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Test cases for NH effects

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1 Presentation Subject

NH effects in dynamics

Test sites

Testing principles

Orographic test cases

Convection test examples

2 NH effects in dynamics

NH effects are distinguished by the amplitude of vertical acceleration
When horizontal resolution becomes large enough:

$$\Delta x,\ \Delta y < 10\ km$$

then vertical acceleration should not be omitted:

$$1 + \frac{1}{g\rho}\frac{\partial p}{\partial z} = 0 \ \Rightarrow \ 1 + \frac{1}{g\rho}\frac{\partial p}{\partial z} = -\frac{dw/dt}{g} = -\varepsilon.$$

How large can become the small quantity

$$\varepsilon = \frac{dw/dt}{g}?$$

How large it must be for NH quality emerging?

Can ε be treated as the characteristic of NH nature of dynamics at all?

In the atmosphere of Earth, two phenomena are recognized as generators of NH behaviour:

Convection (thermally forced)

Orographic flow

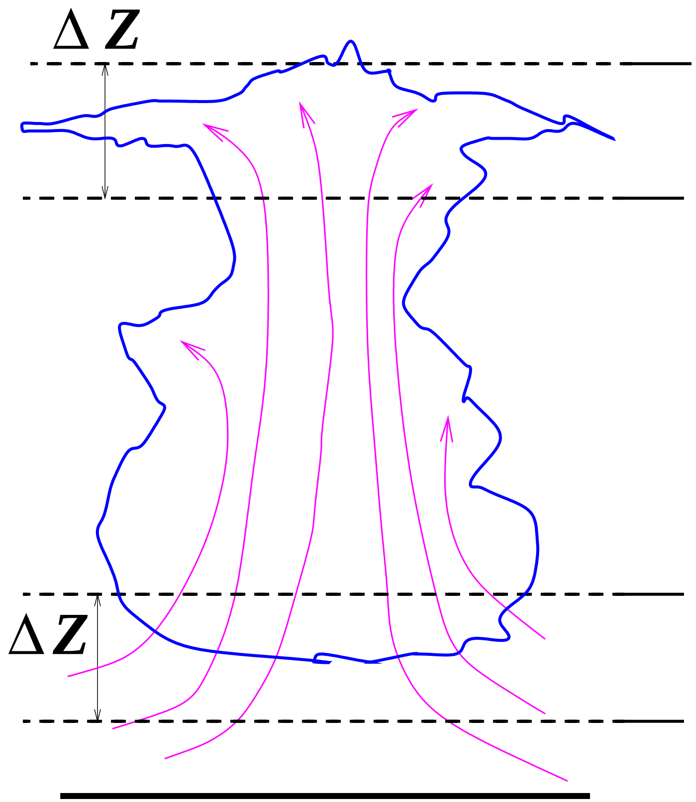
Local convection at very short scales $\Delta x, \Delta y$ $\sim$ 100 m (< 1 km)

$$\frac{1}{g}\frac{\mathrm{d}w}{\mathrm{d}t} \sim 0.001 - 0.1$$

$$\frac{\mathrm{d}w}{\mathrm{d}t} \sim w\frac{\partial w}{\partial z} \sim \frac{(\Delta w)^2}{\Delta z}$$

$$\Delta w \sim 1 - 10 \quad m/s \ ,$$

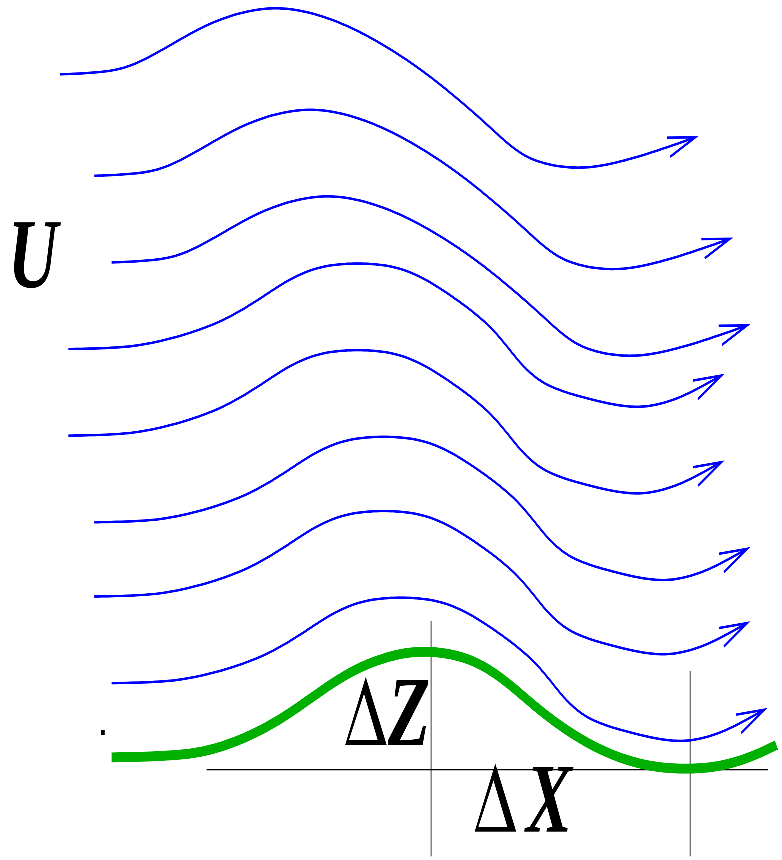
$$\Delta z \sim 100m$$



Orographic flow at short scales

$\Delta x, \Delta y \sim$ 3 km (< 10 km)

$$\frac{1}{g}\frac{\mathrm{d}w}{\mathrm{d}t} \sim \ (<)\ 0.01$$



$$\frac{\mathrm{d}w}{\mathrm{d}t} \sim U\frac{\Delta w}{\Delta x}, \Delta w \sim \frac{U\Delta z}{\Delta x}$$

$$\Rightarrow \frac{\mathrm{d}w}{\mathrm{d}t} \sim \frac{U^2\Delta z}{\Delta x^2}$$

$$U \sim 10 \quad m/s \ ,$$

$$\Delta x = \Delta z = 1 \ km$$

Thus,

(1) In convective events, NH effects become actual at horizontal resolutions $\Delta x \sim$ 100 m (at resolutions which do resolve vertical convection)

(2) In orographic flow case, departure from HS state (in vertical momentum equation) is very small yet it does causes NH quality of flow from resolutions $\Delta x <$ 5 - 10 km

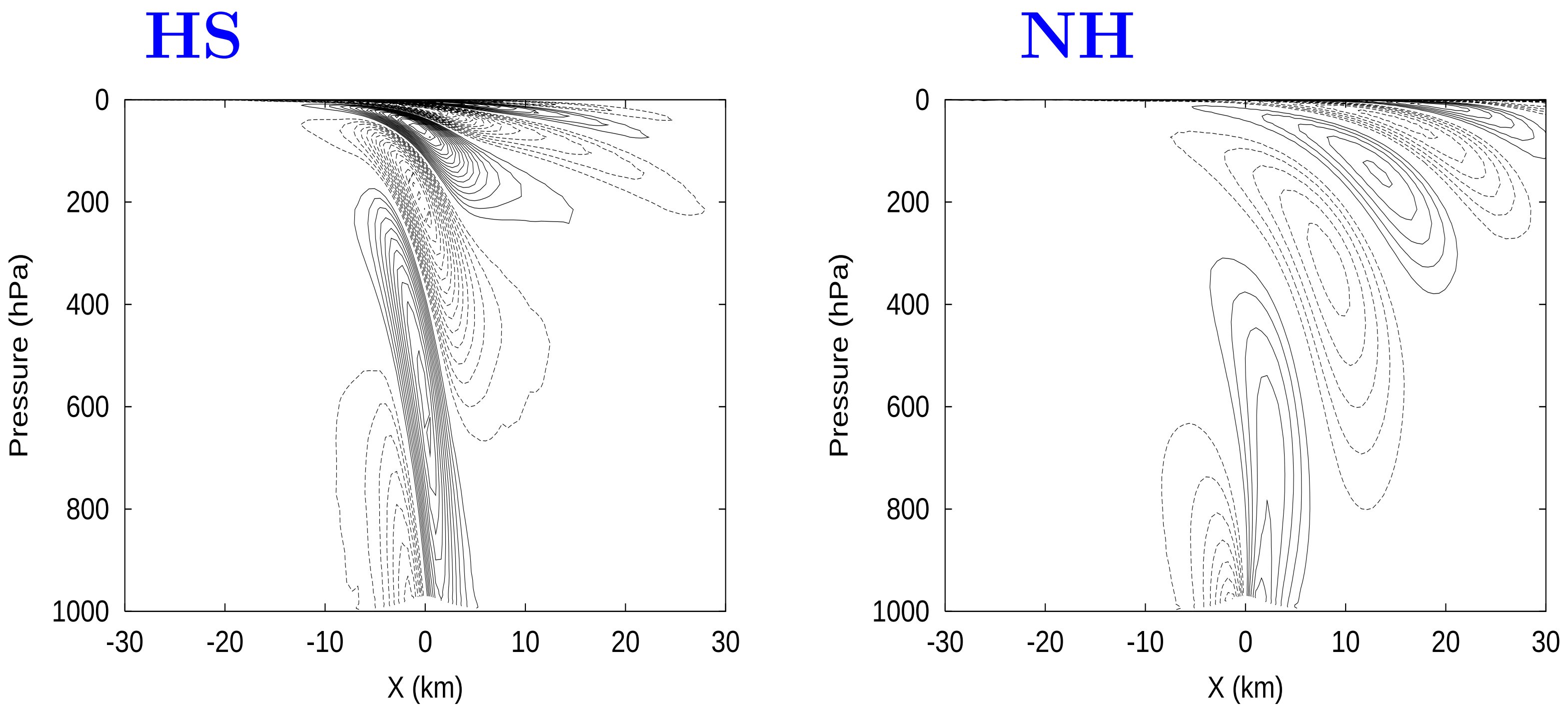
The NH effect manifests itself in different behaviour of buoyancy waves in comparison with HS case.

Vertical acceleration finiteness causes significant changes in group speed direction and magnitude of waves.

The wave amplitude changes,
the wave pattern becomes rather different,
the wave drag modifies essentially.

All this happens at $\varepsilon \sim \mathbf{10^{-3}}$ already.

NH effect in orographic flow



Vertical velocity isolines ($\Delta w = 10$ cm/s) for stationary flow over an isolated 1D hill (ridge) with $a_x = 2.5$ km and $h = 250$ m.

$T =$ const., $U = 15$ m/s ($\varepsilon = 10^{-3}$)

3 SRNWP Test Site

http://www.mmm.ucar.edu/projects/srnwp_tests/

This test site was proposed at the SRNWP (Short Range Numerical Weather Prediction) workshop in Bad Orb, Germany, 27-29 October 2003, and it was then developed by:

W. Skamarock (NCAR), B. Doyle (ONR) , P. Clark and N. Wood (MetOffice).

4 Main principles

Main principles as formulated at SRNWP site:

(1) Tests should be easy to configure

(2) Tests should be easy to evaluate

(3) Tests should require only minimal physics (dissipation, very simple moist physics)

(4) Tests should test something in the solver

(5) Test set should be a minimal set

The SRNWP test-site includes:

(1) Inertia gravity waves in a periodic channel

(2) Density Current

(3) Resting atmosphere

(4) Potential flow over a mountain

(5) 2-D mountain waves (hydrostatic and nonhydrostatic, linear and nonlinear)

(6) 3-D mountain waves

(7) Schär test case

(8) Squall lines and/or supercells?

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Legend: Red: Existing NH tests
Blue: Other existing tests Black: Wanted tests

5 Terrain Forced Flow Test-case

The differences in buoyancy wave properties is the most outstanding feature which makes NH dynamics different from HS primitive equation model dynamics, For NH testing, orographic flows are most salient at 1 - 10 km resolutions

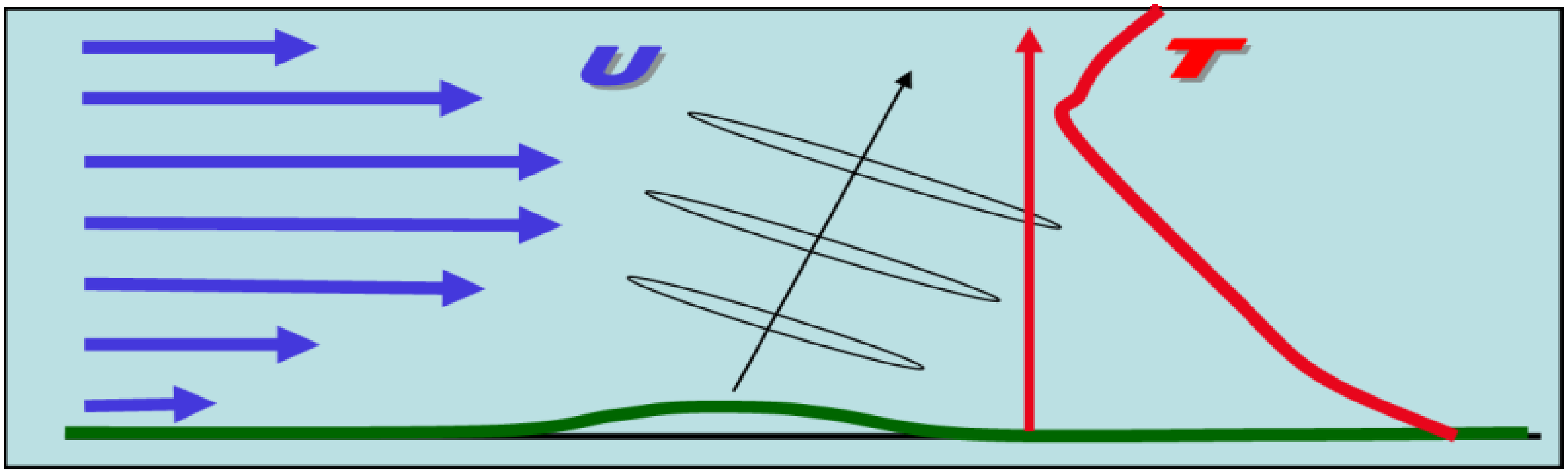
The buoyancy wave properties of the model are not easy to observe and measure in real conditions.

Examples of observed NH wave fields

Vorticity street behind Guadeloupe island

The main idea of (NH) model testing based on terrain forced flow modelling

For given orography, wind and temperature distribution,



in linear flow regime, the numerical model is run until (quasi) stationary state is achieved.

Results are compared to exact linear stationary solution with the same orography, wind and temperature.

Coincidence is looked for macro-parameters of the wave pattern like the amplitude, phase, wave-length.

No line-to-line coincidence is looked for. (WHY?)

The linear stationary reference model must be a NH scheme of guaranteed (high) quality (exact solution)

Fortes/Strong points:

Overall debugging facility

In addition to the main purpose (NH quality testing):

– Check and testing of specific details of numerical scheme (spectral smoothing, decentering, time-(Asselin-)averaging, boundary relaxation scheme)

– Testing of spatial discretization and time step size effects onto model accuracy)

Weaknesses:

– Transient flow regimes are not accessible

– Nonlinear effects are not accessible

(Not as serious deficiency, however, as it may be expected tentatively ...)

6 Test Experiment Componets

1. Orography

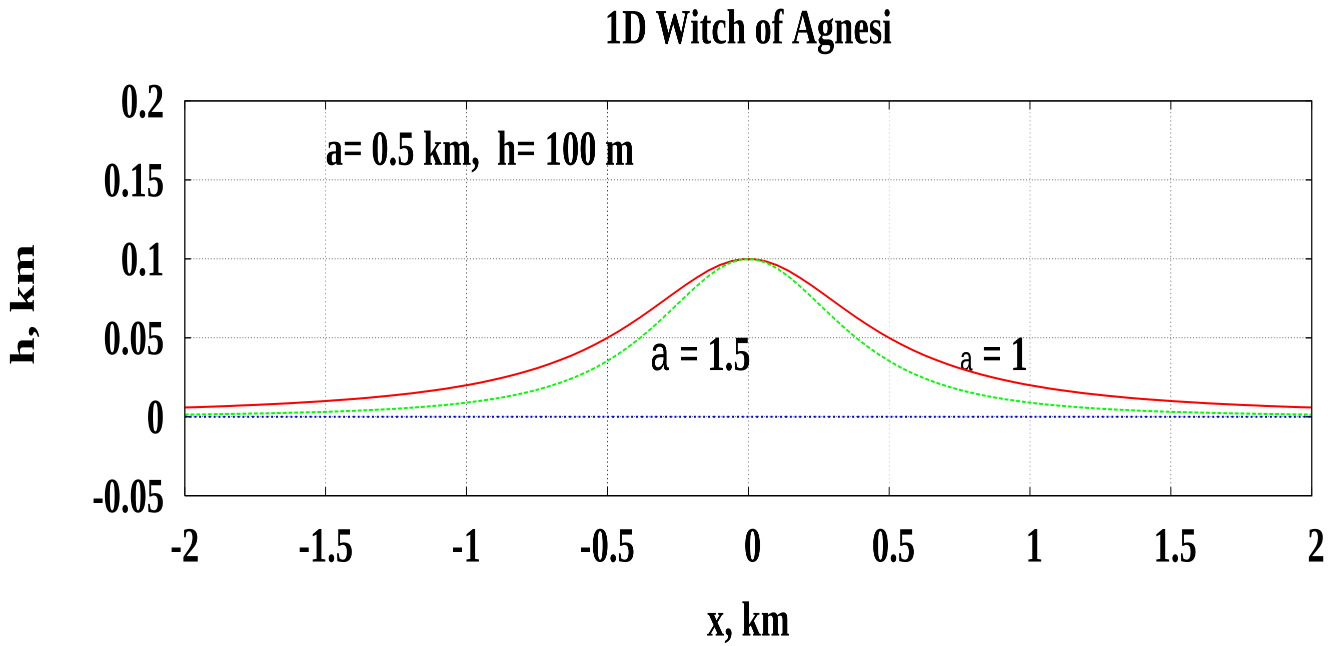
2. Reference atmosphere - wind $\mathbf{V}(z)$ and temperature $T(z)$

3. Exact linear reference solution

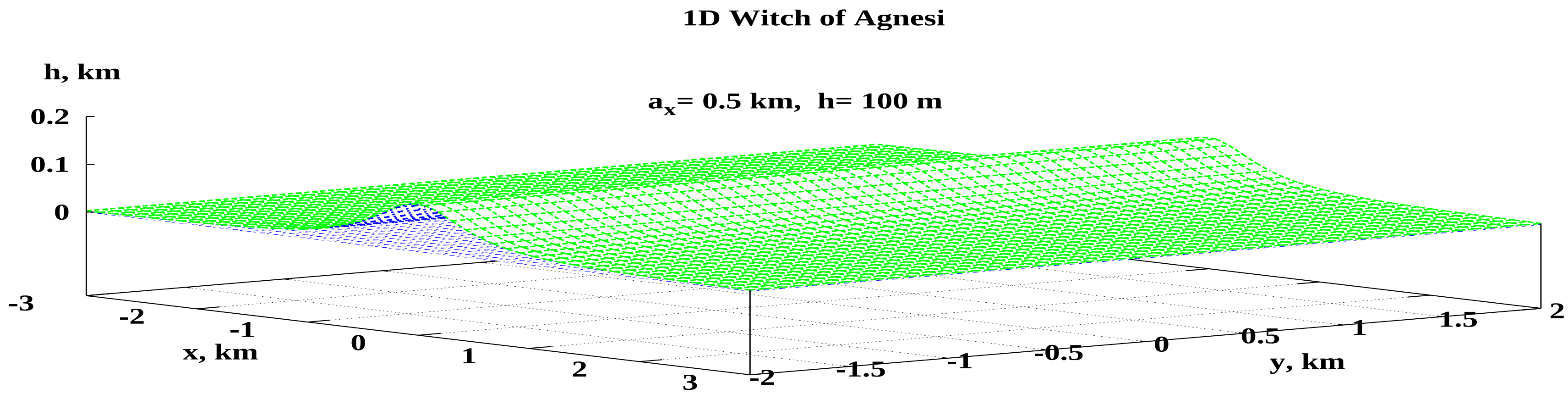
4. Non-linear numerical research model (testing subject)

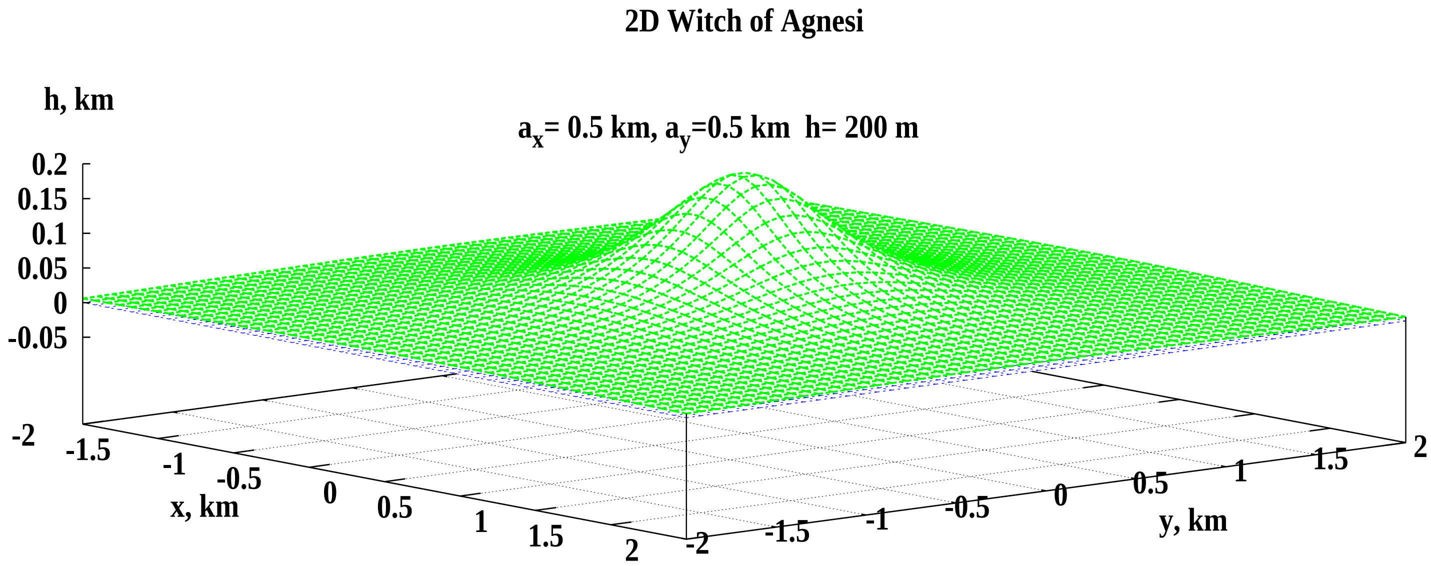
Orography

1. Witch of Agnesi



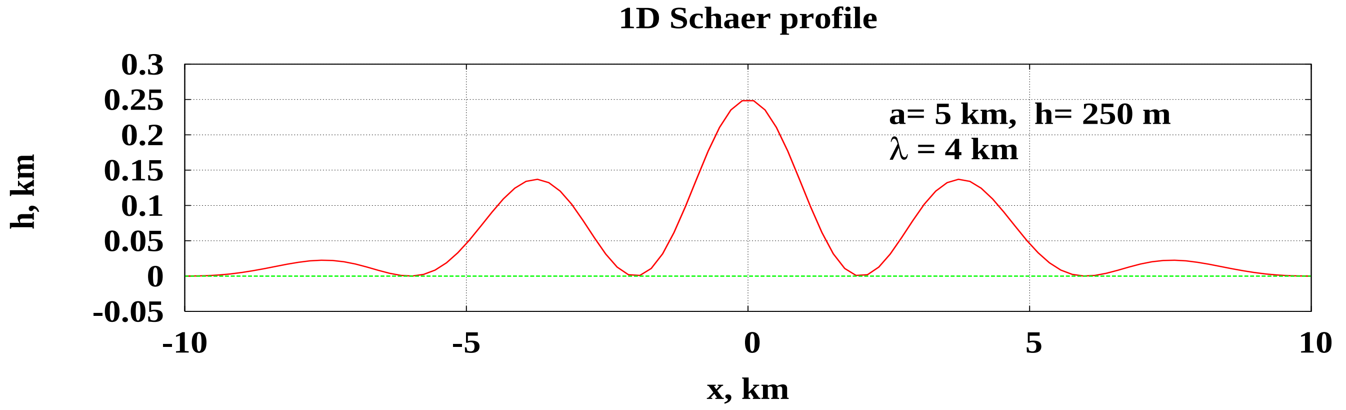
$$h(x,y) = \frac{h_0}{[1 + (x/a_x)^2 + (y/a_y)^2]^\alpha}, \quad \alpha = \begin{cases} 1.5 & (1D), \\ 1.0 & (2D) \end{cases}$$

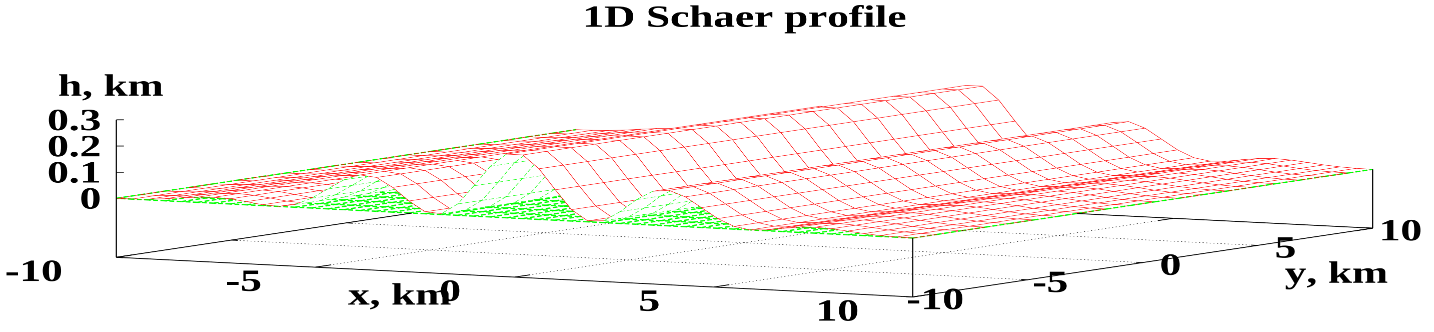

1D Witch of Agnesi
h, km
a_x= 0.5 km, h= 100 m
0.2
0.1
0
-3
-2
-1
0
1
2
3
x, km
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
y, km


2D Witch of Agnesi
h, km
a_x= 0.5 km, a_y=0.5 km h= 200 m
0.2
0.15
0.1
0.05
0
-0.05
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
x, km
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
y, km

Schär orography

$$h(x) = h_0 \exp[-(x/a_x)^2] cos^2(\pi x/\lambda)$$

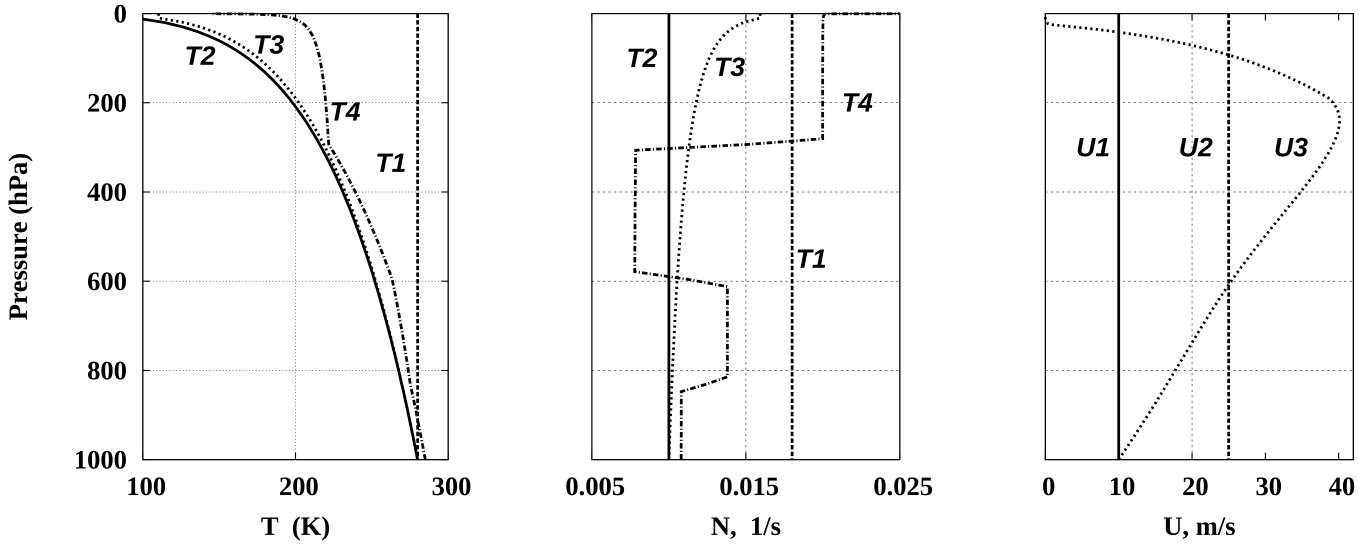




Linear "exact" test solutions

Initially (including the SRNWP test-site), the analytical solution of NH buoyancy-wave equation with constant T and U was applied.

For recent tests of NH HIRLAM, a special numerical solution algorithm of the linear semi-implicit semi-Lagrangian (optionally Eulerian) stationary equations with arbitrary numerical resolution has been developed (Zirk and Rõõm).

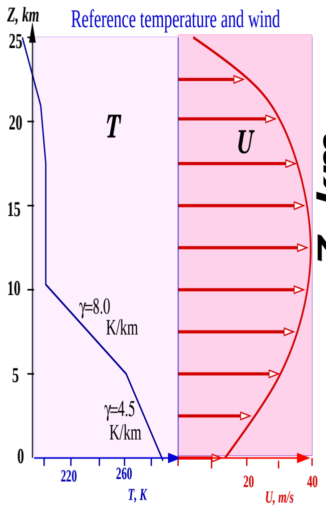


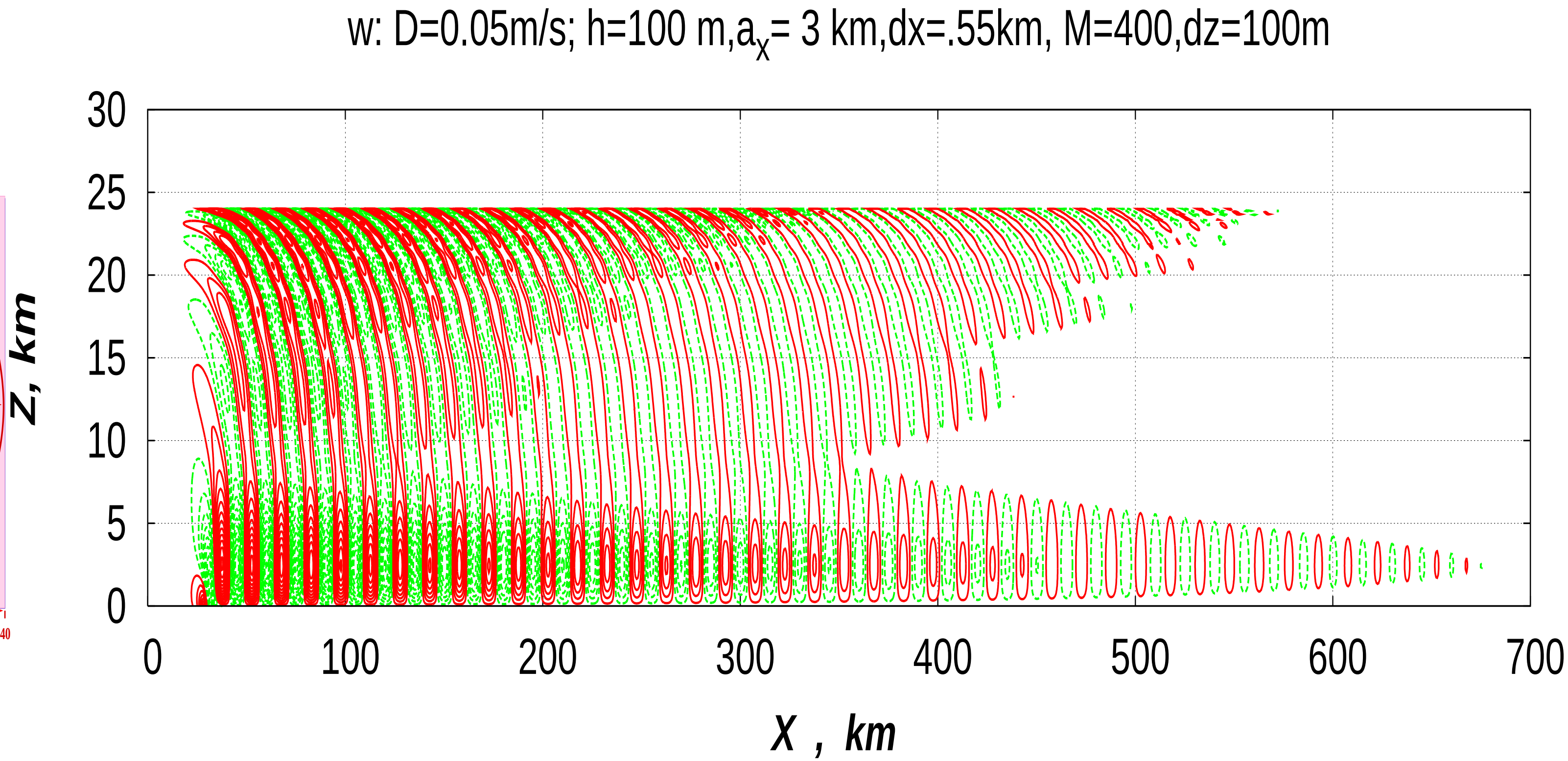
(a) T (b) N (c) U

Reference profiles of height(pressure)-dependent temperature $T(p)$, Brunt-Väisälä frequency $N(p)$ and wind $U(p)$, used in model experiments.

T4 and U3 are proposed by Bouttier and were first used in NH ALADIN - HIRLAM comparisons

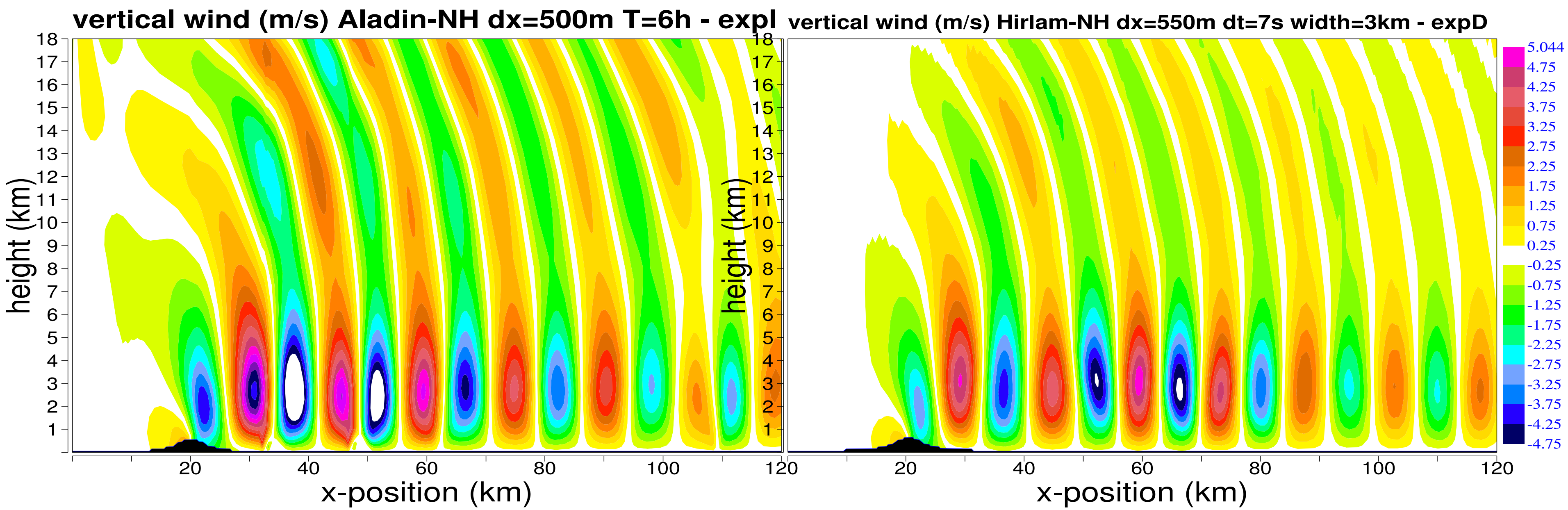
Example of an exact linear solution: vertical velocity waves in stratified atmosphere with wind shear



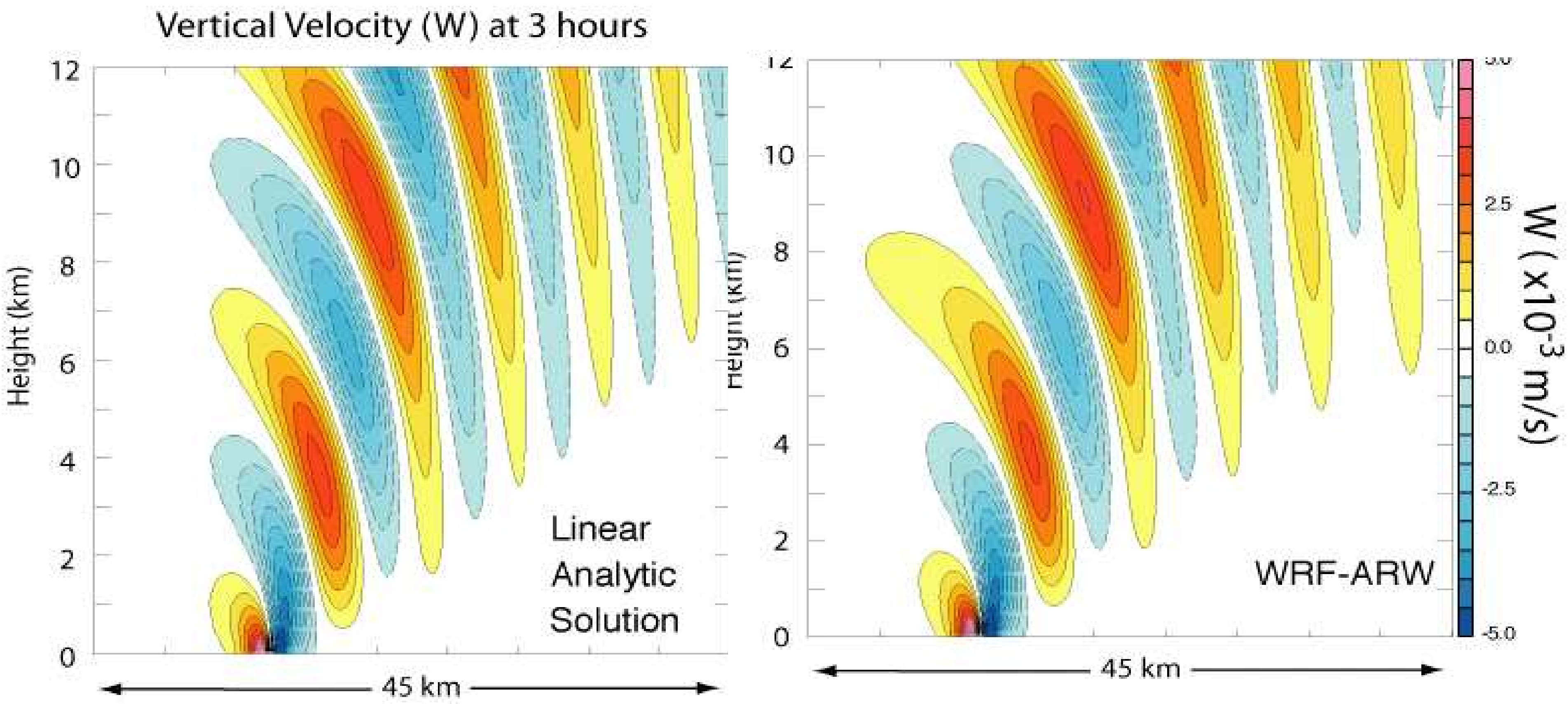


7 Examples of orographic testing

NH SISL ALADIN - NH SI Eulerian HIRLAM comparison



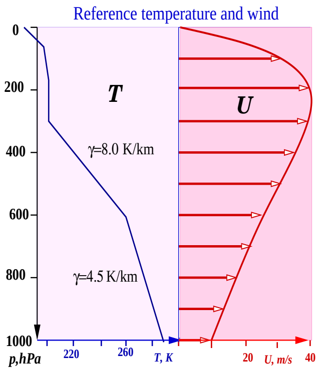
Example of 2-D NH mountain wave modelling from SRNWP test-site

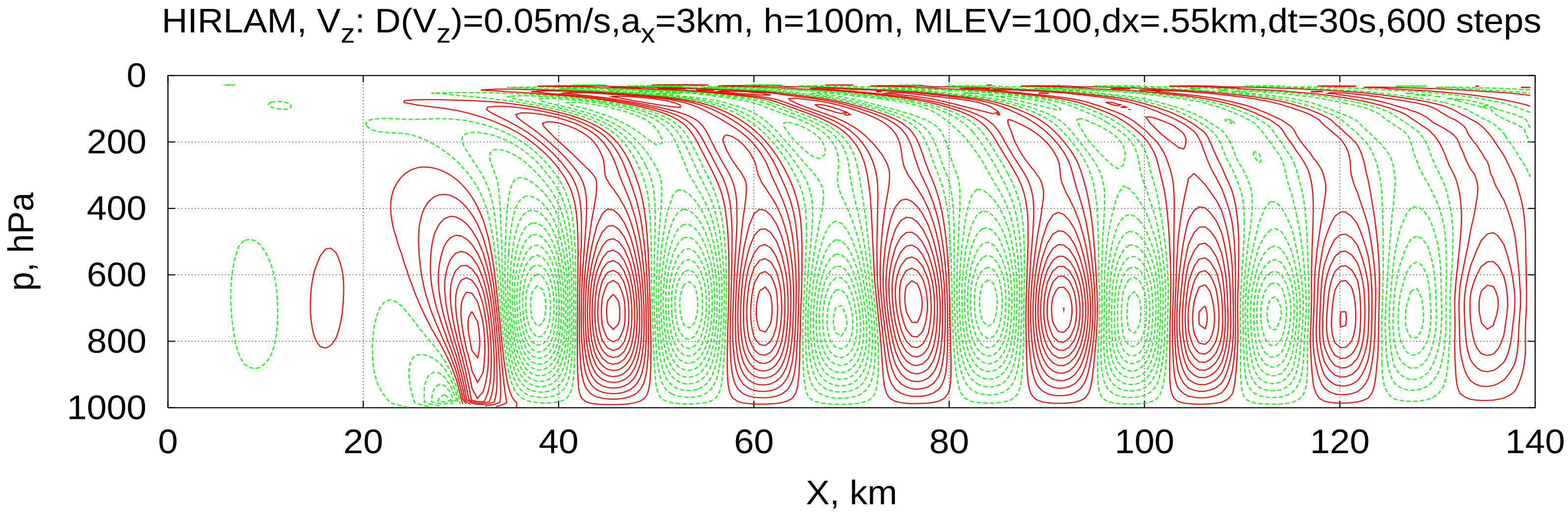


WRF - Weather Research and Forecasting Model (NCAR+NCEP)

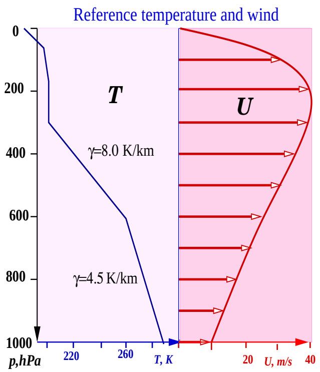
ARW - Advanced Research WRF

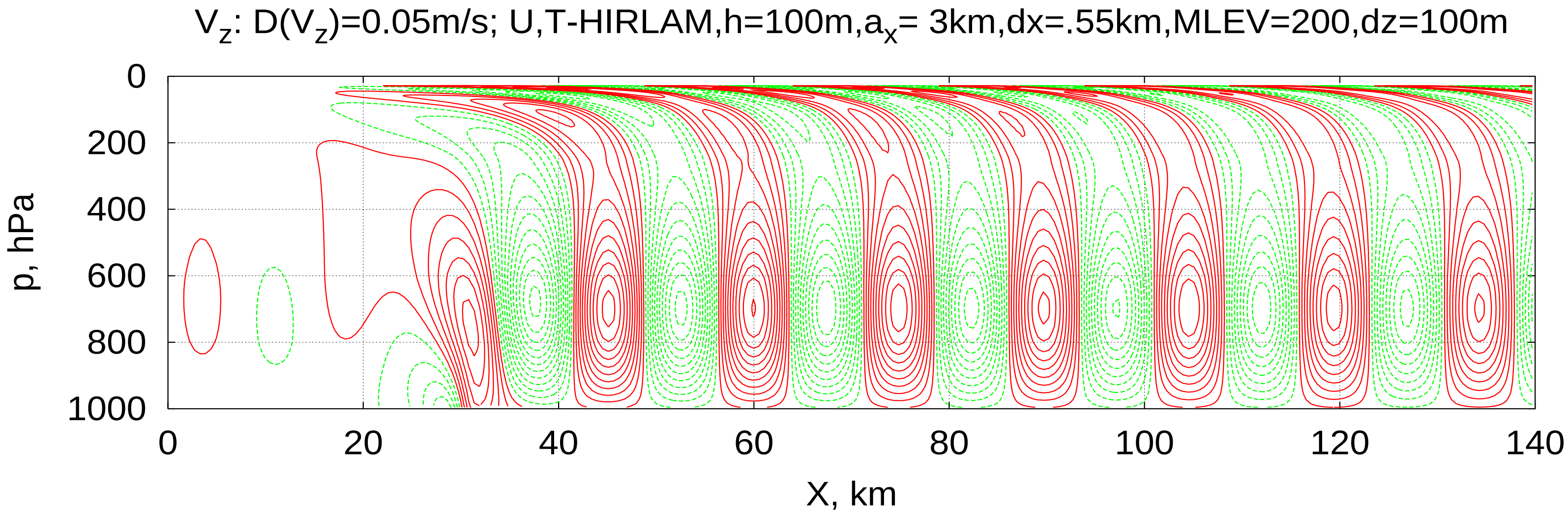
Testing NH HIRLAM: SISL



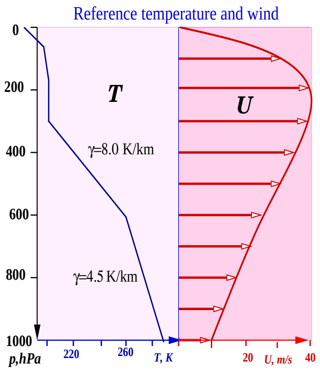


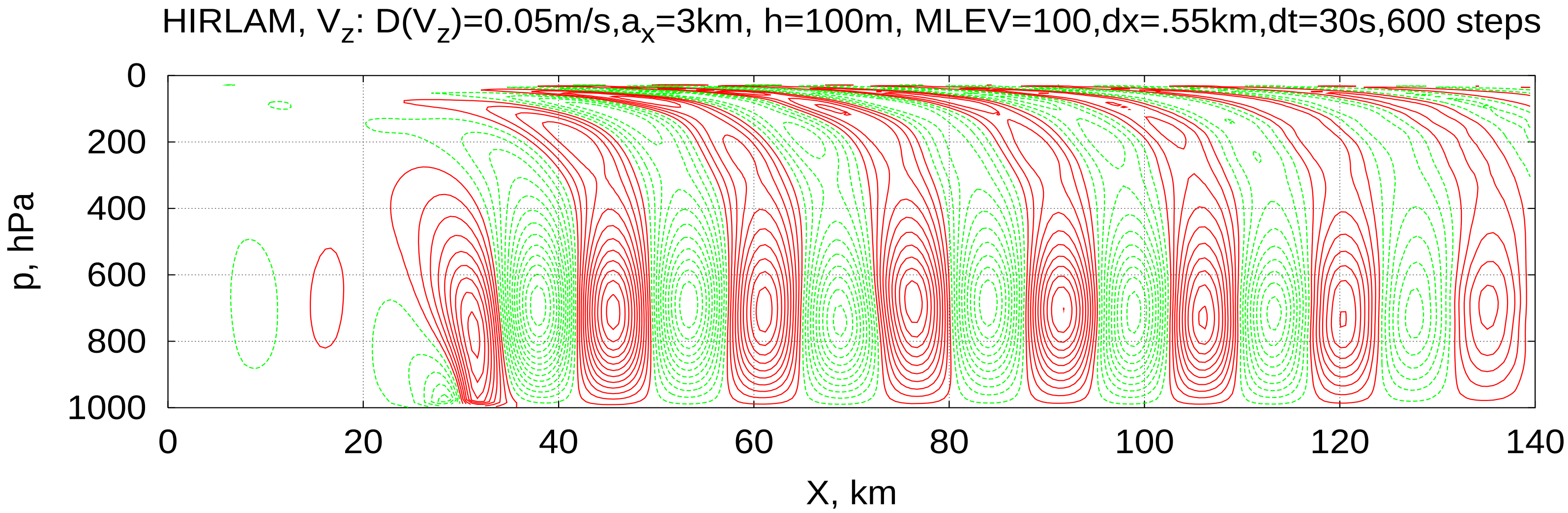
The linear reference solution



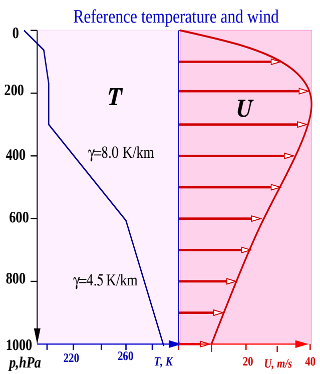


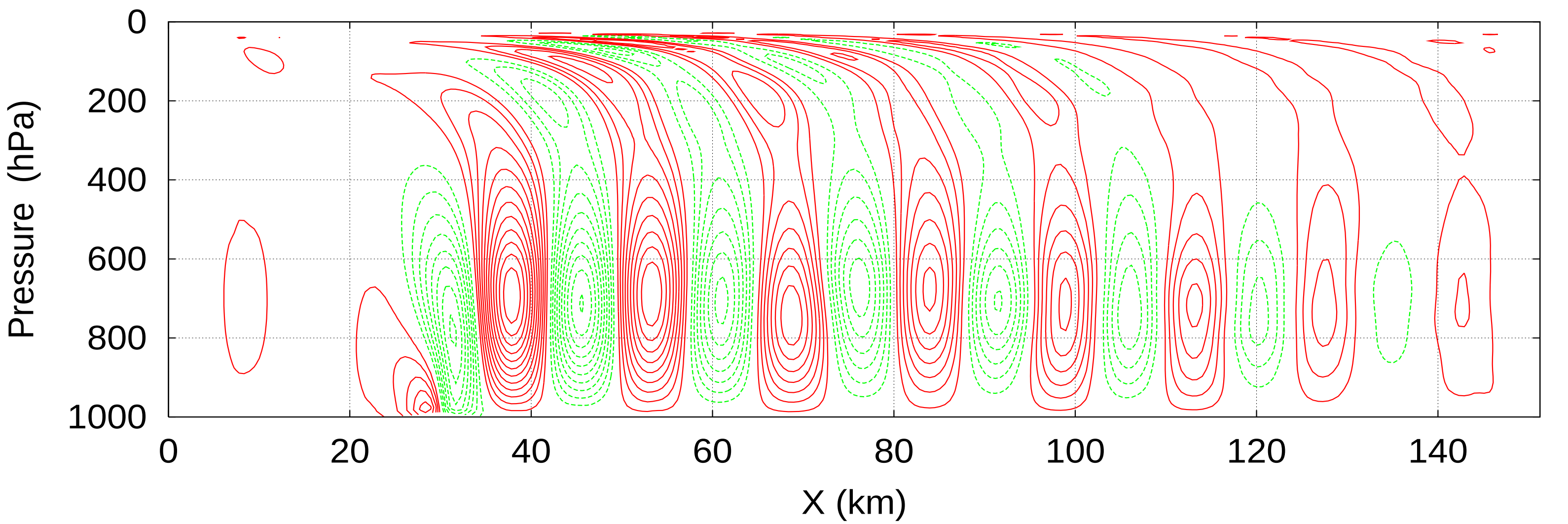
Testing NH HIRLAM: $\varepsilon = 0$



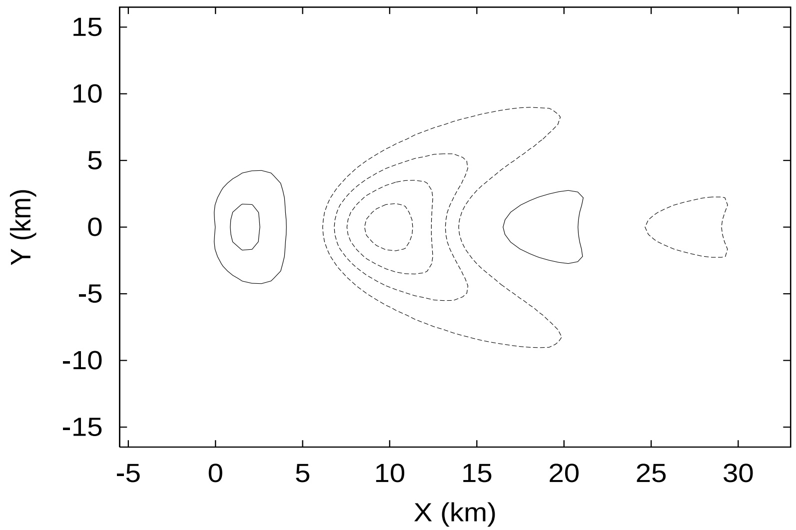


Testing NH HIRLAM: $\varepsilon = 0.05$

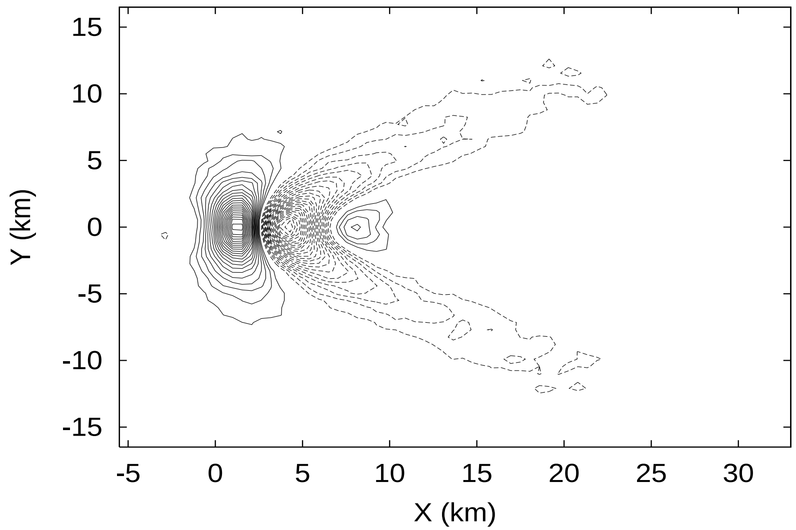




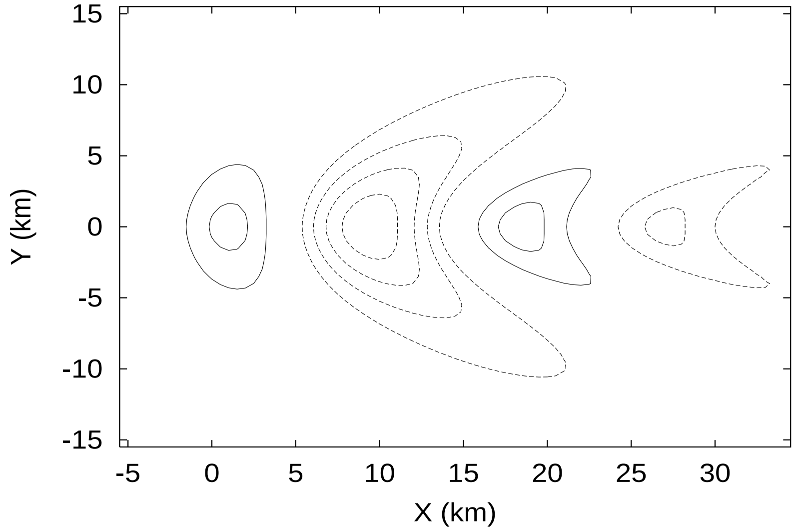
NH SISL HIRLAM



HS SISL HIRLAM



LINEAR MODEL



Vertical velocity waves at Z = 500 hPa. Mountain: $h_0 = 250\ m$, $a_x = a_y = 2.5\ km$. Increasing with height N, constant $U = 25\ m/s$. Contour intervals: $\Delta w = 0.1\ m/s$. Grid $276 \times 100 \times 62$, $\quad \Delta x = \Delta y = 550\ m$

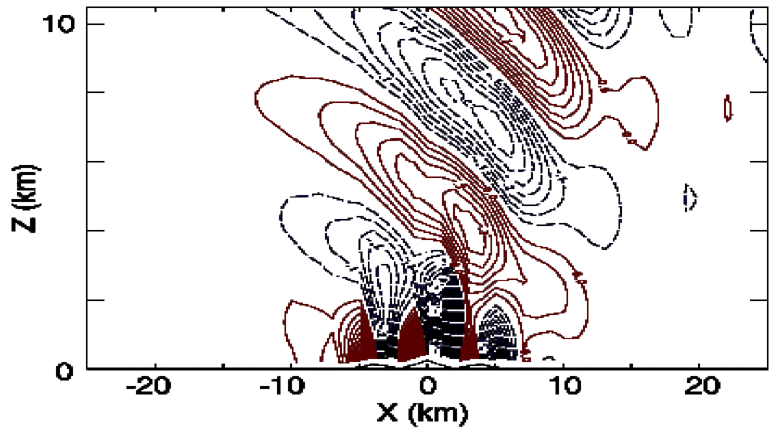
Example from SRNWP test-site with Schär profile

$$h(x) = H \exp(-x^2/a^2) \ \cos^2(\pi x/\lambda)$$

$H = 250$ m $\quad N = 0.01\ s^{-1}$

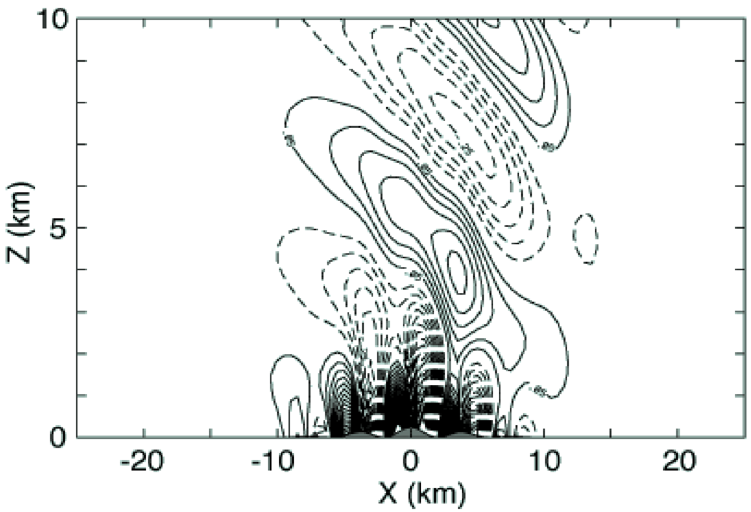
$\lambda = 4000$ m $\quad U = 10\ ms^{-1}$

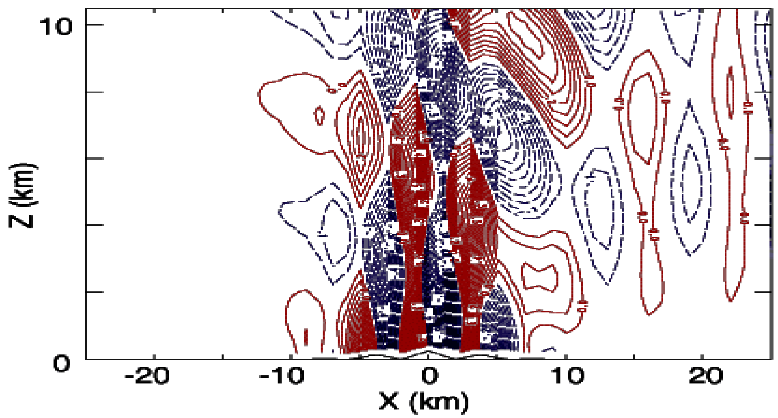
$a = 5000$ m



4th order advection, ω comp.

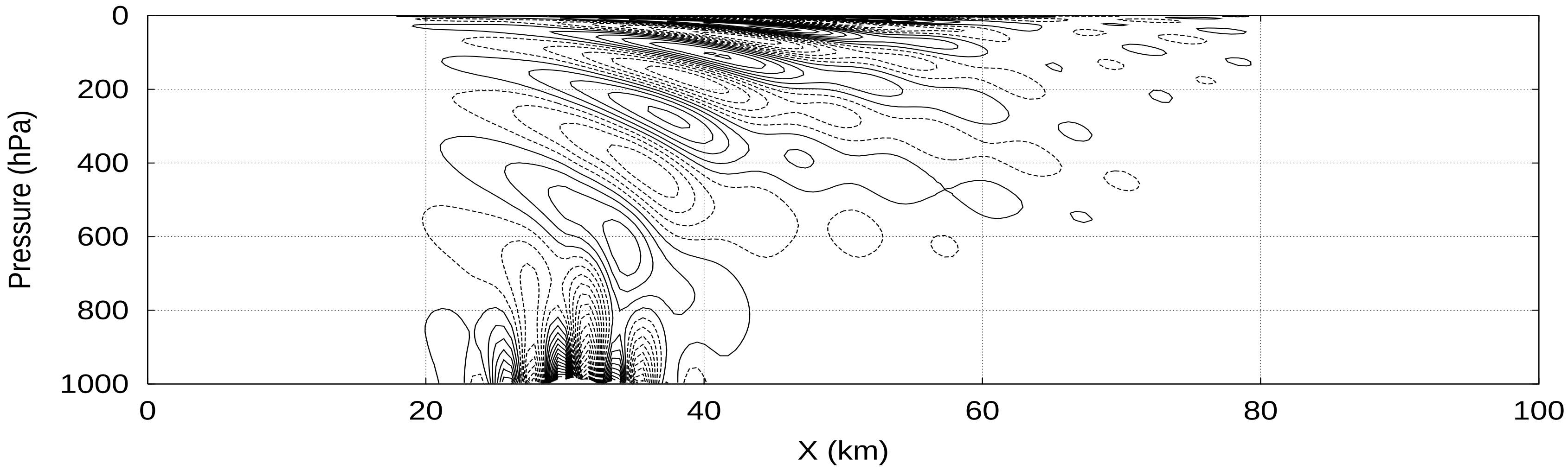
Reference linear analytic solution



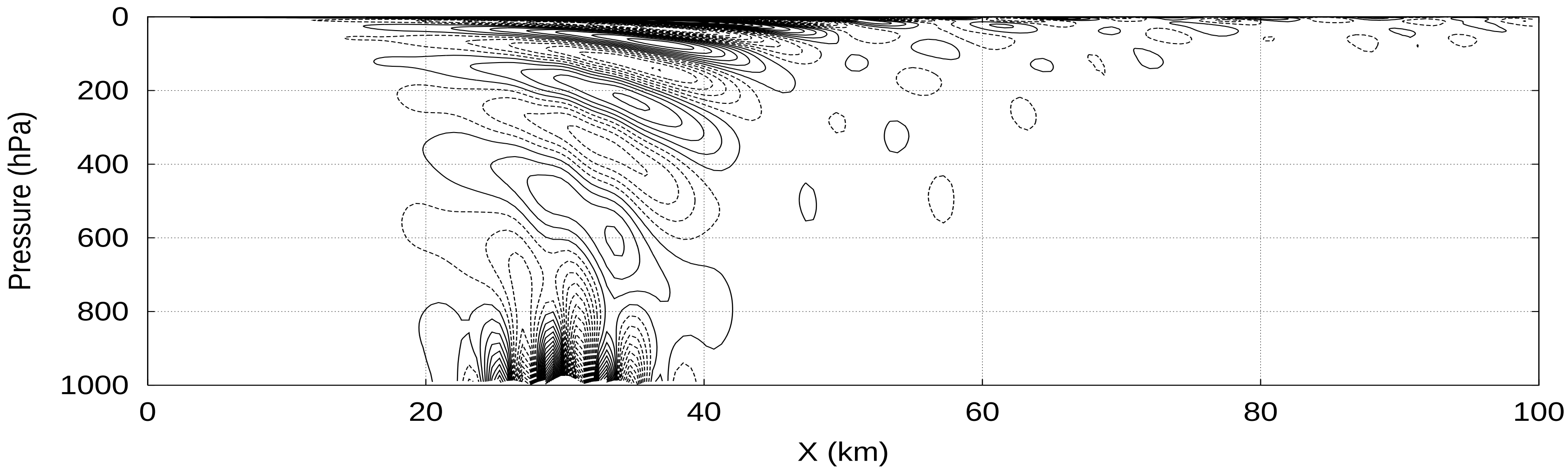


4th order advection,
2nd order ω comp.

NH SISL HIRLAM



LINEAR MODEL



Conclusions to orographic testing

1. The orographic (terrain forced) flow in linear regime is the best test case of NH effect at resolutions 1 - 10 km

2. Semi-elastic SISL HIRLAM resolves NH dynamics properly.

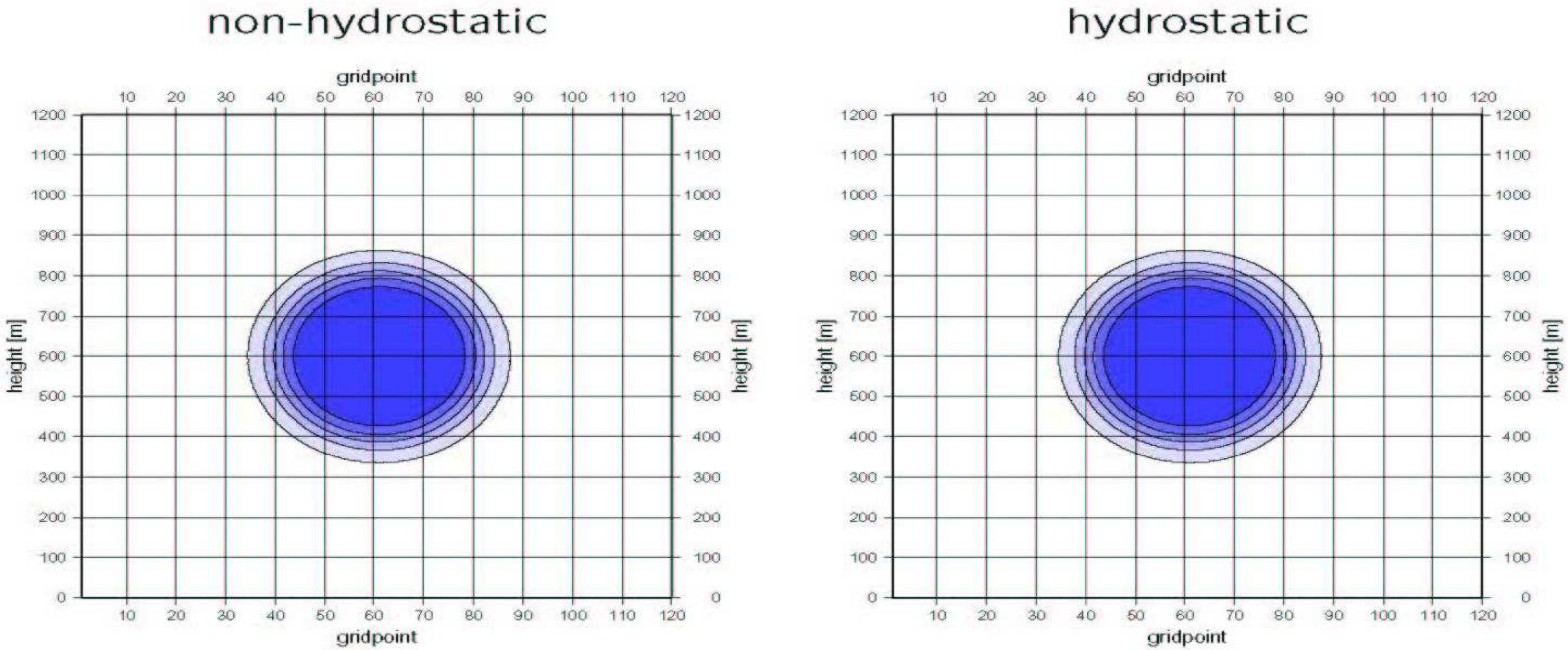
3. In general, numerical NH models have still enough development space in fine detail capturing

8 Convection tests

Modeling of cold bubble sinking was carried out by Jan Mašek, Slovak Hydrometeorological Institute, using 2D NH and HS models (both derived from NH ALADIN)

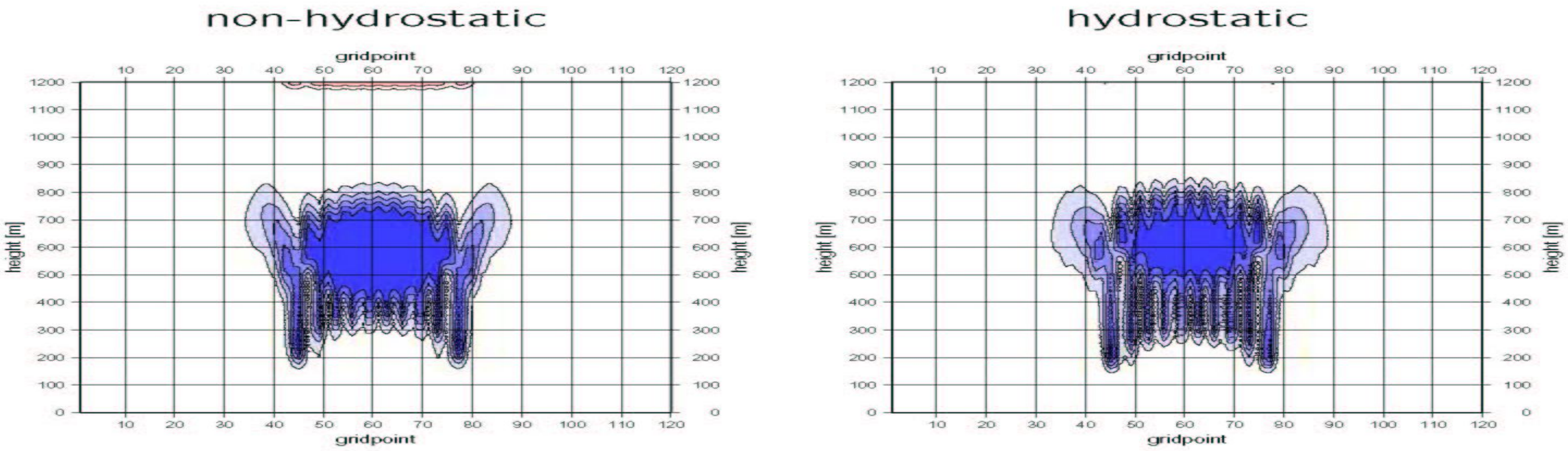
Though this experiment is not a full-scale test case (due to lack of 'exact' reference solution), it presents a good example of differenct NH/HS convection handling and can be used for model intercomparisons.

Initial state

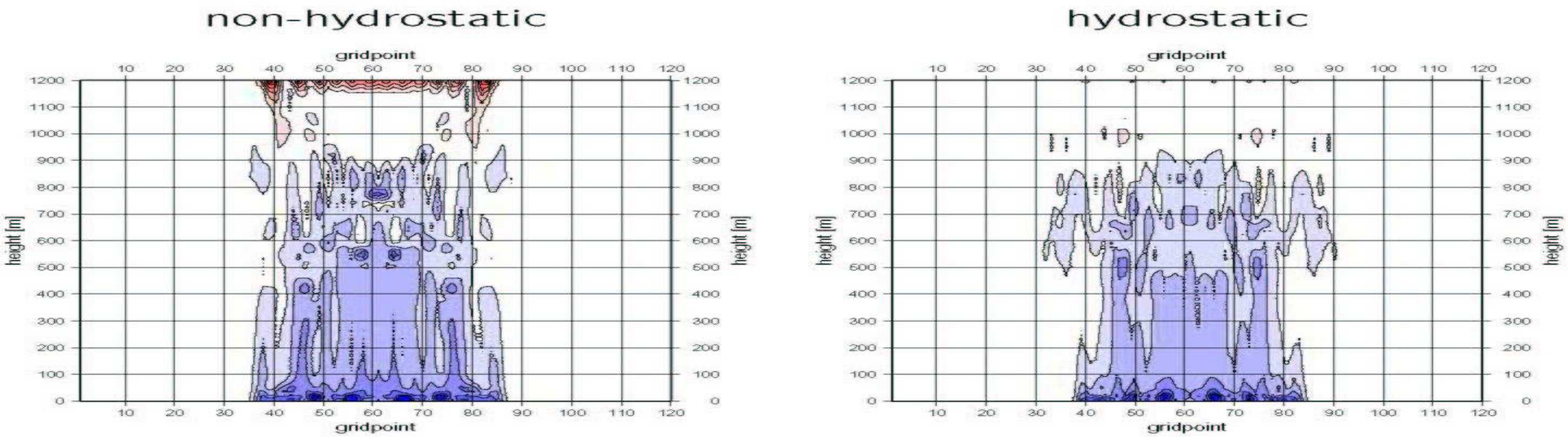


$\Delta x = 1\,\text{km},\ t = 0\,\text{min}$

1. Shallow convection, $\Delta x = 1$ km

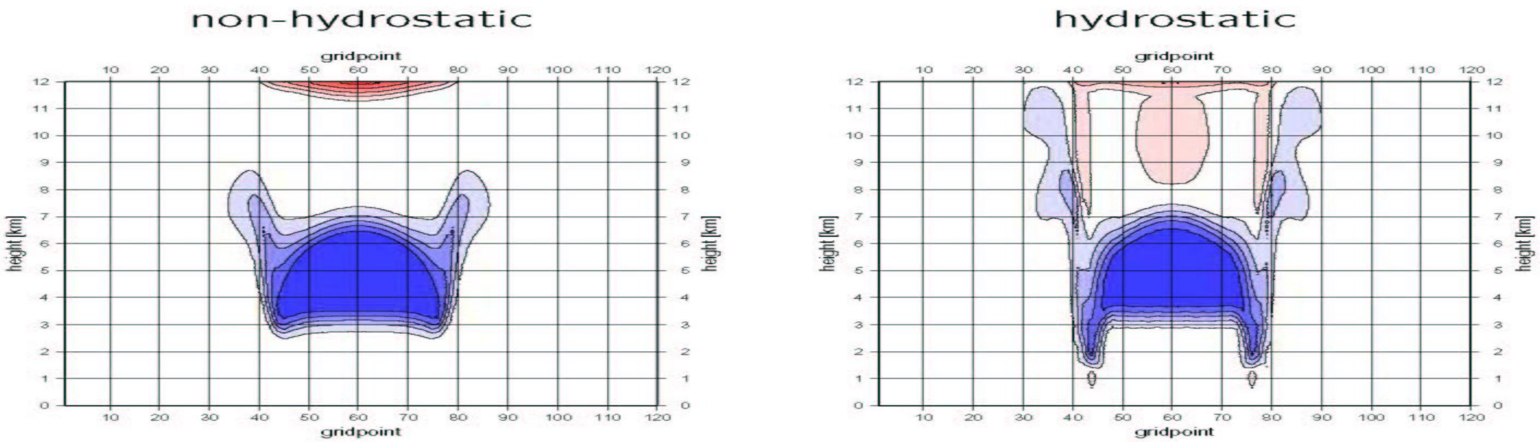


$\Delta x = 1$ km, $t = 1$ h

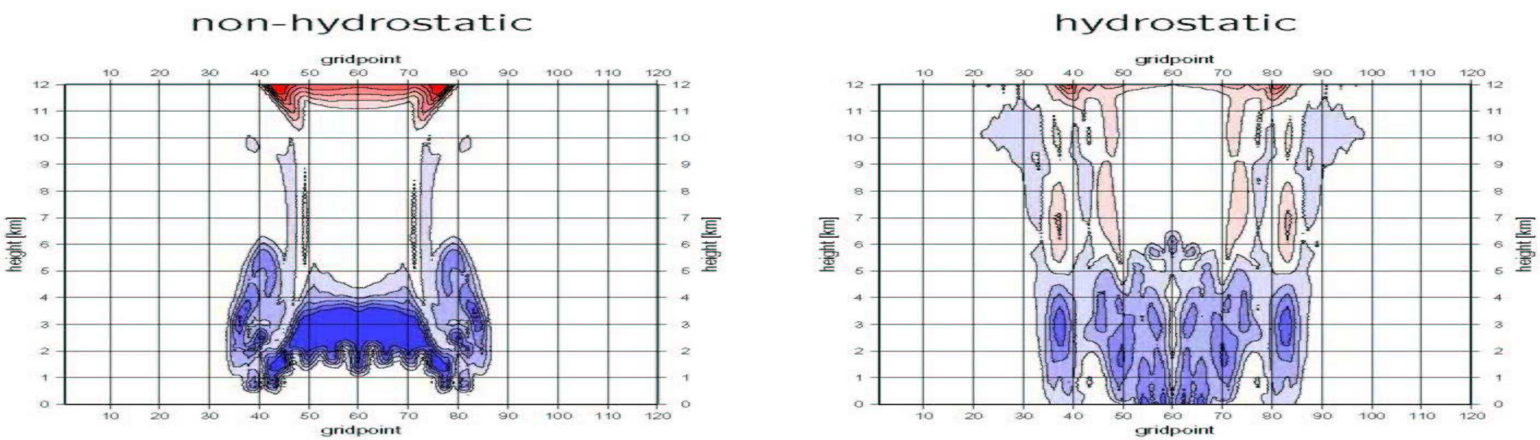


$\Delta x = 1$ km, $t = 2$ h

1. Deep convection, $\Delta x = 1$ km

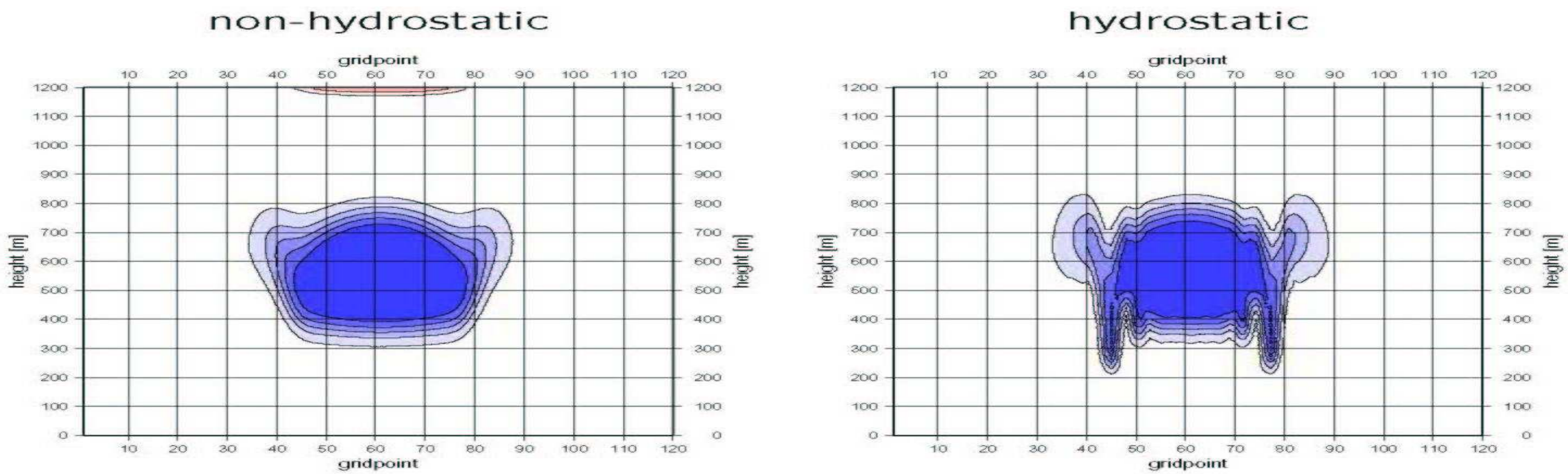


$\Delta x = 1\,\mathrm{km},\ t = 8\,\mathrm{min}$

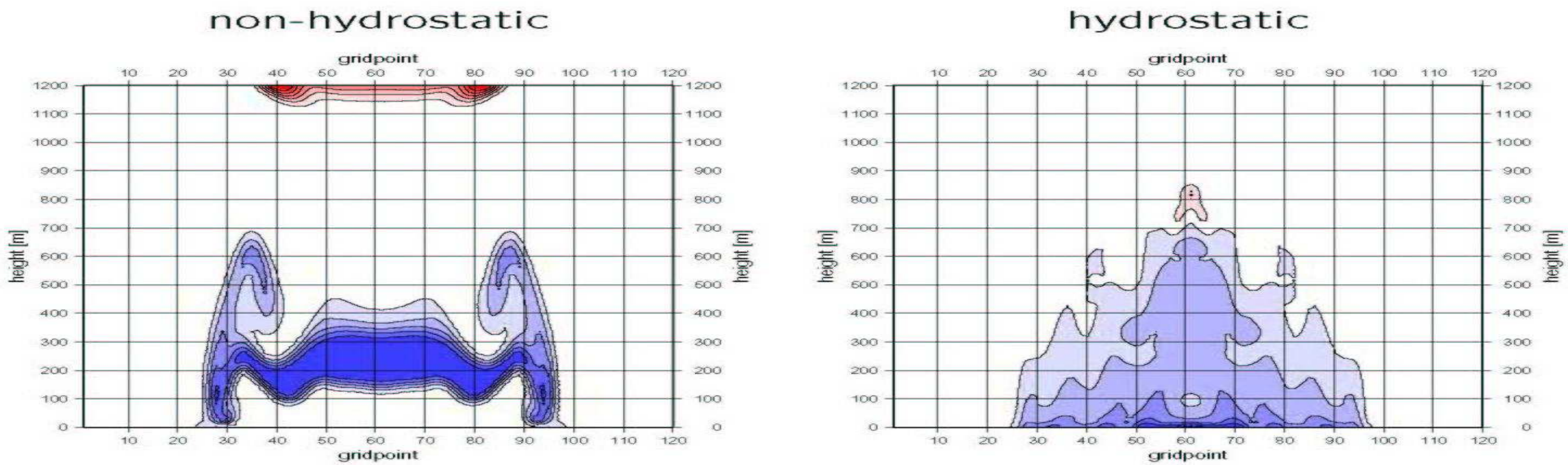


$\Delta x = 1\,\mathrm{km},\ t = 16\,\mathrm{min}$

1. Shallow convection, $\Delta x = 0.1$ km



$\Delta x = 100\,\mathrm{m},\ t = 400\,\mathrm{s}$



$\Delta x = 100\,\mathrm{m},\ t = 1600\,\mathrm{s}$

Conclusions to convection tests

1. At shorter scales, $\Delta x < 1$ km, convection modelling becomes more appropriate for NH effect study.

2.The NH effect in dynamics is really strong at horizontal resolutions ~ 100 m.

3. High-presision reference solutions are still wanted in convection modeling experiments.

4. In general, numerical NH models have still enough development space in fine detail presentation.

THE END