# The EULAG dynamical core – idealized and semi idealized tests

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# OUTLINE

## 1. Motivation

## 2. Idealized tests

- cold density currents (Straka et al., 1993)
- rising termal (Robert, 1993; Giraldo, 2008)
- inertia-gravity waves (Skamarock and Klemp, 1994)
- mountain waves (Bonaventura, 2000)

## 3. Semi-idealized tests

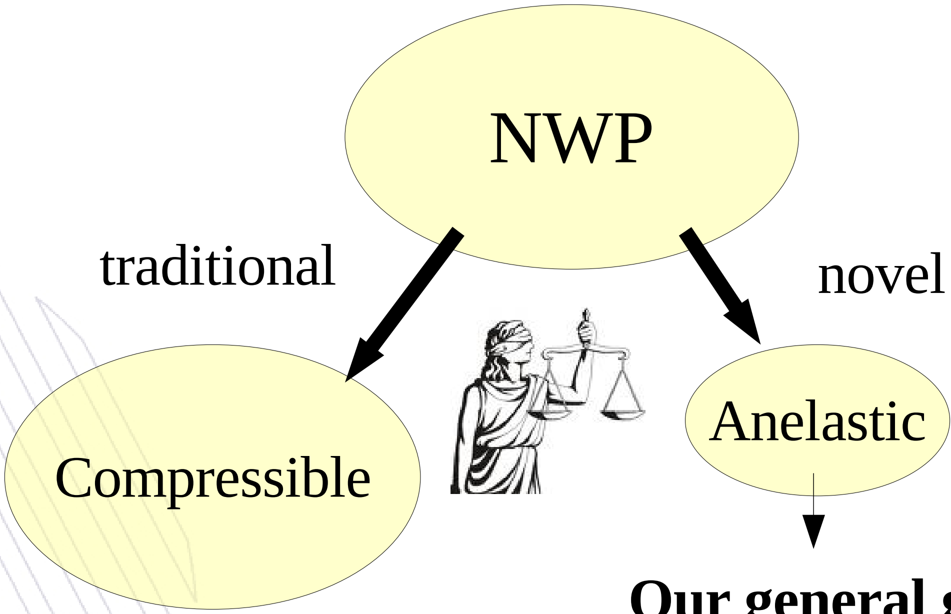
- idealized flows over realistic (Alpine) topography

## 4. Computational issues

- computational efficiency
- scalability

## 5. Summary and future plans

# 1. MOTIVATION




**Our general goal:** Testing the EULAG dynamical core as a prospective dynamical core of a future operational weather prediction COSMO model for very high horizontal resolutions

EULAG – computational research model for multiscale flows (over 20 years of history), nonhydrostatic anelastic, employing finite volume non-oscillatory positive definite transport algorithm able to solve the flow equations both in Eulerian and Lagrangian framework

## CDC Project Plan specifies a series of tasks for testing the EULAG model, starting with:

### Task 1.1: Idealized tests of the EULAG dynamical core

*Simulate 2D and 3D idealized flows over mountains and 2D and 3D potential flows to compare with COSMO results, laboratory flows and analytic solutions. Run a series of experiments involving valley flows in an idealized setup to compare with COSMO (and possibly other models) results. (...)*

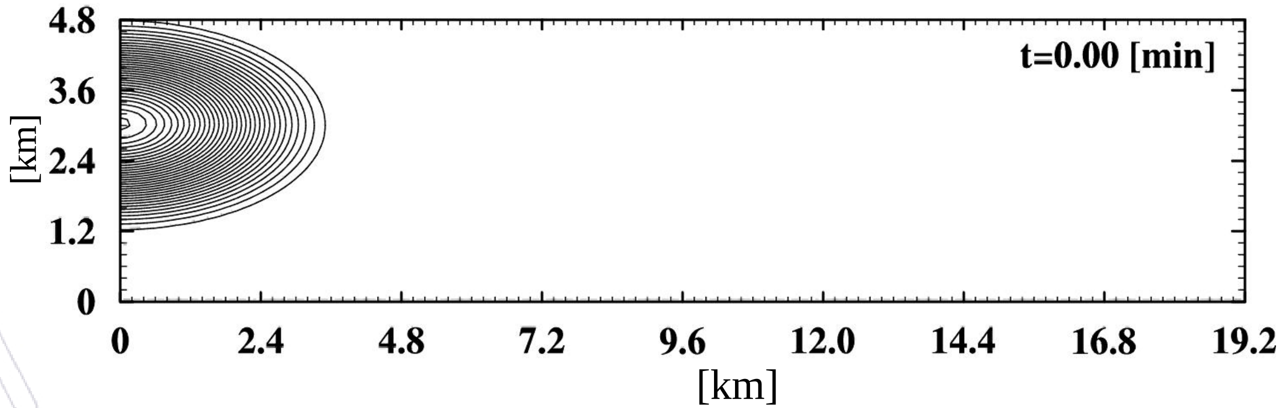
### Task 1.2: Tests of the EULAG dynamical core for realistic flows over the Alpine topography

*Simulate realistic flows over the Alpine topography (in particular orography containing deep valleys), with resolution ranging from 2.2 km, 1.1 km to 0.25 km, case studies for different weather regimes ranging from simple (without much weather), to summer (convective) and winter (frontal) situations. (...)*

# Cold density current

reference:

*Straka J. M, R. B. Wilhelmson, L. J. Wicker, J. R. Anderson and K. K. Droegemeier. Numerical solutions of a nonlinear density current – a benchmark solution and comparisions. International Journal for Numerical Methods in Fluids, 17(1):1-22,* ***1993***



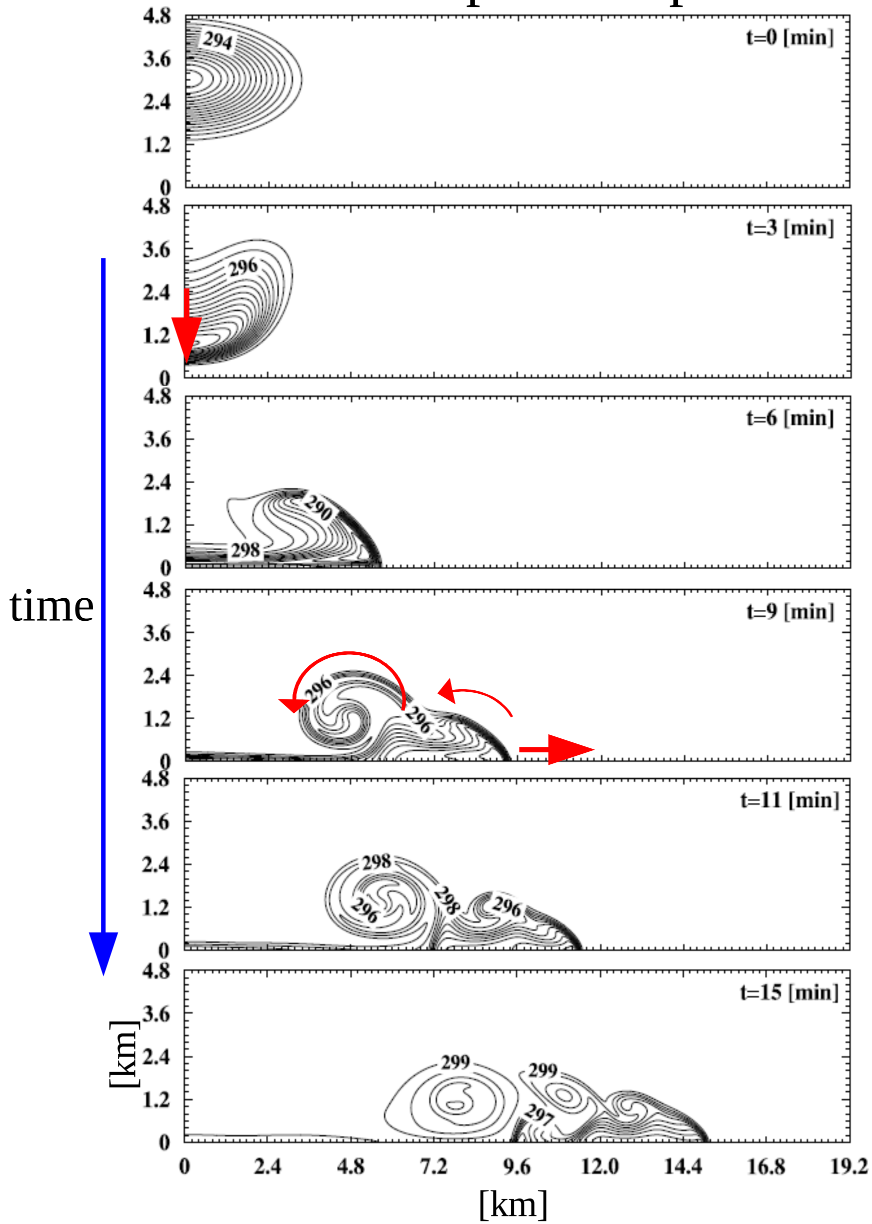

## Setup overview

(details in Straka et al. 1993):

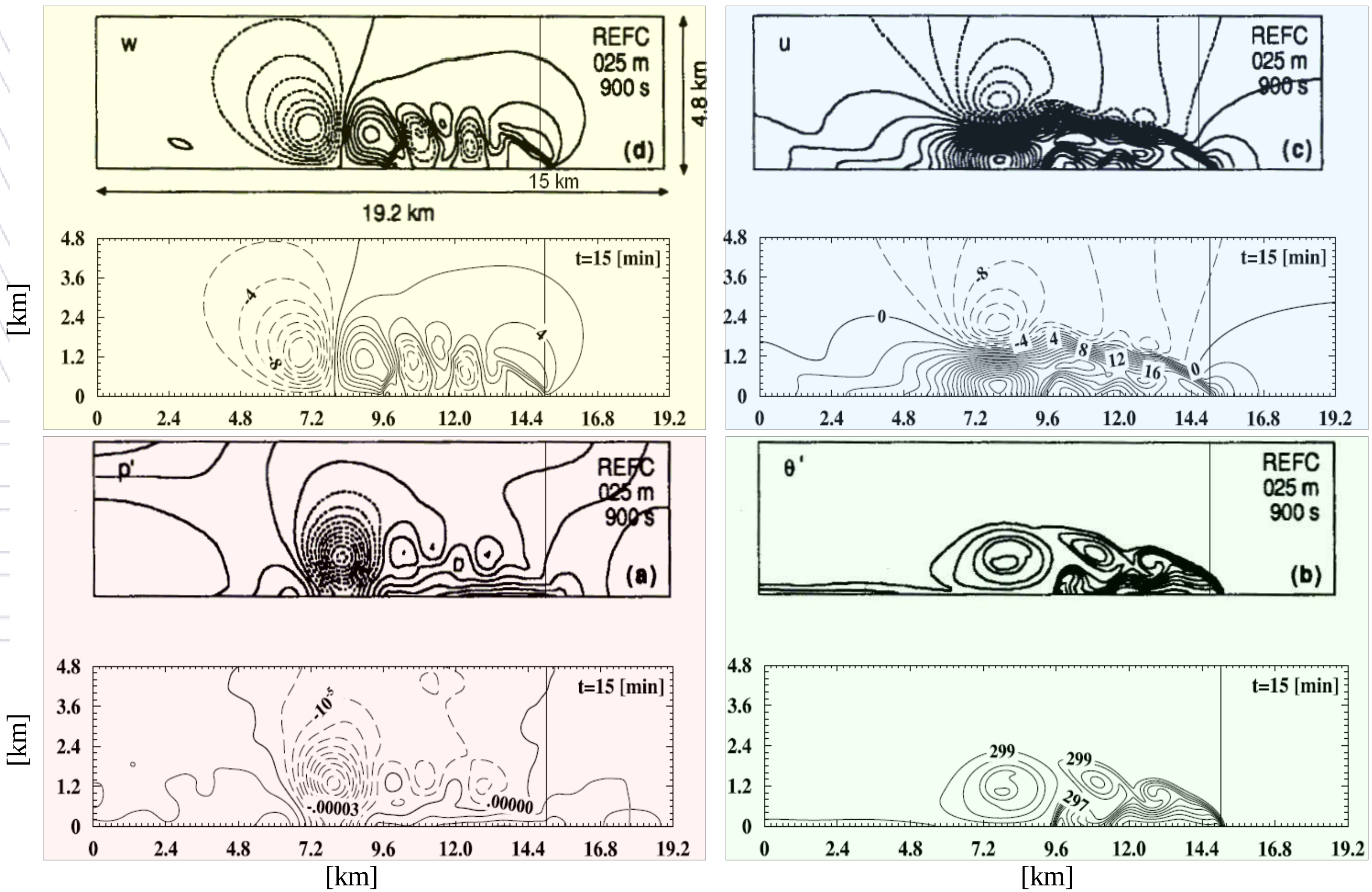
- isentropic atmosphere, $\theta(z)$=const (300K)
- periodic lateral boundaries
- free-slip bottom b.c.
- constant subgrid mixing, $K=75m^2/s$
- domain size 51.2km x 6.4km
- bubble min. temperature -15K
- bubble size 8kmx4km
- no initial flow
- integration time 15min

No analytic solution

## Potential temperature perturbation



# Comparison of velocity (u, w), pressure perturbation (p') and potential temperature perturbation (θ') after 15min.



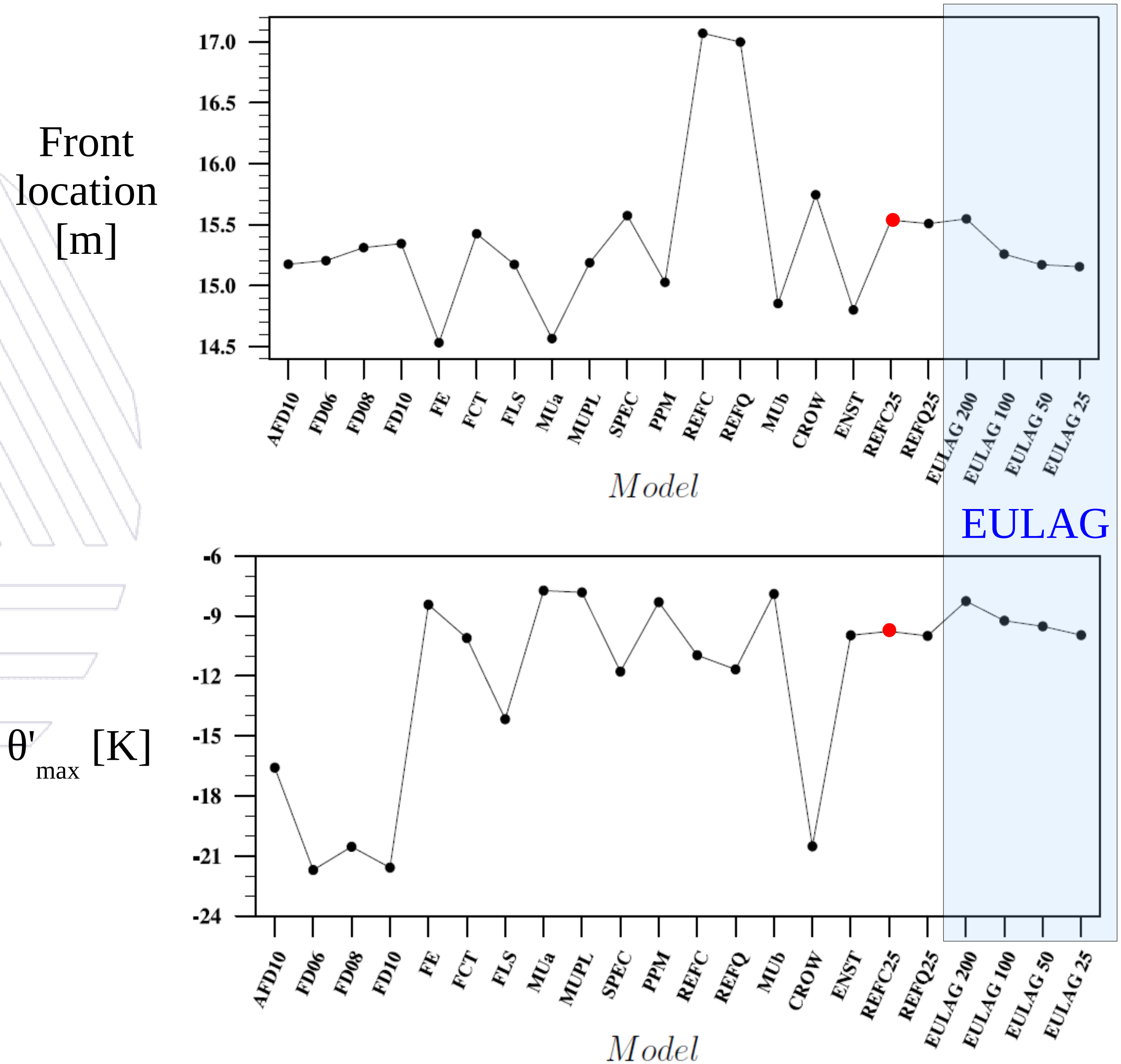

Straka et al. (1993) (fully compress.)

EULAG

Straka et al. (1993) (fully compress.)

EULAG

# EULAG vs ensemble from Straka et al. 1993



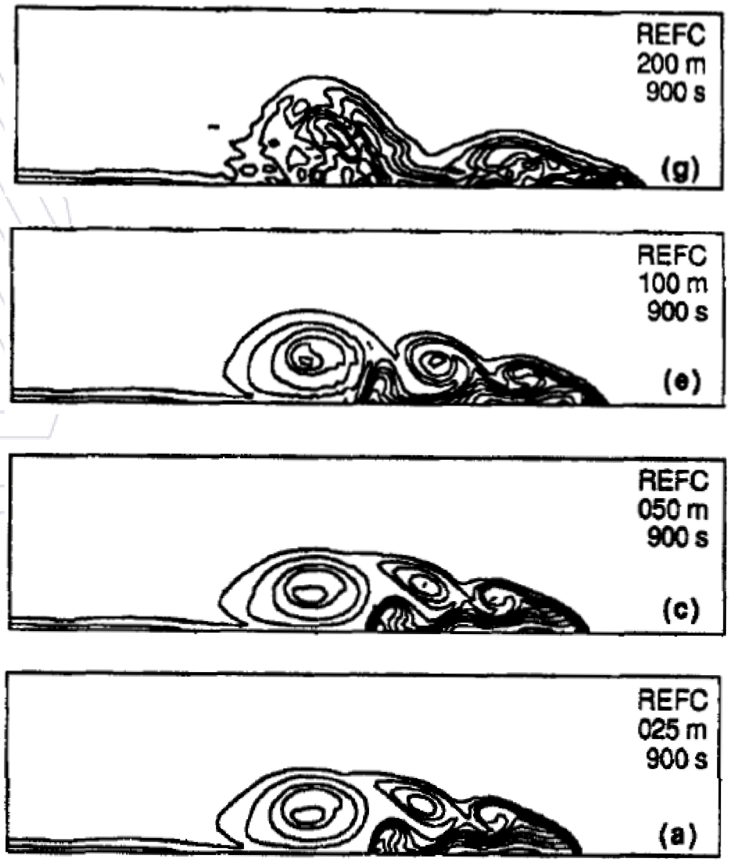

Straka's ensemble includes models:
- incompressible
- quasi-compressible
- anelastic
- fully compressible

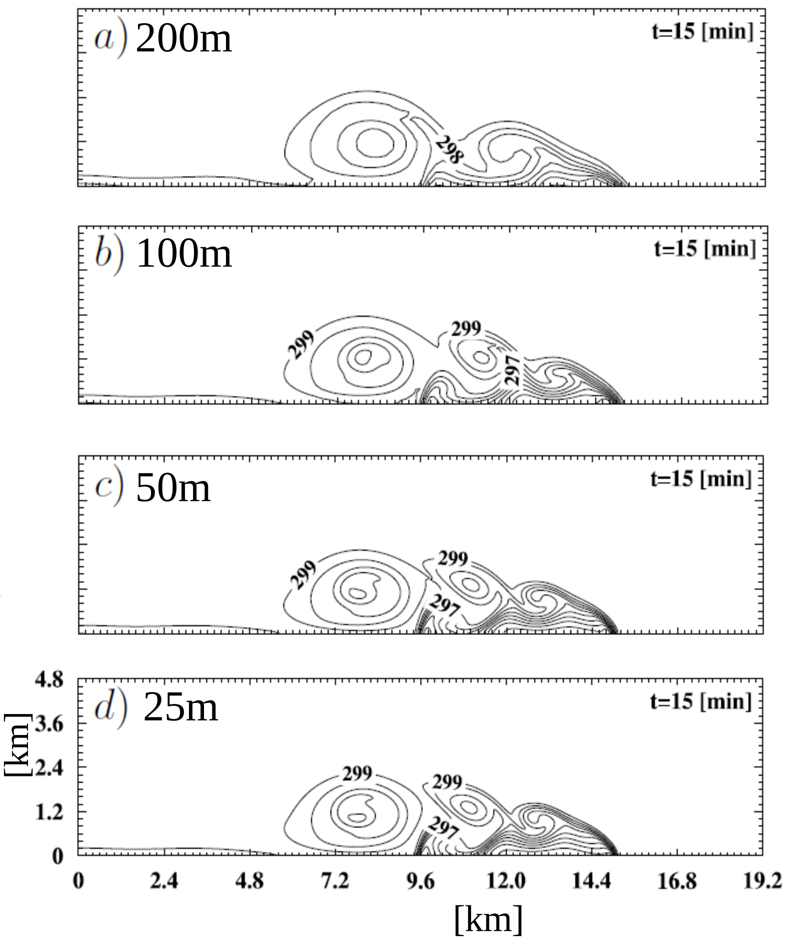
- REFC25 - reference model, compressible, 25m resolution

# Convergence study for resolution

Straka et al. 1993
(reference fully compress.)

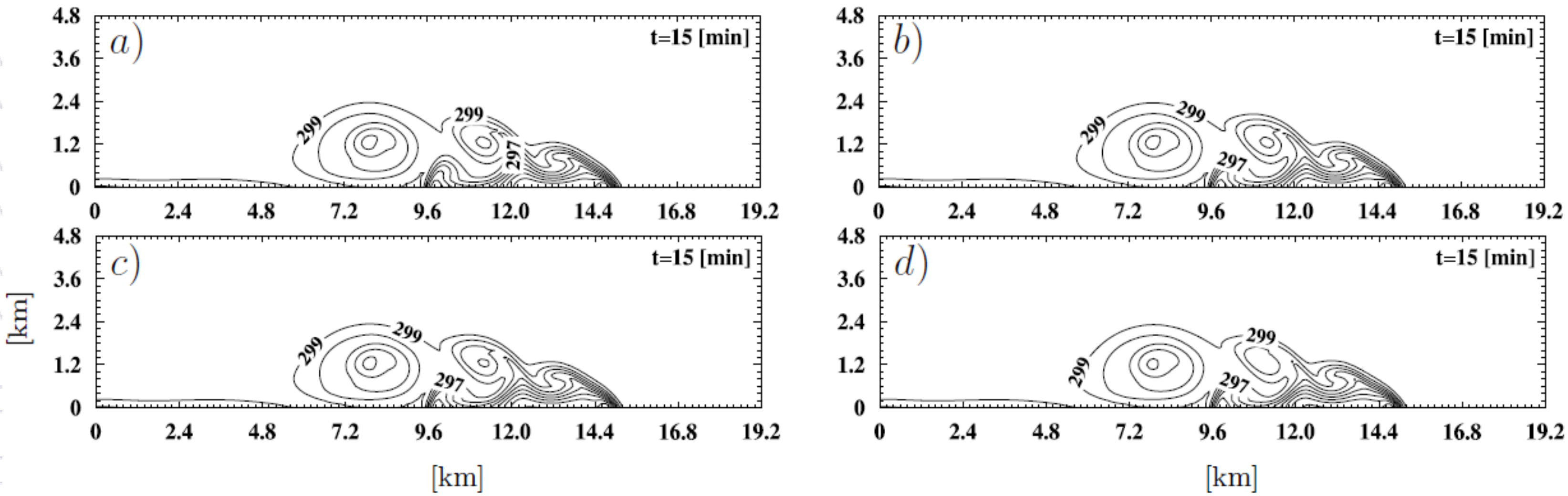
EULAG (2009)
(anelastic)




dx/dz=1

# Dependence on Courant number
## (resolution 100m)




| | Front location [m] | |
|---|---|---|
| *a)* | dt | 15279 |
| *b)* | 2dt | 15276 |
| *c)* | 4dt | 15269 |
| *d)* | 8dt | 15260 |

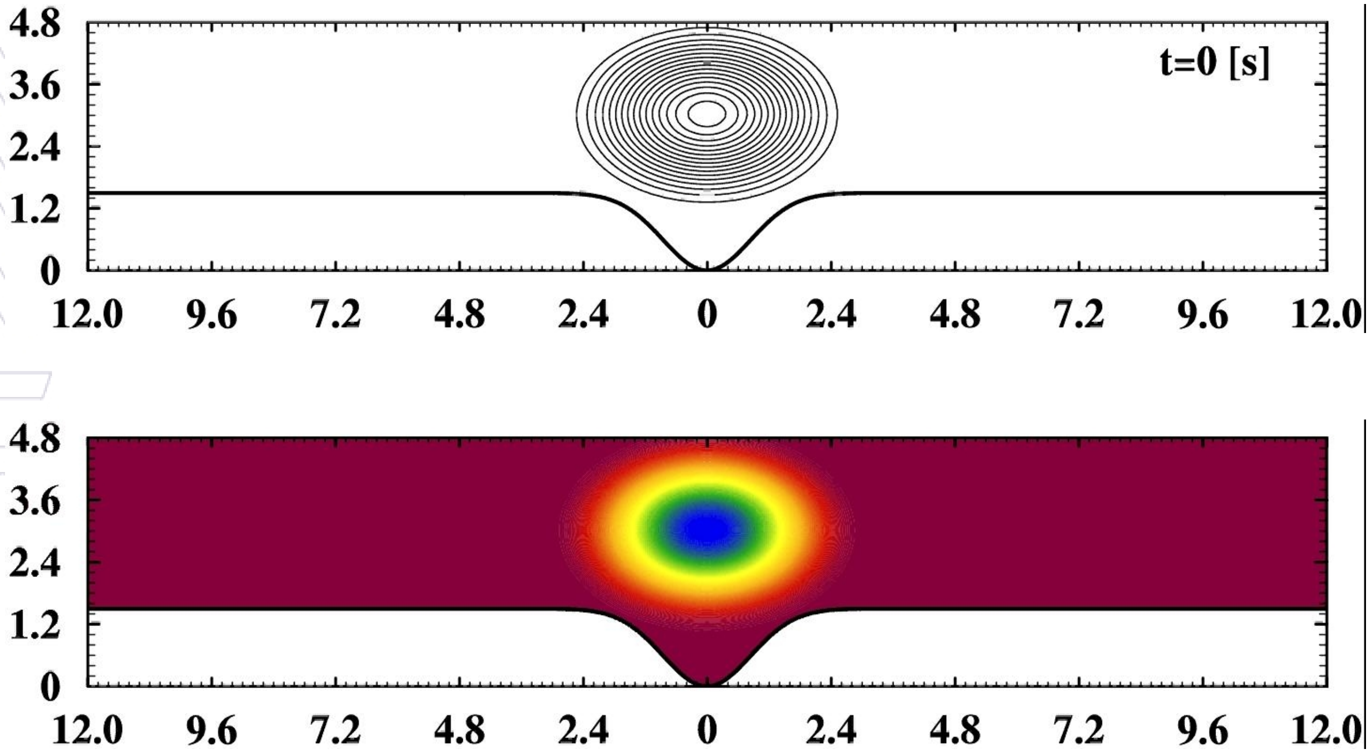
error ~0.12%

We tested also dependence on:
- Prandtl number
- turbulence diffusion coeff.
- different numerical schemes
- various density profiles

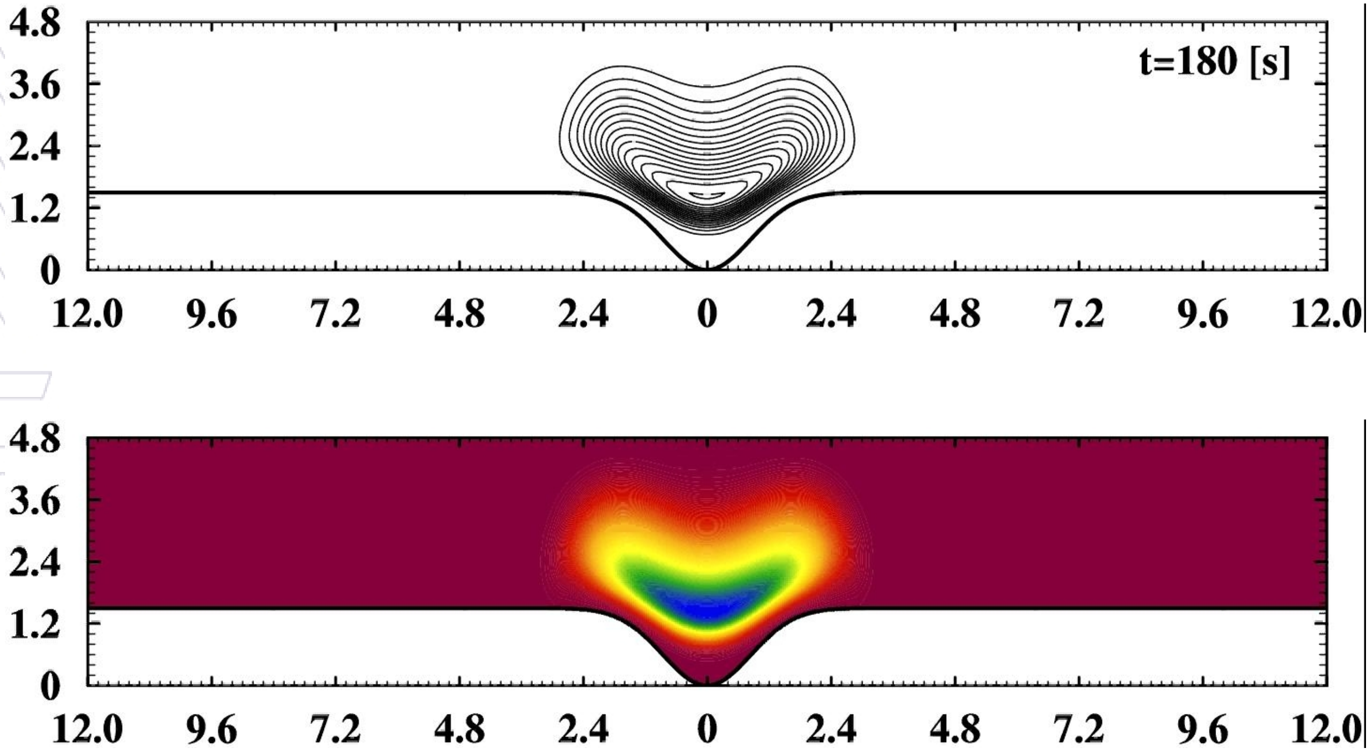
# Additional qualitative tests involving influence of orography

- gaussian valley
- gaussian mountain
- sinusoidal orography

# Gaussian valley



# Gaussian valley



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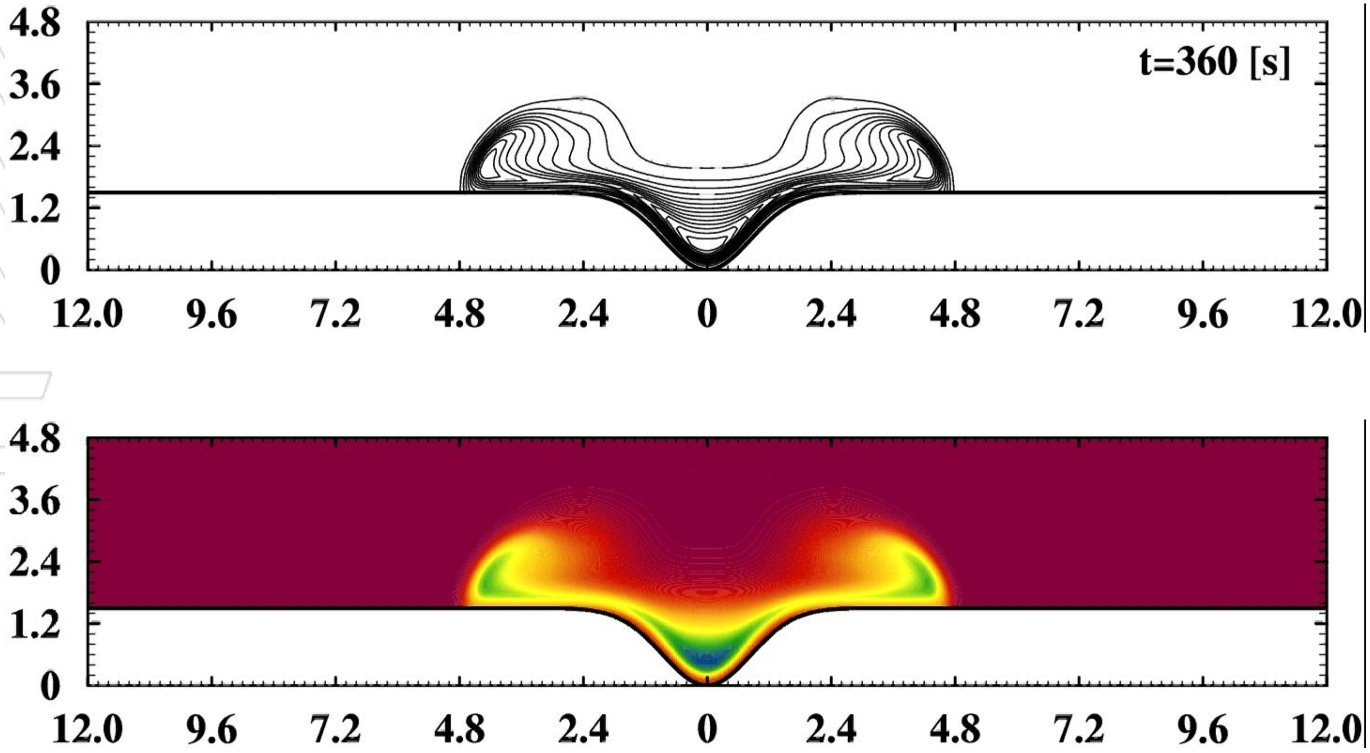
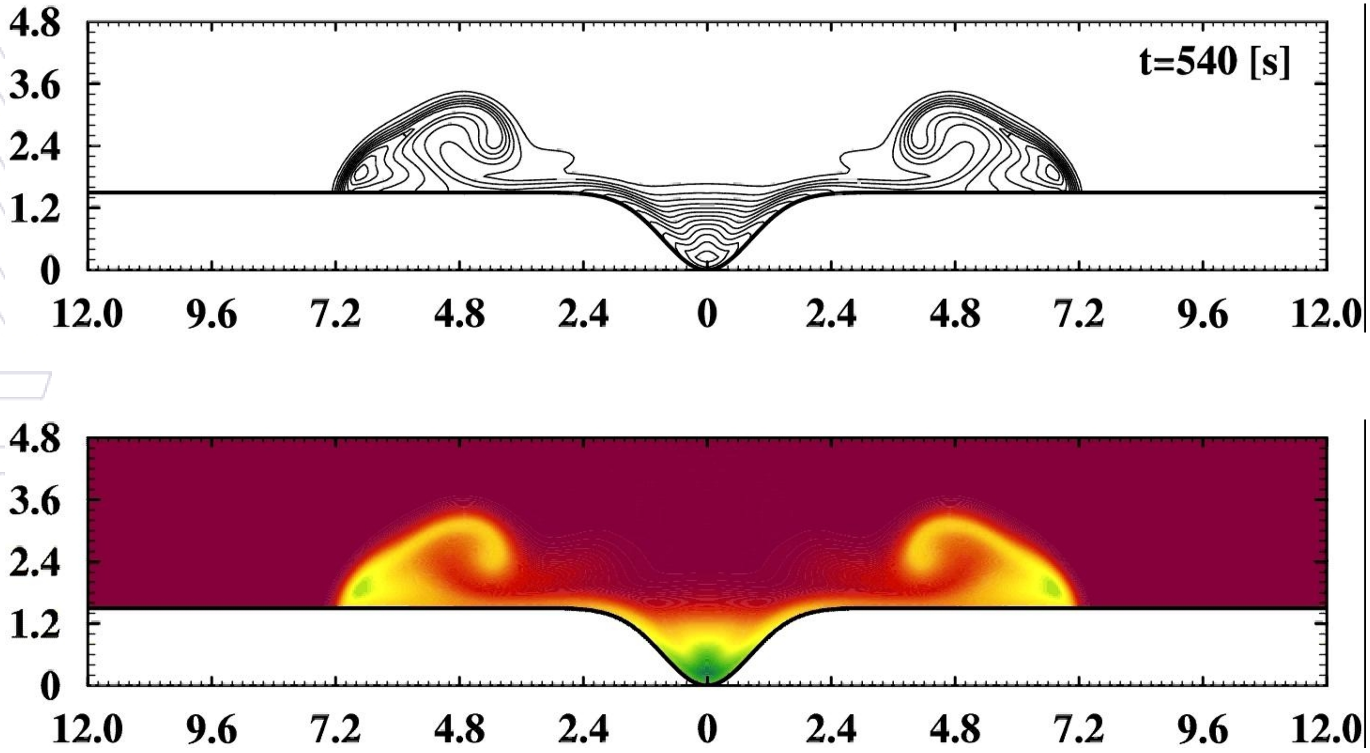
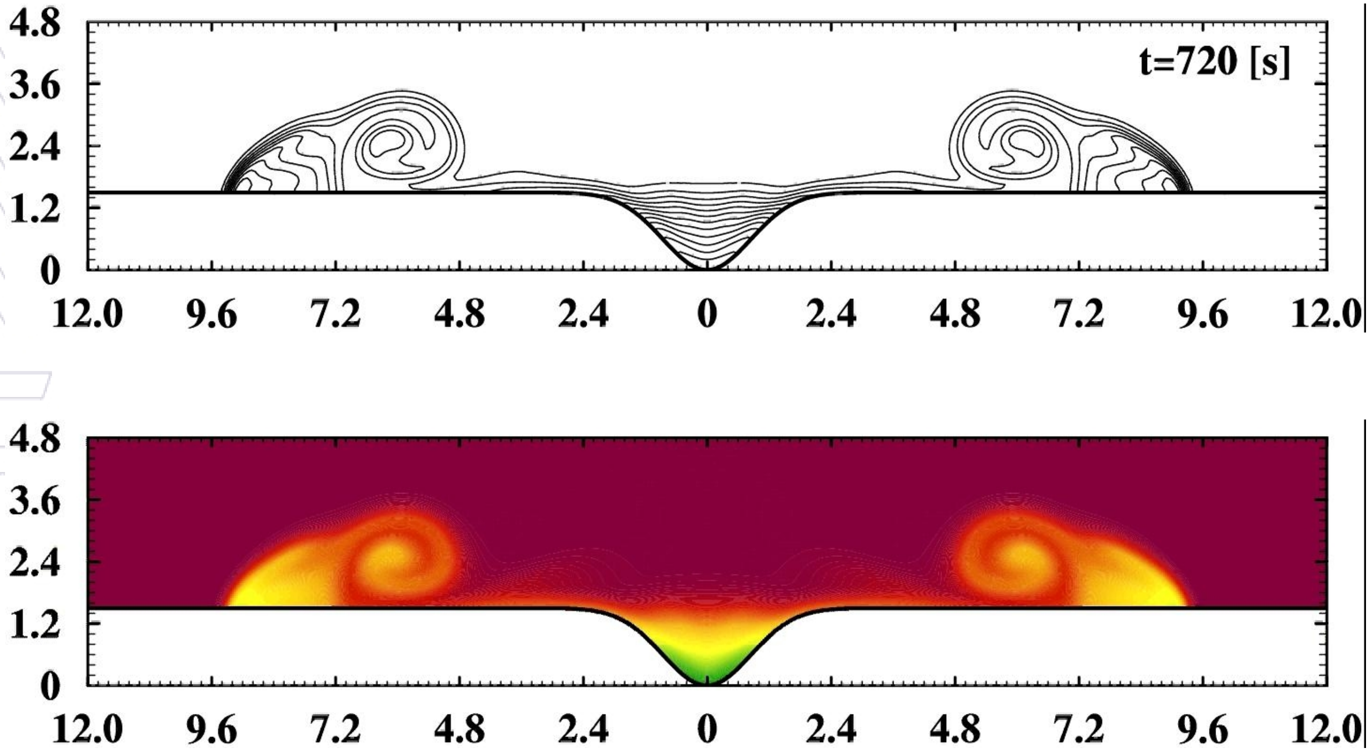


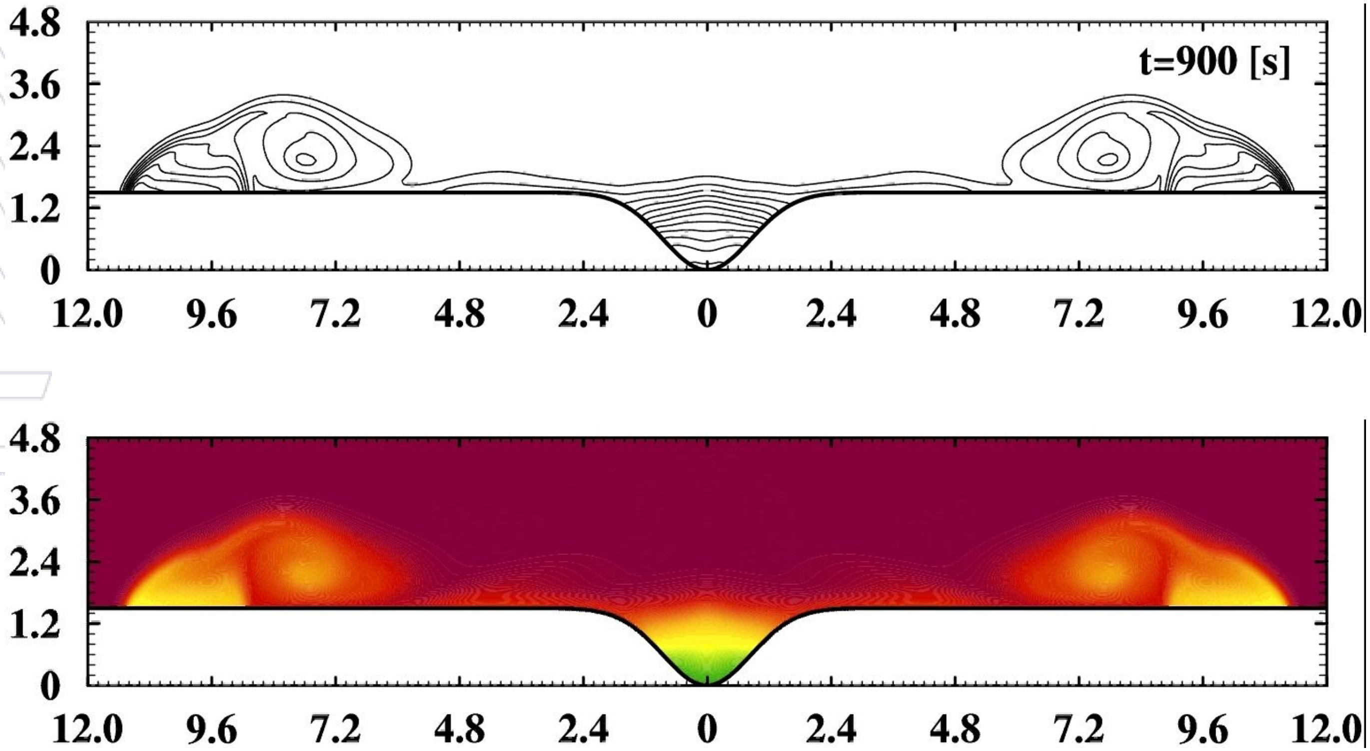
# Gaussian valley



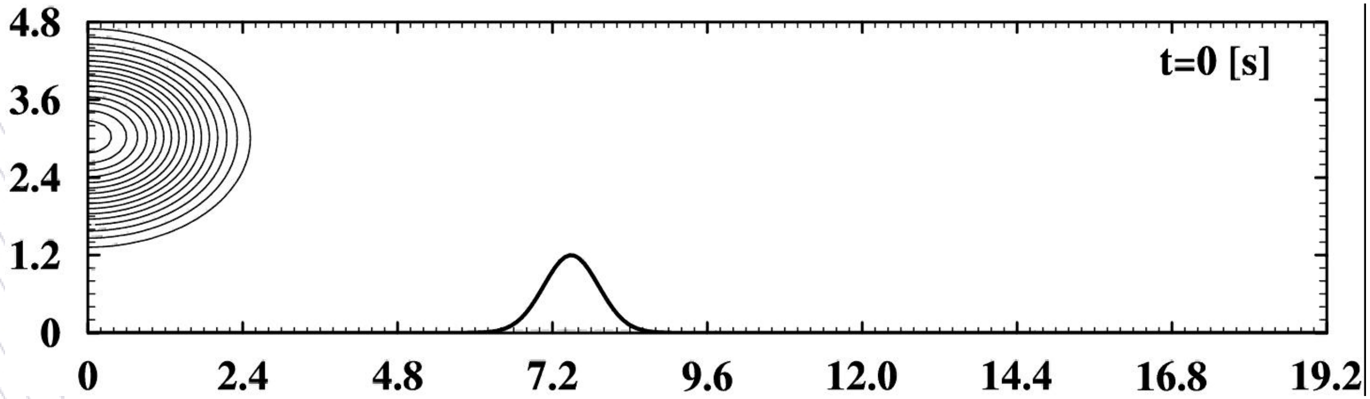
# Gaussian valley

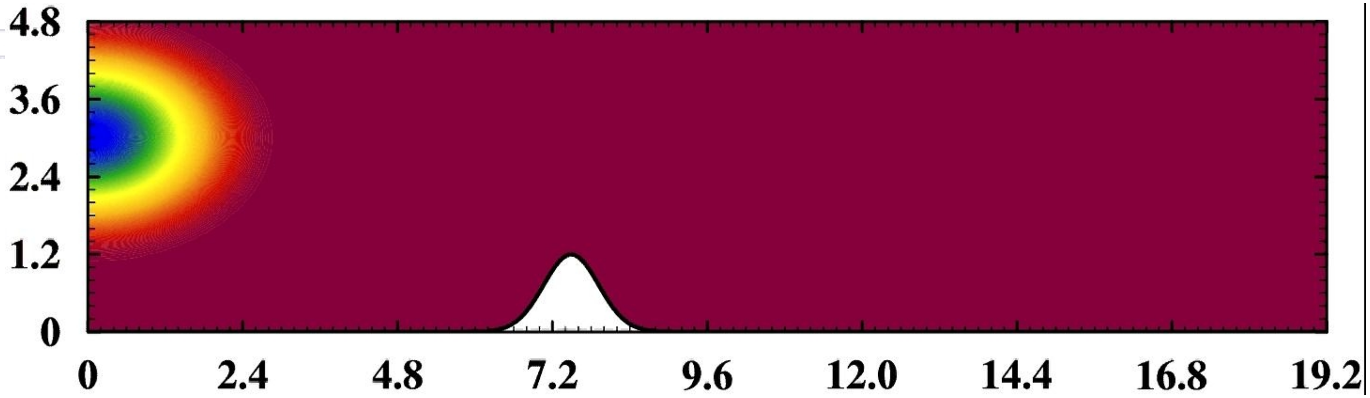


# Gaussian valley

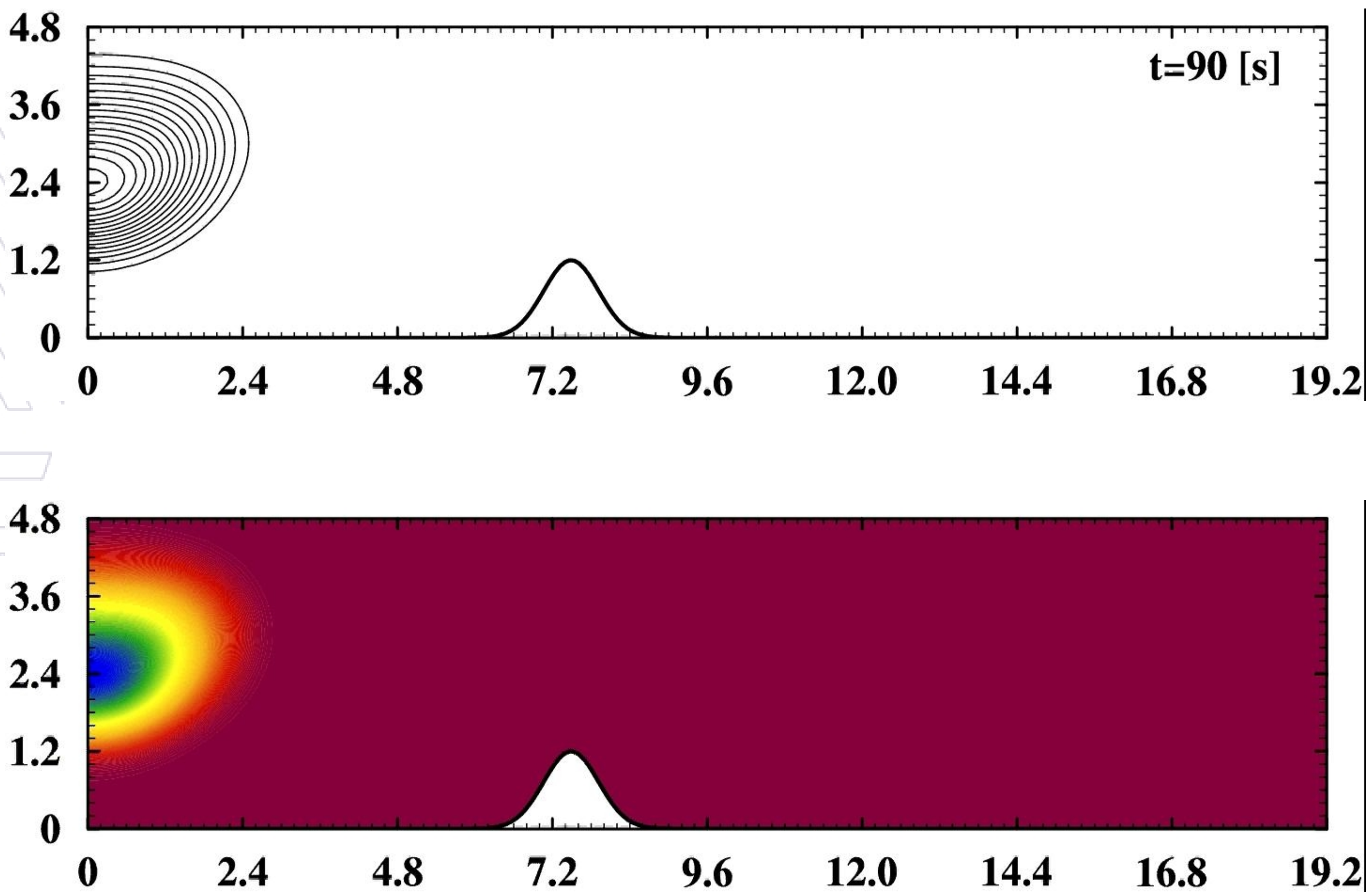


# Gaussian mountain

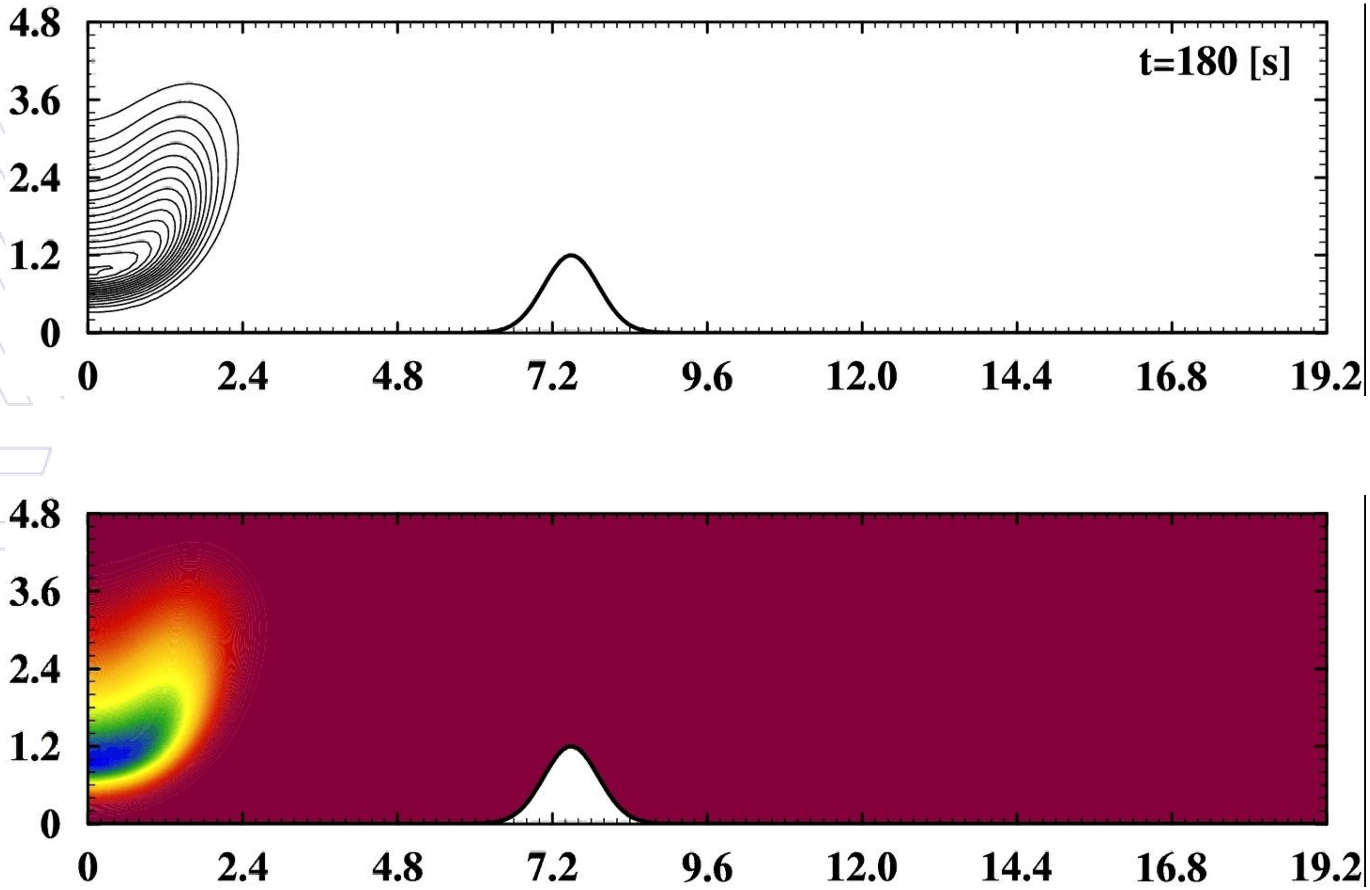


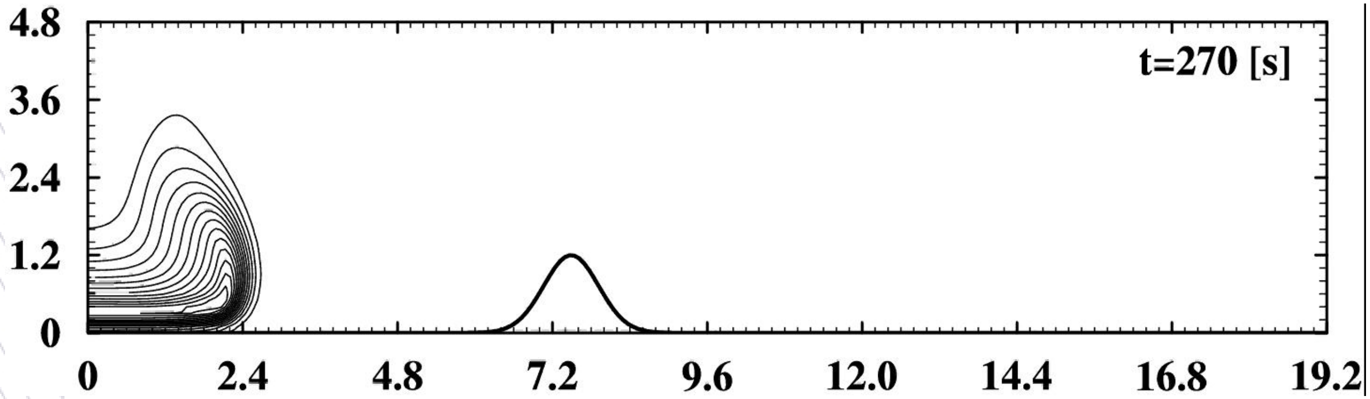
## Gaussian mountain

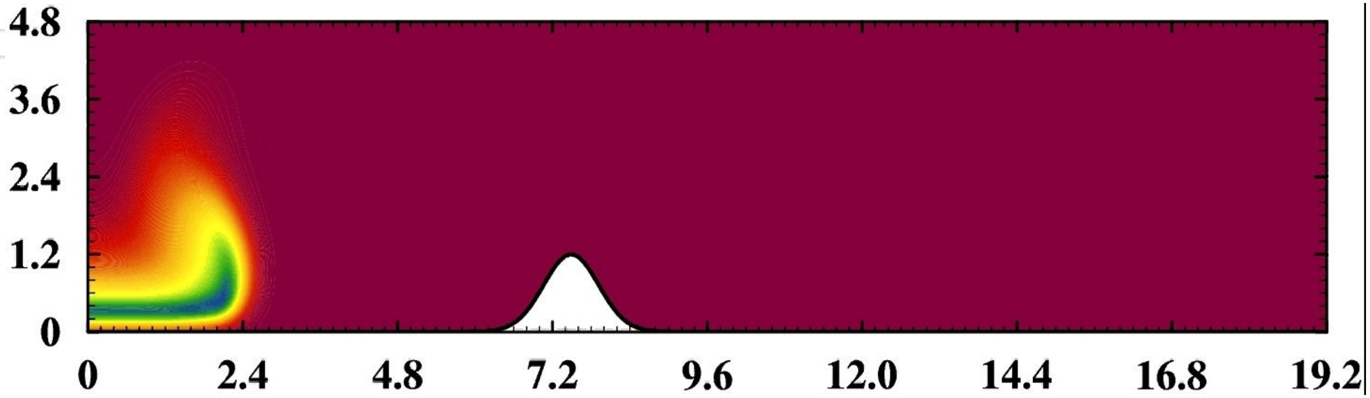


# Gaussian mountain



# Gaussian mountain



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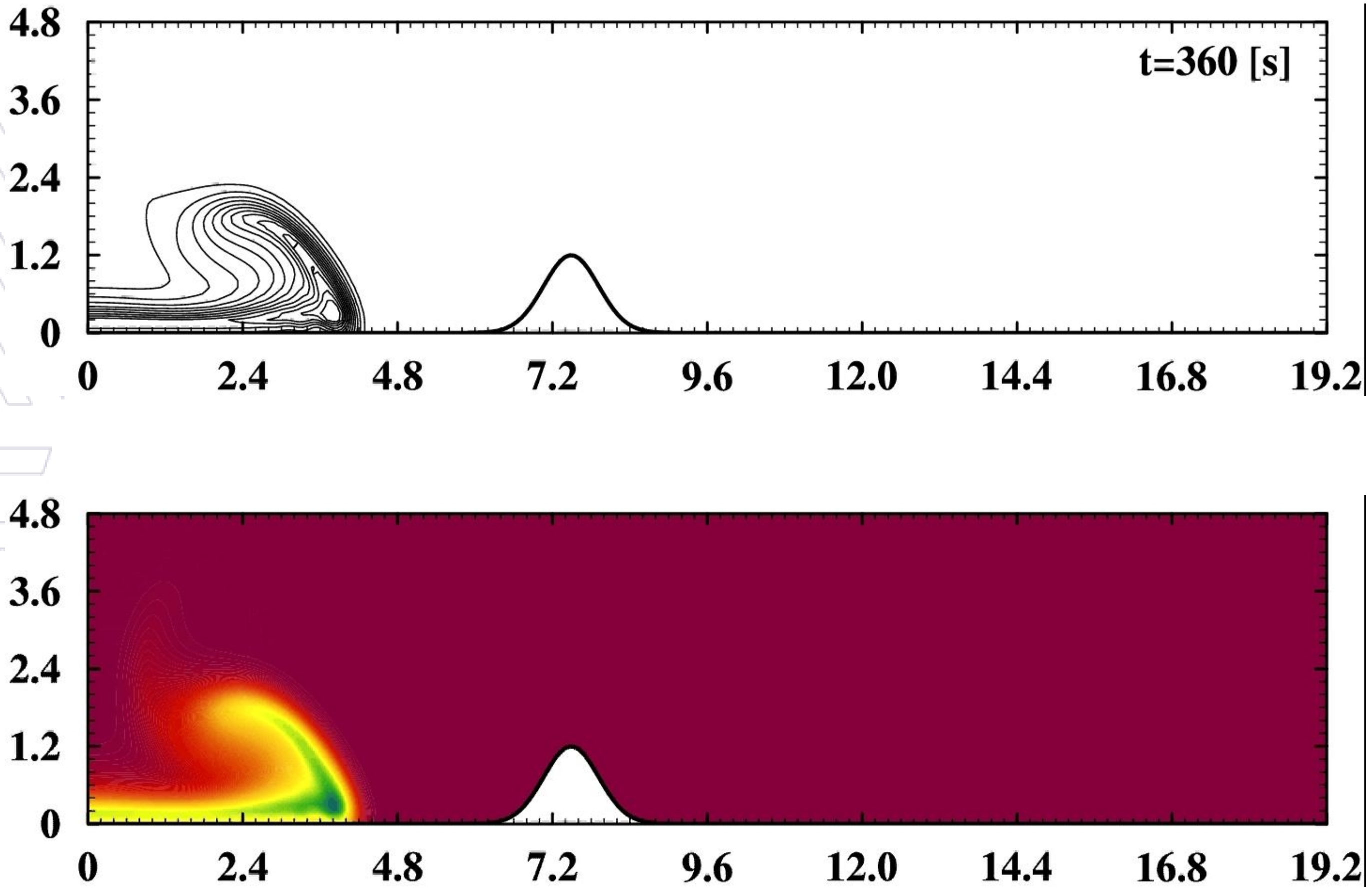

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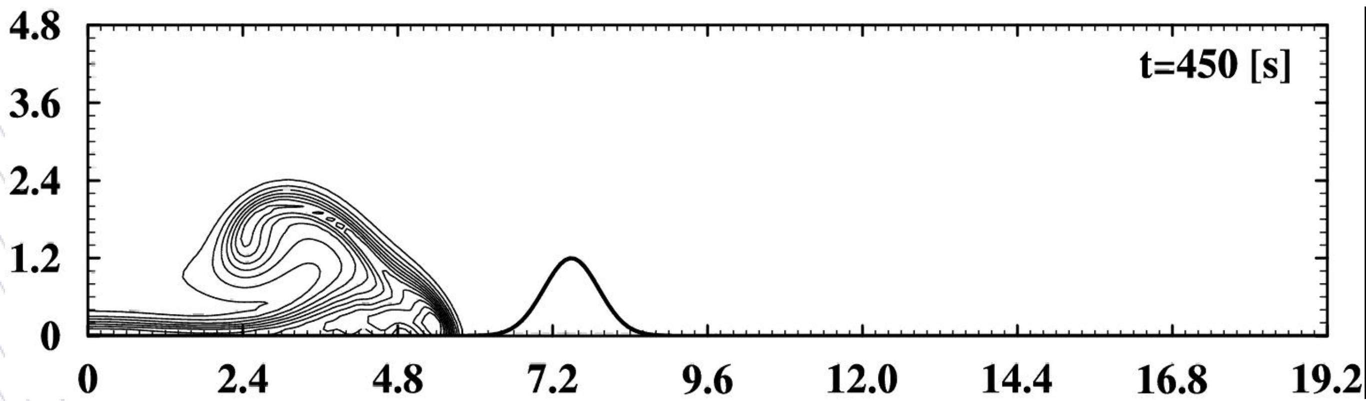


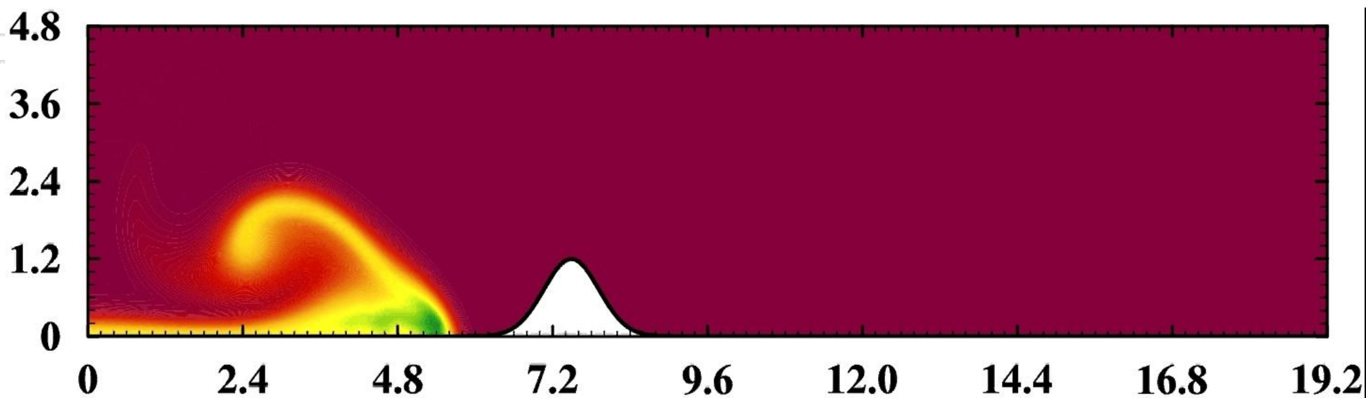

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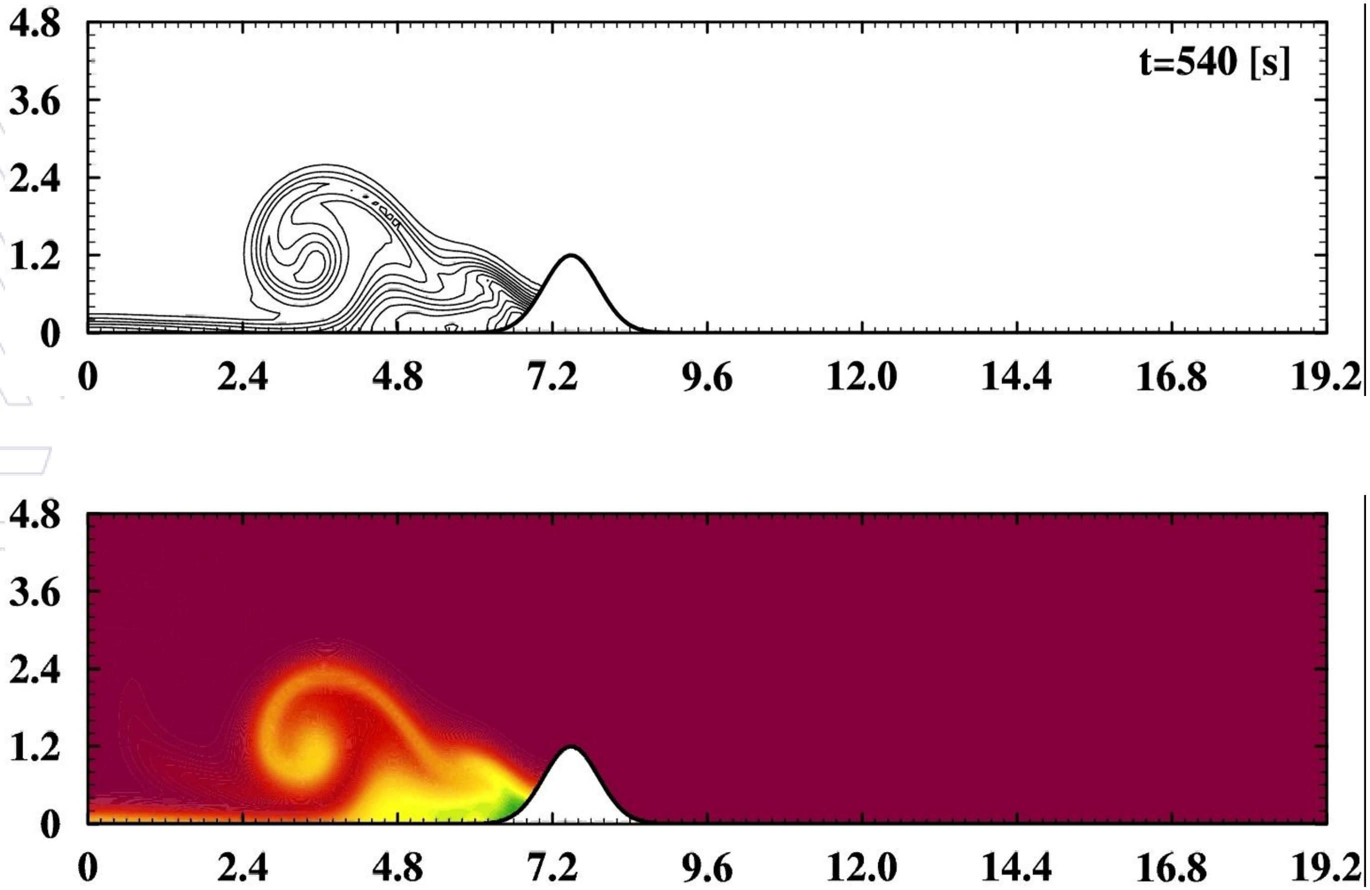
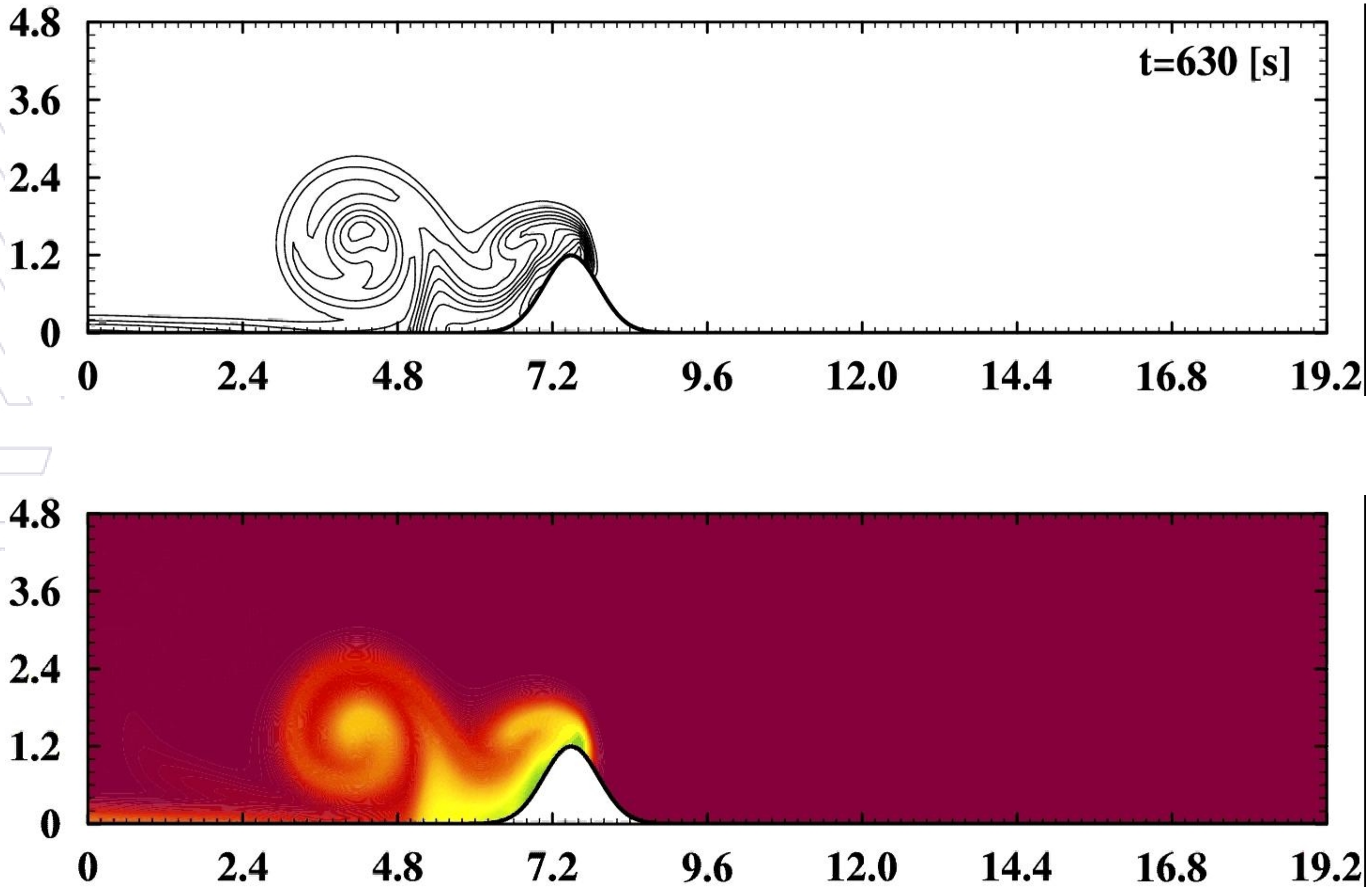


## Gaussian mountain



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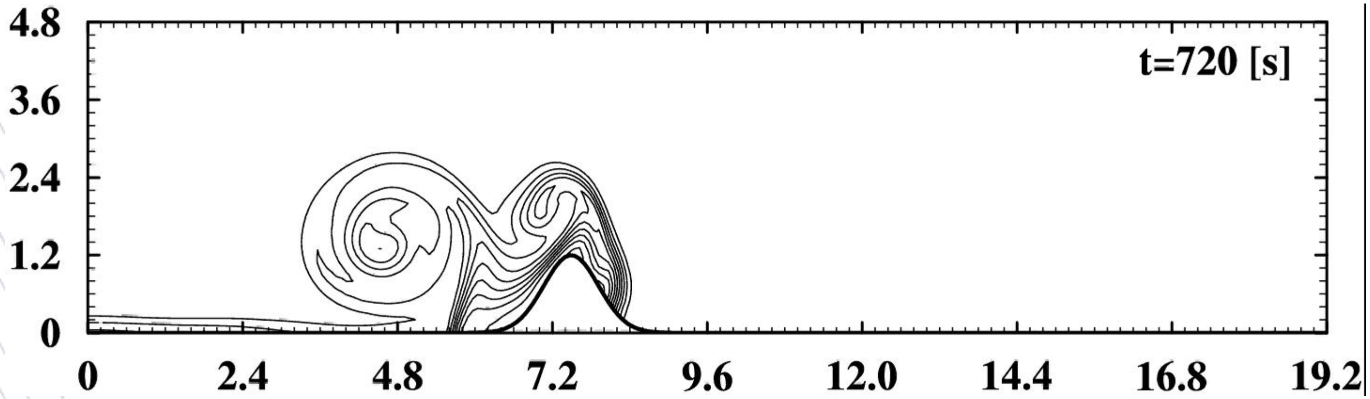
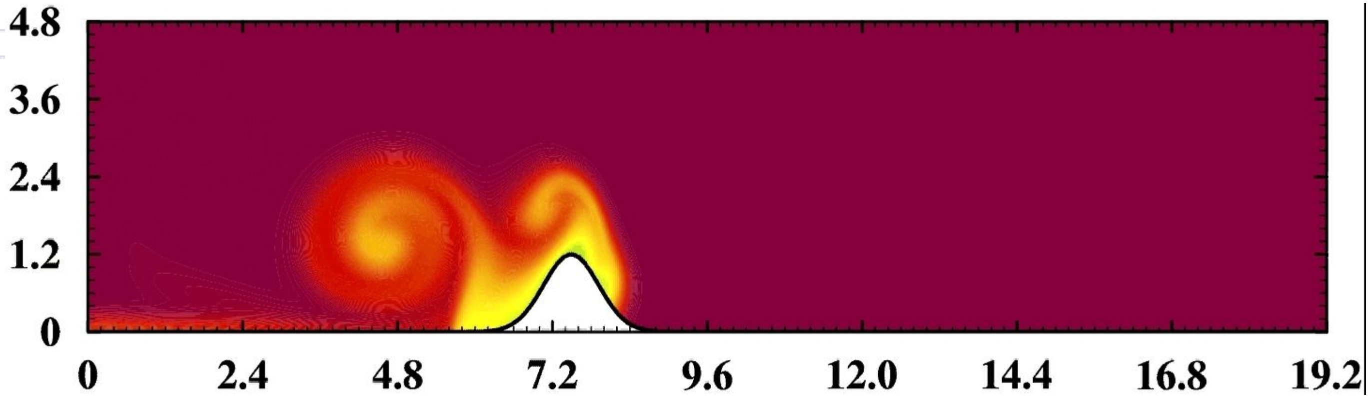
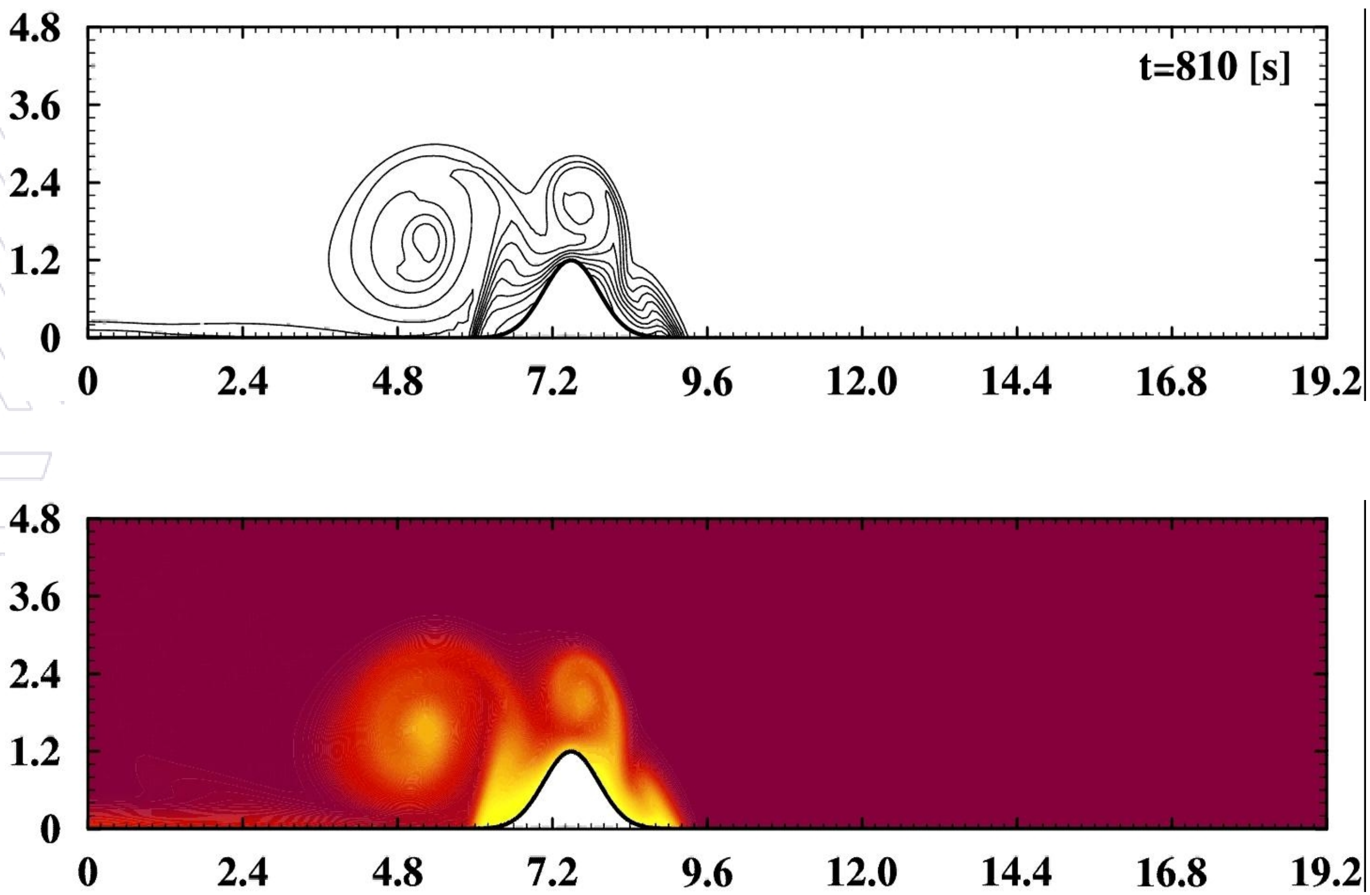


Gaussian mountain



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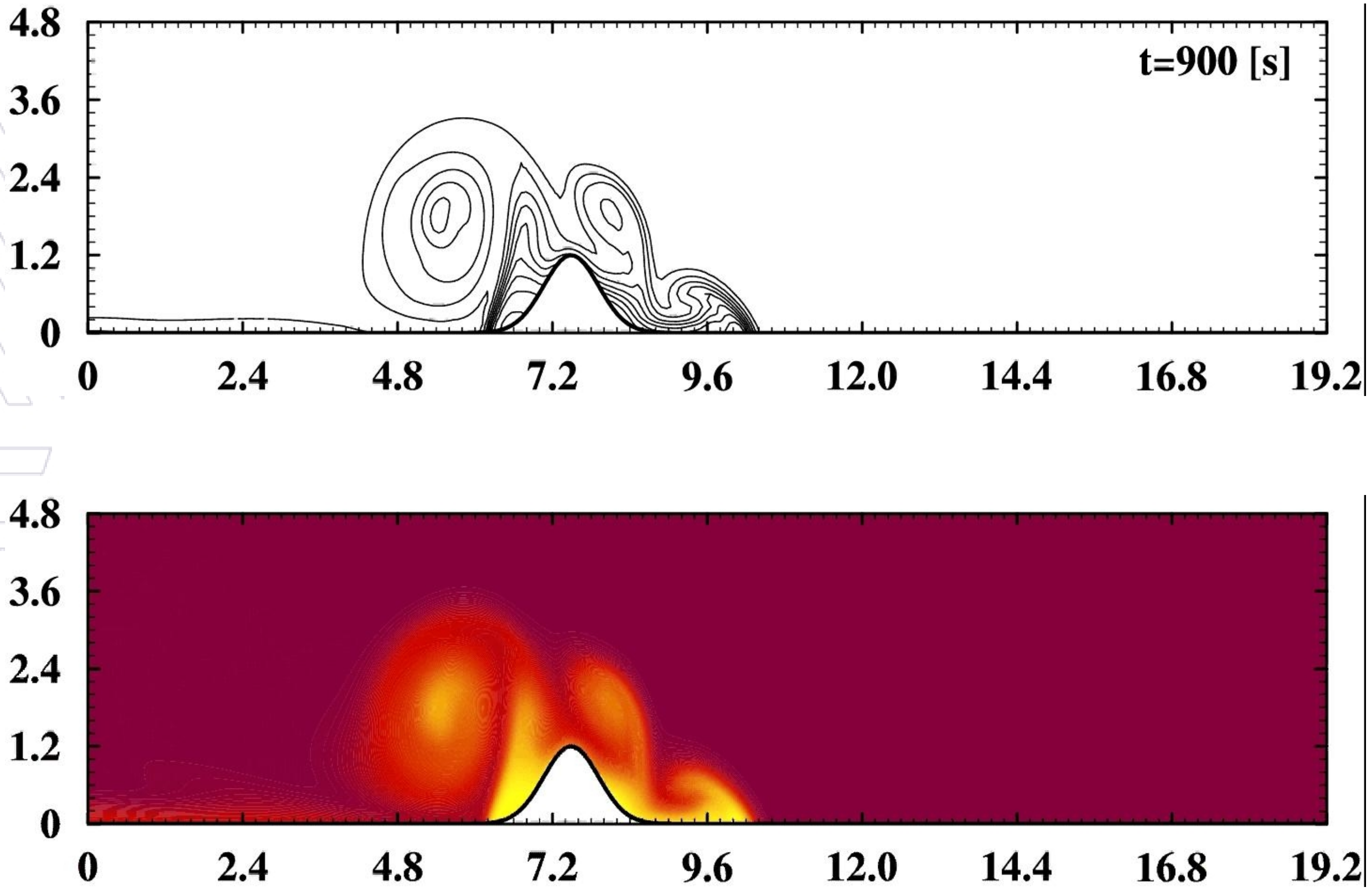

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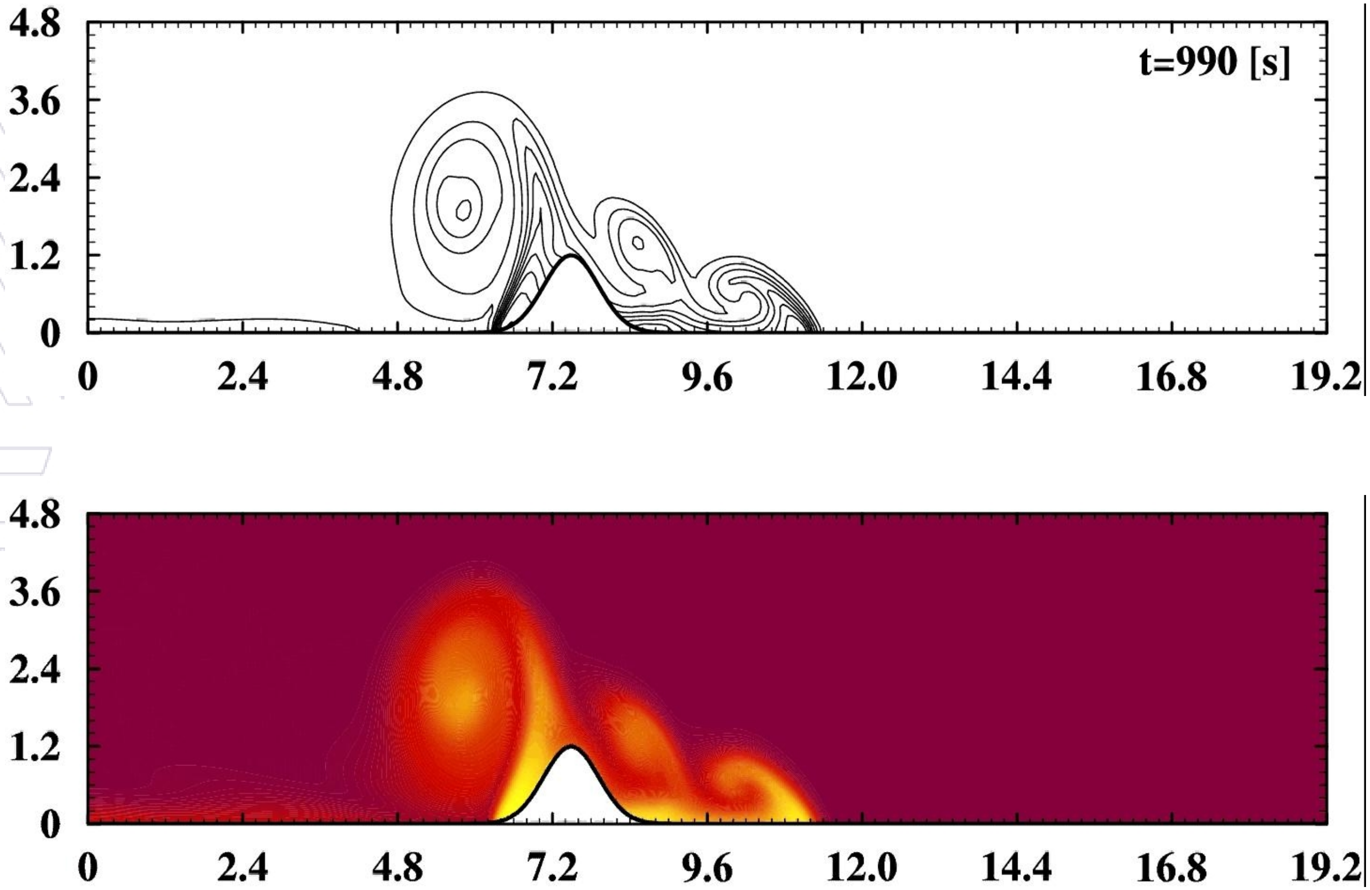

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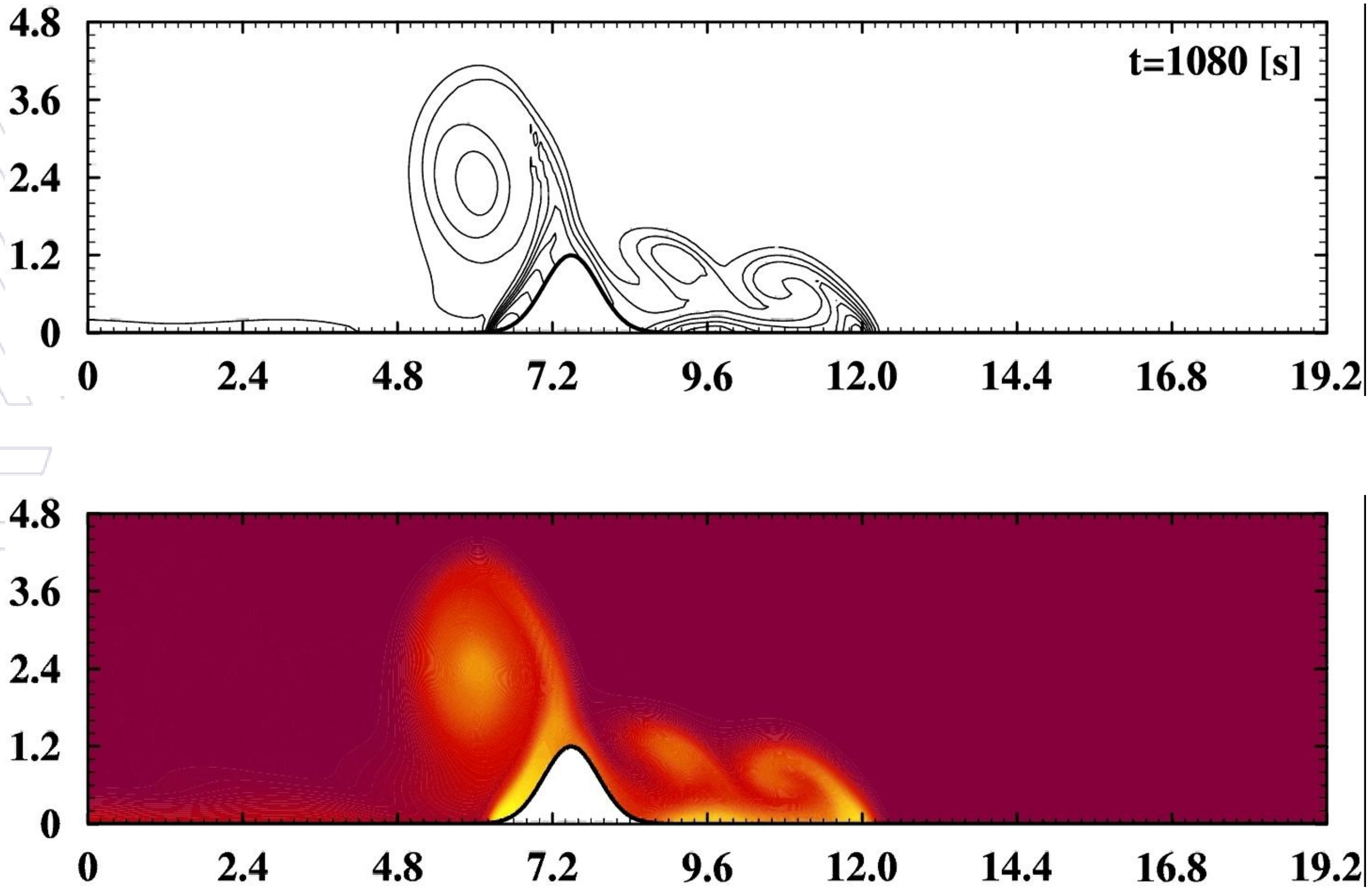

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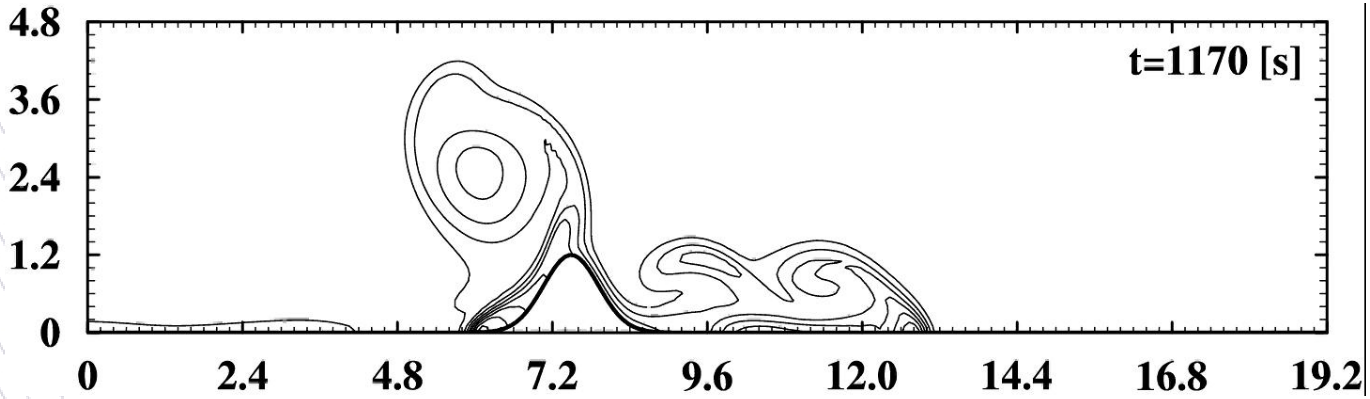


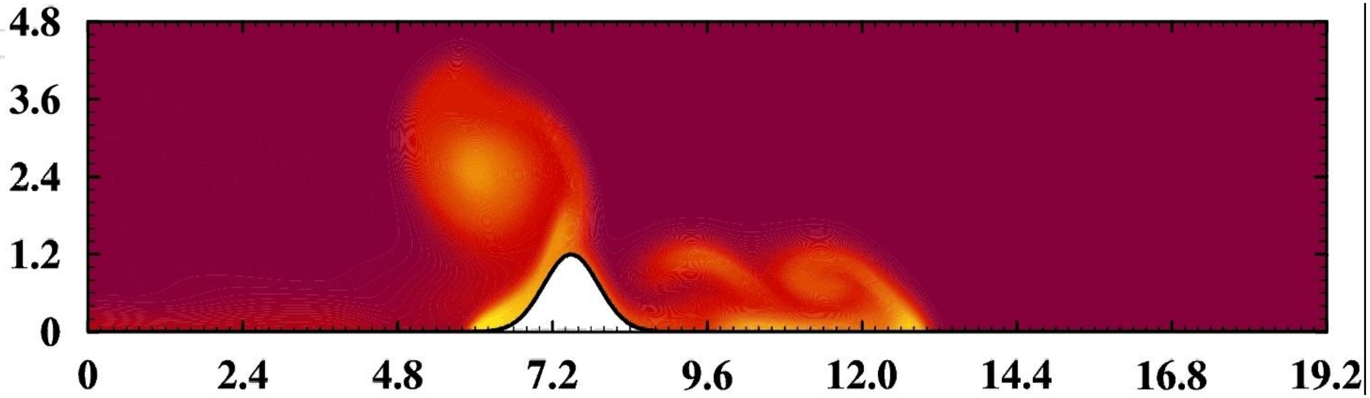

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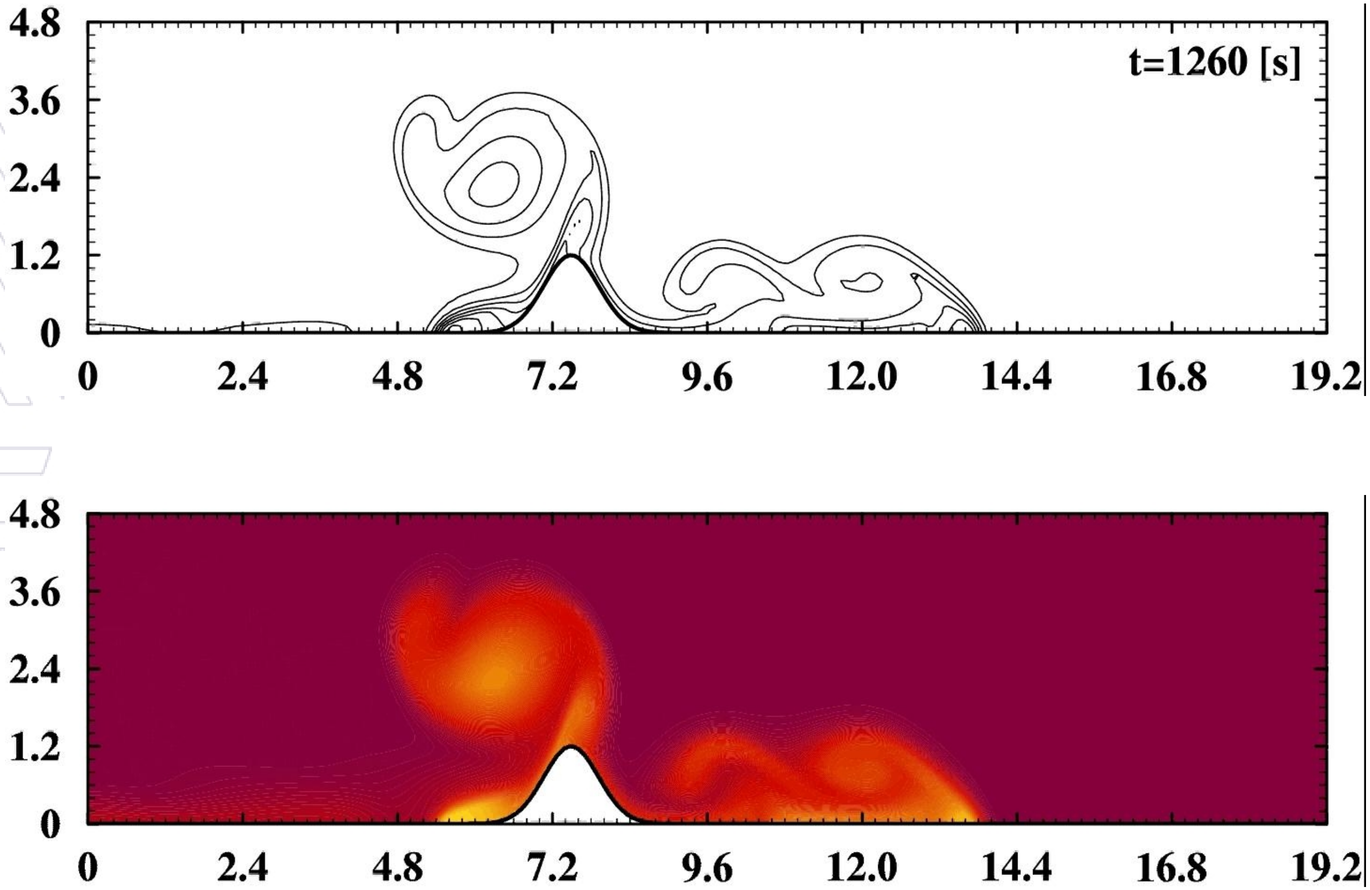

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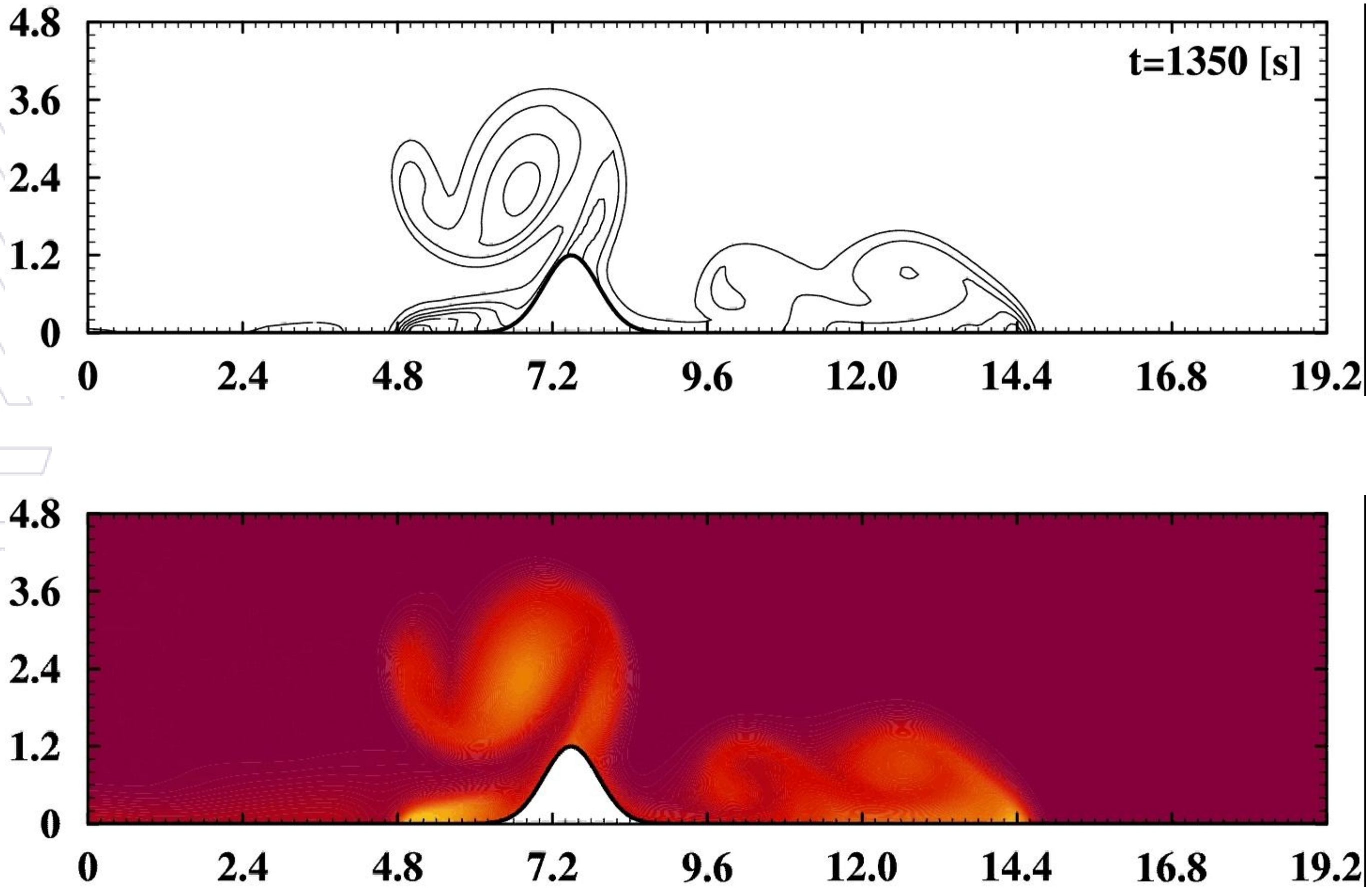

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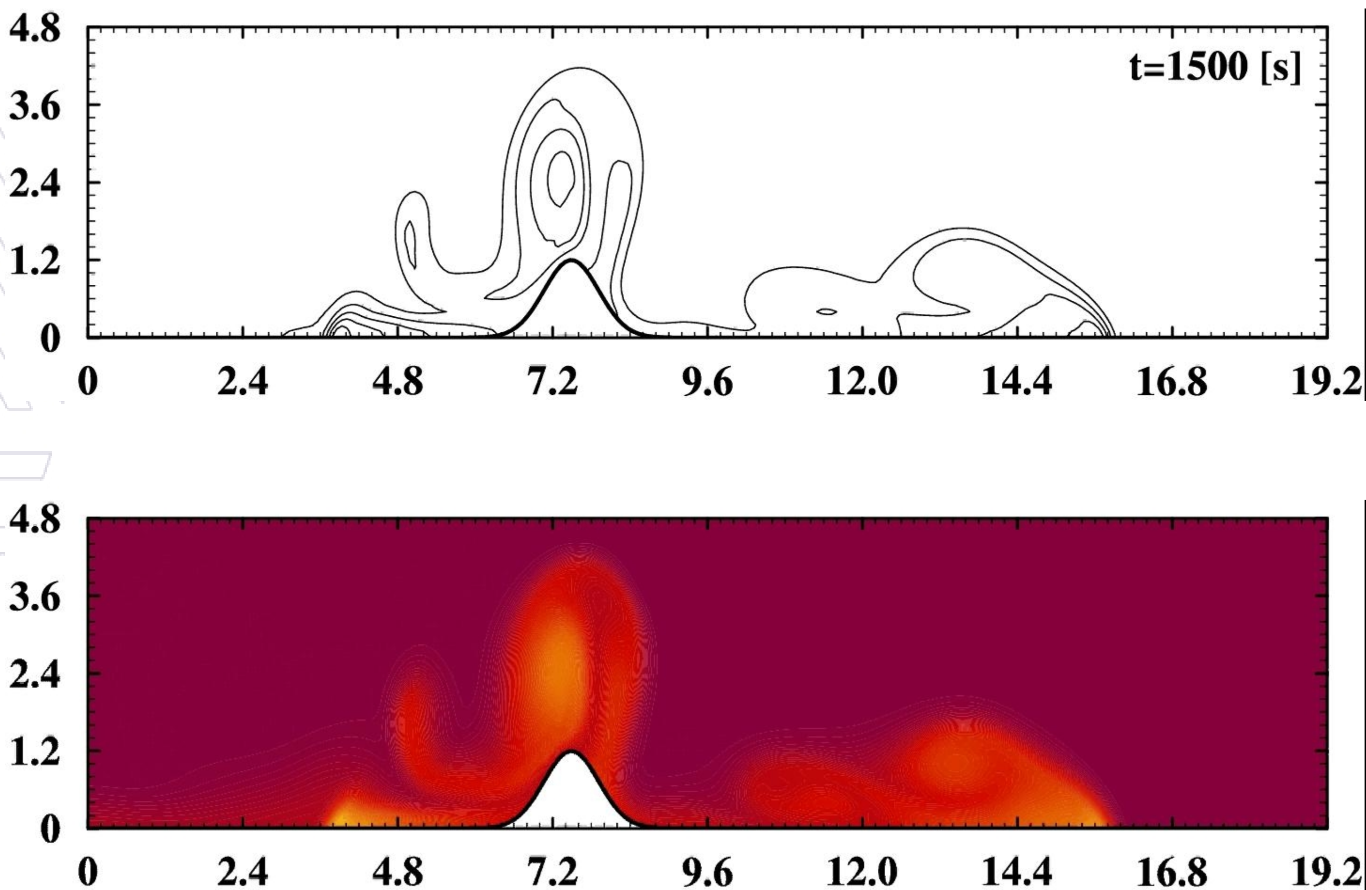
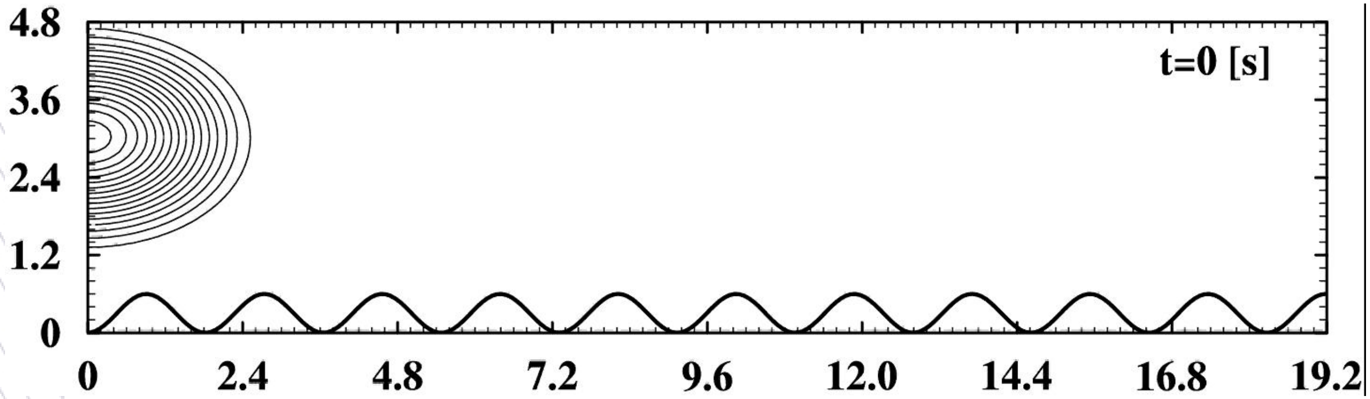
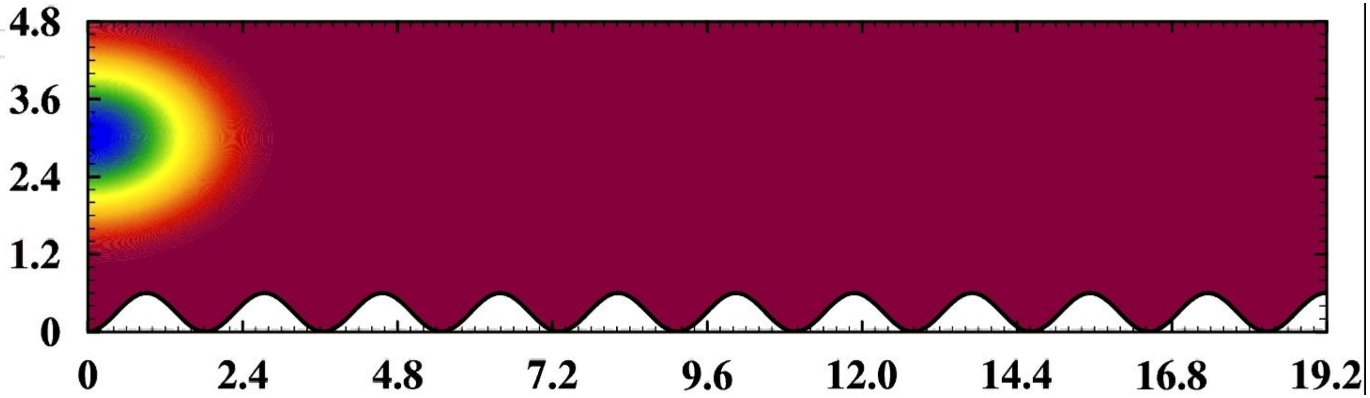


## Sinusoidal orography



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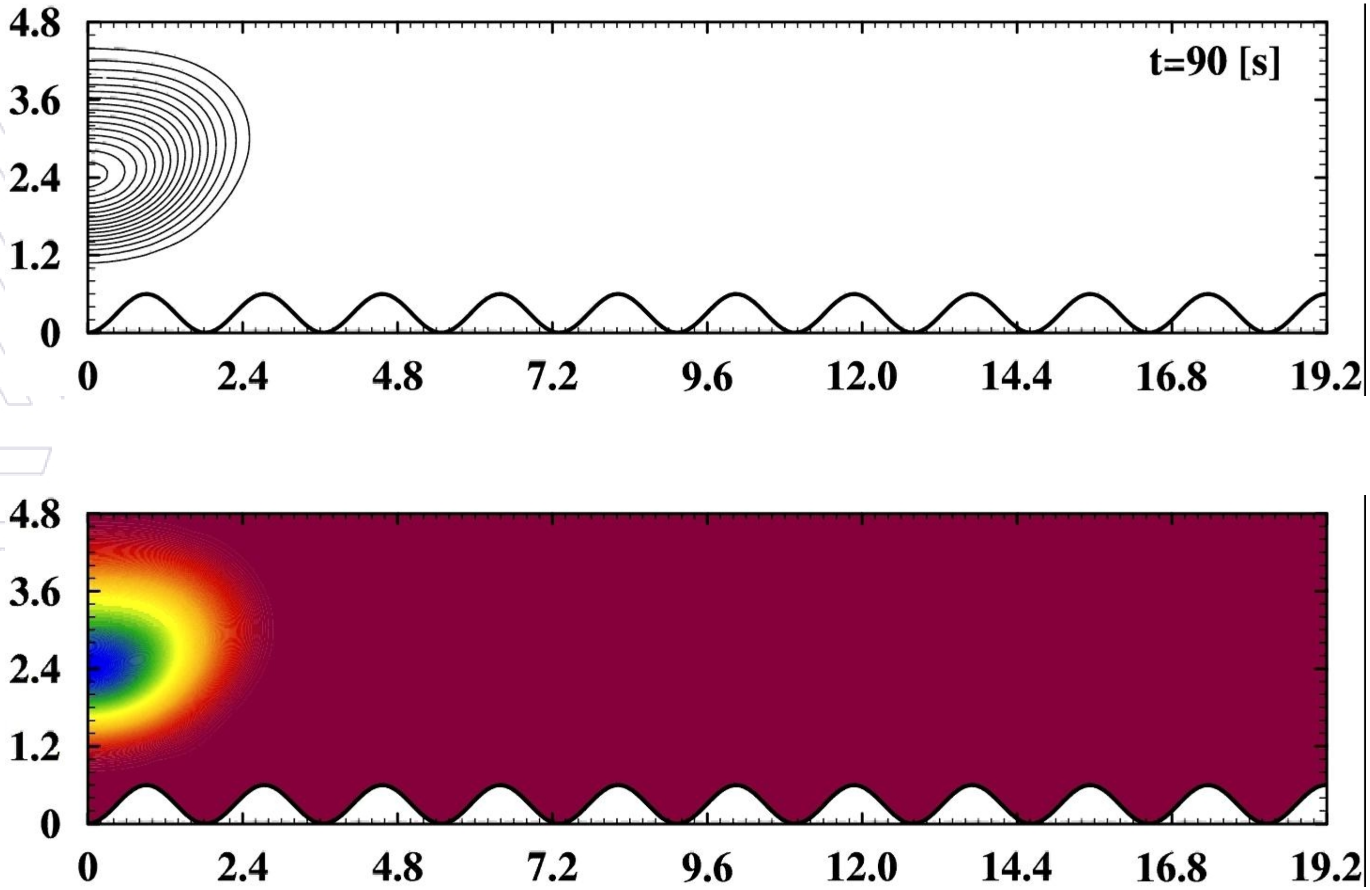

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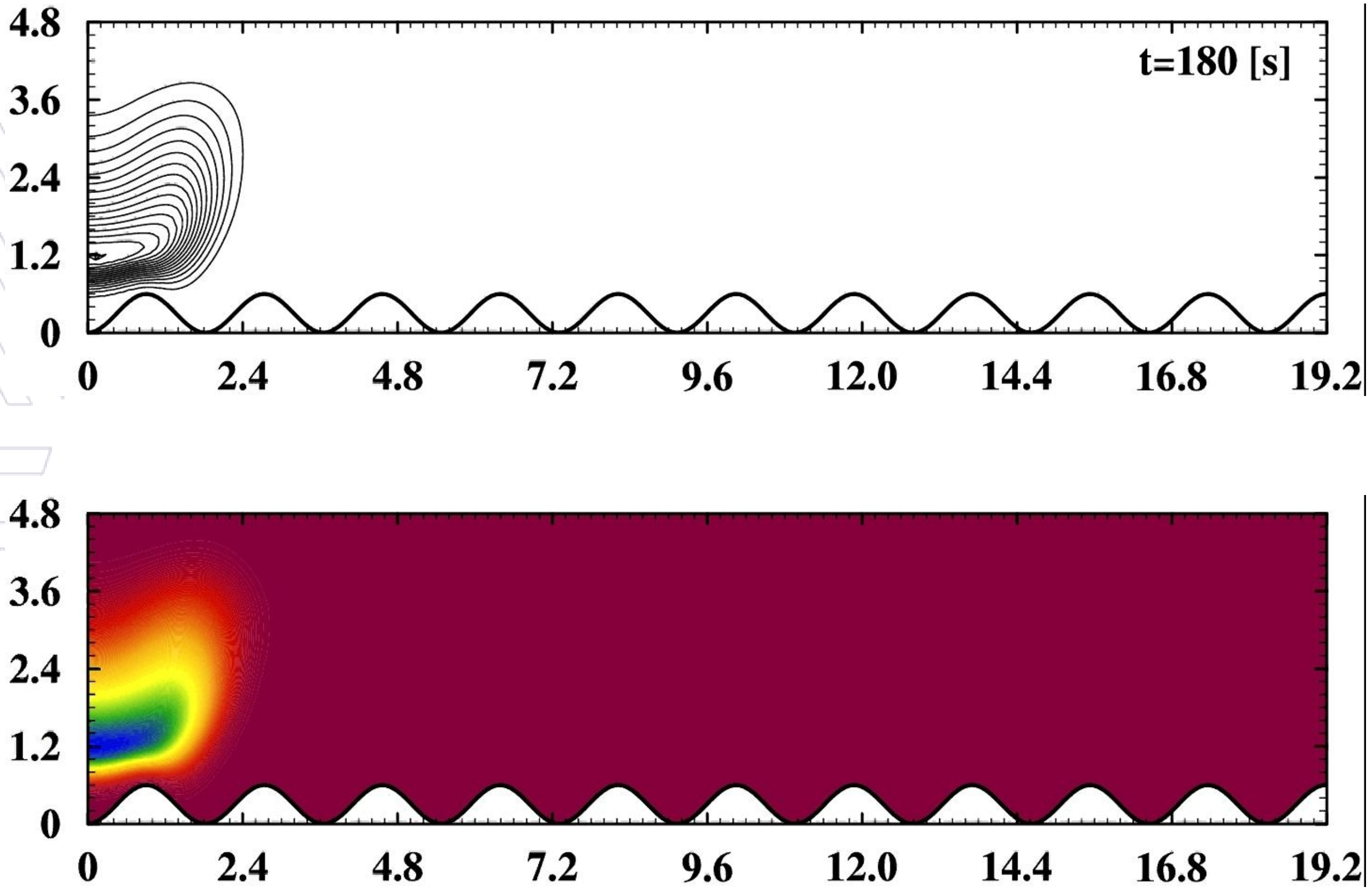
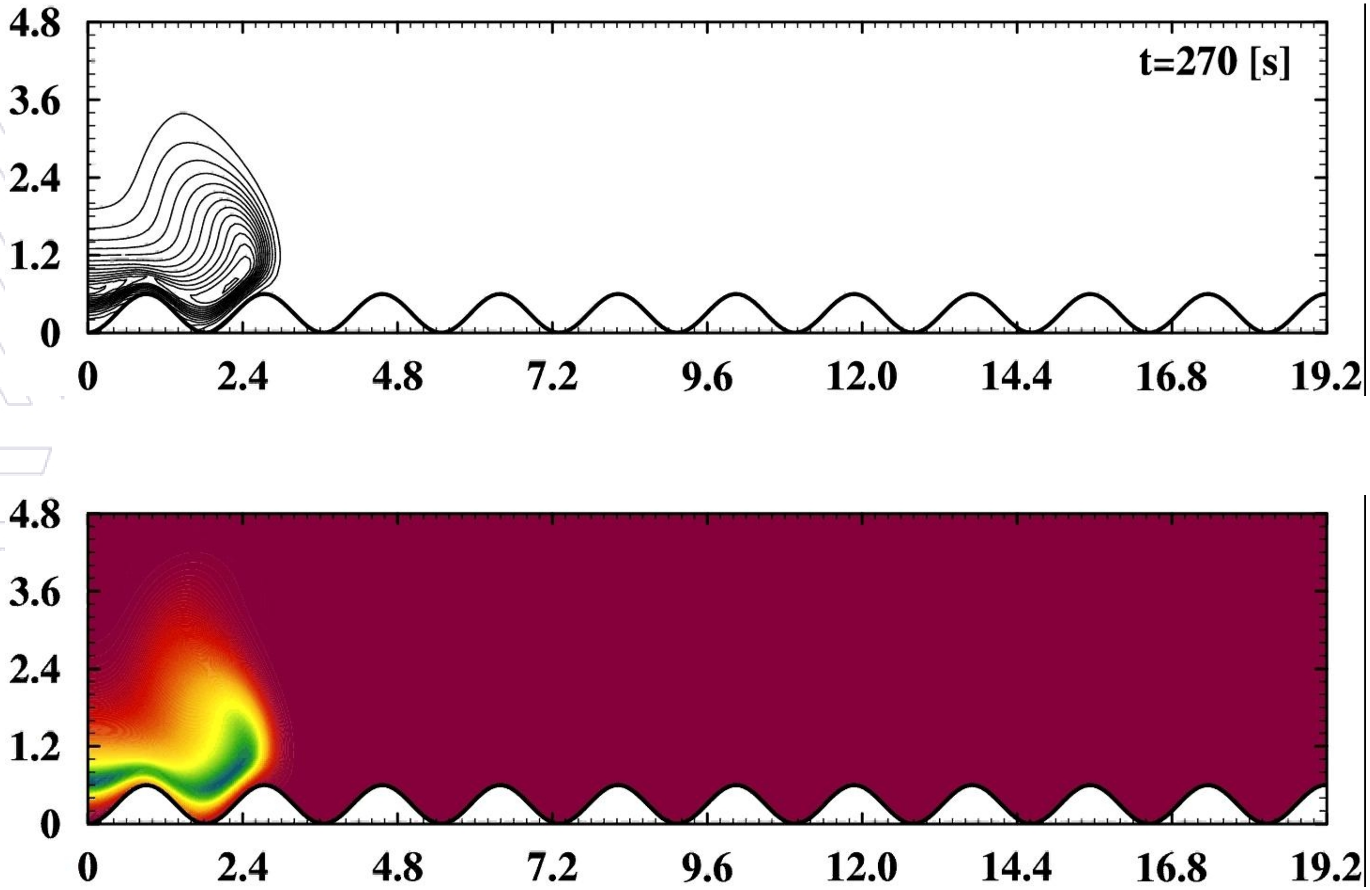


## Sinusoidal orography



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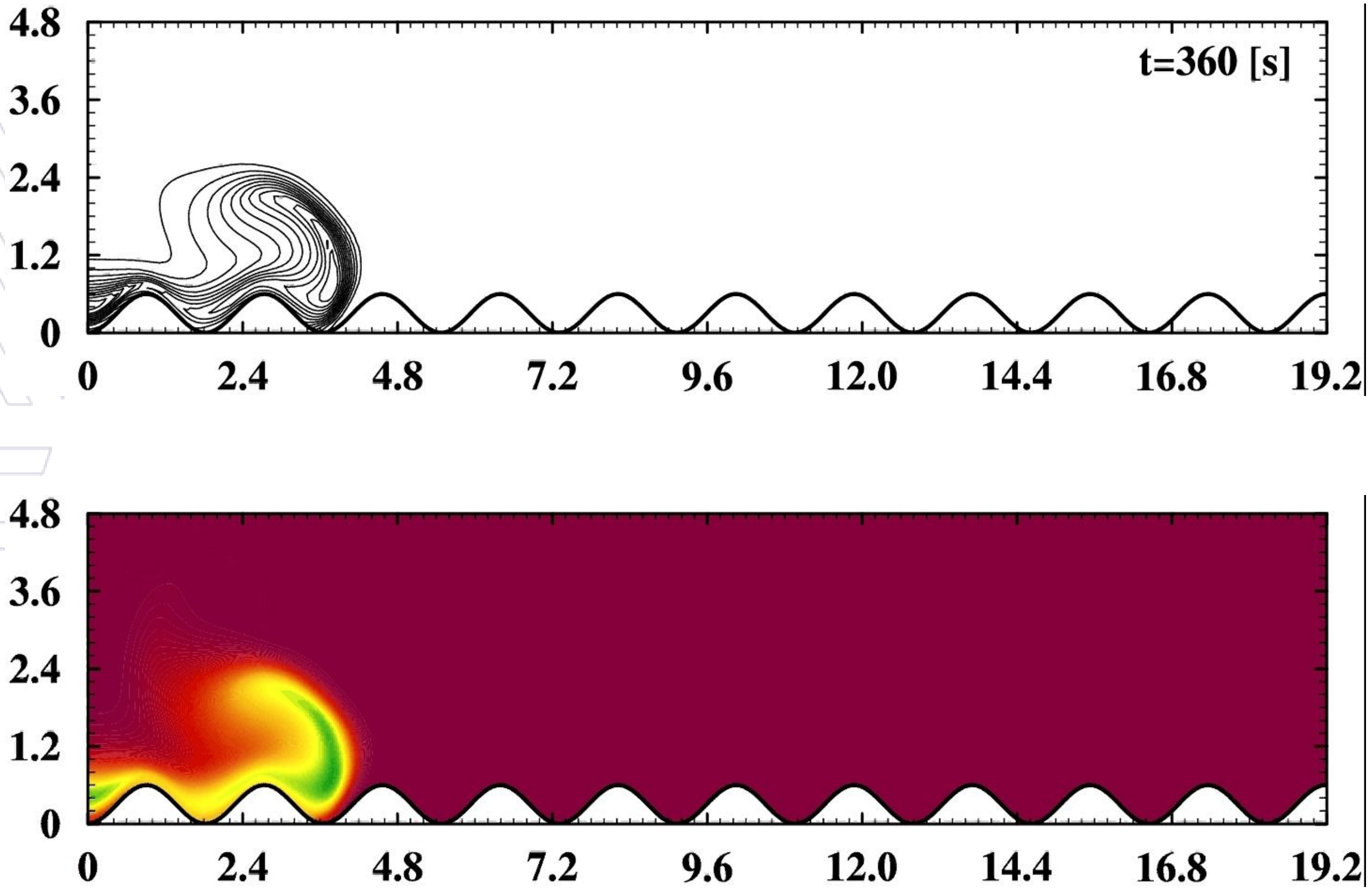

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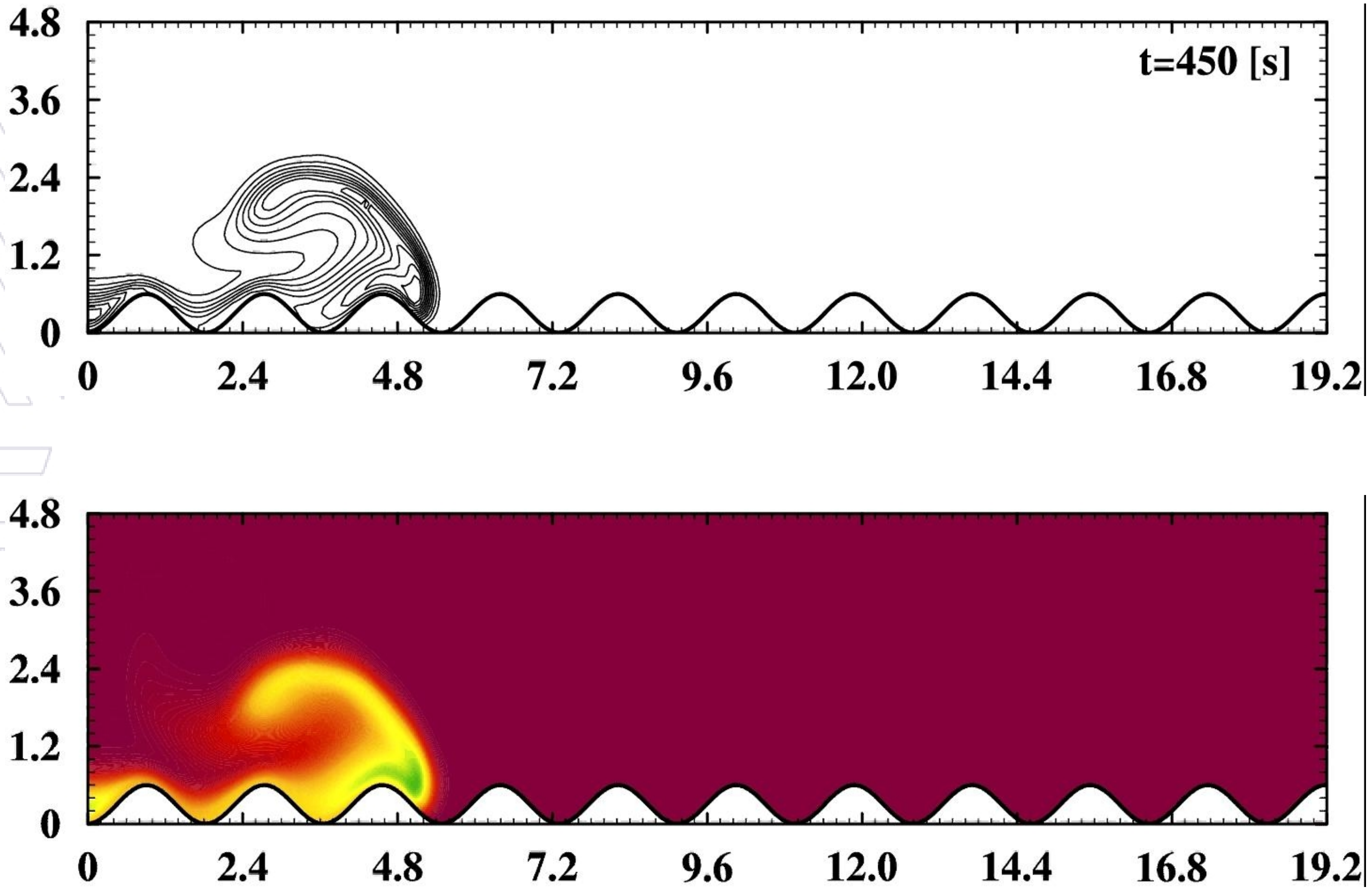

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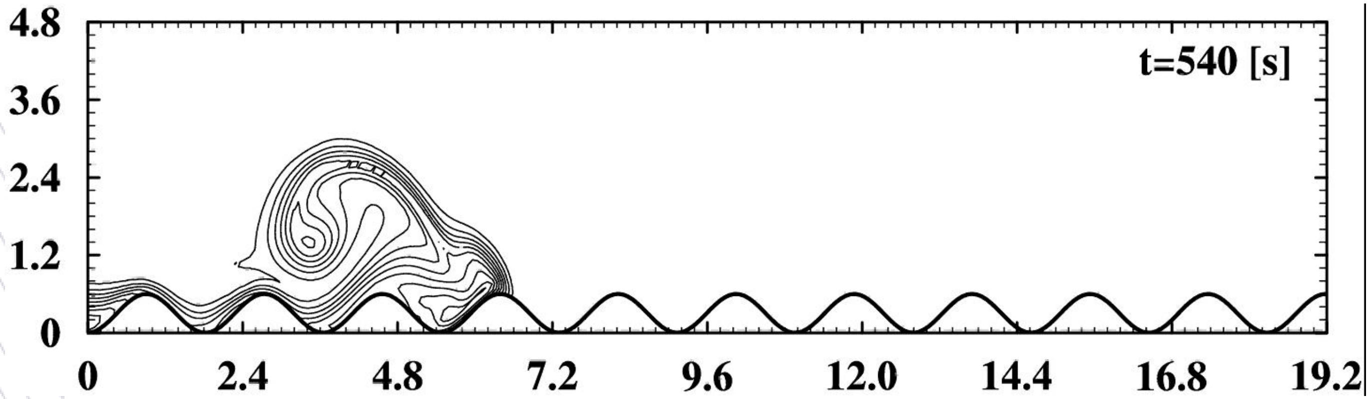


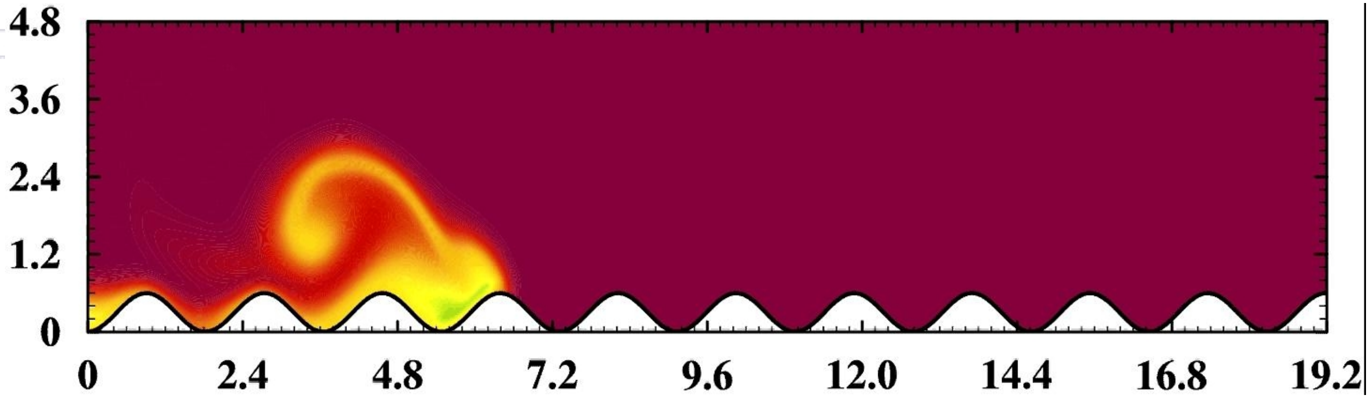

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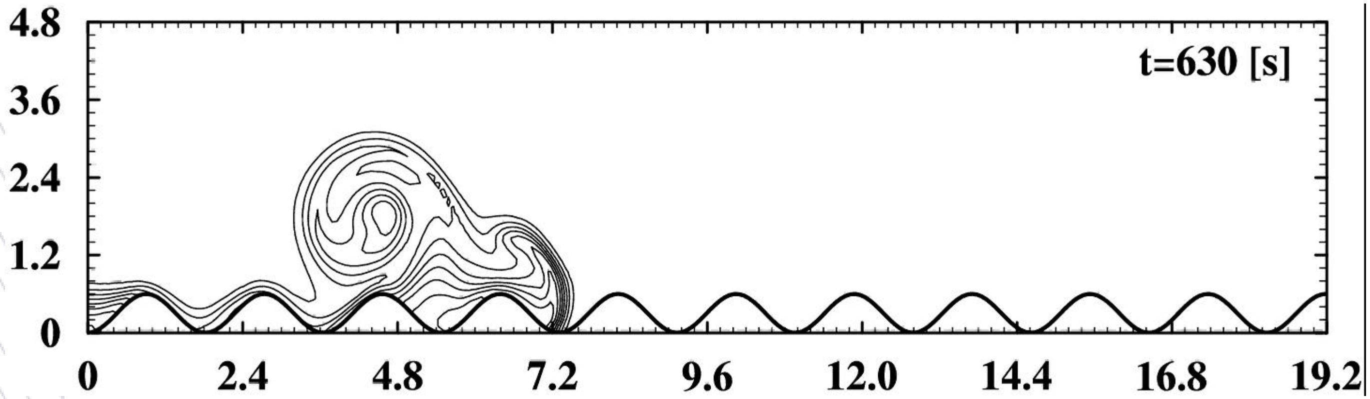
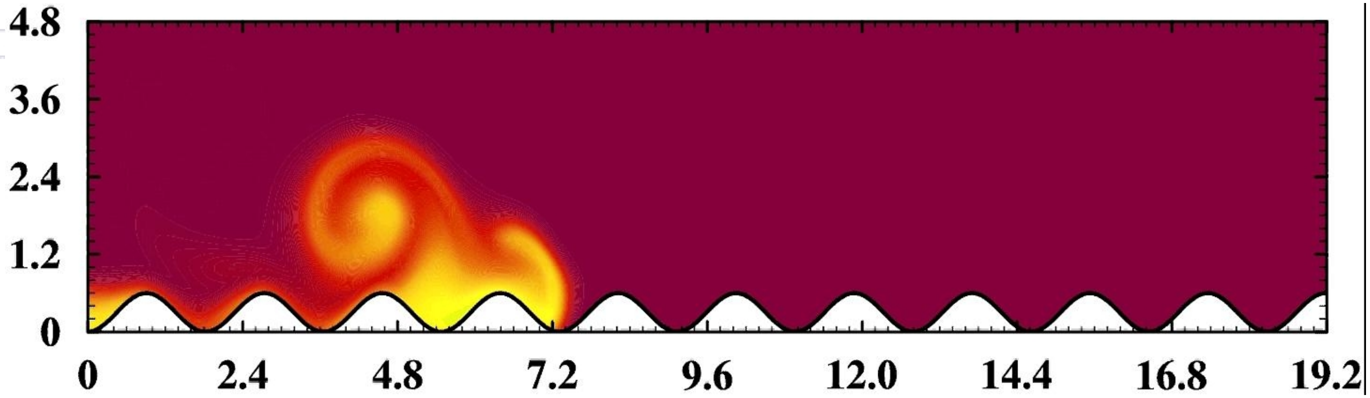
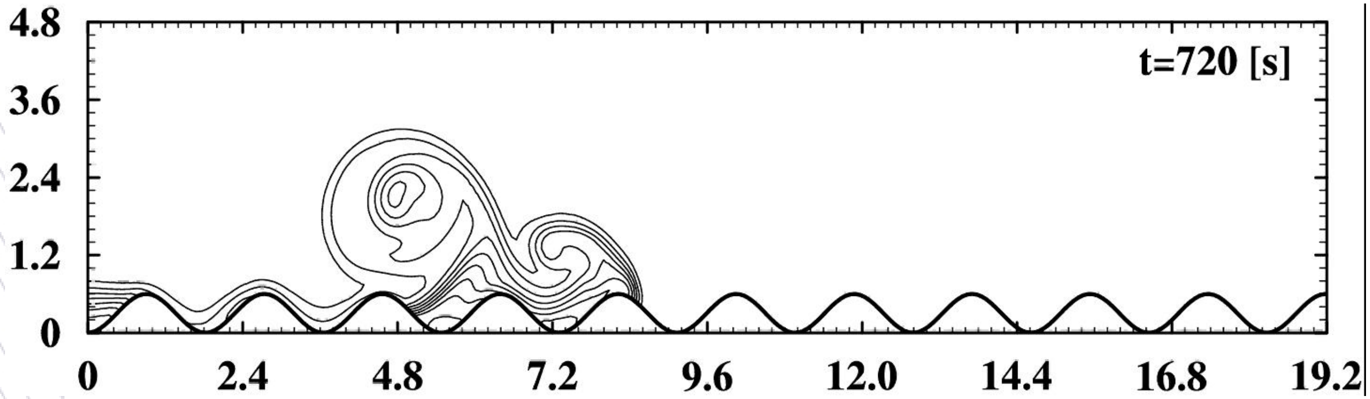
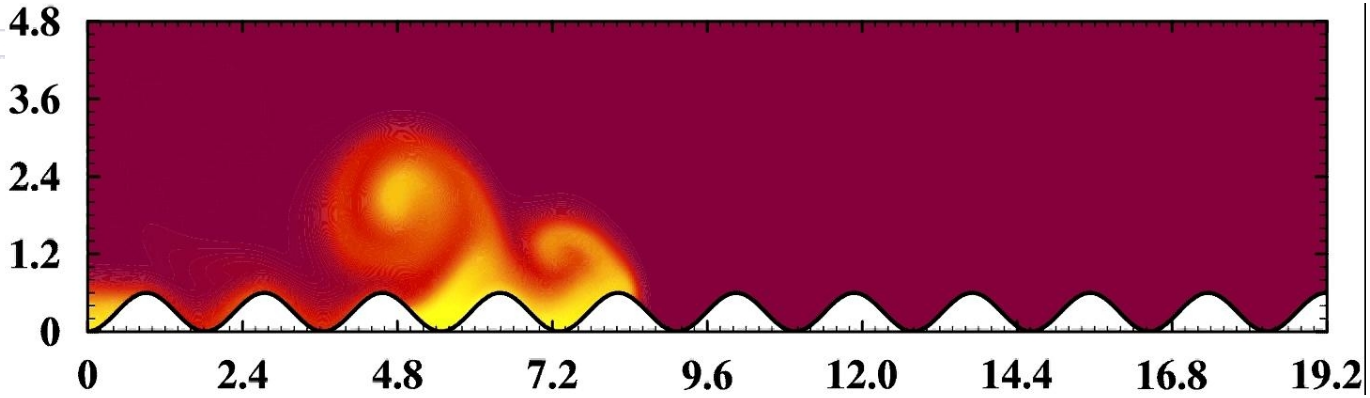


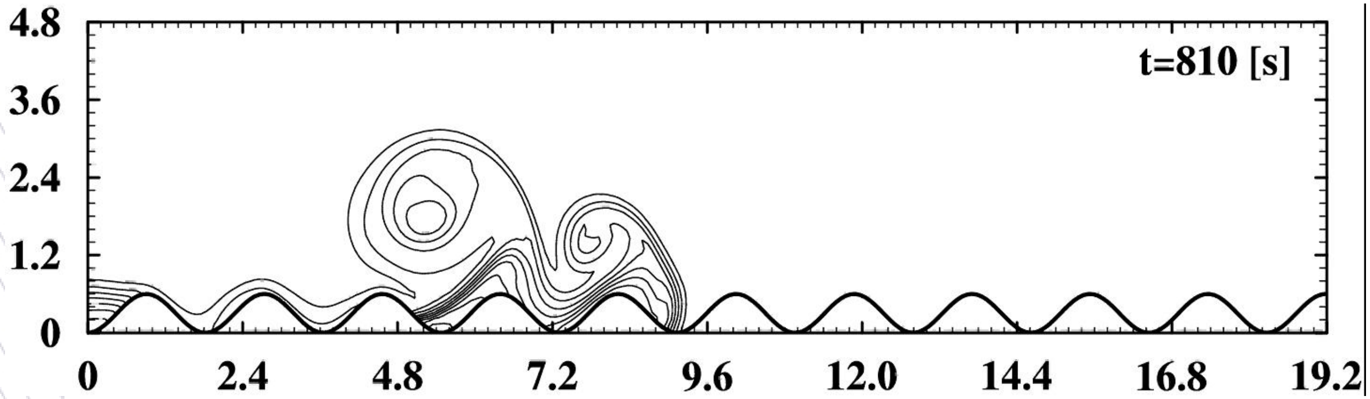



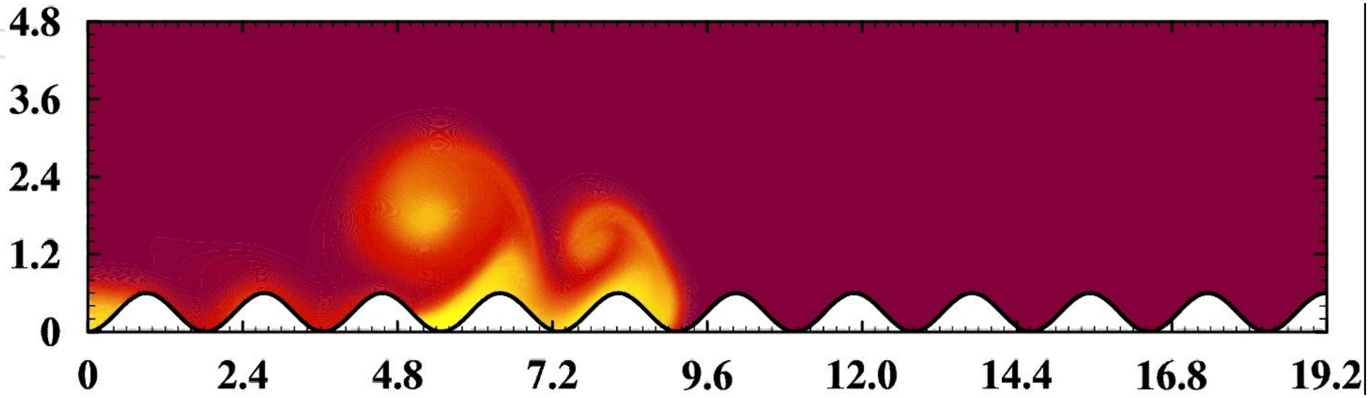
# Sinusoidal orography



## Sinusoidal orography



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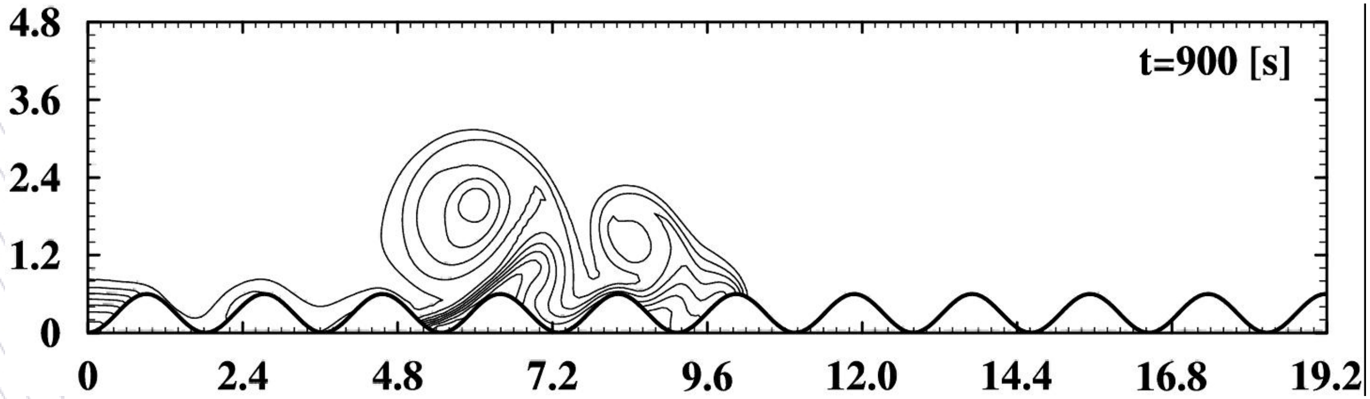


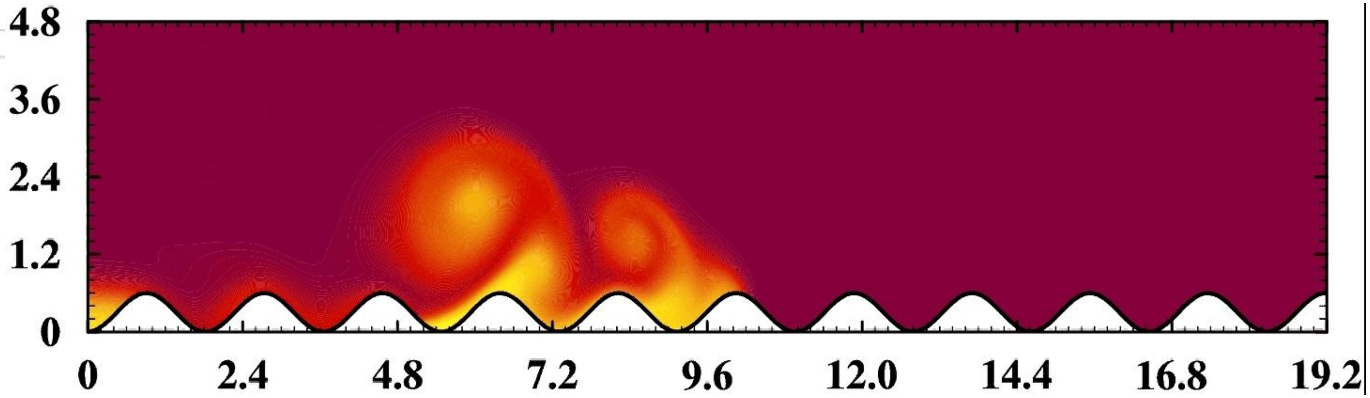

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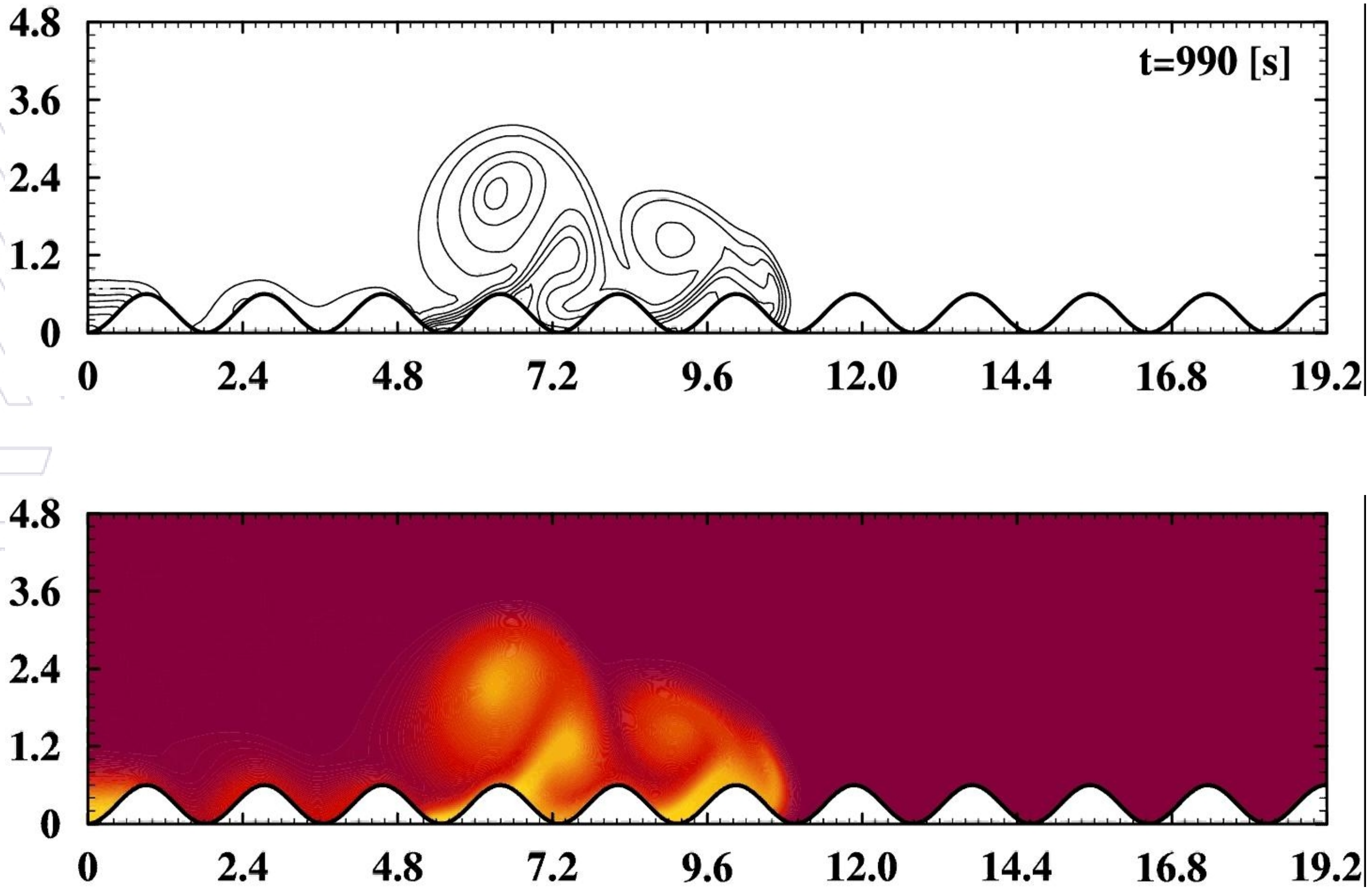
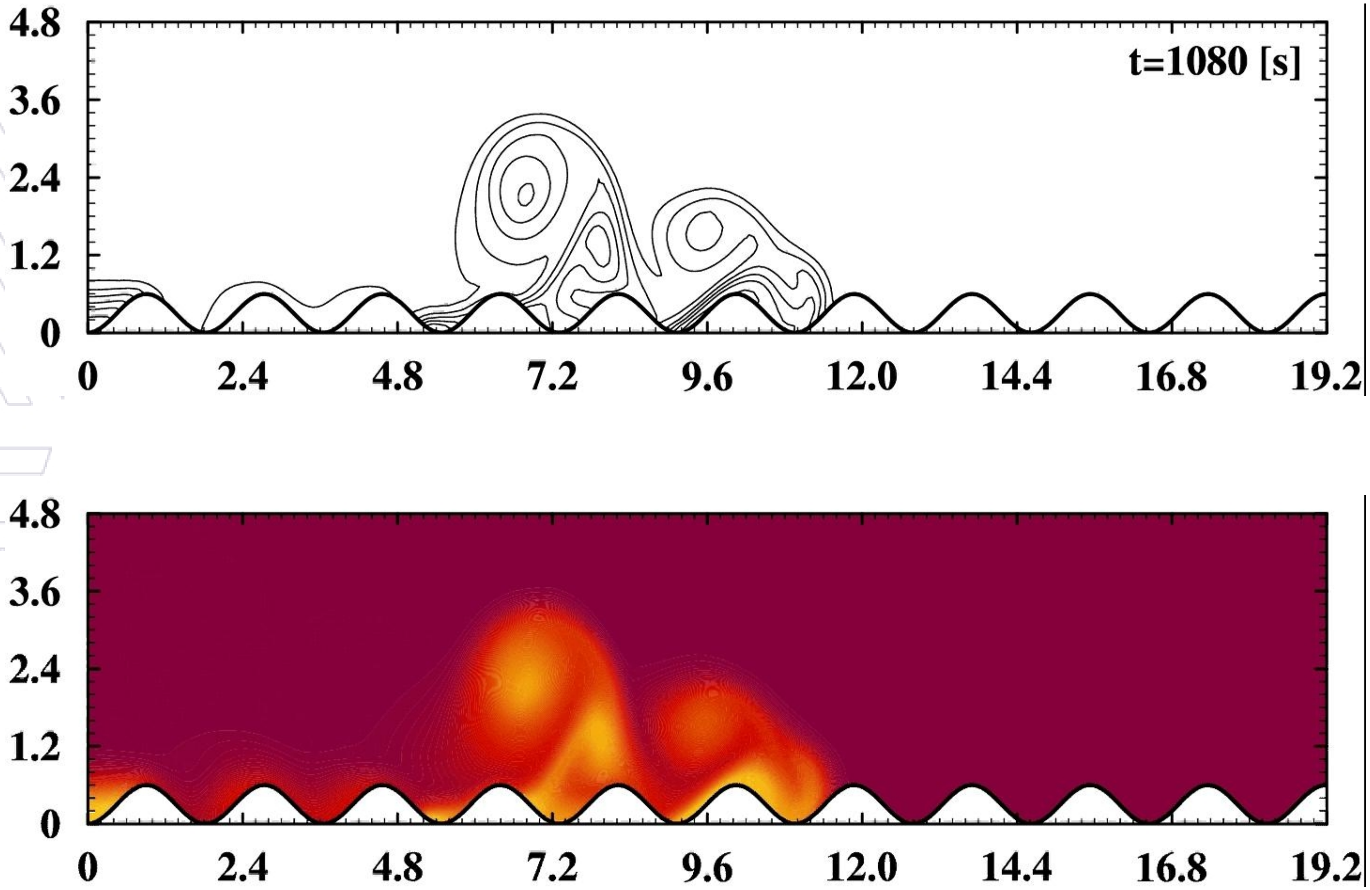


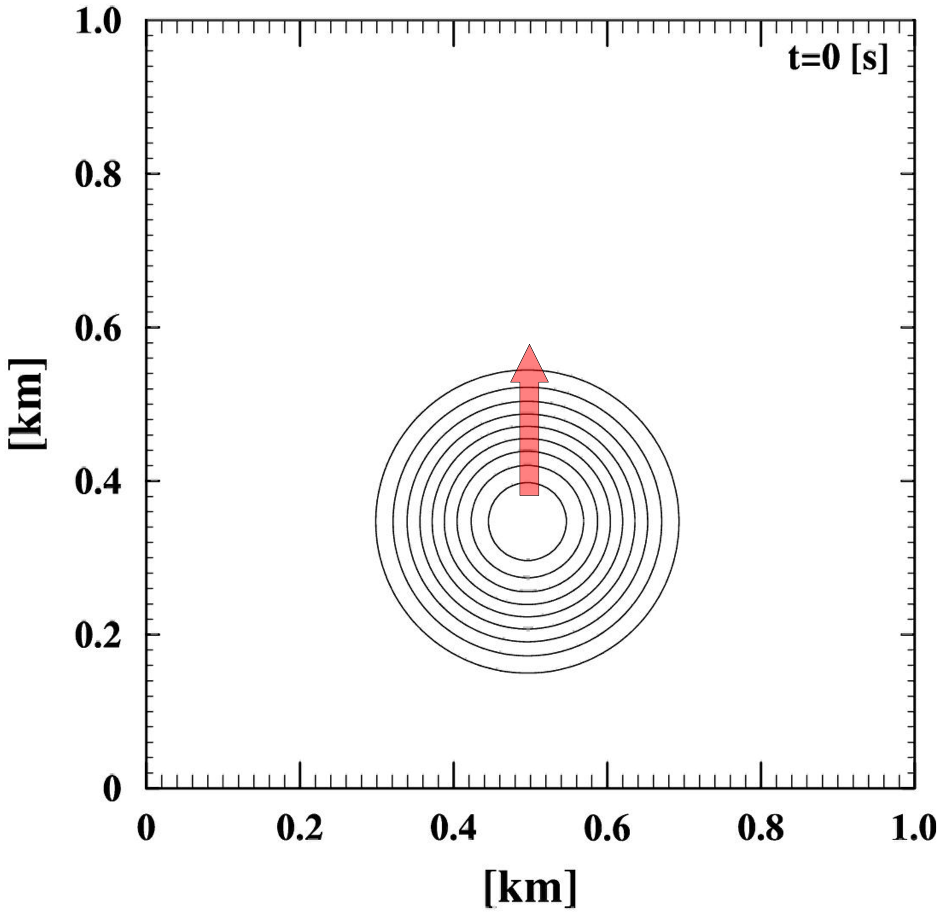
## Sinusoidal orography



# Rising thermal

reference:

*Giraldo, F. X. and M. Resteli. A study of spectral element and discontinuous Galerkin methods for the Navier-Stokes equations in nonhydrostatic mesoscale atmospheric modelling: equation sets and test cases. J. Comp. Phys., 227:3849-3877,* ***2008***

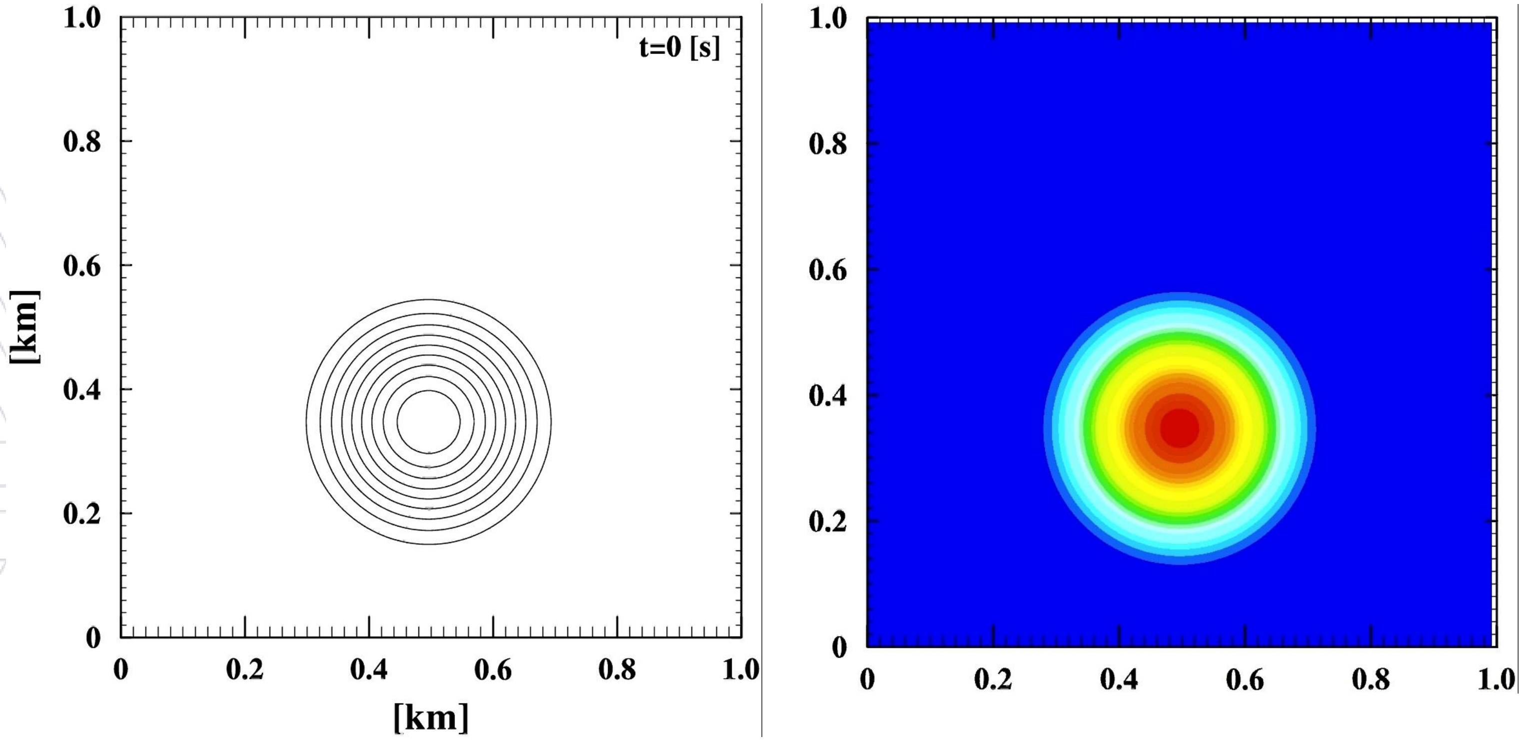



## Setup overview:

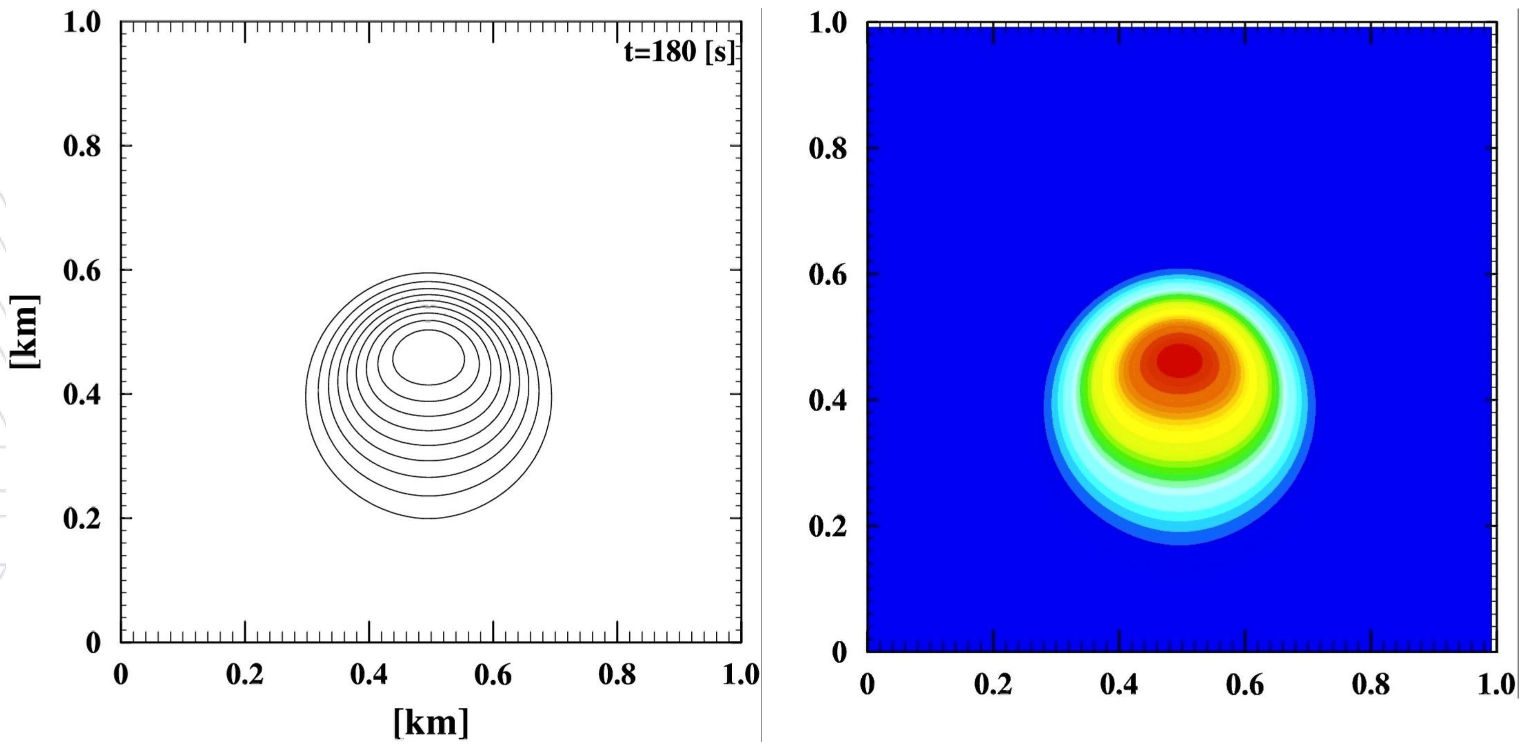
- domain size 1km x 1 km
- resolution 16x16m, 8x8m, 4x4m
- free-slip b.c.
- rigid boundaries
- isentropic (θ=const)
- no external flow
- inviscid
- max. temperature 0.5K

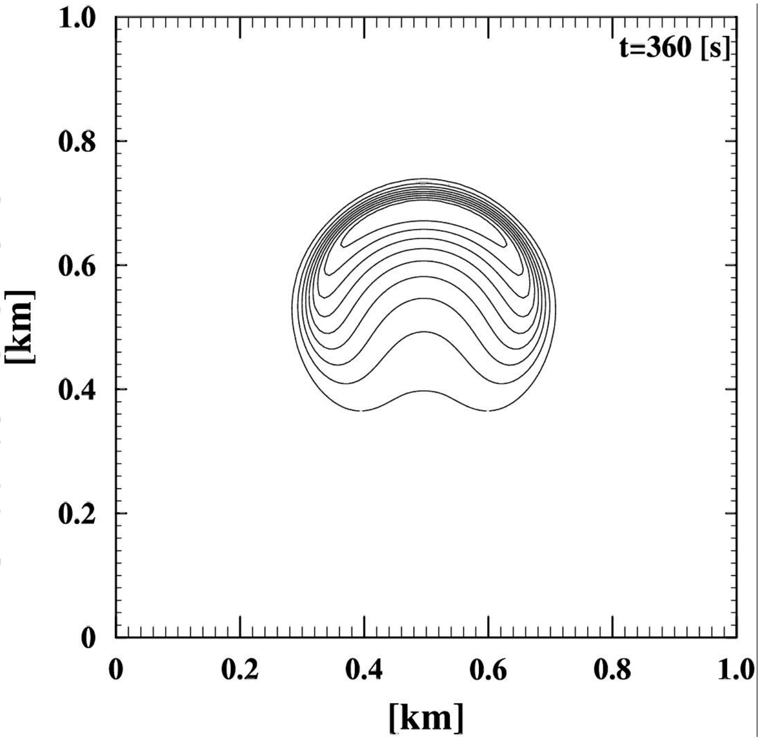
$$\frac{\theta_c}{2}\left[1+\cos\left(\frac{\pi_c r}{r_c}\right)\right]$$

No analytic solution

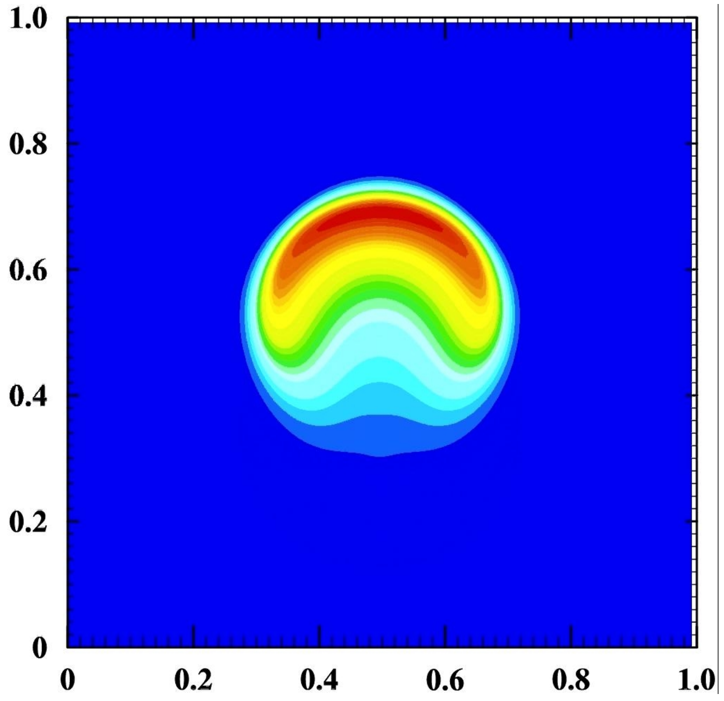

t=0 [s]
1.0
0.8
0.6
0.4
0.2
0
[km]
0
0.2
0.4
0.6
0.8
1.0
[km]

# 2. IDEALIZED TESTS

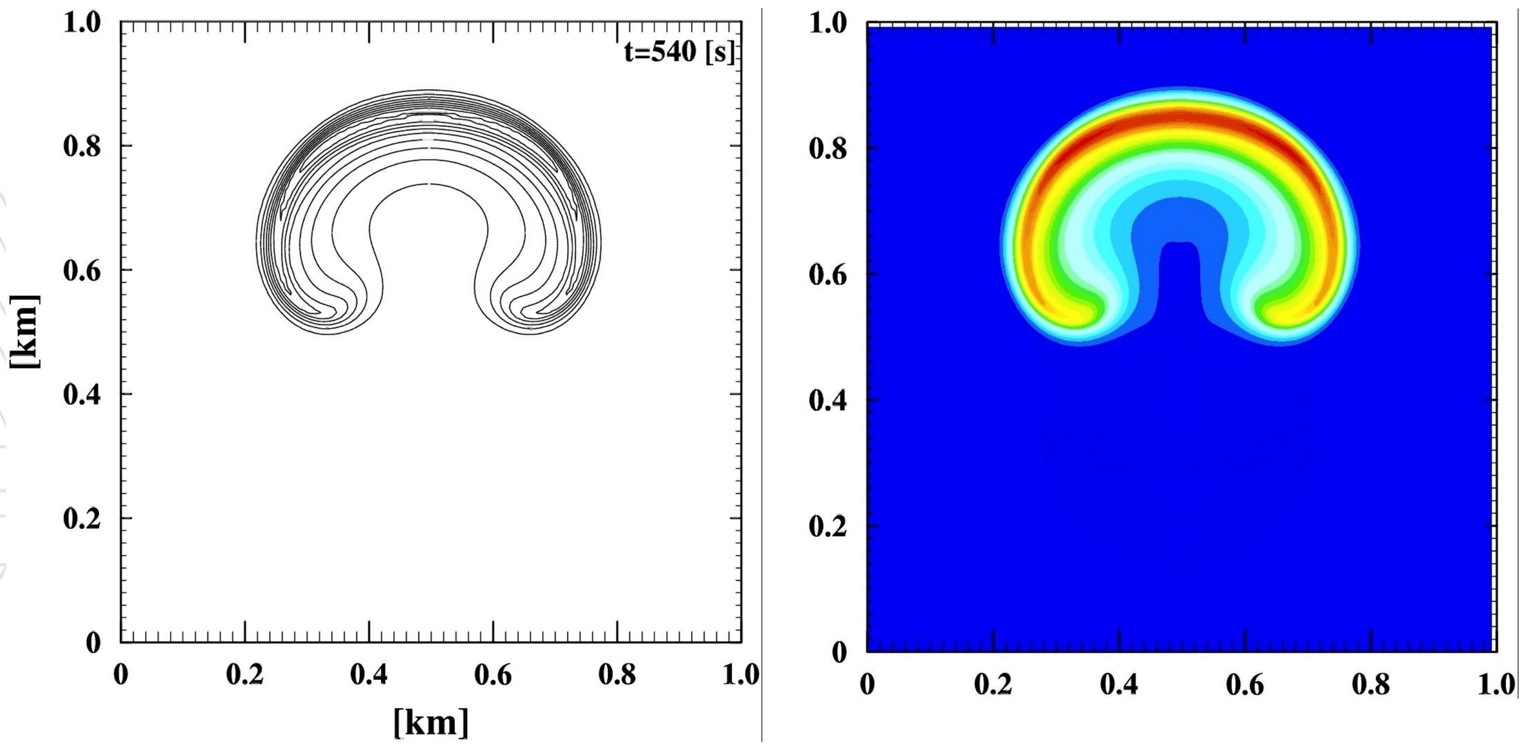


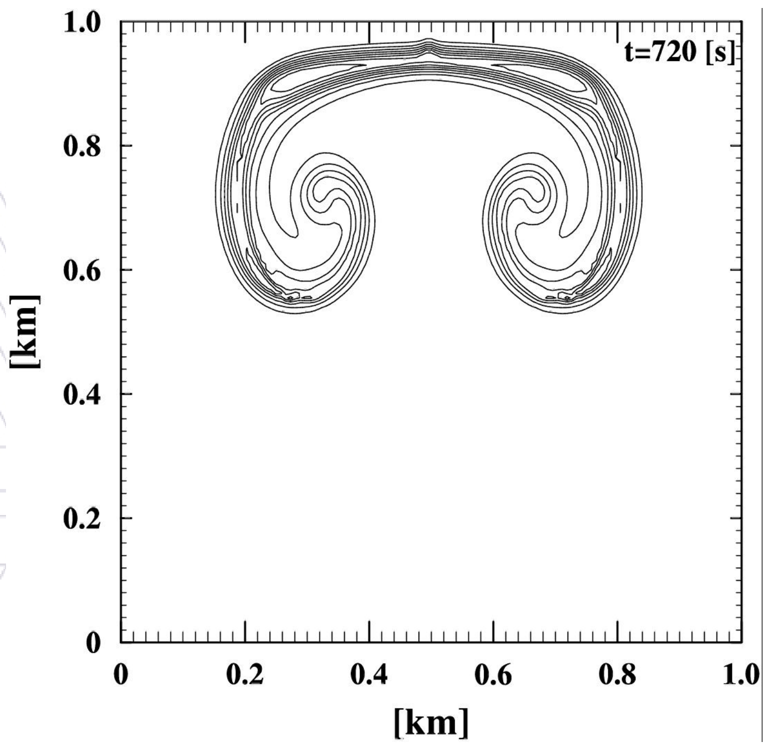


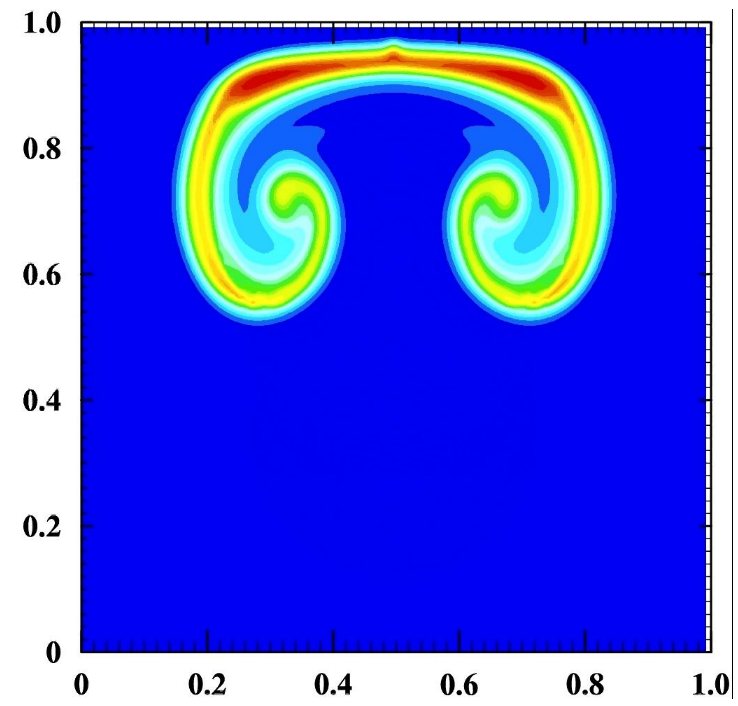
1.0
0.8
0.6
0.4
0.2
0
[km]
t=360 [s]
0
0.2
0.4
0.6
0.8
1.0
[km]

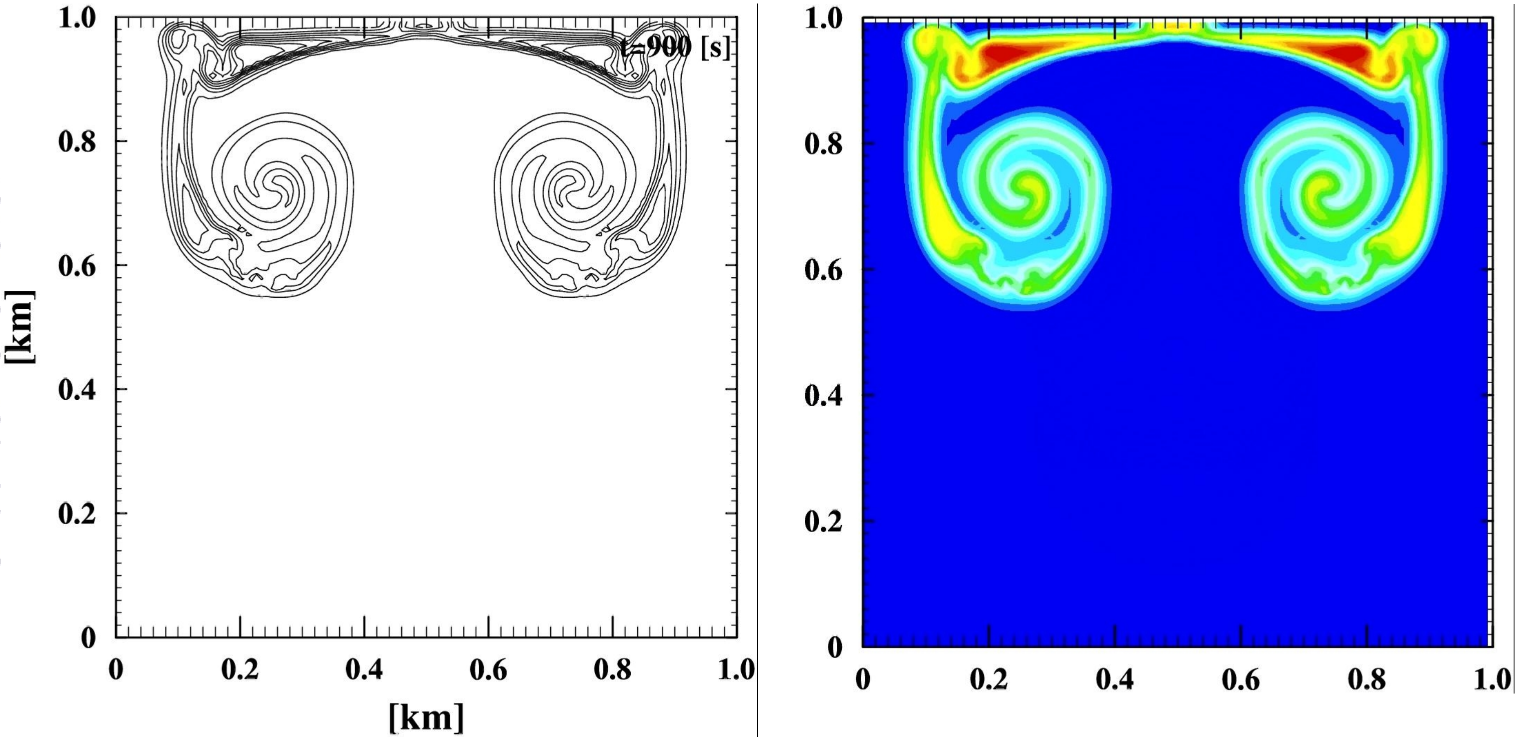



1.0
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1.0


t=540 [s]
1.0
0.8
0.6
0.4
0.2
0
[km]
0
0.2
0.4
0.6
0.8
1.0
[km]


t=720 [s]
1.0
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1.0
[km]
[km]

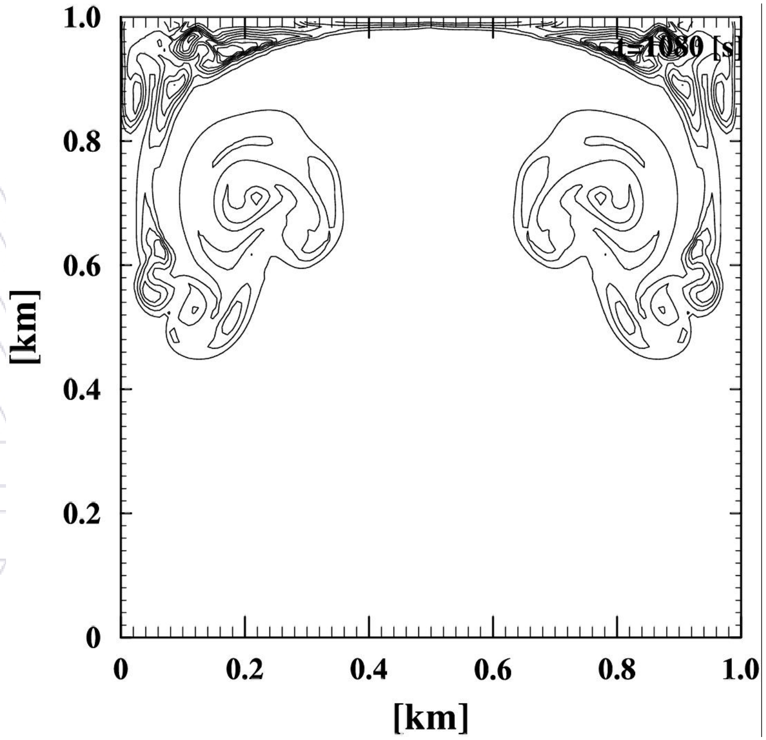

1.0
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1.0

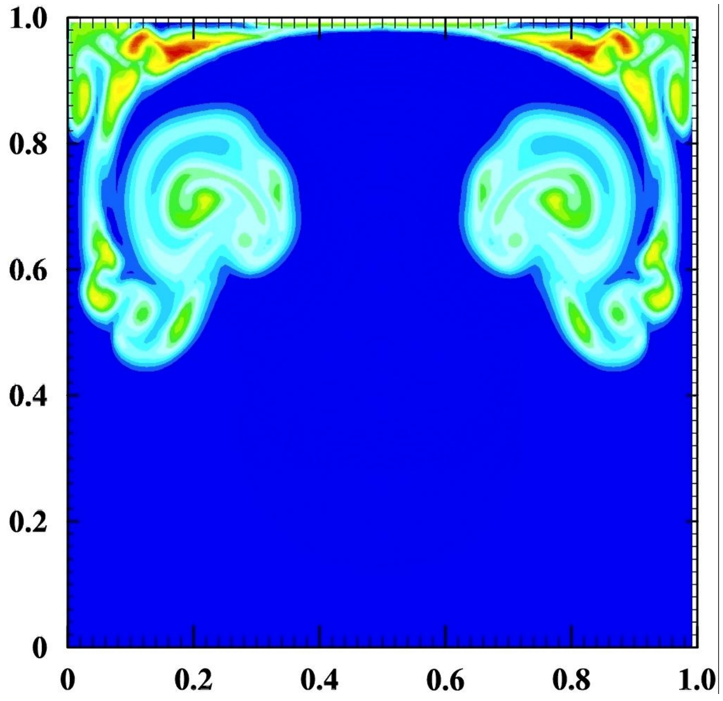


t=900 [s]
[km]
[km]
1.0
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1.0

# 2. IDEALIZED TESTS



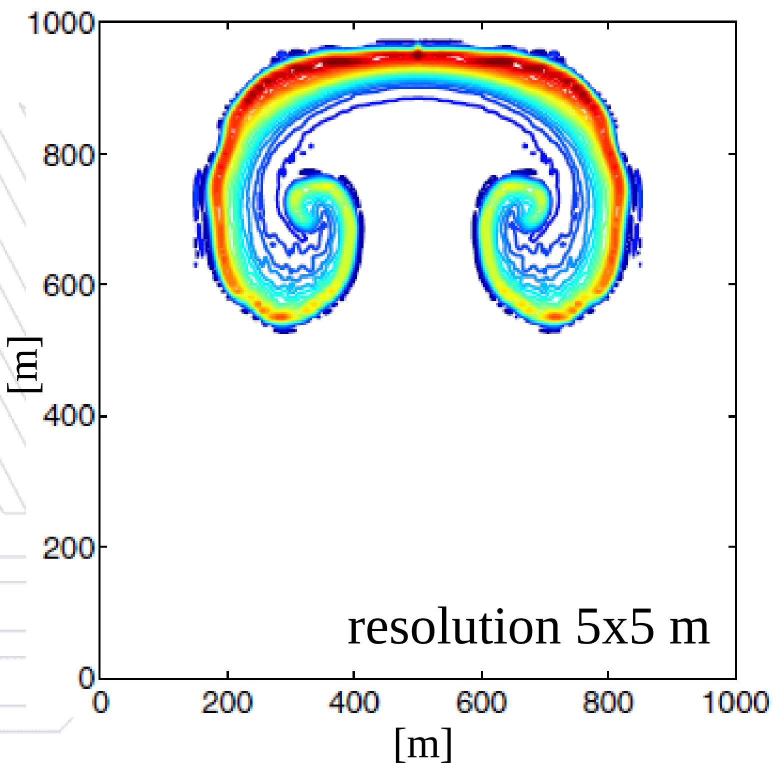


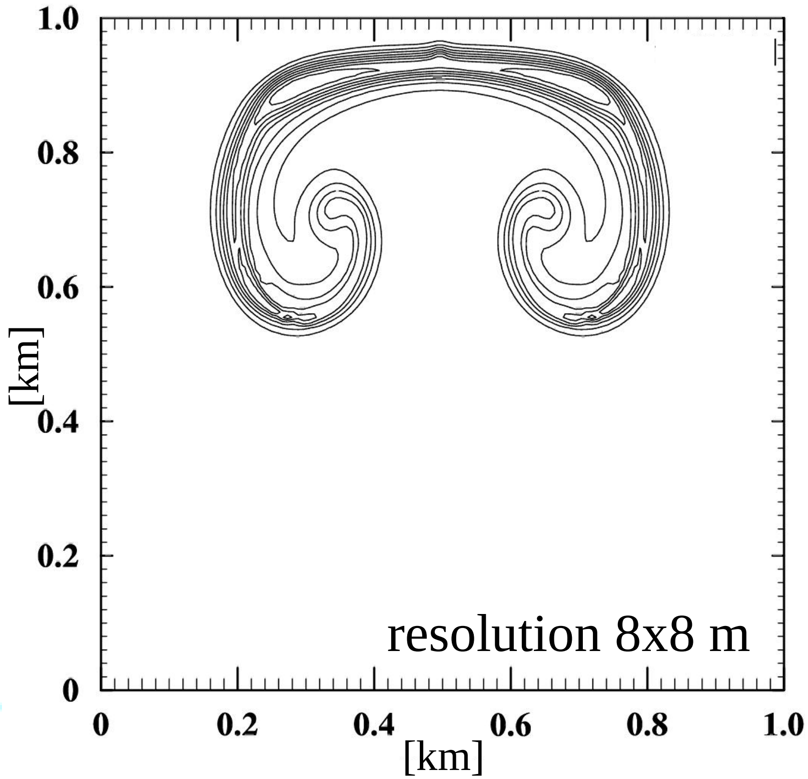
# 2. IDEALIZED TESTS



Giraldo and Reseti (2008)
(fully compressible)




EULAG (2009)
(anelastic)

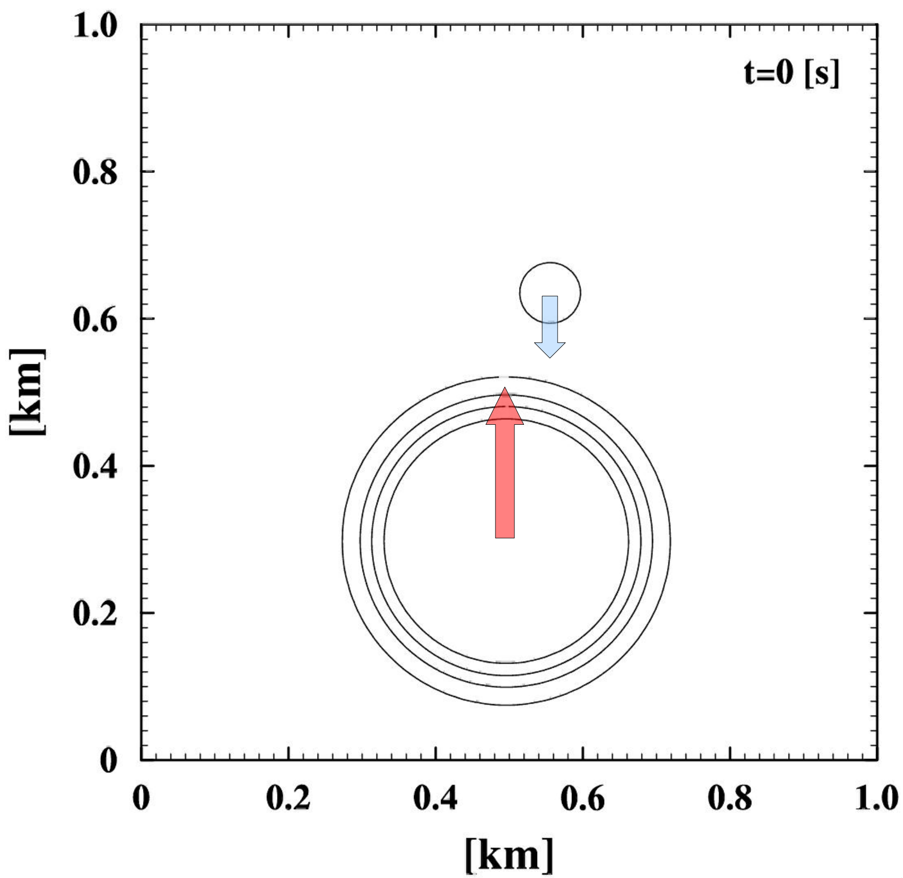



Potential temperature perturbation
after 700s

# Interacting bubbles

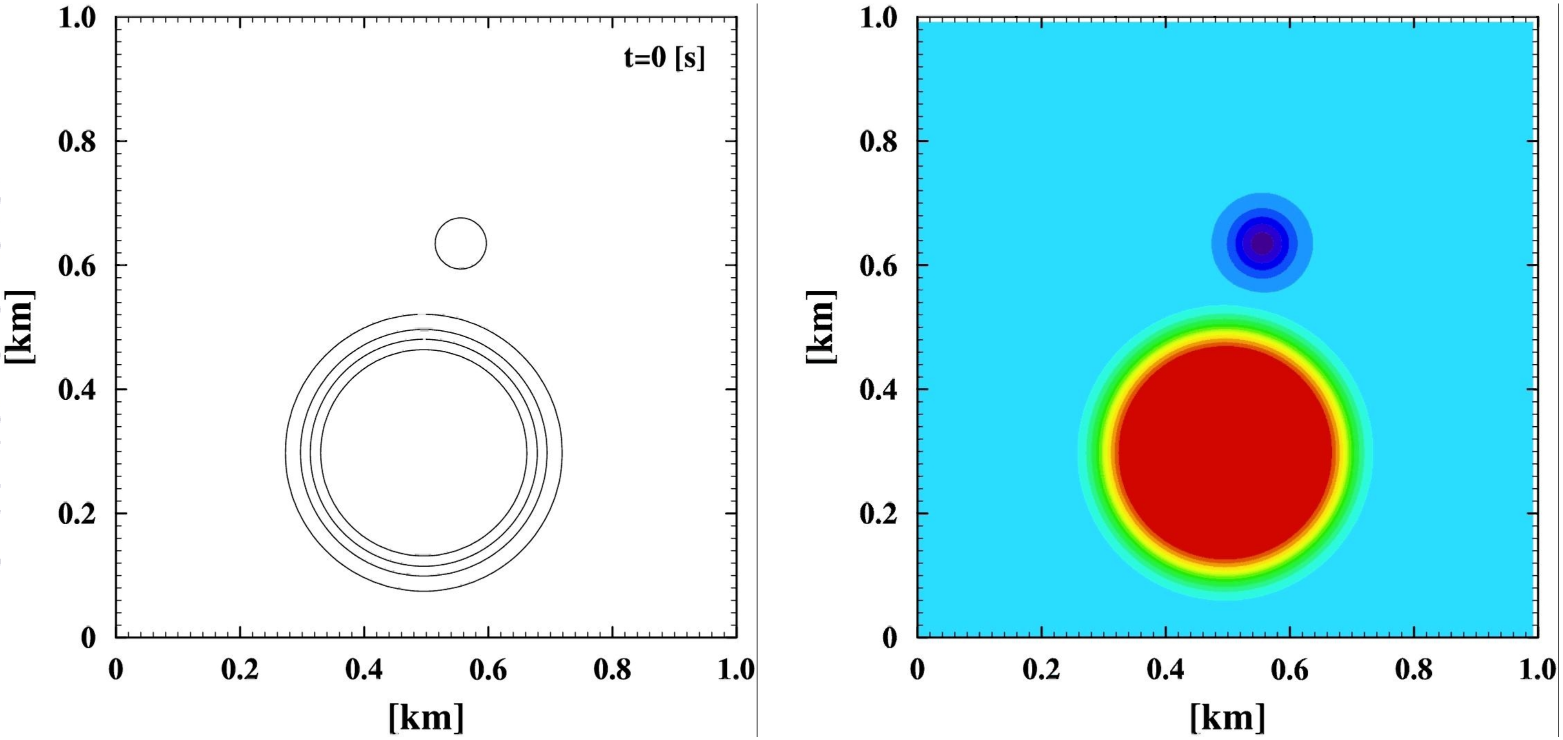
reference:

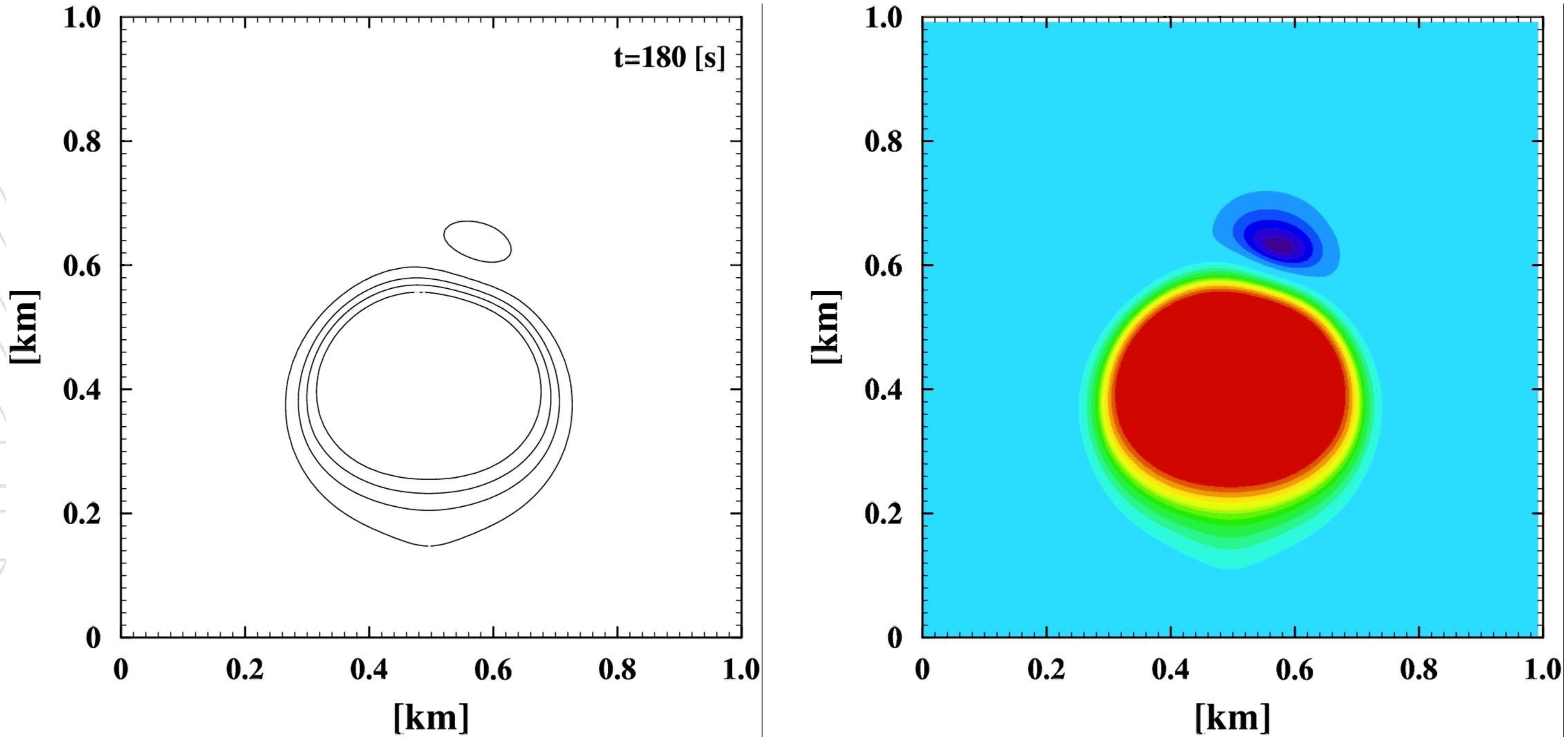
Robert, A., *Bubble convection experiments with a semi-implicit formulation of the Euler equations. J. Atmos. Sci., 50: 1865-1873,* ***1993***

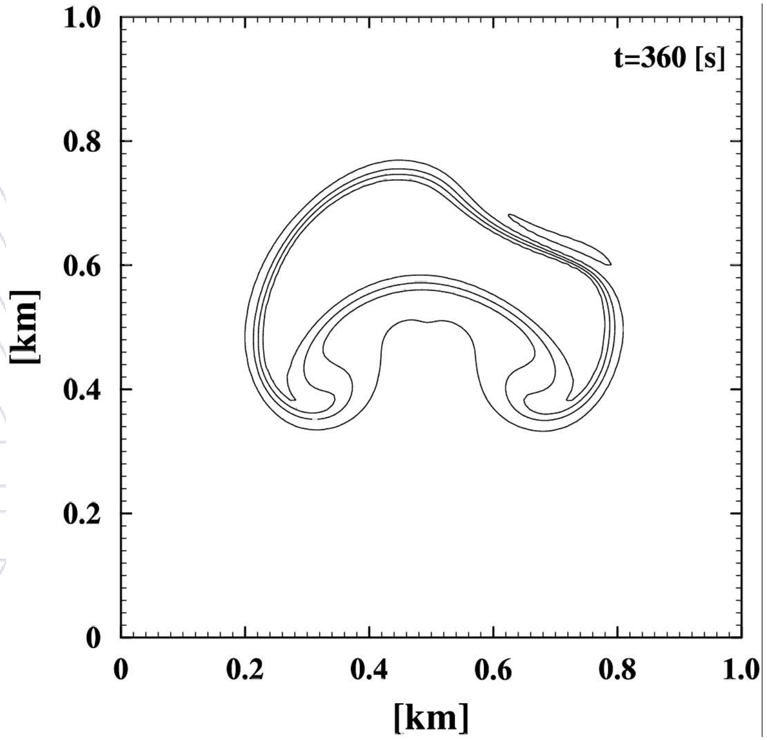


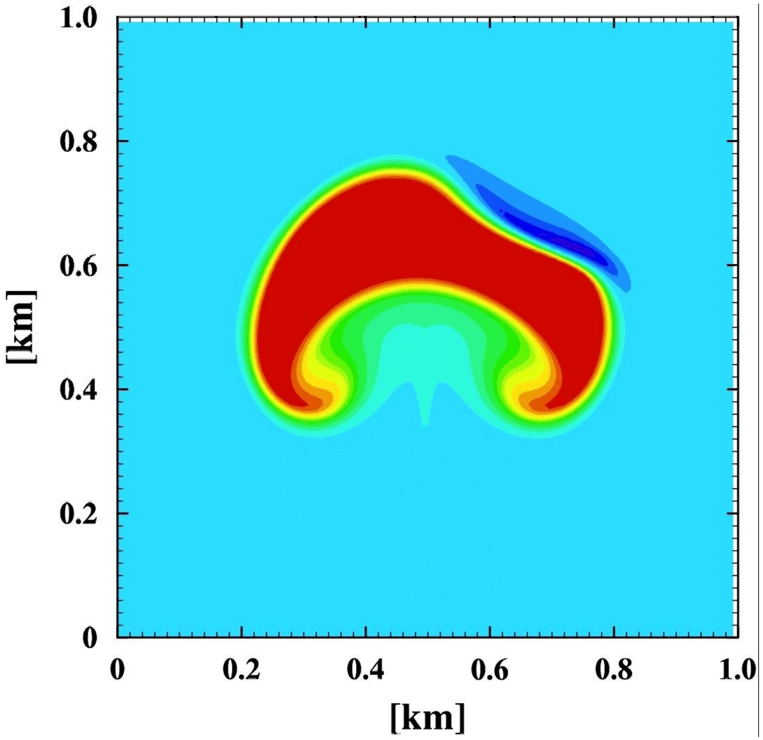

## Setup overview:

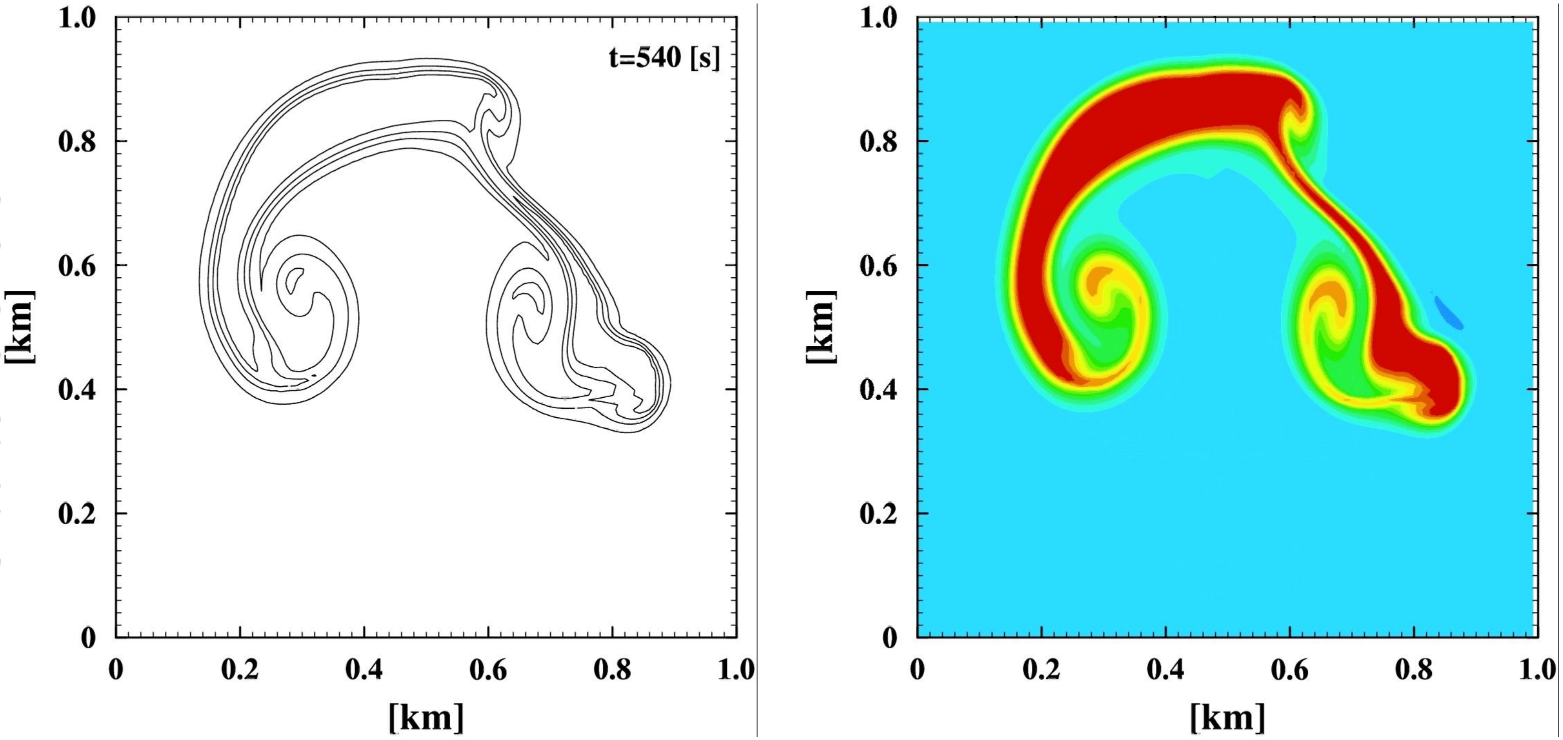
- domain size 1km x 1 km
- resolution 16x16m, 8x8m, 4x4m
- free-slip b.c.
- rigid boundaries
- no external flow
- no subgrid mixing
- min. temperature:
  0.5K (big bubble)
  -0.1K (small bubble)

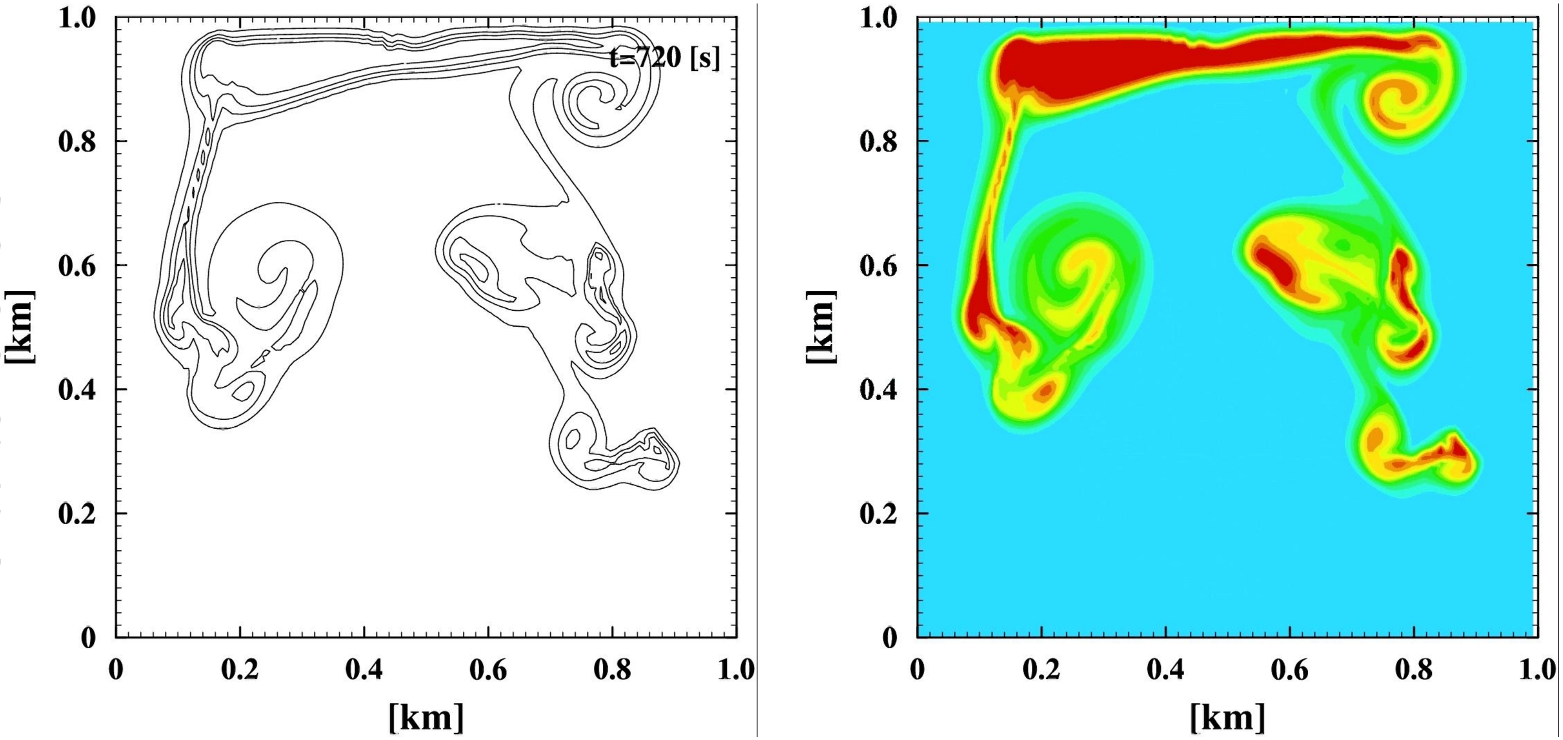

t=0 [s]
1.0
0.8
0.6
0.4
0.2
0
[km]
0
0.2
0.4
0.6
0.8
1.0
[km]

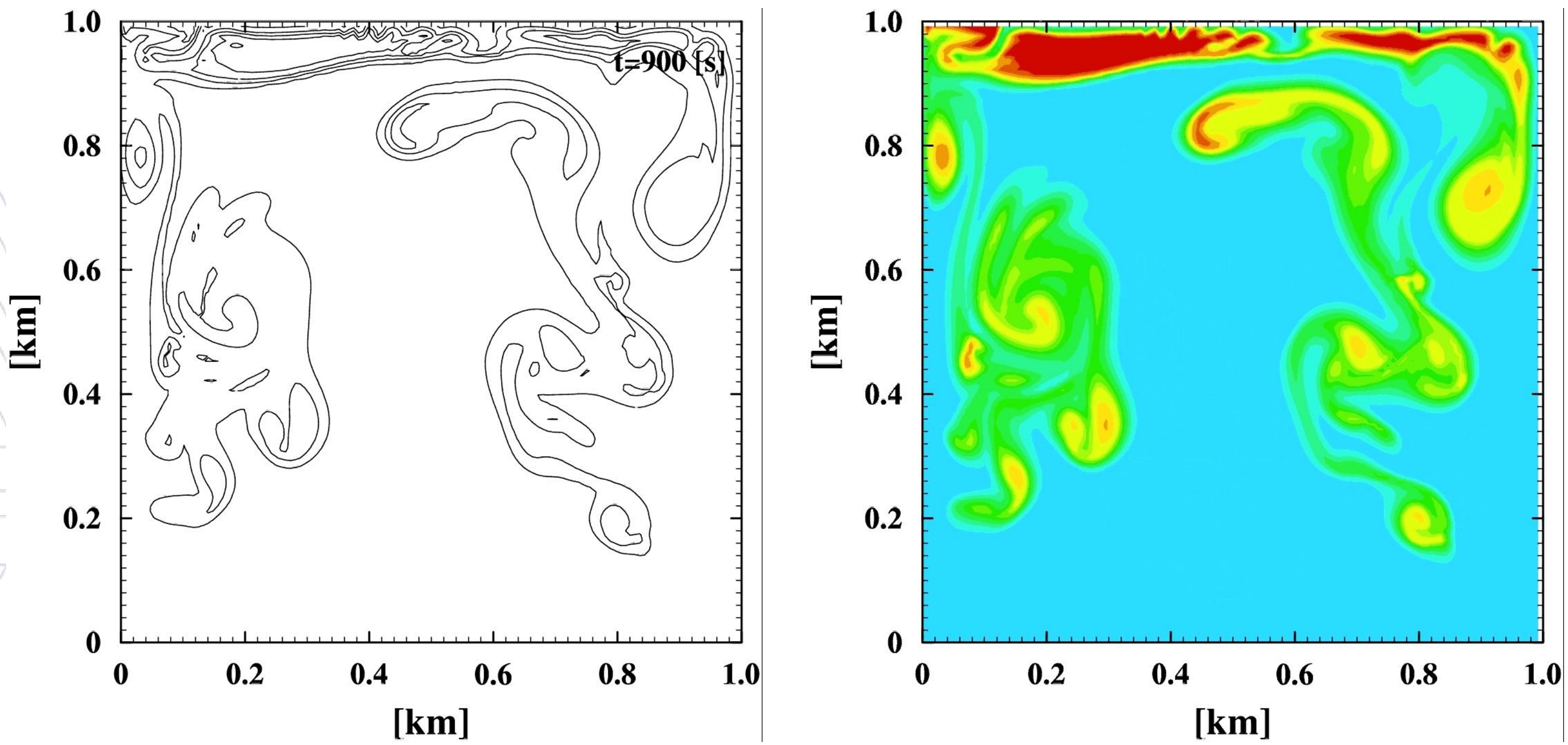

t=180 [s]
1.0
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1.0
[km]
[km]

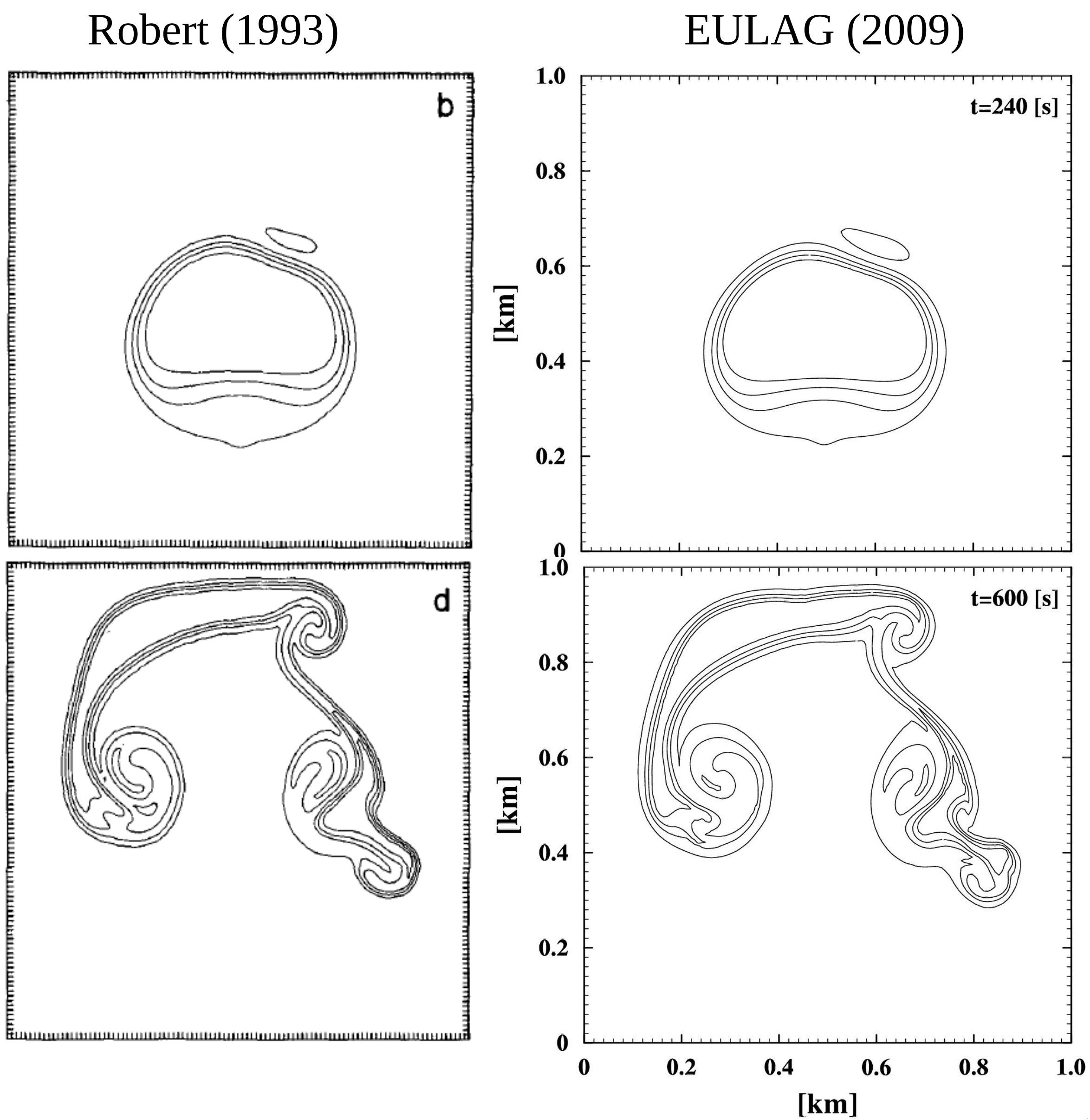

t=360 [s]
1.0
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1.0
[km]
[km]


1.0
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1.0
[km]
[km]


t=540 [s]
1.0
0.8
0.6
0.4
0.2
0
[km]
0
0.2
0.4
0.6
0.8
1.0
[km]


1.0
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1.0
[km]
[km]
t=720 [s]
1.0
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1.0
[km]
[km]


t=900 [s]
1.0
0.8
0.6
0.4
0.2
0
[km]
0
0.2
0.4
0.6
0.8
1.0
[km]



Robert (1993)
EULAG (2009)
b
d
t=240 [s]
t=600 [s]
1.0
0.8
0.6
0.4
0.2
0
[km]
0.2
0.4
0.6
0.8
1.0
[km]

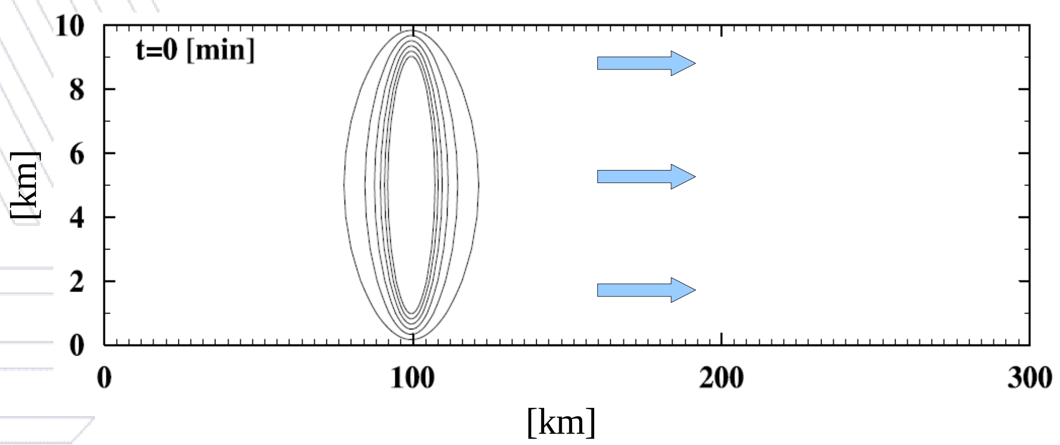
# Inertia-gravity waves

reference:

Skamarock W. C. and Klemp J. B. Efficiency and accuracy of Klemp-Wilhelmson time-splitting technique. *Mon. Wea. Rev.* 122(11):2623-2630, **1994**

# Constant flow within a short channel (300km)

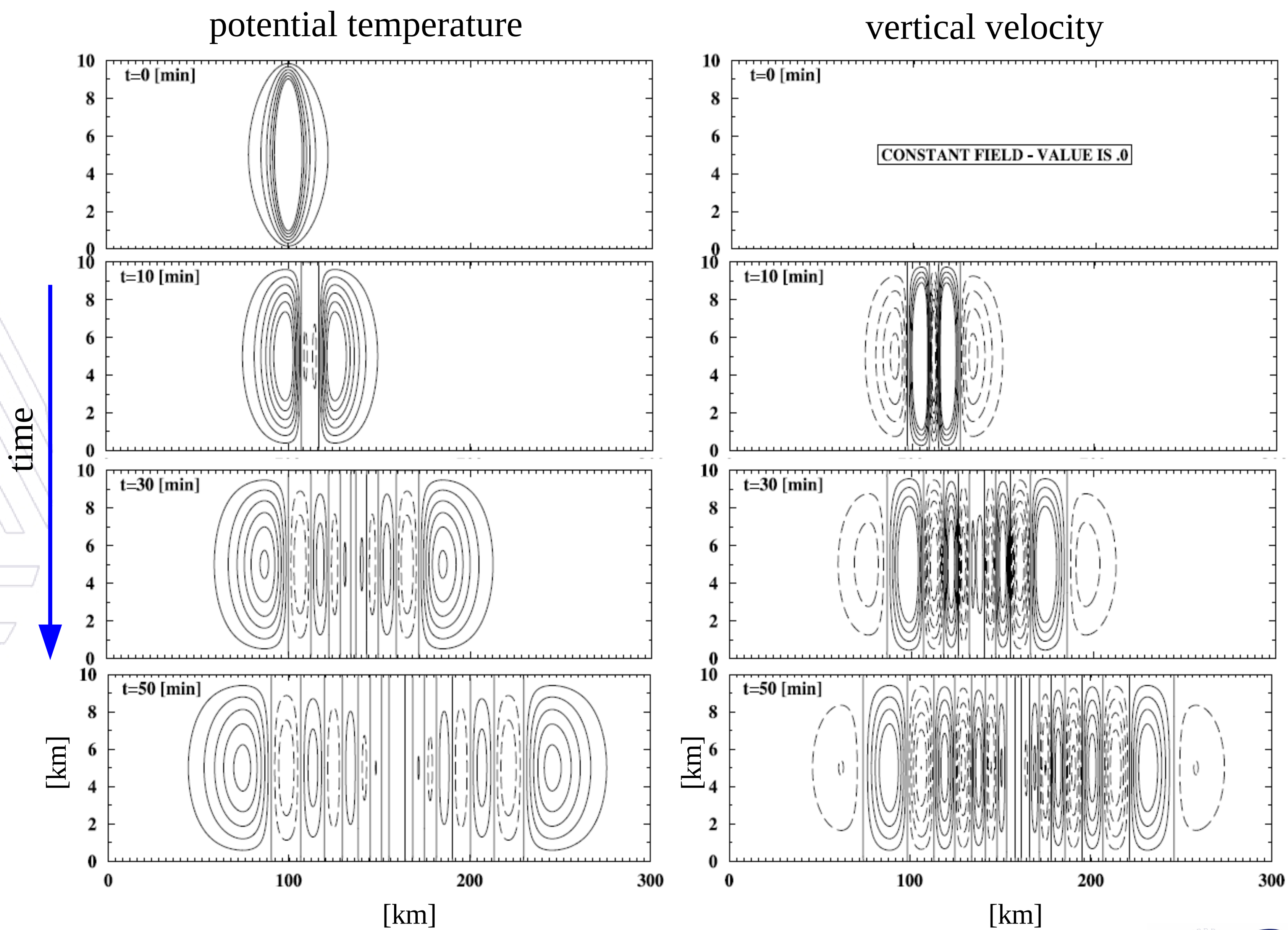
Initial potential temperature perturbation




Testing model for subtle phenomenon

## Setup overview:

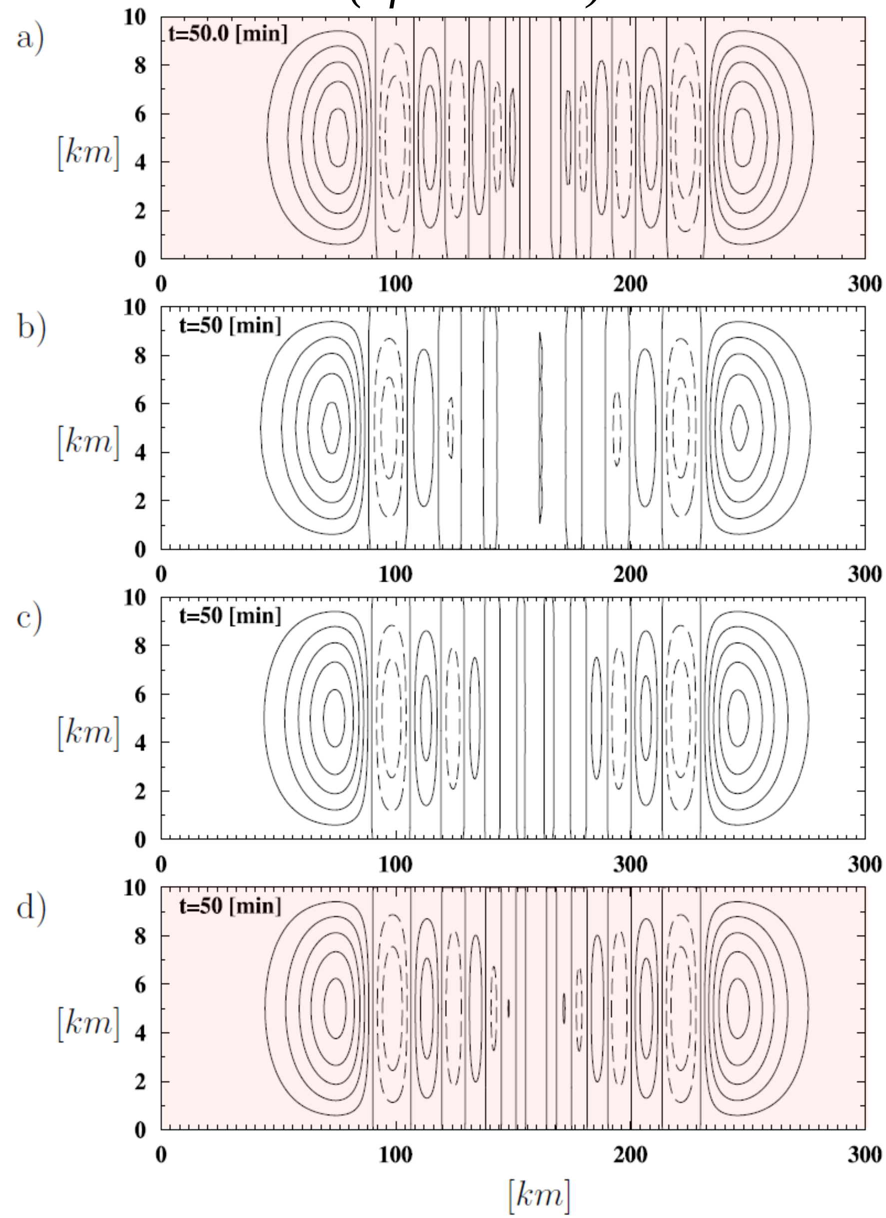
- domain size 300x10km
- resolution 1x1km, 0.5x0.5km, 0.25x0.25km
- rigid free-slip b.c.
- periodic lateral boundaries
- constant horizontal flow 20m/s
- no subgrid mixing
- hydrostatic balance
- stable stratification $N=0.01\ s^{-1}$
- max. temperature perturbation 0.01K


potential temperature
vertical velocity
time
t=0 [min]
t=10 [min]
t=30 [min]
t=50 [min]
CONSTANT FIELD - VALUE IS .0
[km]
[km]
[km]
[km]

dx=dz=0.25km

# Convergence study for resolution

θ' *(after 50min)*




analytic solution

dx=dz=1km

dx=dz=0.5km

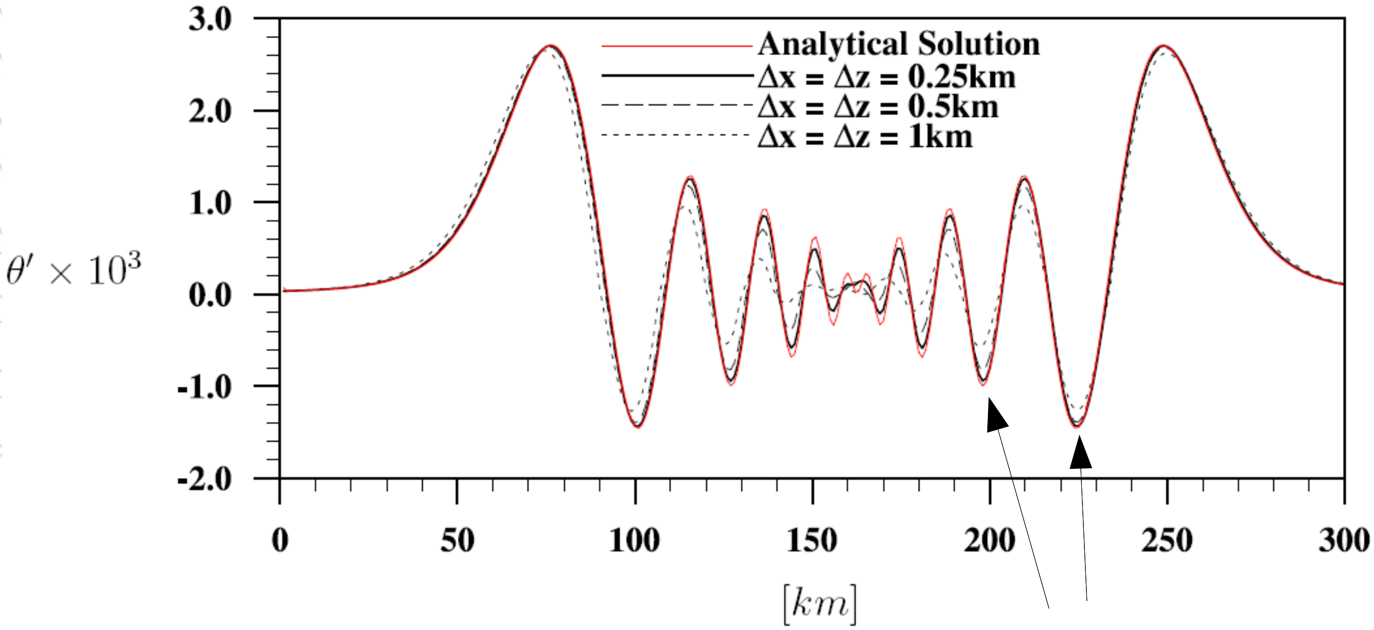
dx=dz=0.25km

EULAG incompressible Boussinesq

→ Convergence to analytic solution!

# Convergence study for resolution

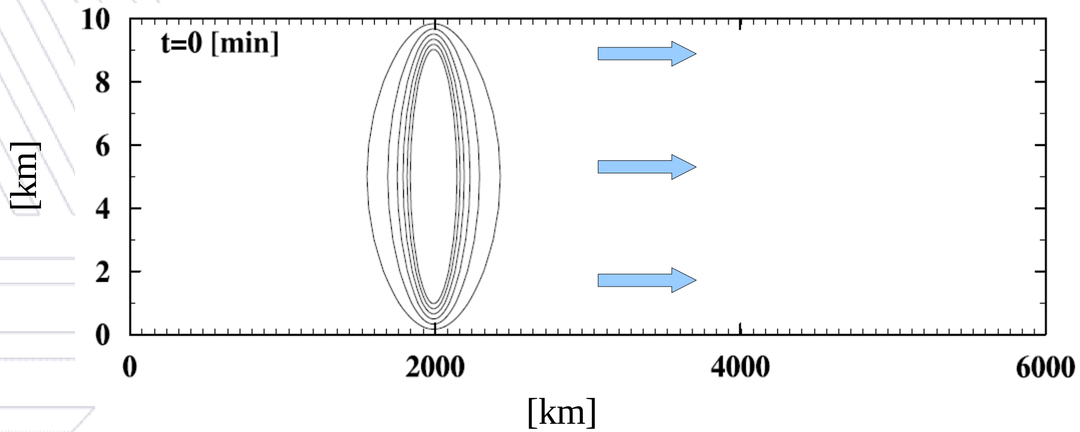
Profiles of potential temperature along 5000m height




convergence to analytic

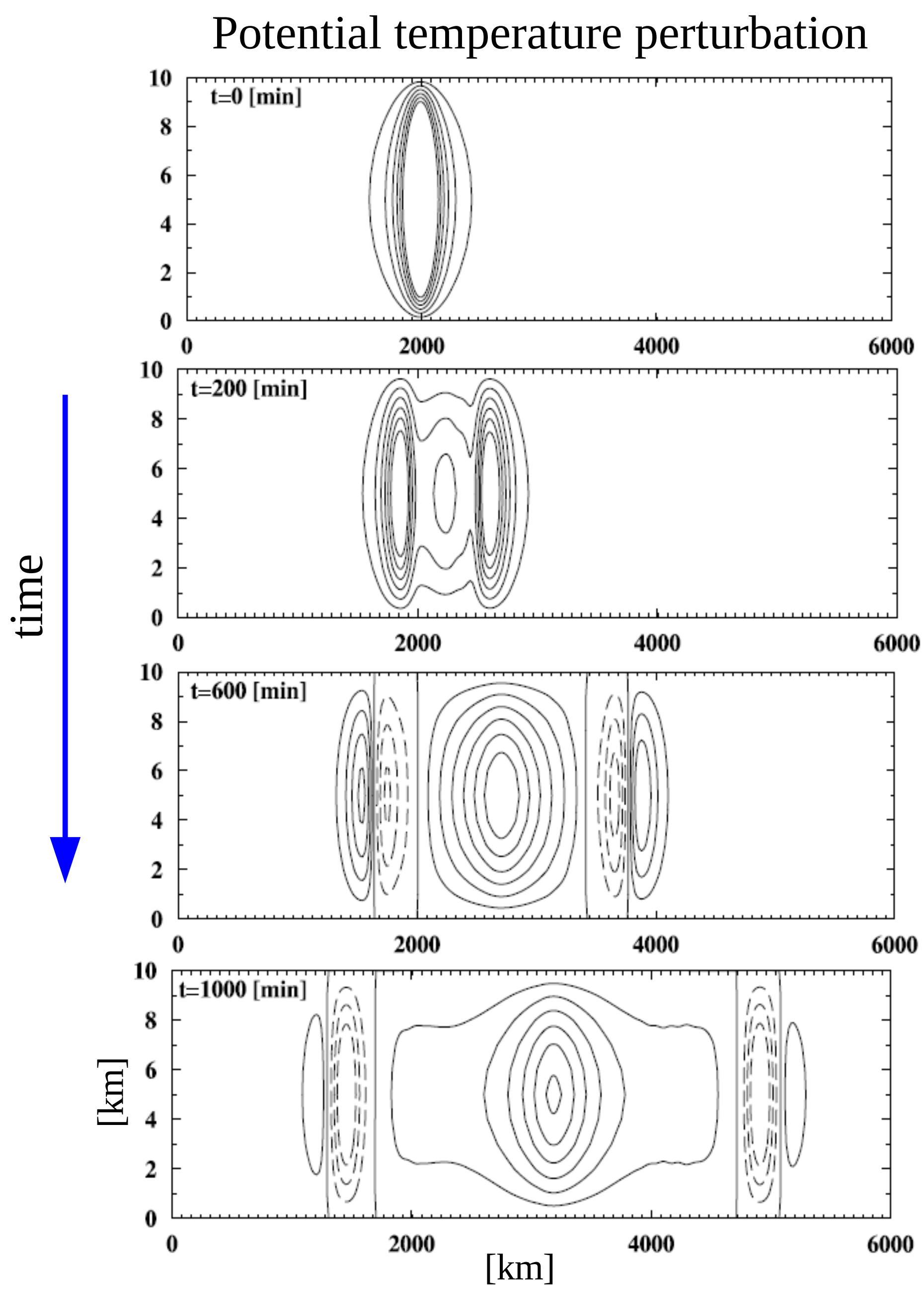
# Constant flow within a long channel (6000km)

Initial potential temperature perturbation




## Setup overview:

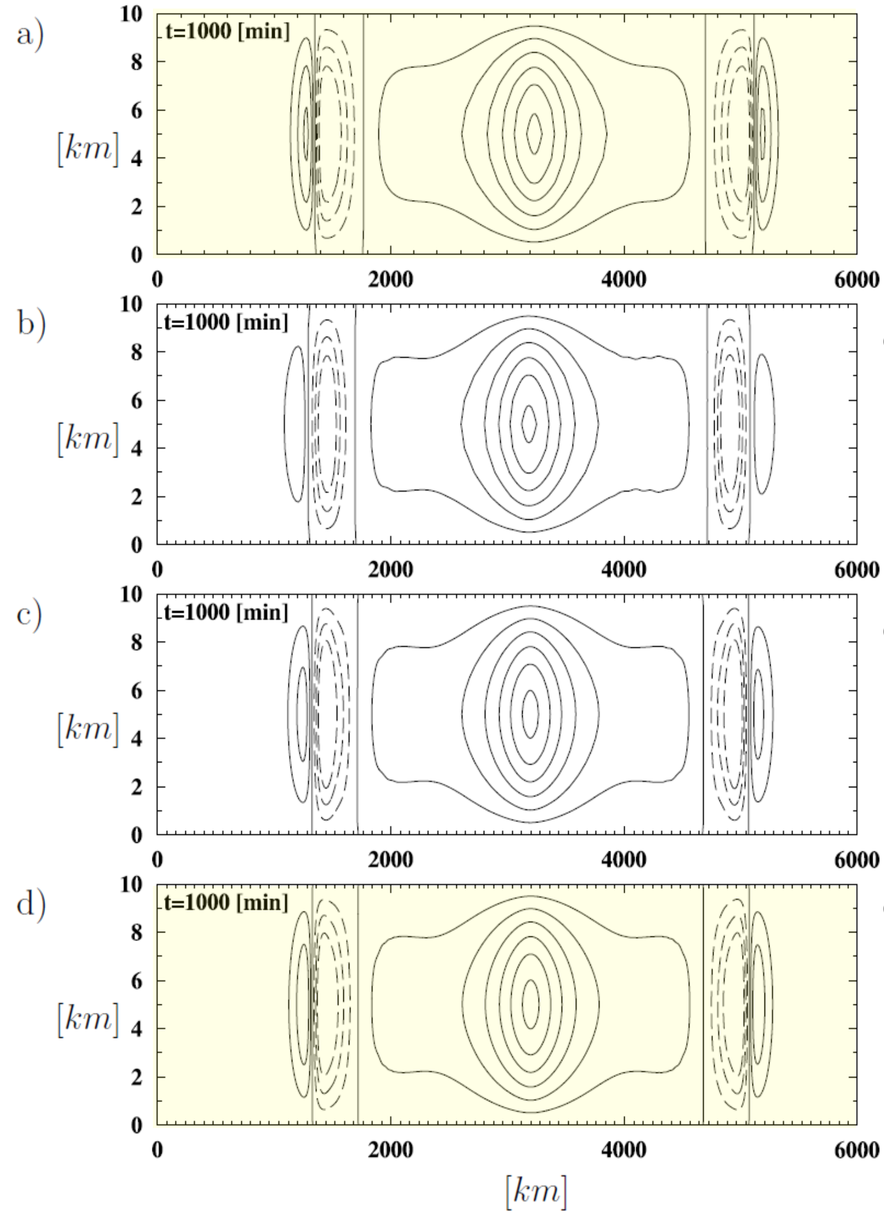
- same as for a short channel except that the domain size is 6000 x 10 km ($\Delta x/\Delta z=20$)
- integration time is 1000min




dx=20km, dz=1km

# Convergence study for resolution

$\theta'$ *(after 1000min)*




analytic solution

dx/dz = 20km/1km

dx/dz = 10km/0.5km

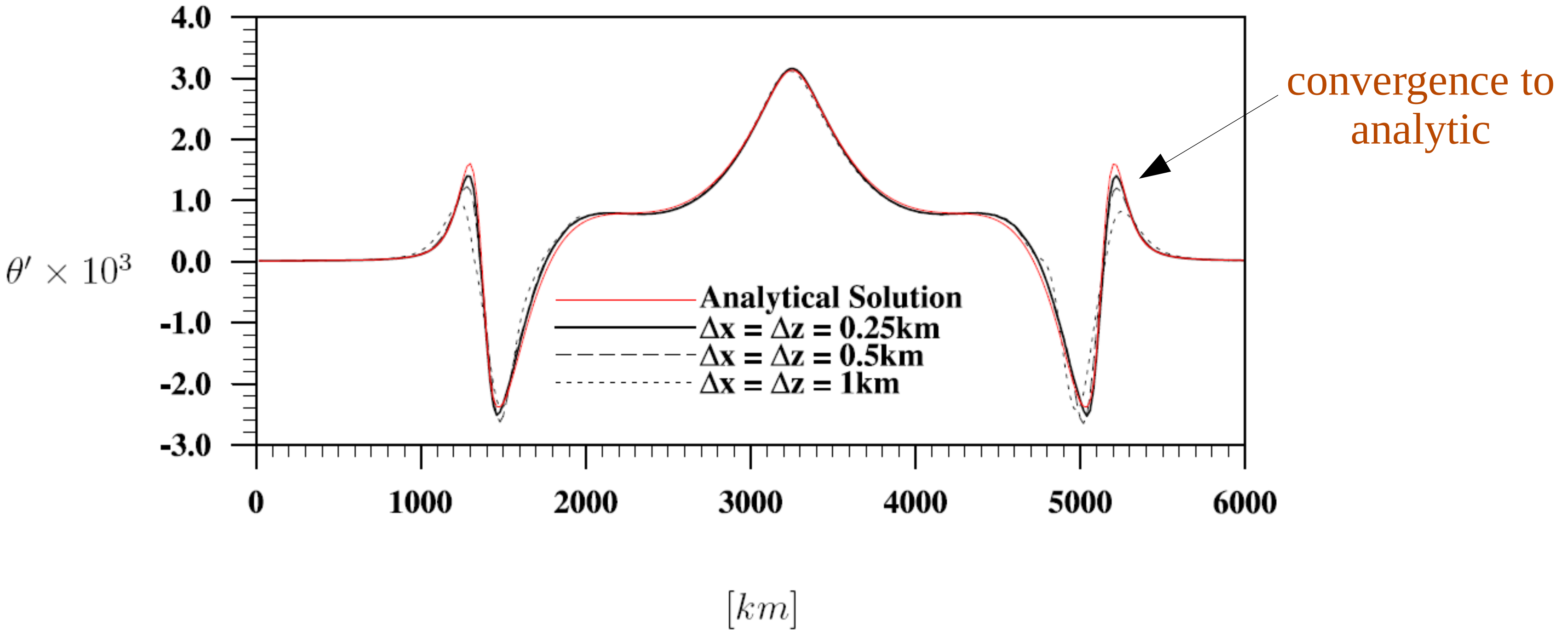
dx/dz = 5km/0.25km

EULAG incompressible Boussinesq

→ Convergence to analytic solution!

# Convergence study for resolution

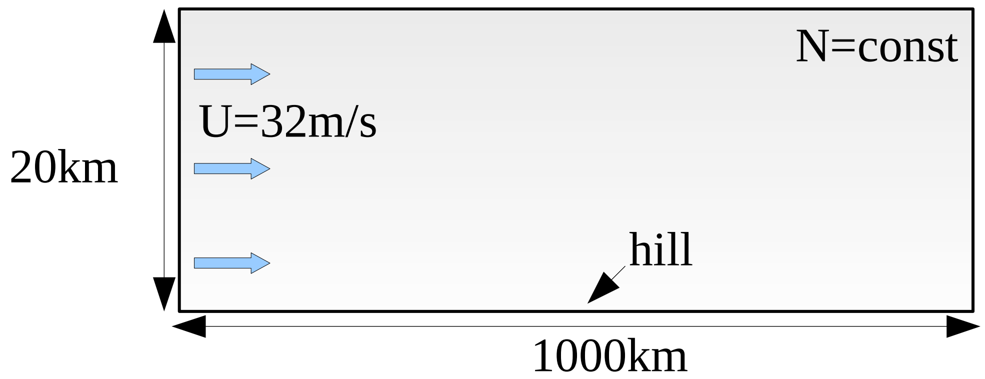
Profiles of potential temperature along 5000m height



# Mountain waves

reference:

Bonaventura, L., A semi-implicit semi-Lagrangian scheme using the height coordinate for a nonhydrostatic and fully elastic model of atmospheric flows. J. Comput. Phys. 158(2):186-213, **2000**

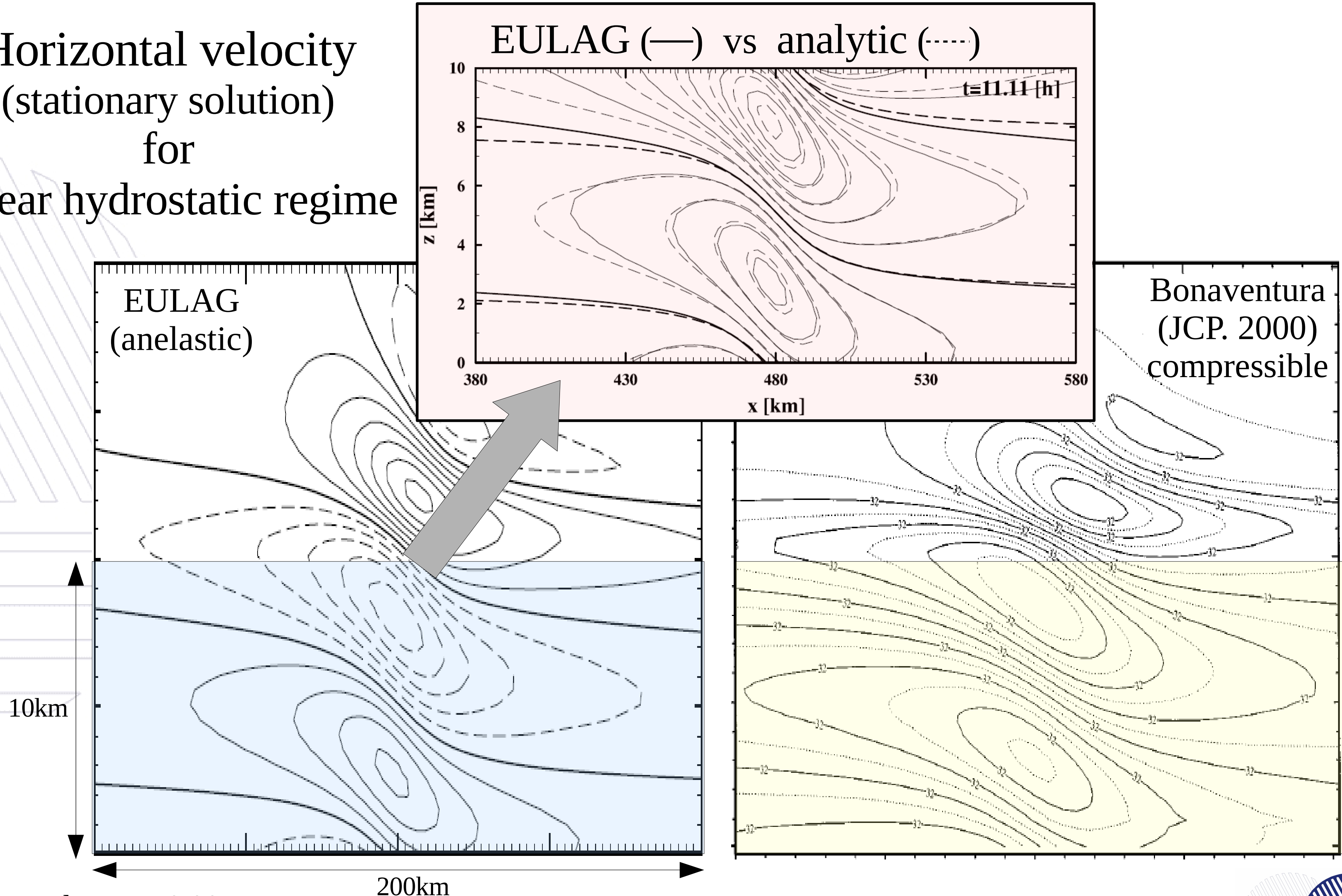



hydrostatic waves generated in stable air passing over mountain

## Setup overview:

- resolution 3x0.25km
- constant horizontal flow (32m/s)
- open lateral b.c.
- free-slip bottom b.c.
- isothermal atmosphere, i.e. constant stratification (N=0.0187 $s^{-1}$)
- absorbers (top and lateral) as in Pinty et al. MWR 1995)
- Agnesi mountain (height **1m**, half-width **16km**)

# Horizontal velocity
(stationary solution)
for
linear hydrostatic regime




U intervals every 0.005m/s

# Flows over the Alps

# 3D Eulag setup based on Cosmo2 700x700 (2.2km) *unfiltered* orography

## Setup overview

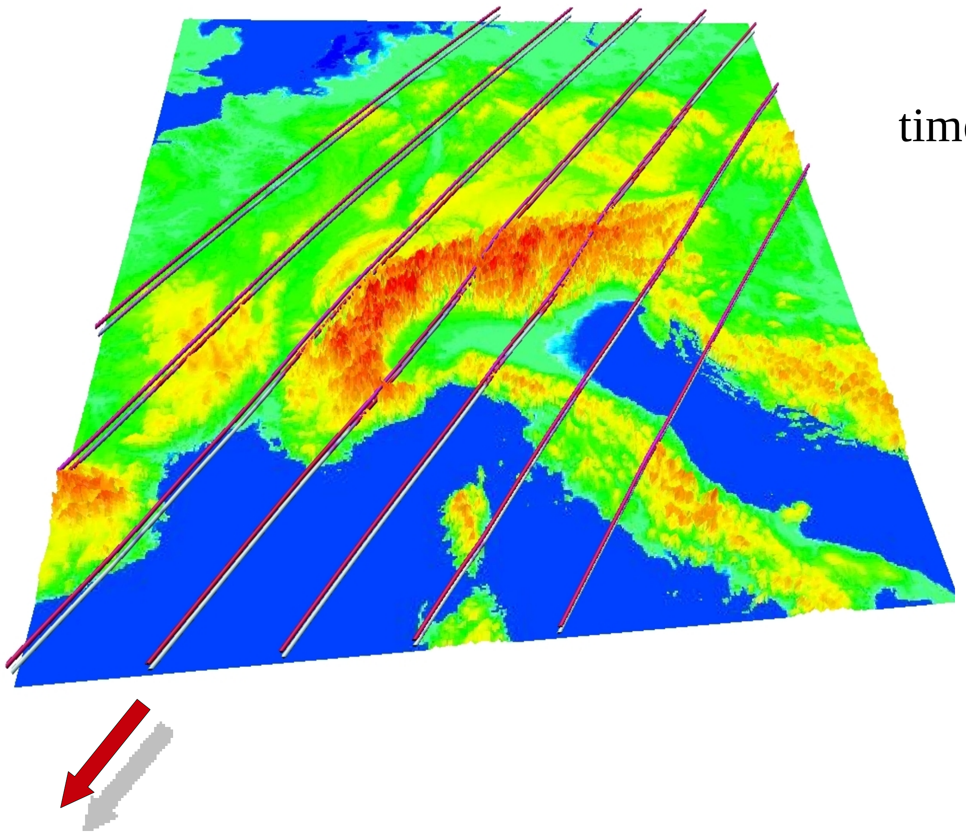
- simple setup with ambient [-5,-5] m/s wind (also various directions)
- open b.c.
- bulk moist model applied, allowing warm rain
- no surface fluxes
- no explicit subgrid turbulence (inviscid)
- equally spaced vertical levels
- terrain-following coordinates
- 2 tests: **actual** and **double** height (i.e. max ~ 8km)

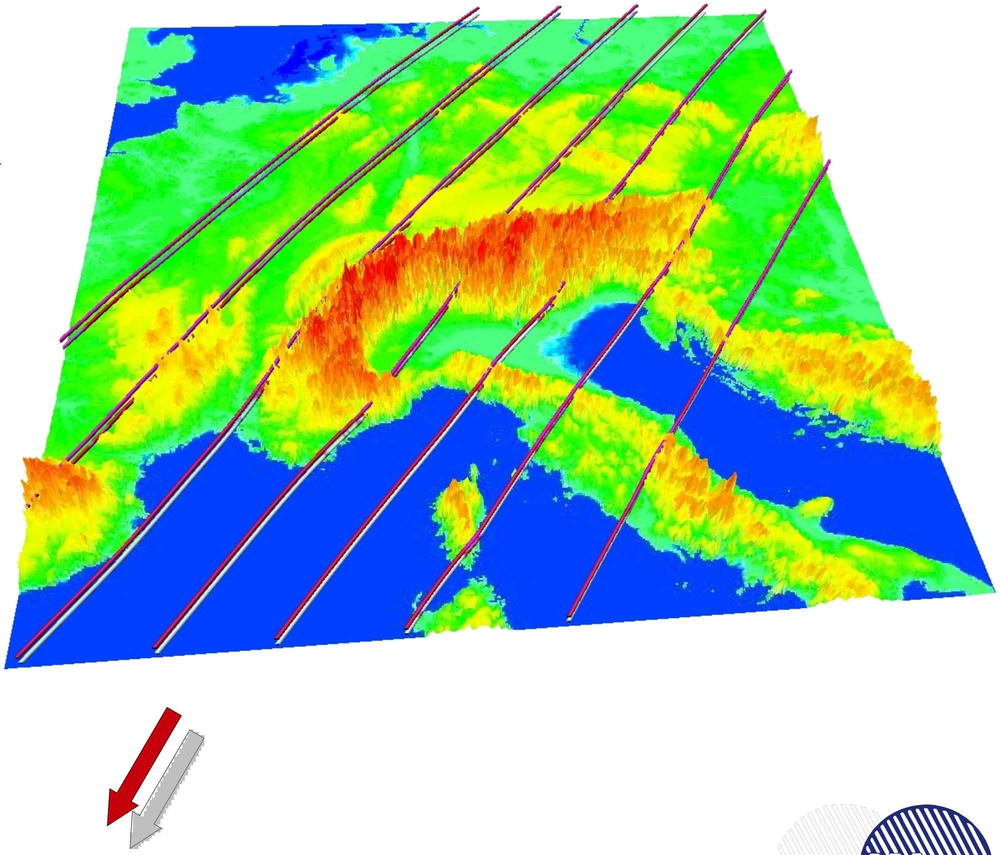
# 3. SEMI-IDEALIZED TESTS

actual orography

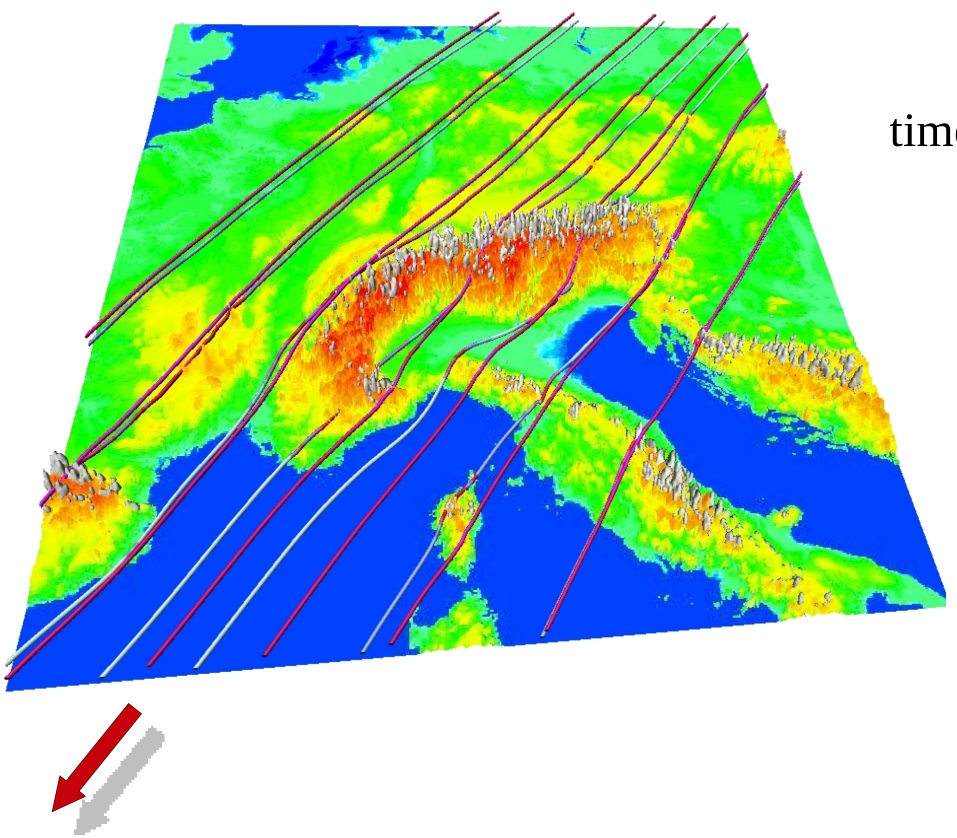
double height

time=0h



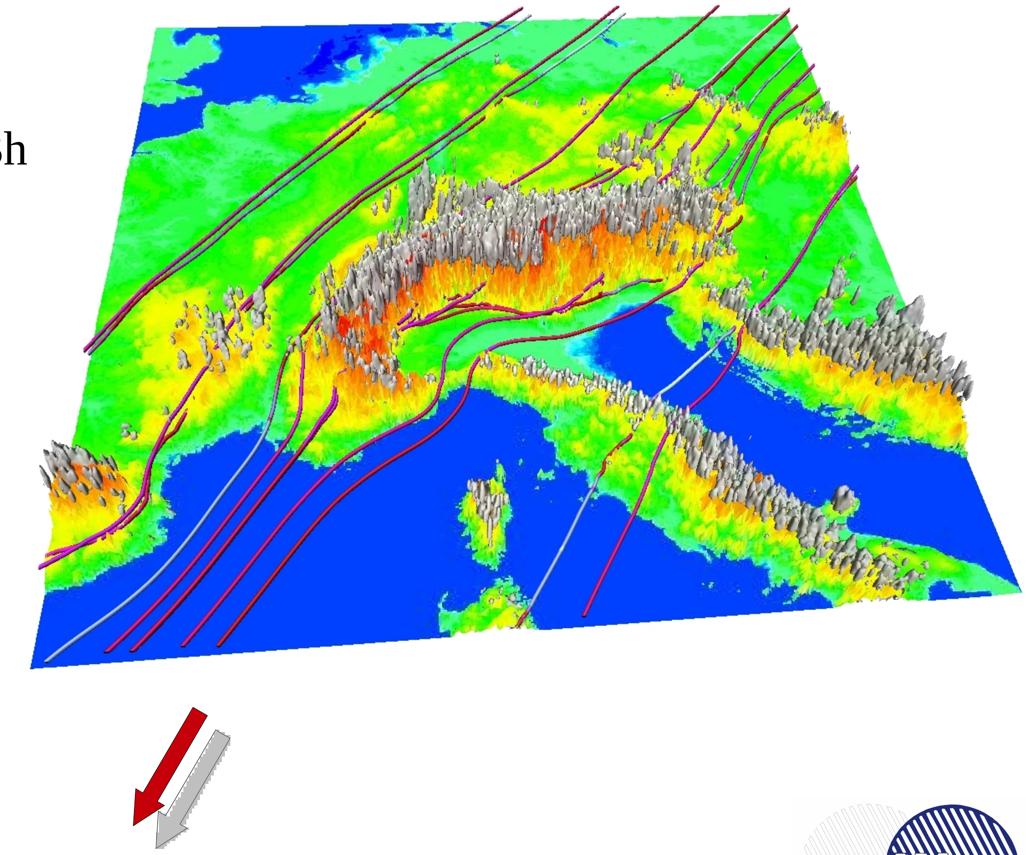


actual orography



time=3h

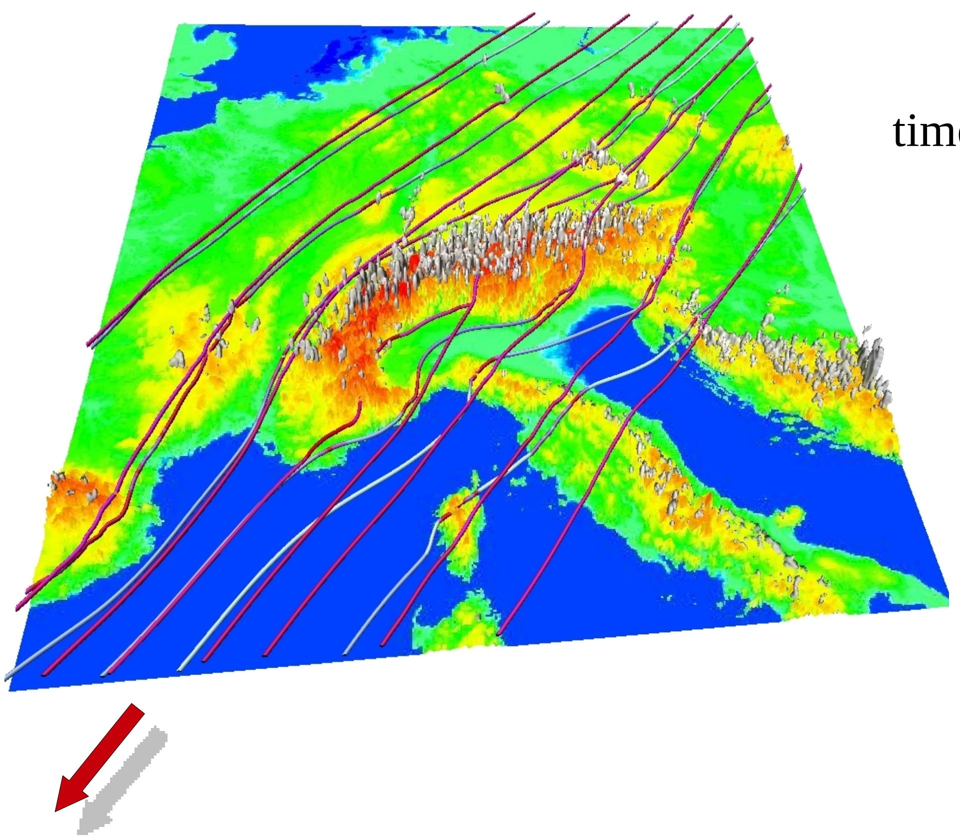
double height



# 3. SEMI-IDEALIZED TESTS

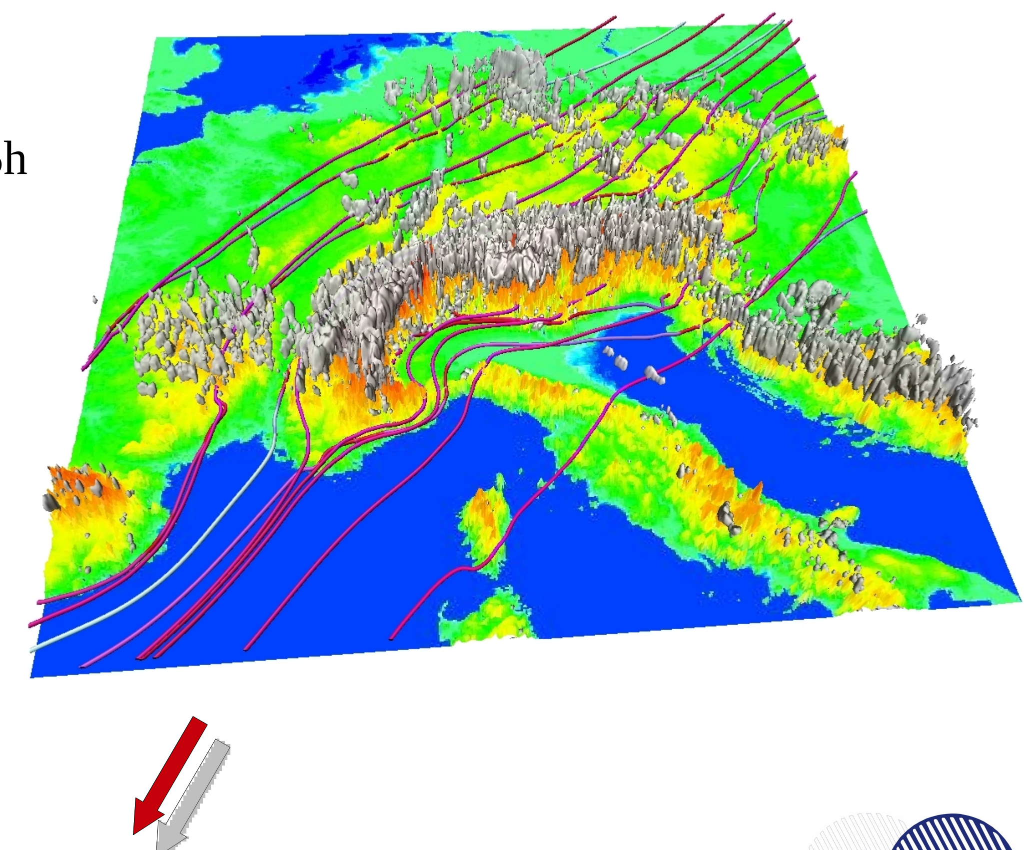


actual orography



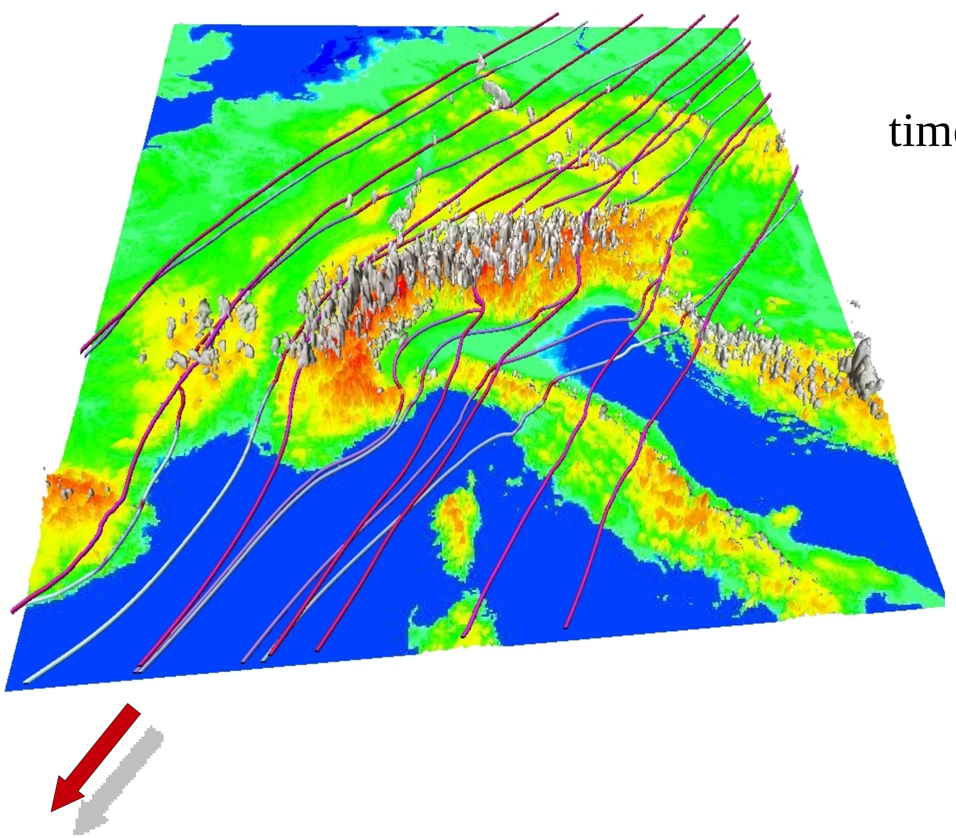
time=5h

double height



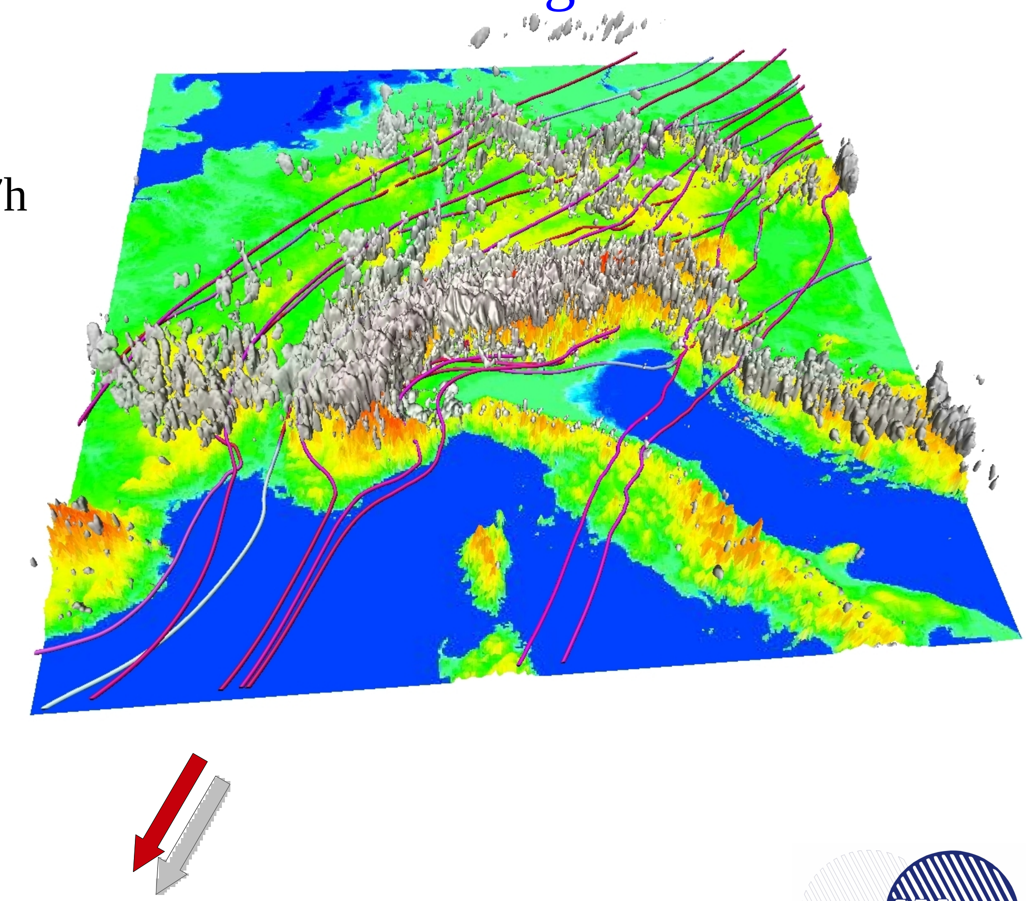
# 3. SEMI-IDEALIZED TESTS

actual orography



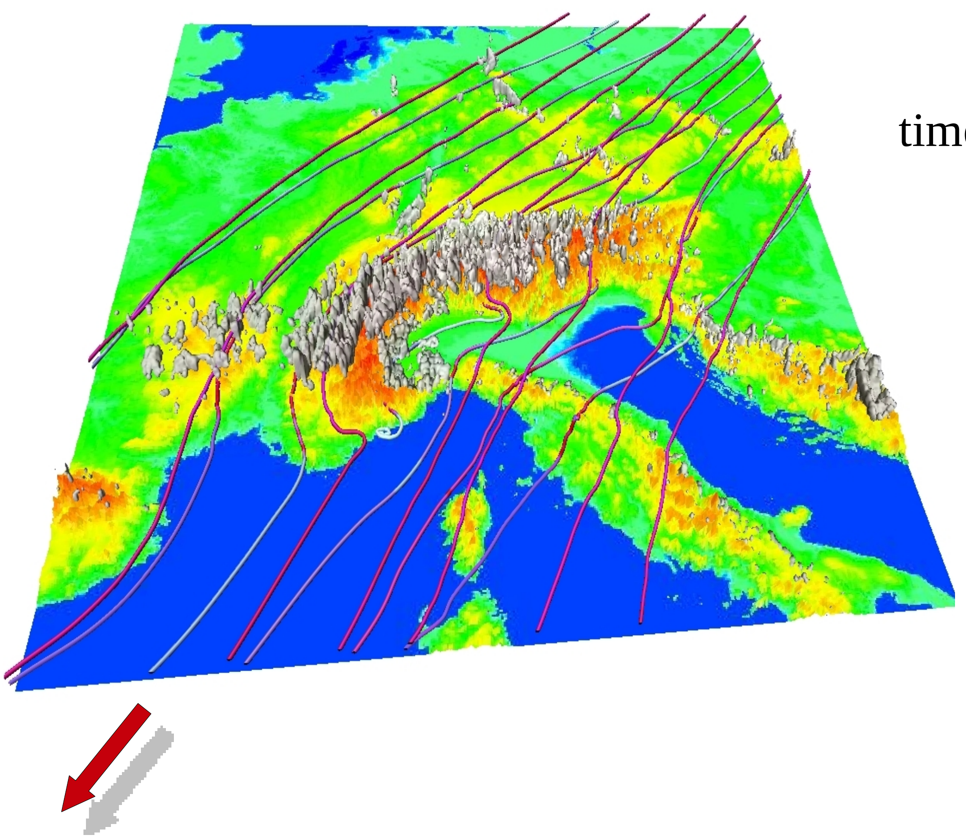
time=7h

double height



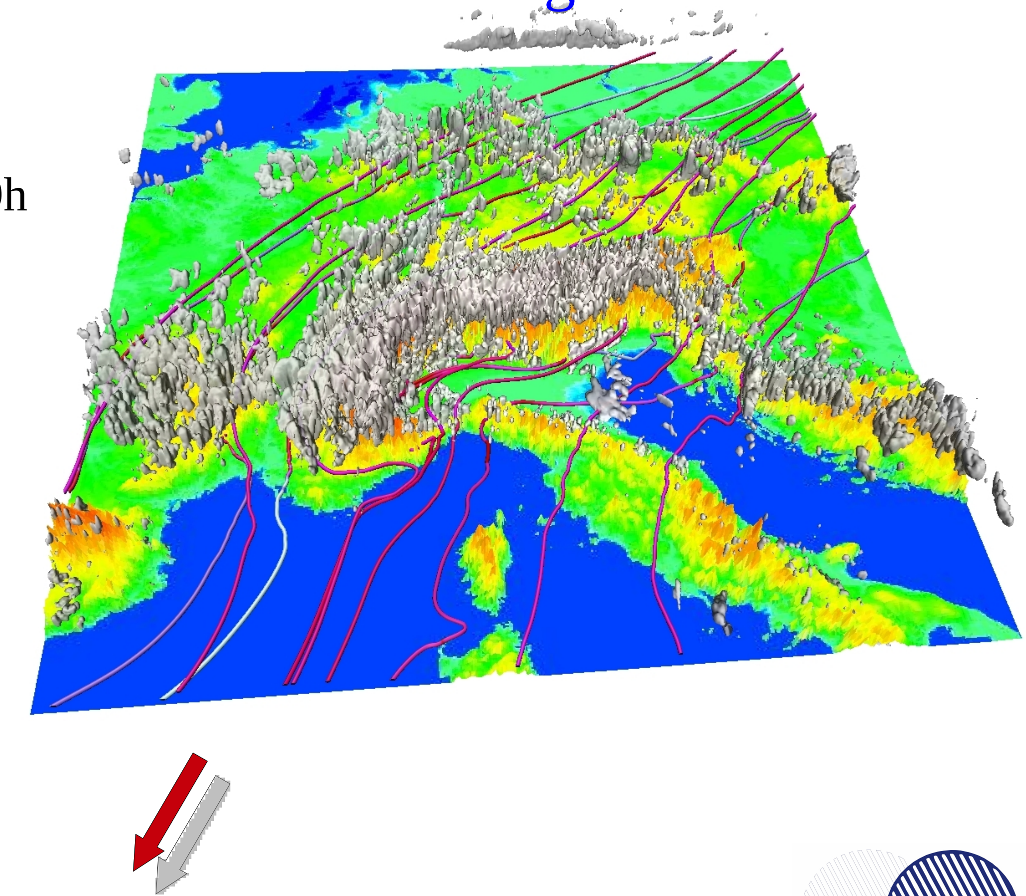
# 3. SEMI-IDEALIZED TESTS

actual orography



time=9h

double height

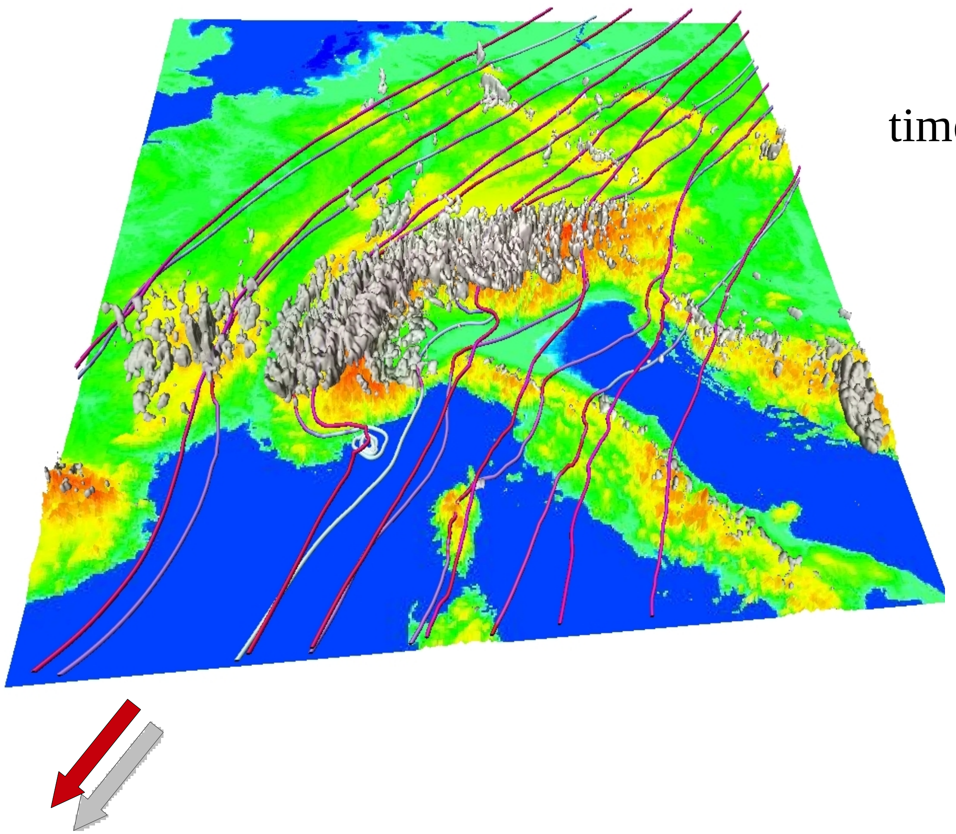


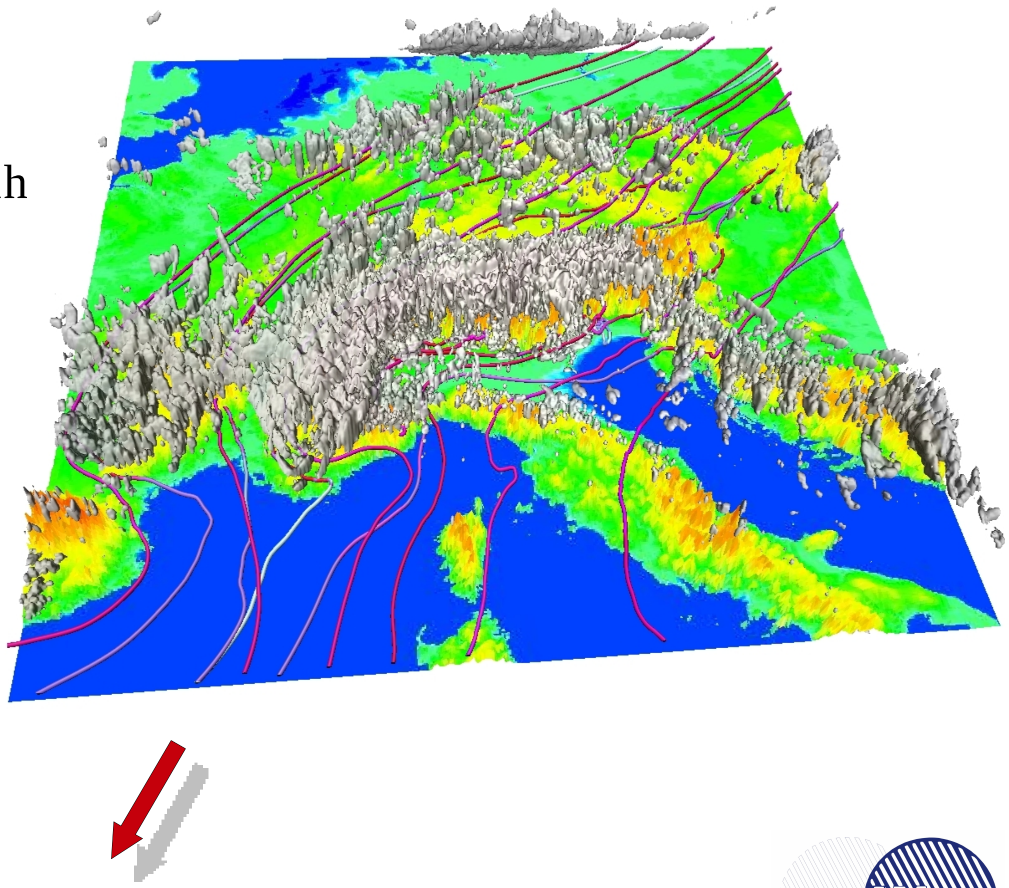
- the flow has realistic features even for very steep orography
- no numerical/computational problems were reported during model run

actual orography

double height

time=11h





# Computational issues: computational efficiency and scalability

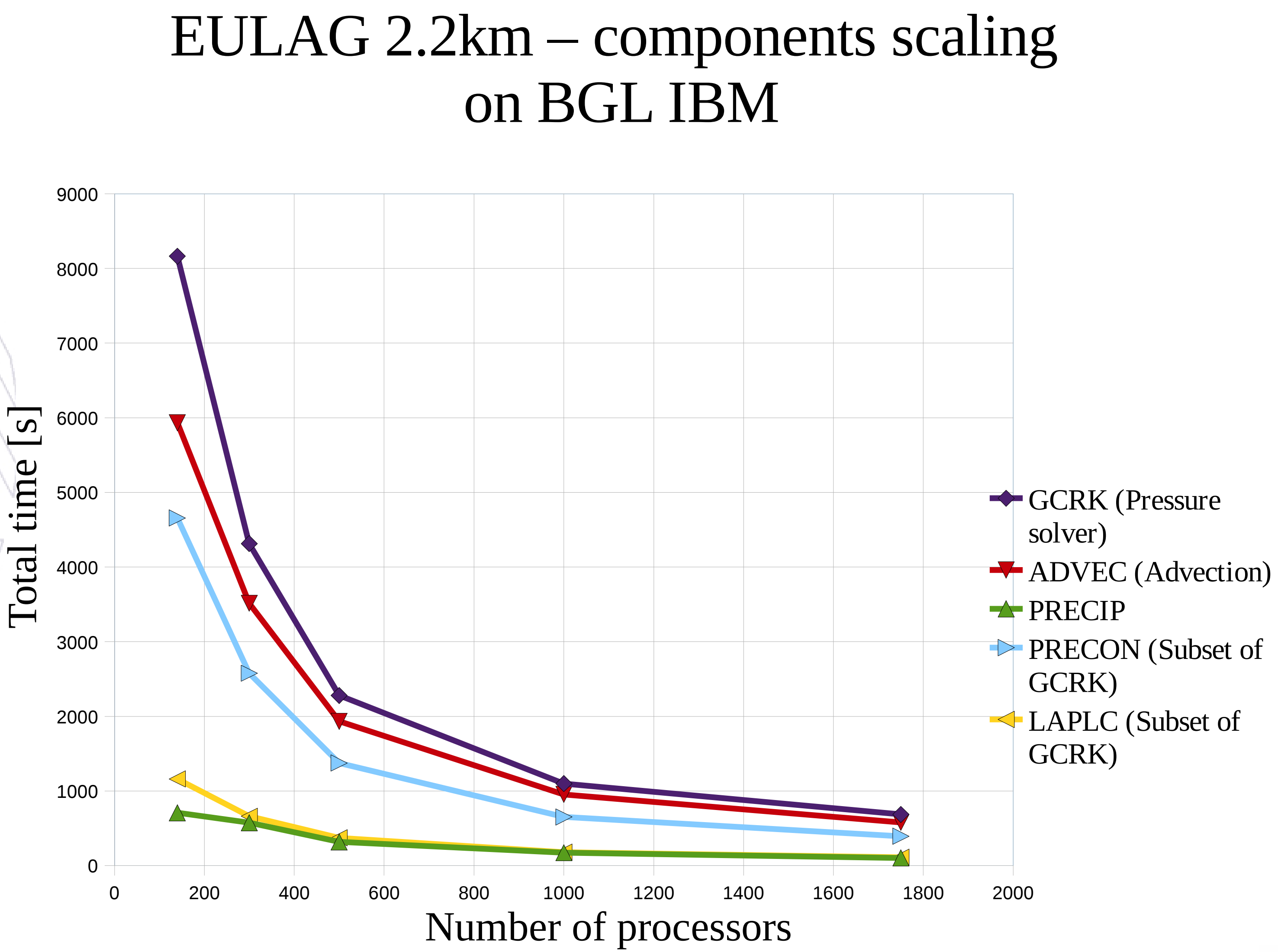
Tests of scalability were performed on 3 different platforms/architectures with use of TauProfiler:

- **IBM BGL** (BlueGene, NCAR, Boulder) – series of experiments
- **Linux cluster** (TASK, Gdańsk) – series of experiments
- **Cray XT/4** (MeteoSwiss) – a model run (comparison with COSMO)

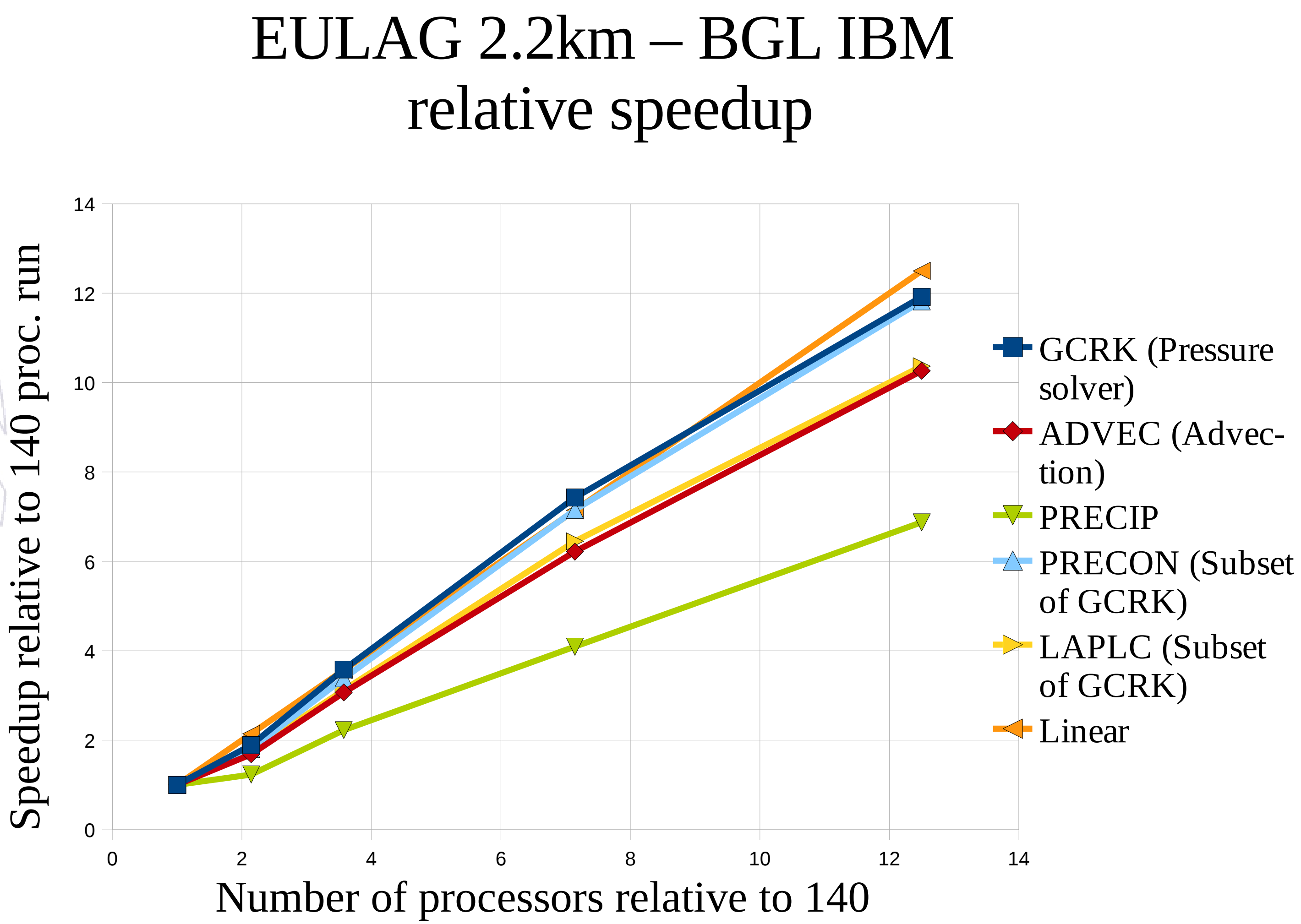
Model setup:

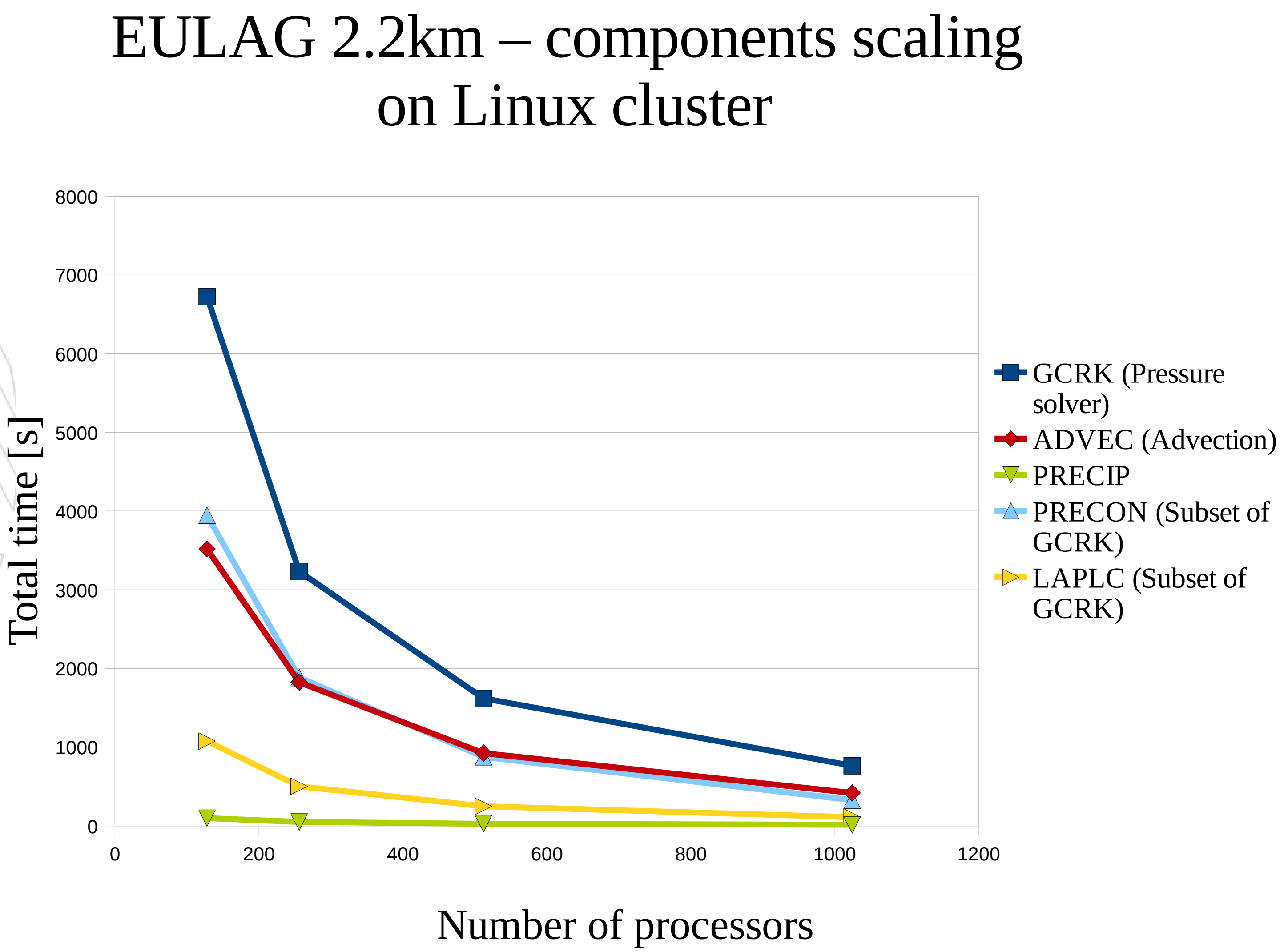
as for semi-idealized flow
over the Alps (COSMO2 2.2km)

# 4. EULAG MODEL PERFORMANCE

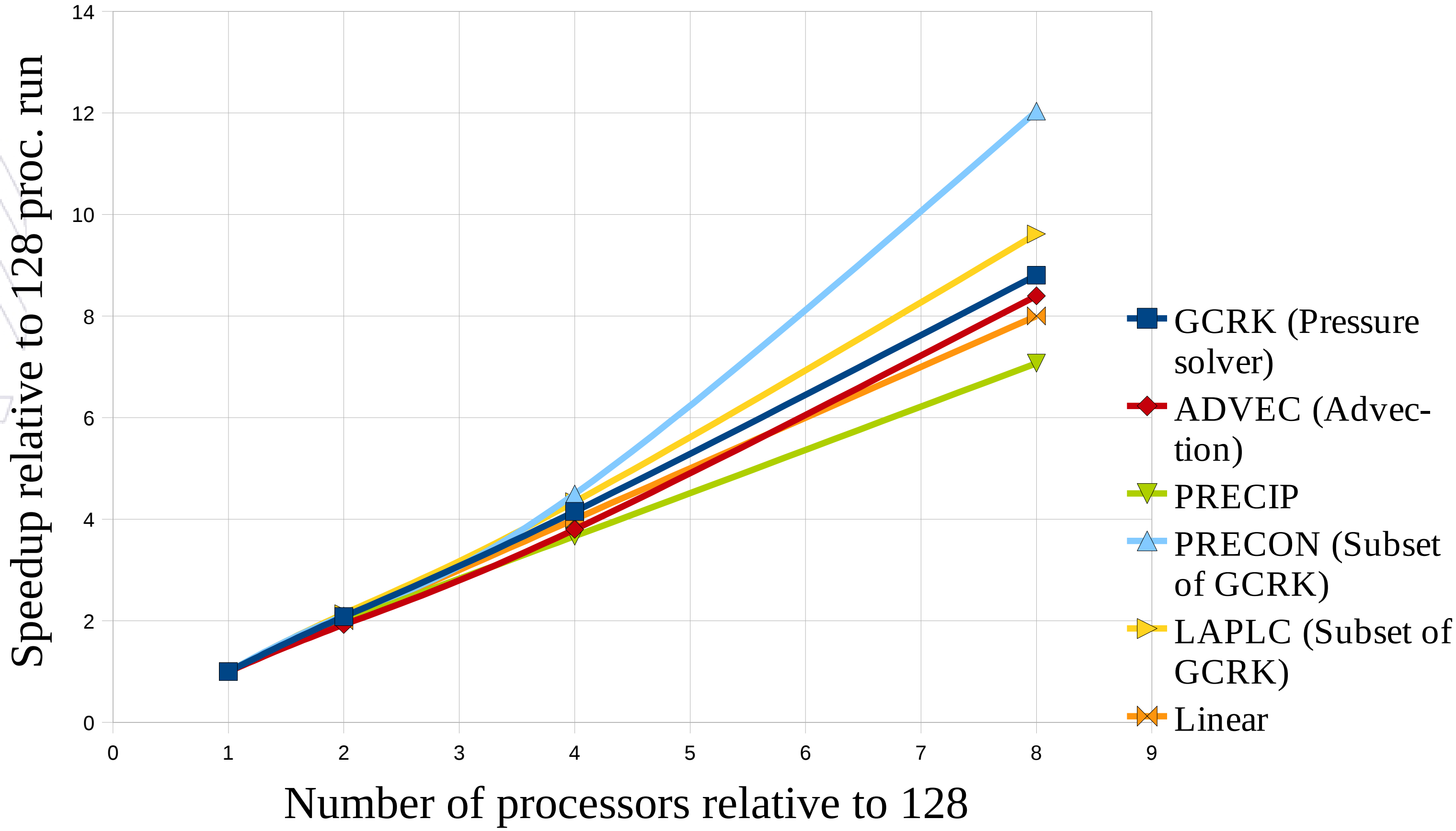


# 4. EULAG MODEL PERFORMANCE




EULAG 2.2km – components scaling
on Linux cluster
Total time [s]
8000
7000
6000
5000
4000
3000
2000
1000
0
0
200
400
600
800
1000
1200
Number of processors
GCRK (Pressure solver)
ADVEC (Advection)
PRECIP
PRECON (Subset of GCRK)
LAPLC (Subset of GCRK)

## EULAG 2.2km – Linux cluster relative speedup



# Computational efficiency – comparison with operational COSMO run on Cray XT/4 (MeteoSwiss)

Summary of 24h forecast

| | EULAG | COSMO | |
|---|---|---|---|
| setup | semi-idealized with bulk microphysics | fully operational | |
| # of processors | 650 | 800 | |
| total time | 24 minutes | 22 minutes | SIMILAR |

# Results, so far ...

- good agreement of the results with the reference numerical and analytic solutions for idealized flows

- realistic solutions for semi-idealized  tests with steep orography

- lack of numerical problems imposed by steep slopes or orographicaly driven moist (bulk) processes

- good scalability and the computational efficiency similar to COSMO model (more tests needed?)

# Future

- Continuation of task 1.1:
  - complete idealized tests (with documentation)

- Continuation of task 1.2
  - realistic Alpine flows
  - solving the problem of determination of full pressure
  - complete tests of computational efficiency and scalability

- Next steps: task 1.3 and task 1.4:
  task 1.3: Tests of the EULAG dynamical core for realistic flows over the Alpine topography with simplified physics parametrization
  task 1.4: Choice of the anelastic equation system

# Thank you