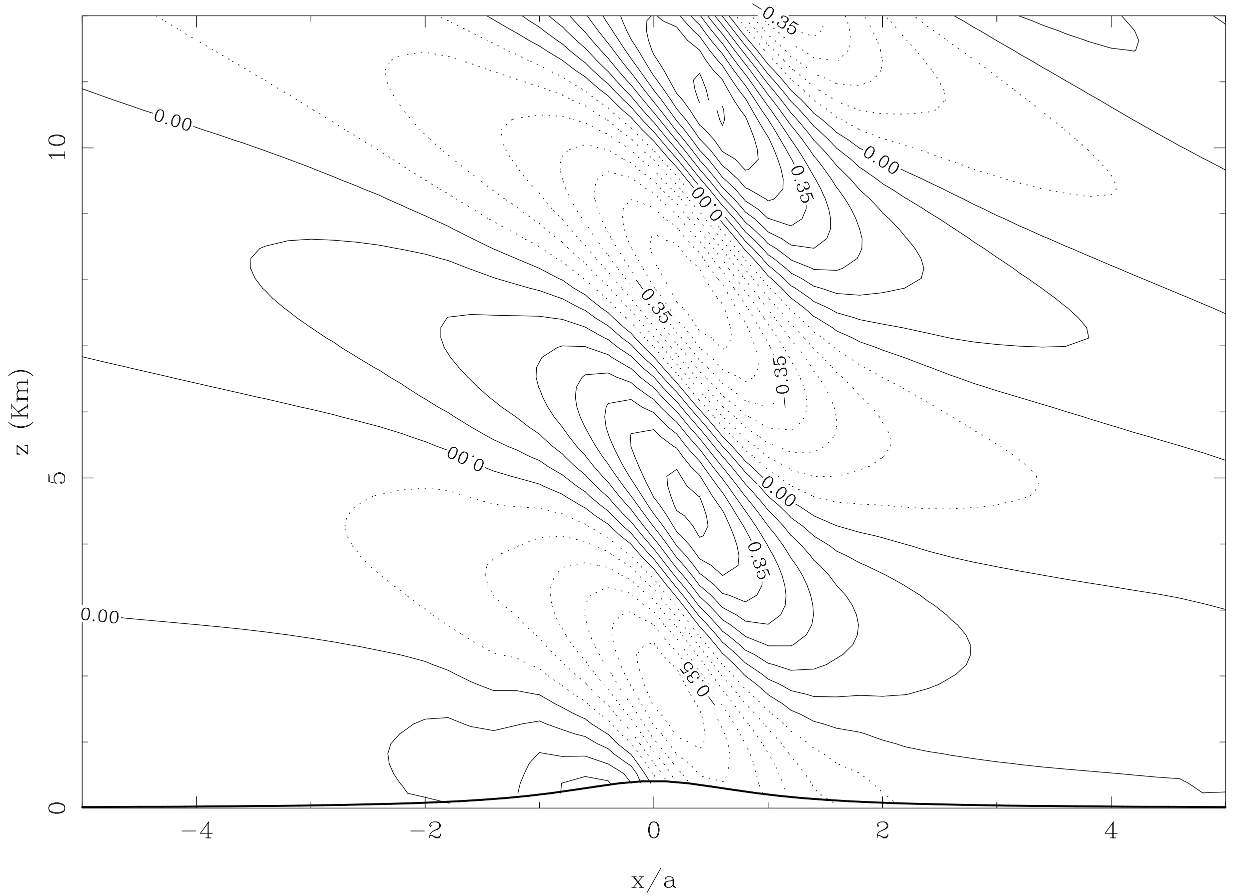
$\Delta t = 10\,s$

$H = 400\,m$

$a = 10\,Km$

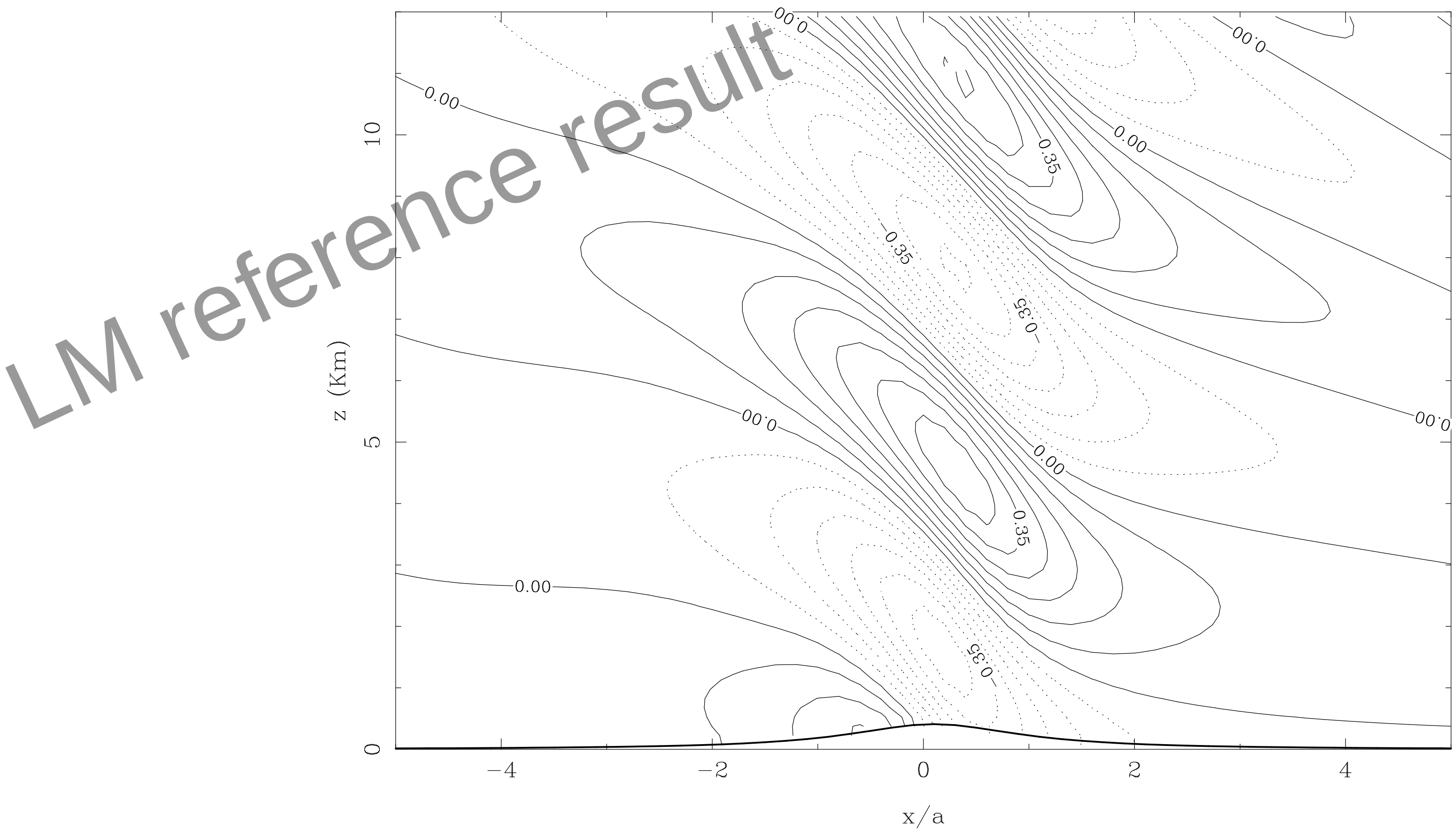
$U = 10\,m/s$

Hydrostatic regime



Vertical velocity, contour interval $0.07\,m/s$

2d flow over an obstacle: Gallus-Klemp test case



Vertical velocity, contour interval $0.07\,m/s$

2d flow over an obstacle: Gallus-Klemp test case

$\Delta x = 200\,m$

$\Delta z = 150\,m$

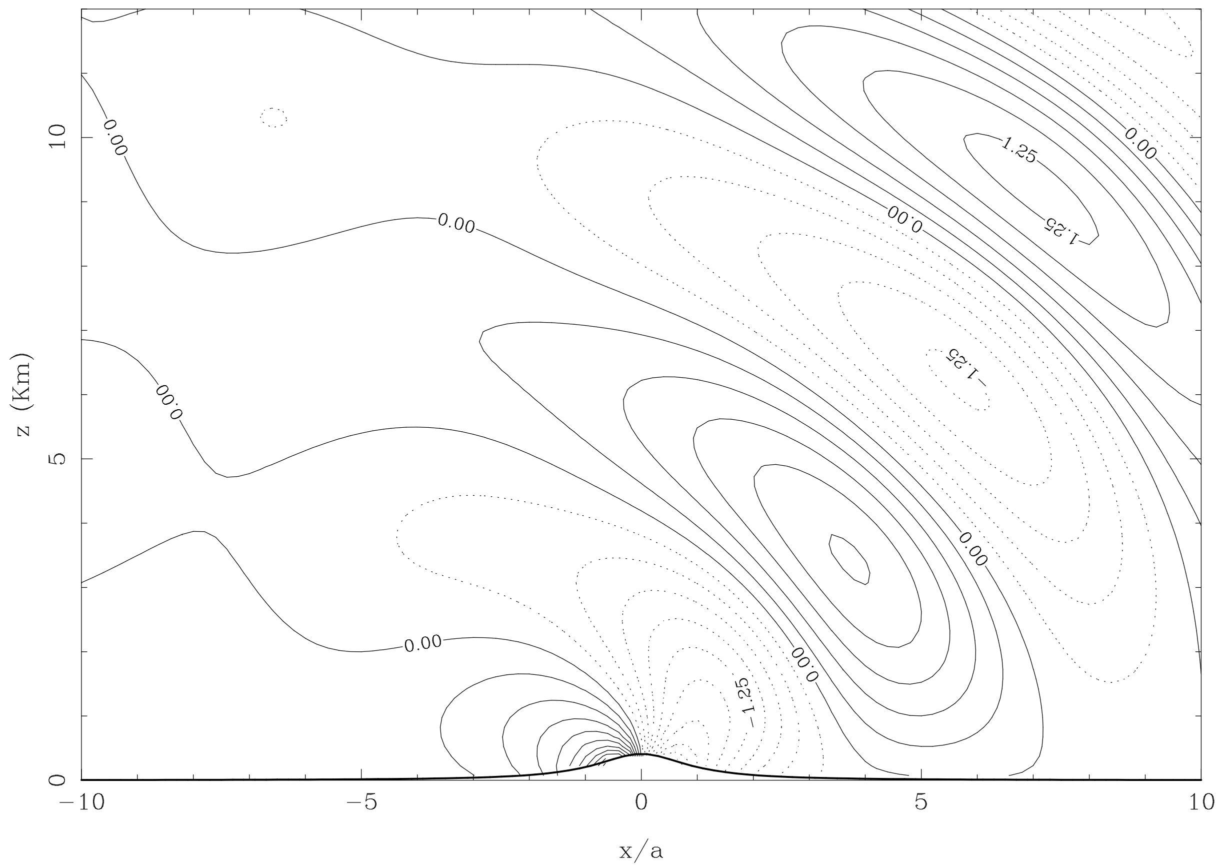
$\Delta t = 5\,s$

$H = 400\,m$

$a = 1\,Km$

$U = 10\,m/s$

Non-hydro regime



Vertical velocity, contour interval $0.25\,m/s$

Conclusions

Z coordinate+SI+finite volume

- The efficiency of the solver does not depend on the orography steepness

Z coordinate+SL advection+cut cell+RBF:

- The flow can be correctly represented regardless of the orography steepness
- The trajectories are (almost 100%) guaranteed not to cross the domain boundaries - no need to take artificial measures
- Computationally expensive but applied only to a small subset of grid cells

Future plans

- Implement into LM z-library
  - Partly done during the visit of H-W Bitzer in Bologna
- Further test of SL advection in 3d, at $CFL > 1$ and with small cell elements
- Add treatment of vertical diffusion terms and interaction with physical parameterisations
- Optimize the code (e.g. simplify advection over the top of the orography)
- Improve parallelization for semi-Lagrangian advection (allowing high Courant numbers without exchanging many boundary lines when unneeded)

Future plans

Further development and testing will be part of the “VHREM” [a] project, currently under submission as a NEST[b]-Adventure EU project, if funded.

Involved partners: **University of Leeds** School of Environment, ARPA-SIM Bologna, DWD, ETH Zürich Institute of Atmospheric sciences, MeteoSwiss, Politecnico di Milano MOX-dept. of Mathematics, WSL-SLF Davos.

...more about this on Friday (L. Bonaventura)

---

[a] Very High Resolution Environmental Modelling

[b] New and Emerging Science and Technology