Why do we need NH model? (explicit convection case)

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Why explicit convection?

- hydrostatic approximation assumes balance between two forces: vertical pressure gradient force (buoyancy) and gravity
- convection is caused by local imbalance between these forces
- there is a good chance that hydrostatic approximation will distort evolution of explicitly resolved convective systems

Cold bubble test

- good candidate for demonstrating differences between H and NH systems is a cold bubble test:
  - restriction to xz-plane
  - flat orography
  - resting initial state ($u, w = 0$) with horizontally constant surface pressure ($\pi_S = \text{const}$)
  - neutral background stratification ($\overline{\theta} = \text{const}$)
  - bubble perturbation in initial θ field ($\theta = \overline{\theta} + \theta'$)

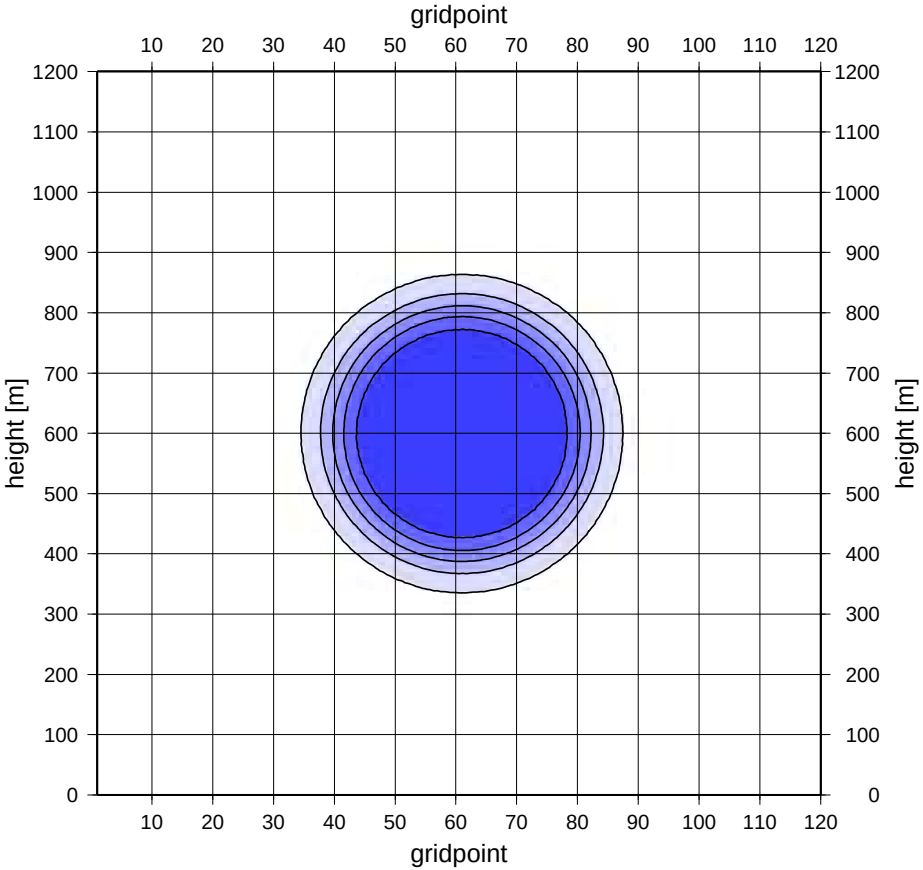
- since linear theory is not able to explain bubble evolution, results of numerical simulations will be used

Simulations at 10 m horizontal resolution

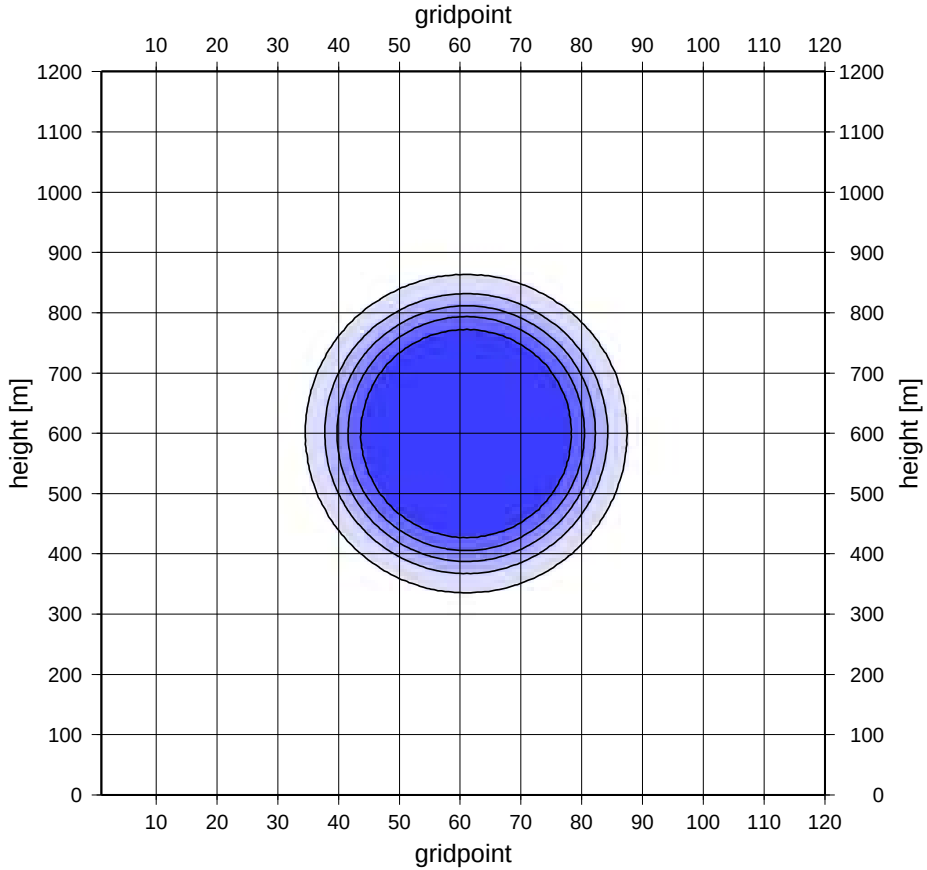
- computational domain 1200×1200 m with $\Delta x = \Delta z = 10$ m plus additional 30 layers at the top with isothermal stratification
- horizontally periodic domain (no extension/coupling zone)
- initial state with $\pi_S = 101\,325$ Pa and $\overline{\theta} = 300\,K$
- circular bubble with $r = 150$ m and $\theta'_{\text{max}} = -0.5$ K placed 600 m above ground
- adiabatic SL2TL integration with $\Delta t = 0.4$ s in H/NH mode
- 4^{th}-order horizontal diffusion
- in order to get clean H solution, sponge had to be applied in layer between 1000 and 1500 m

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



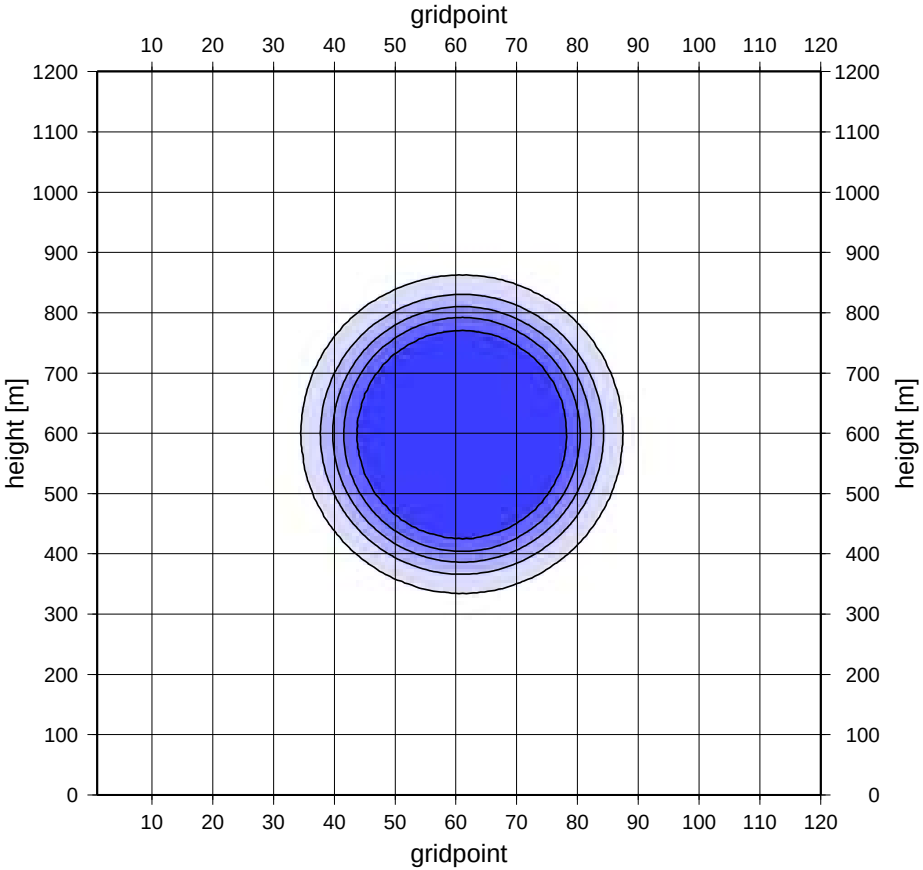
hydrostatic



$\Delta x = 10\,\mathrm{m},\ t = 0\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



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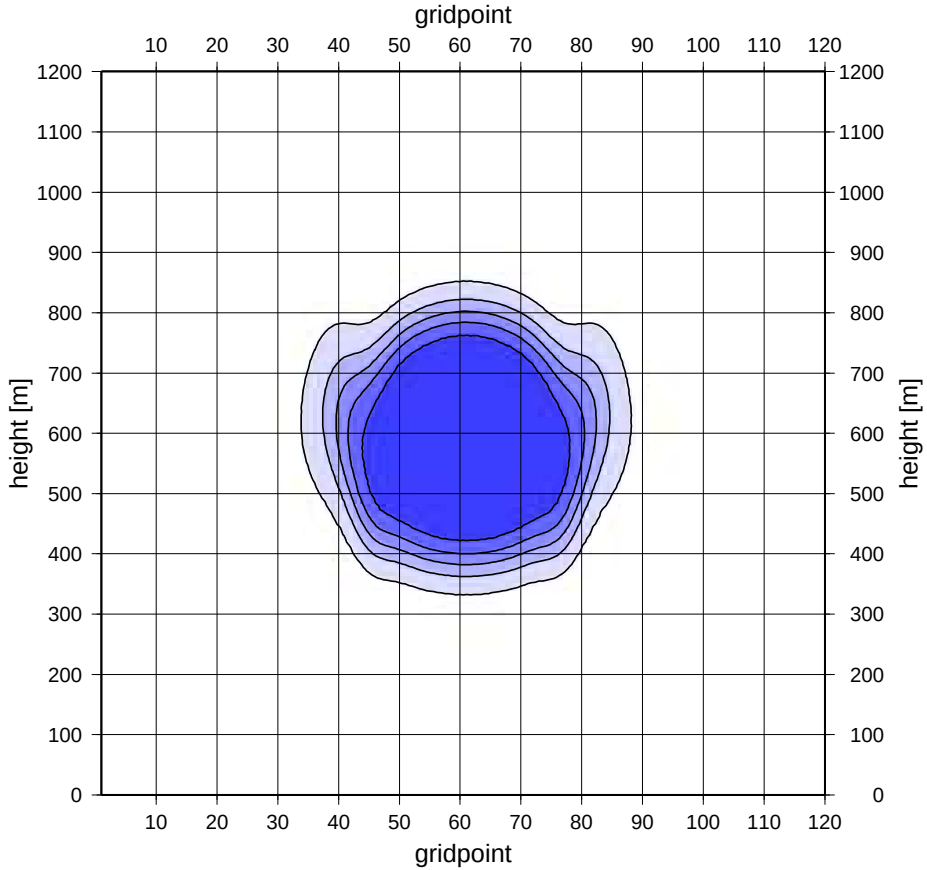
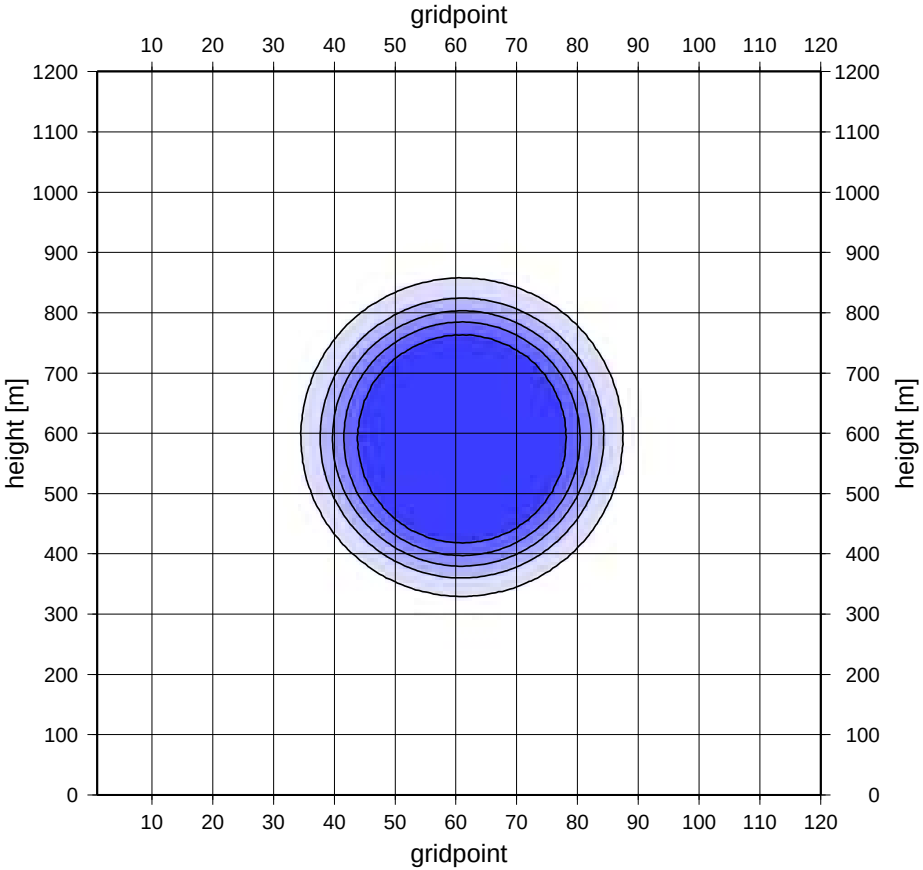


$\Delta x = 10\,\mathrm{m},\ t = 20\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



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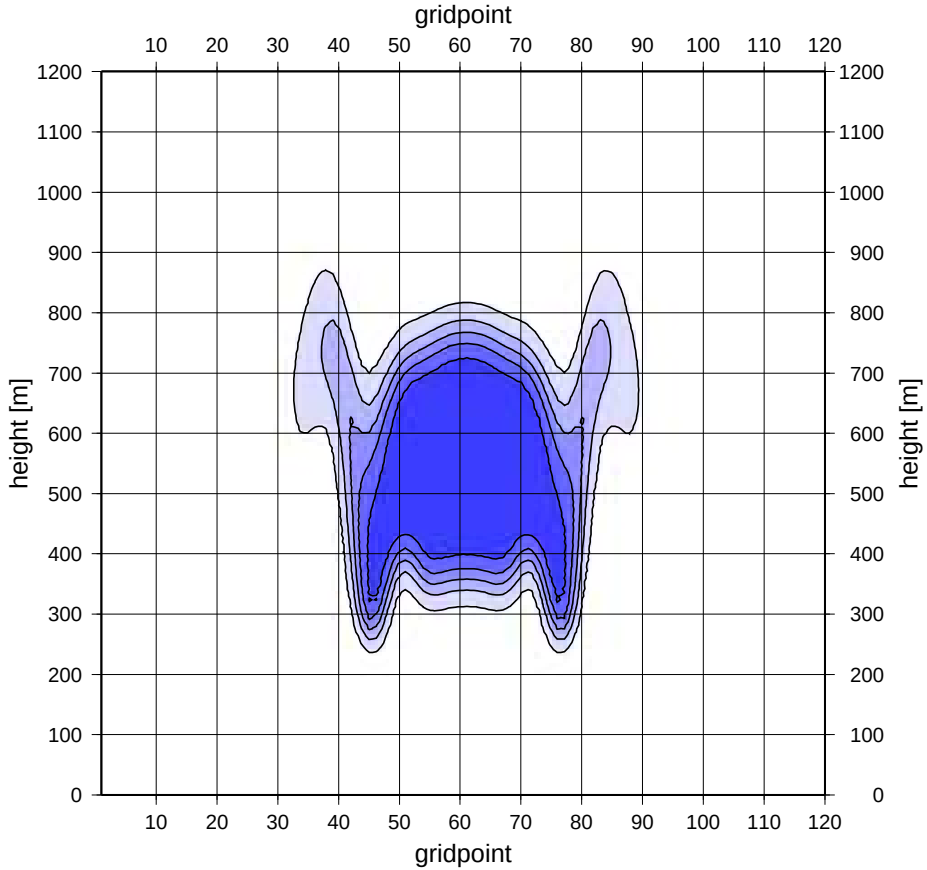
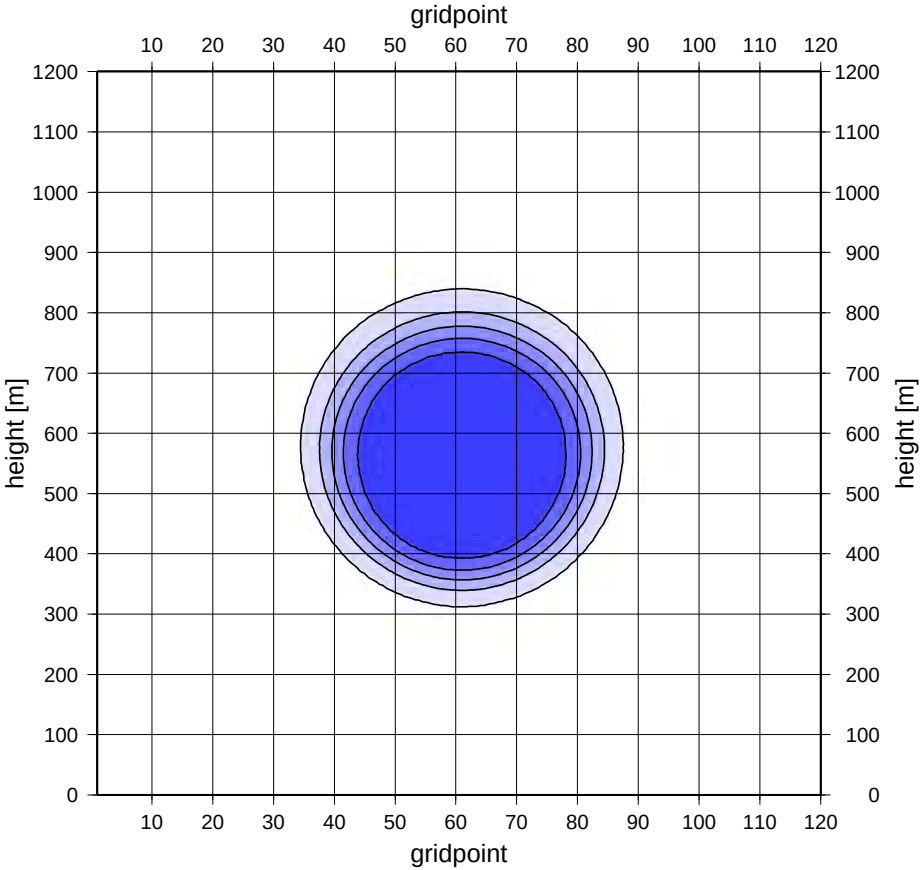


$\Delta x = 10\,\mathrm{m},\ t = 50\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



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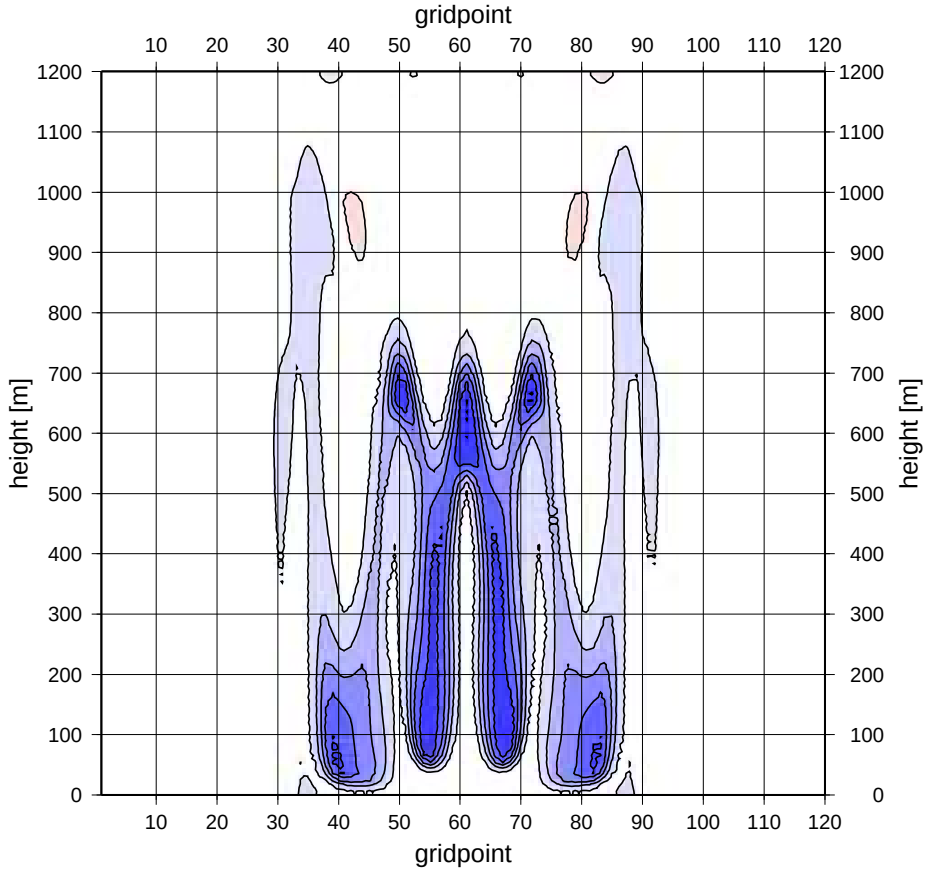
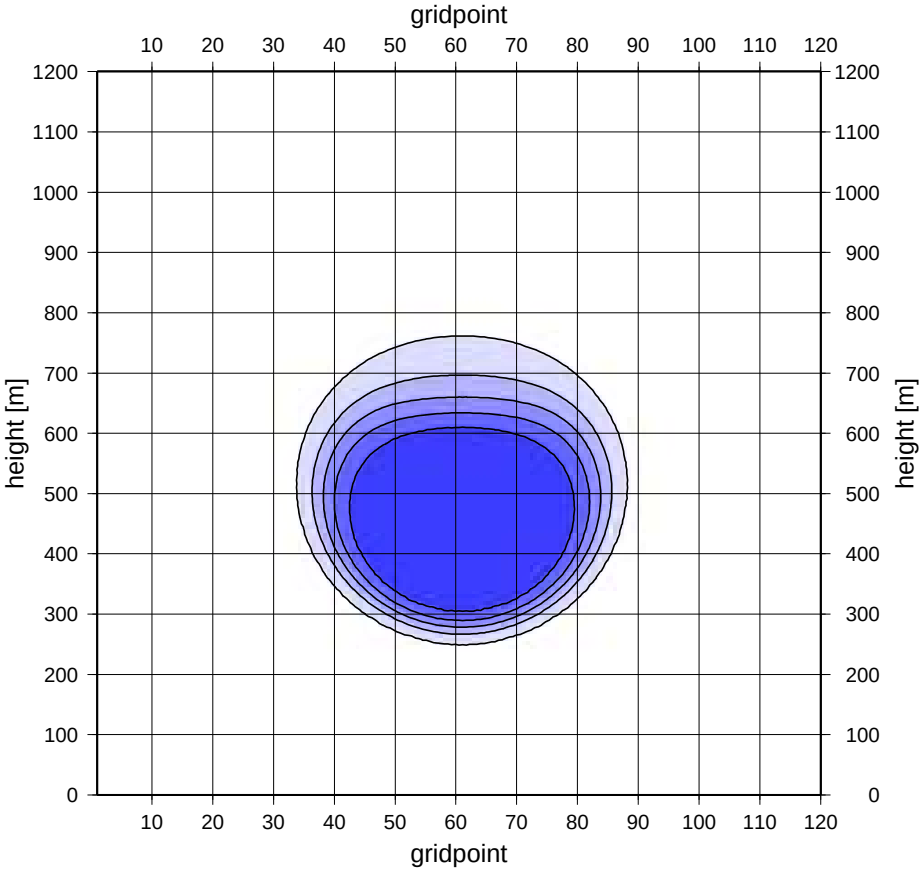


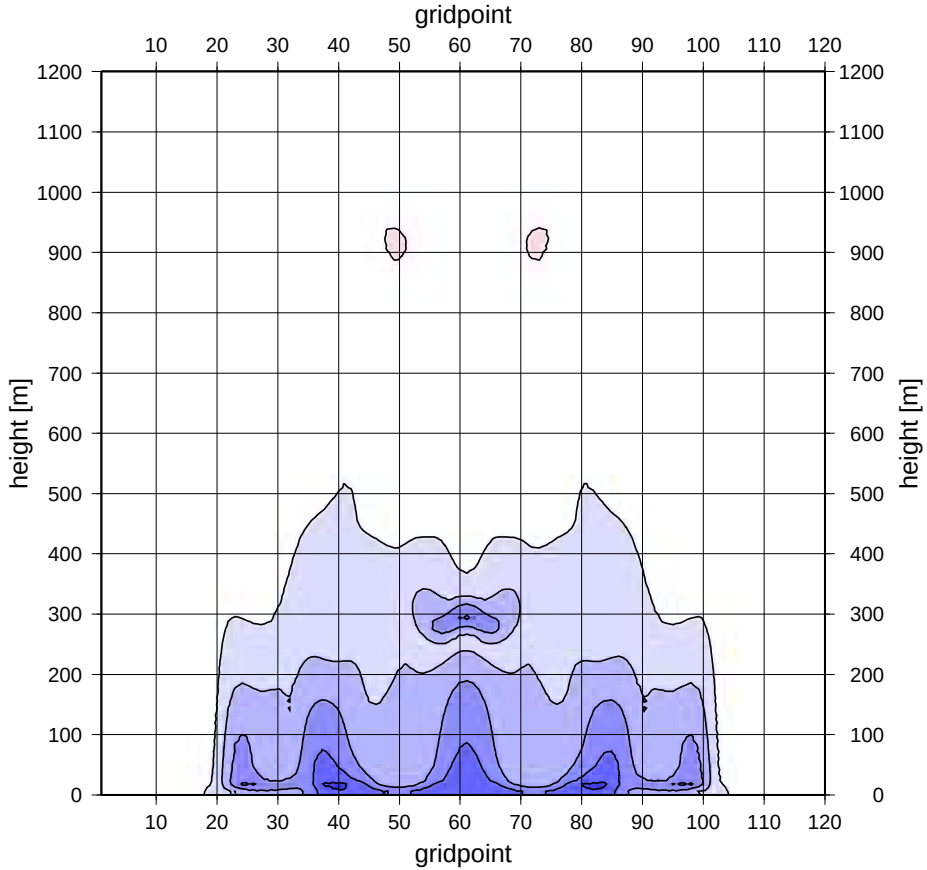
$\Delta x = 10\,\mathrm{m},\ t = 100\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



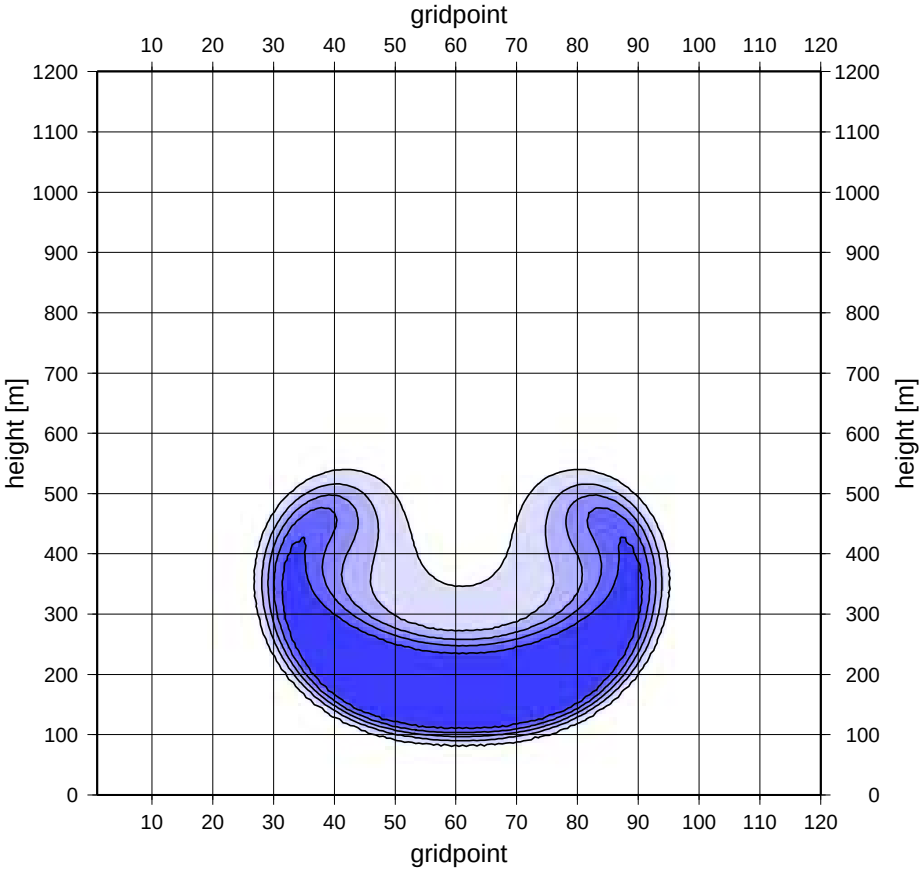
hydrostatic



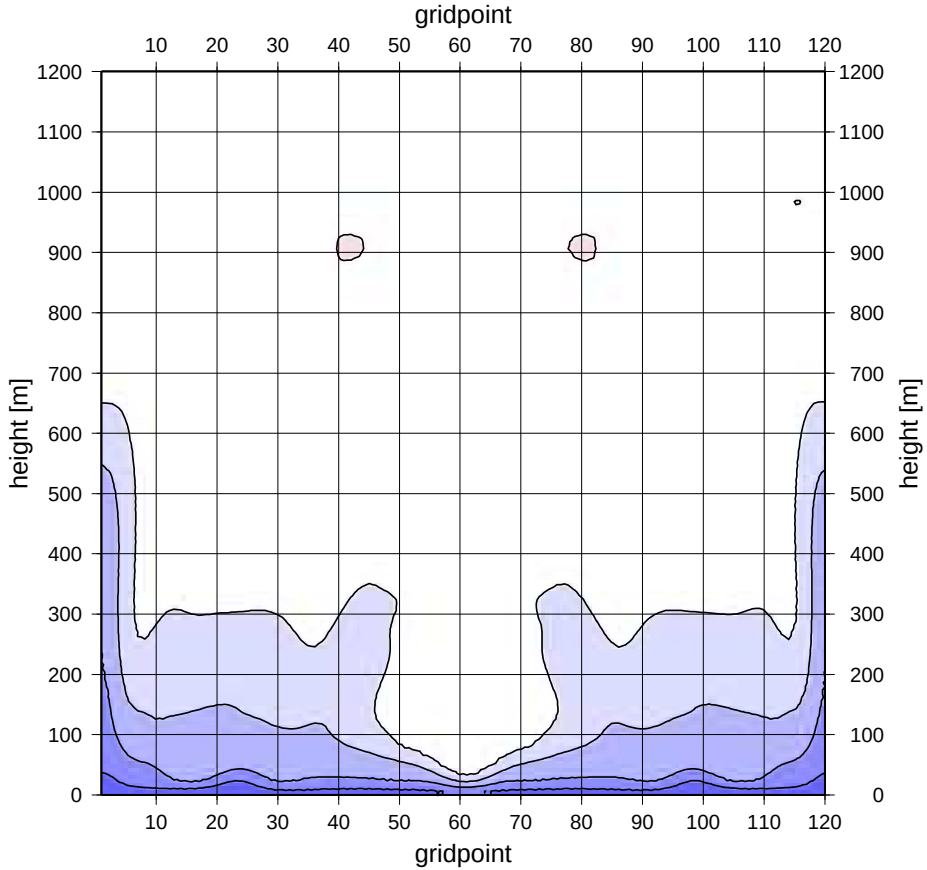
$\Delta x = 10\,\mathrm{m},\ t = 200\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



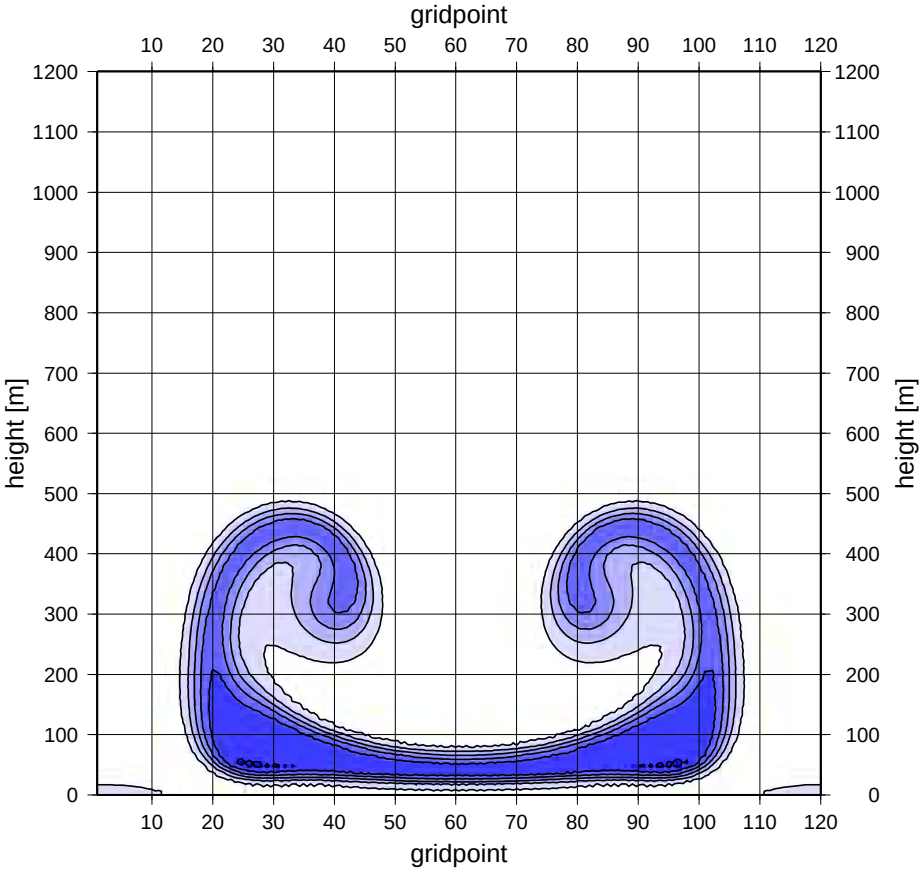
hydrostatic



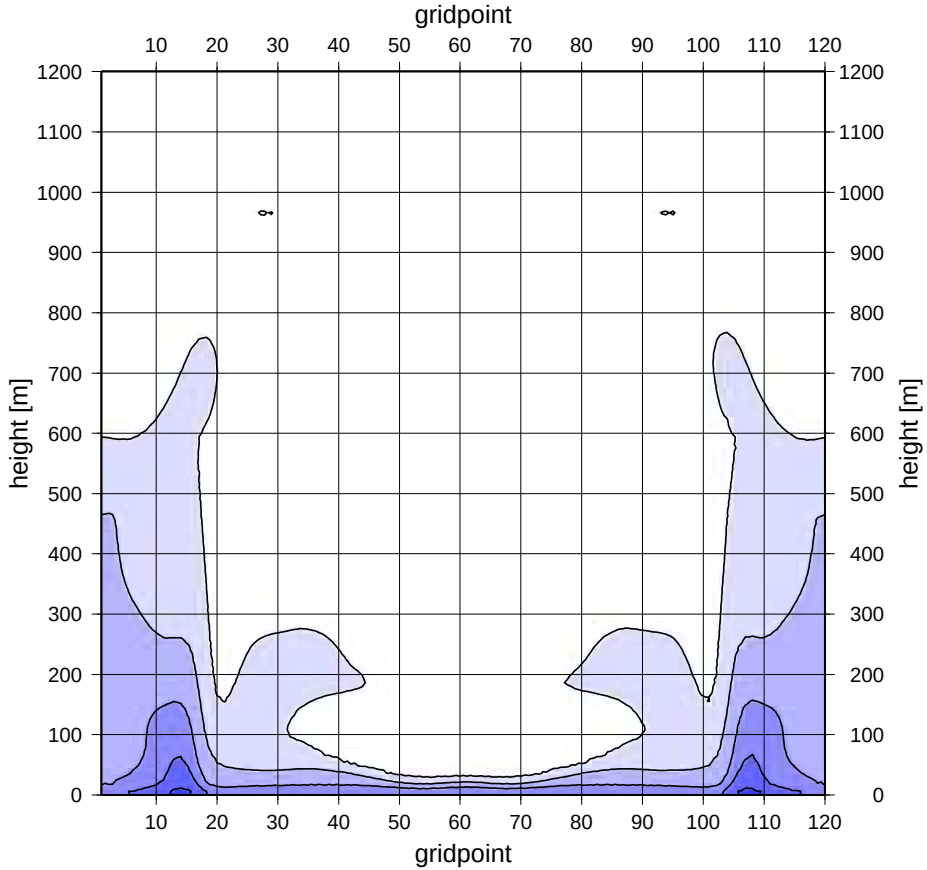
$\Delta x = 10\,\mathrm{m},\ t = 400\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



hydrostatic



$\Delta x = 10\,\mathrm{m},\ t = 600\,\mathrm{s}$

Results at 10 m horizontal resolution

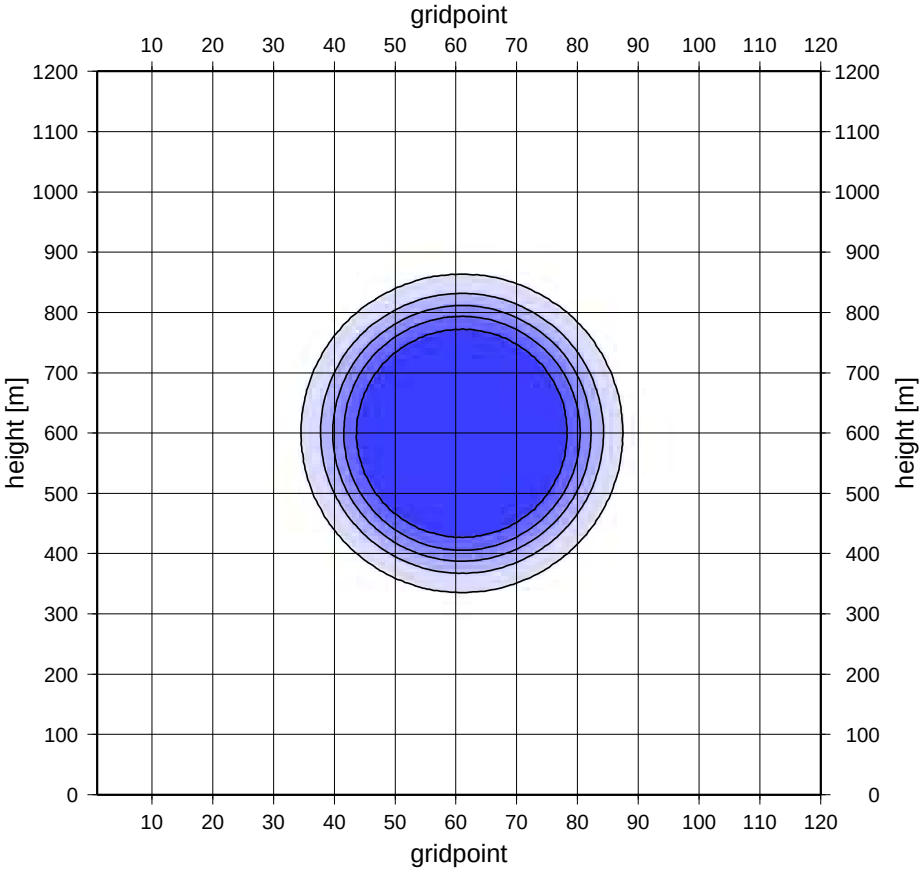
- NH model is able to realistically evolve cold bubble, while H model is not
- in H simulation cold bubble descends too fast, distorts and decays into smaller cells
- in spite of this, H simulation tends to meaningful final state, with stabilized stratification

Are numerical results from NH simulation trustable?

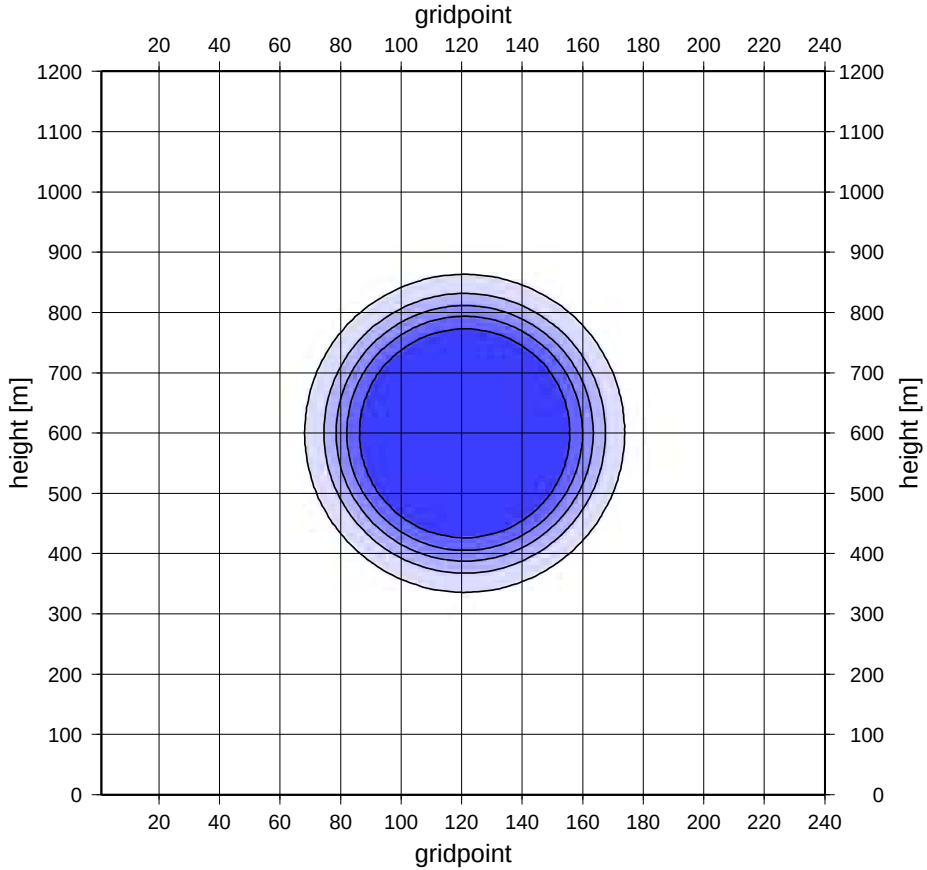
- they fit to our intuition, but one should be careful
- convection (like turbulence) is a non-linear phenomena consisting of multiple interacting scales
- in reality, subgrid convective scales can have significant influence on resolved ones, which leads to the necessity of their parameterization
- simple test to judge if this is the case is to increase horizontal resolution and redo the simulation
- if the results are not changed dramatically, influence of subgrid convective scales is weak, i.e. there is no need for their parameterization

perturbation of potential temperature $\theta - \overline{\theta}$

$\Delta x = 10\,\mathrm{m}$



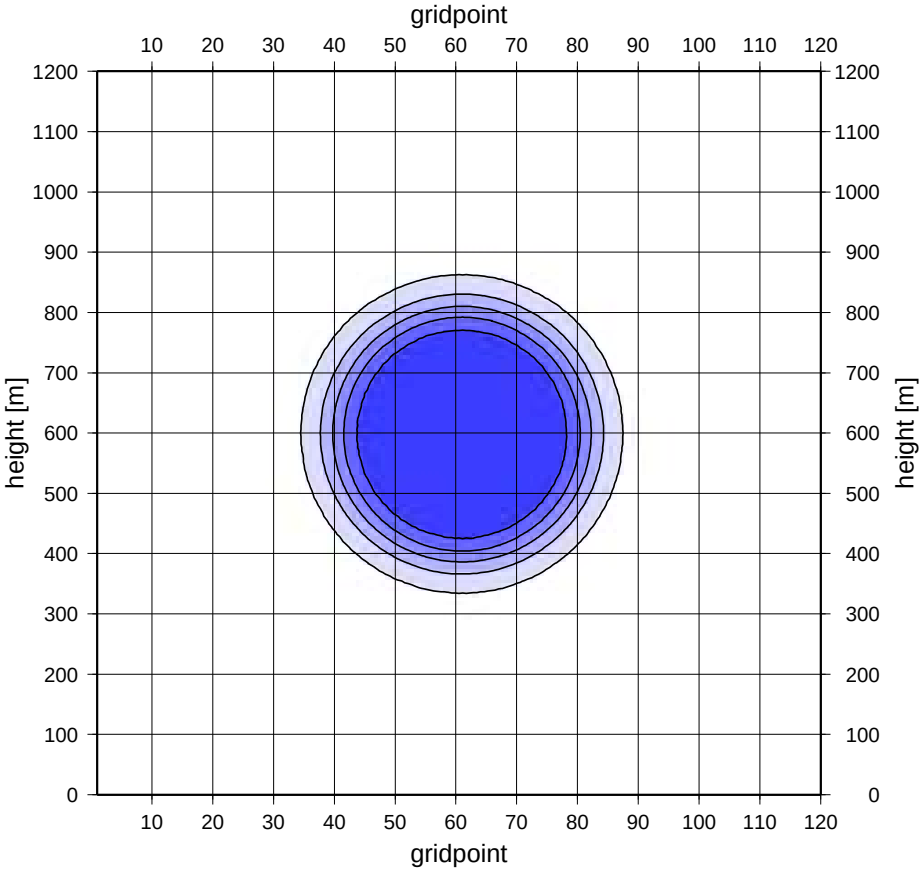
$\Delta x = 5\,\mathrm{m}$



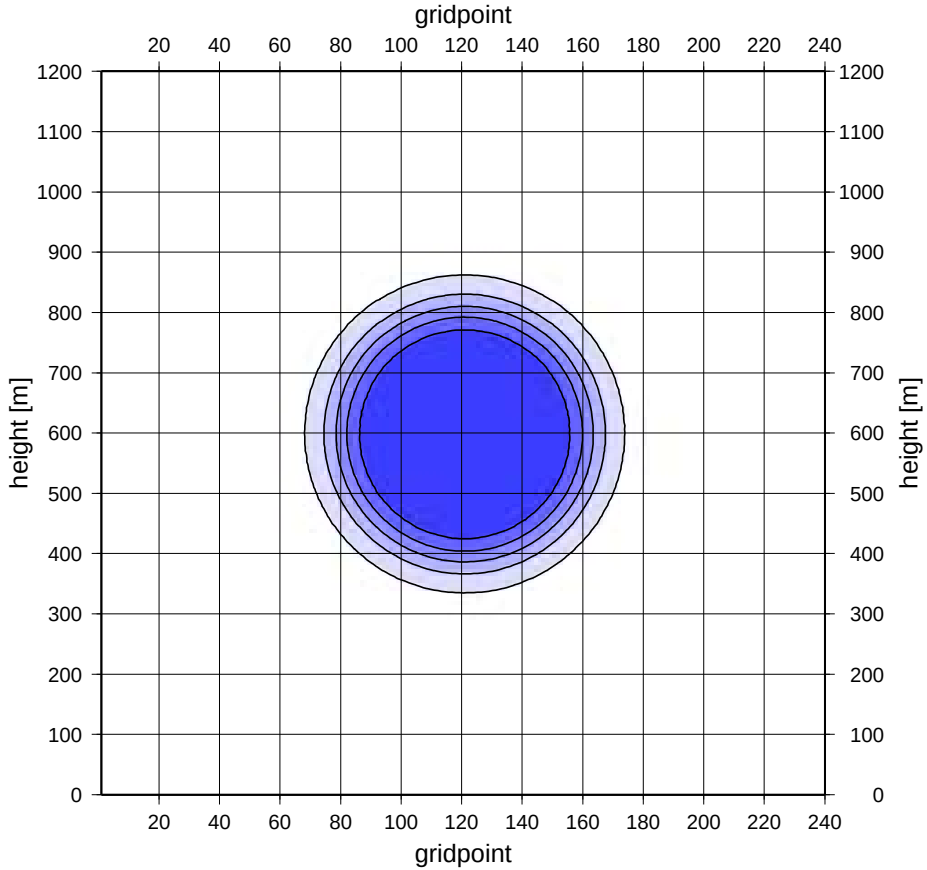
non-hydrostatic run, $t = 0\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

$\Delta x = 10\,\mathrm{m}$



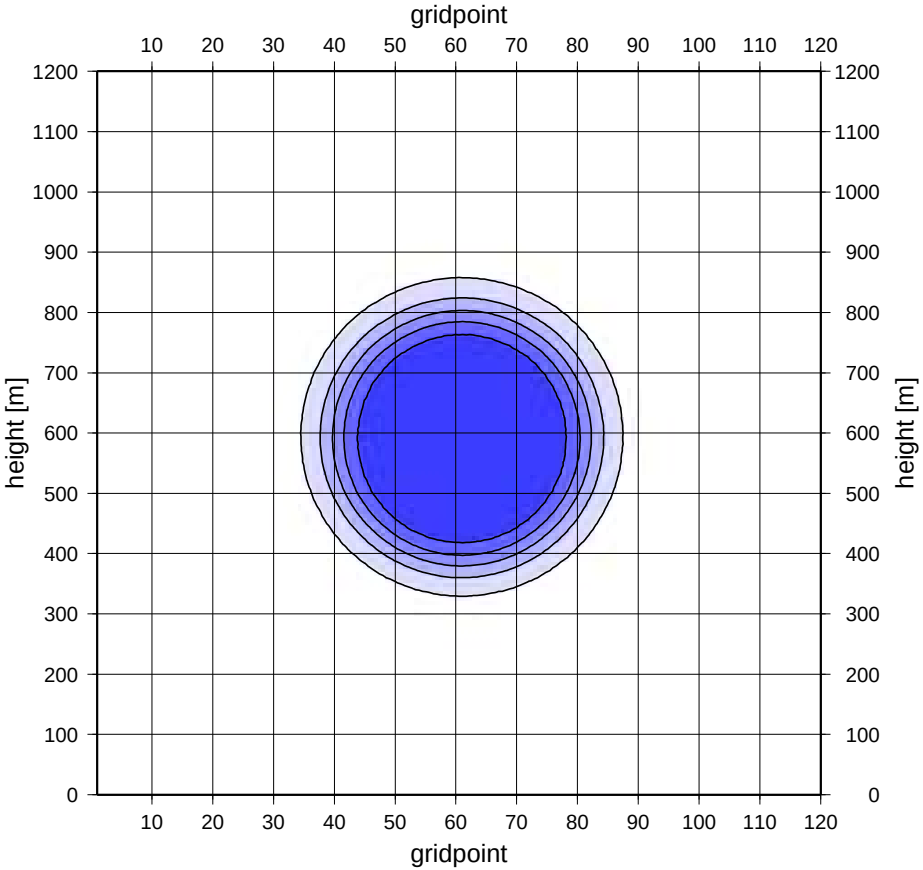
$\Delta x = 5\,\mathrm{m}$



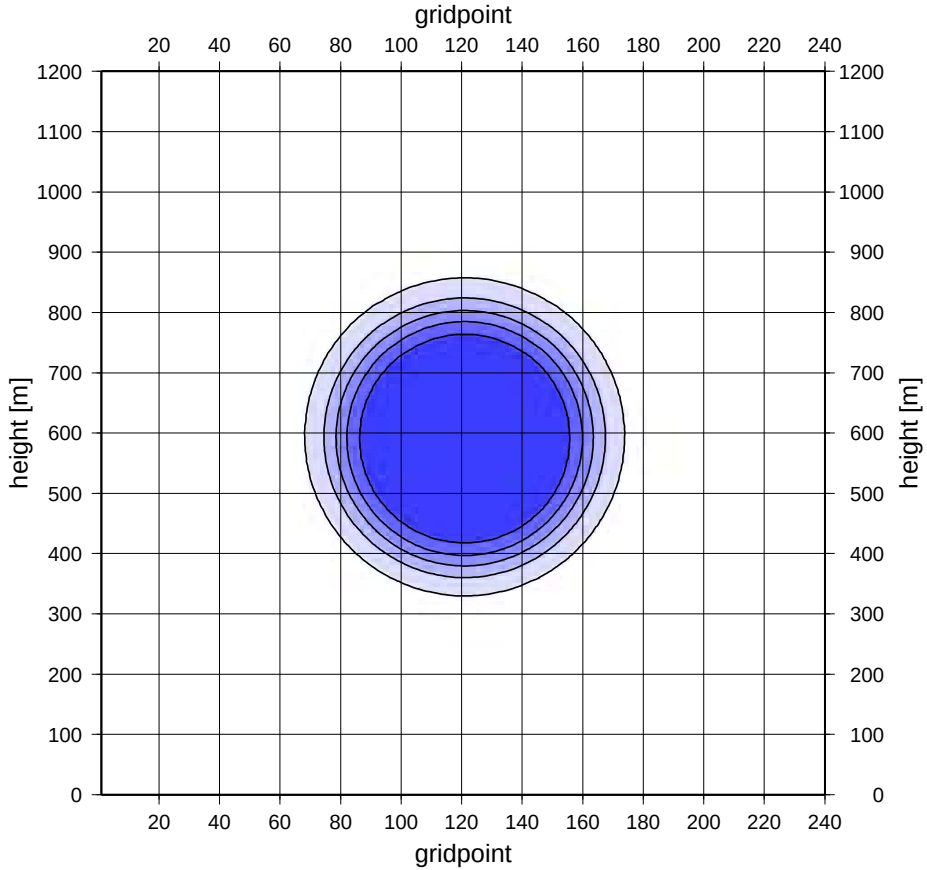
non-hydrostatic run, $t = 20\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

$\Delta x = 10\,\mathrm{m}$



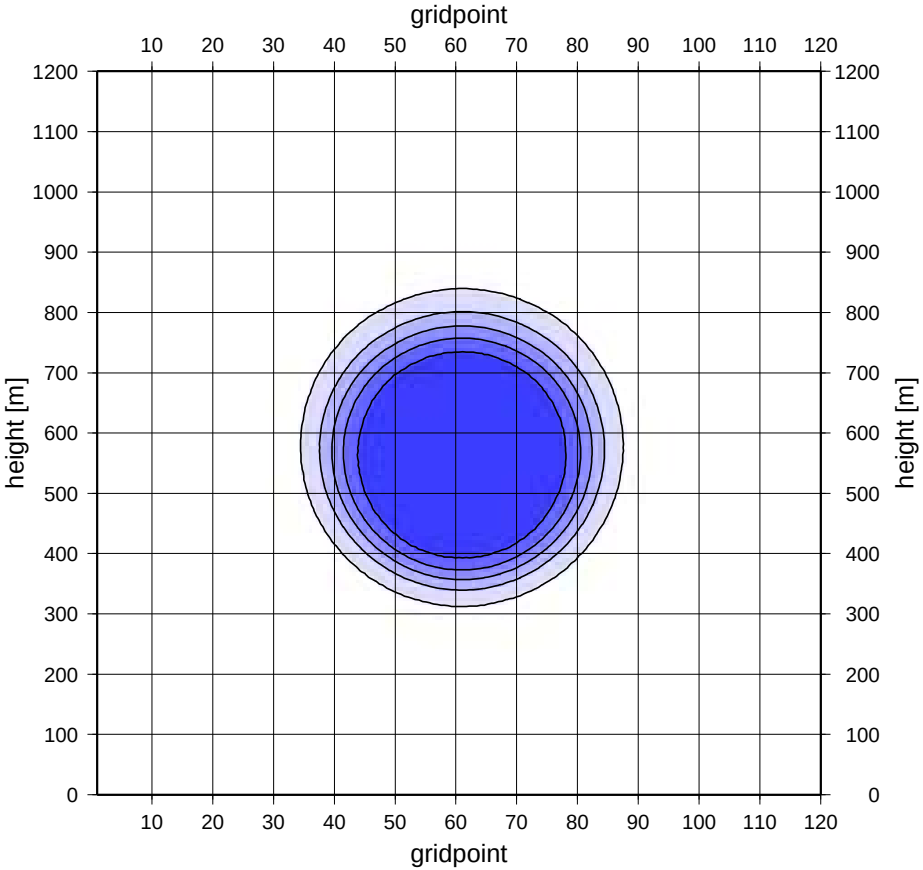
$\Delta x = 5\,\mathrm{m}$



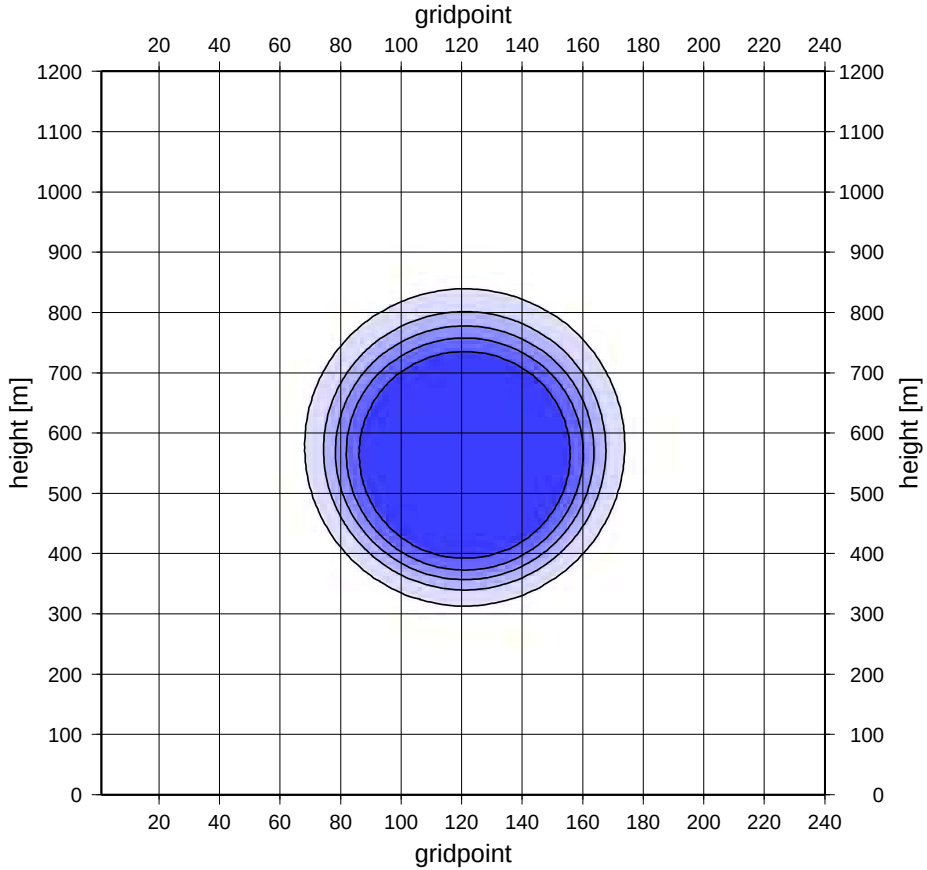
non-hydrostatic run, $t = 50\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

$\Delta x = 10\,\mathrm{m}$



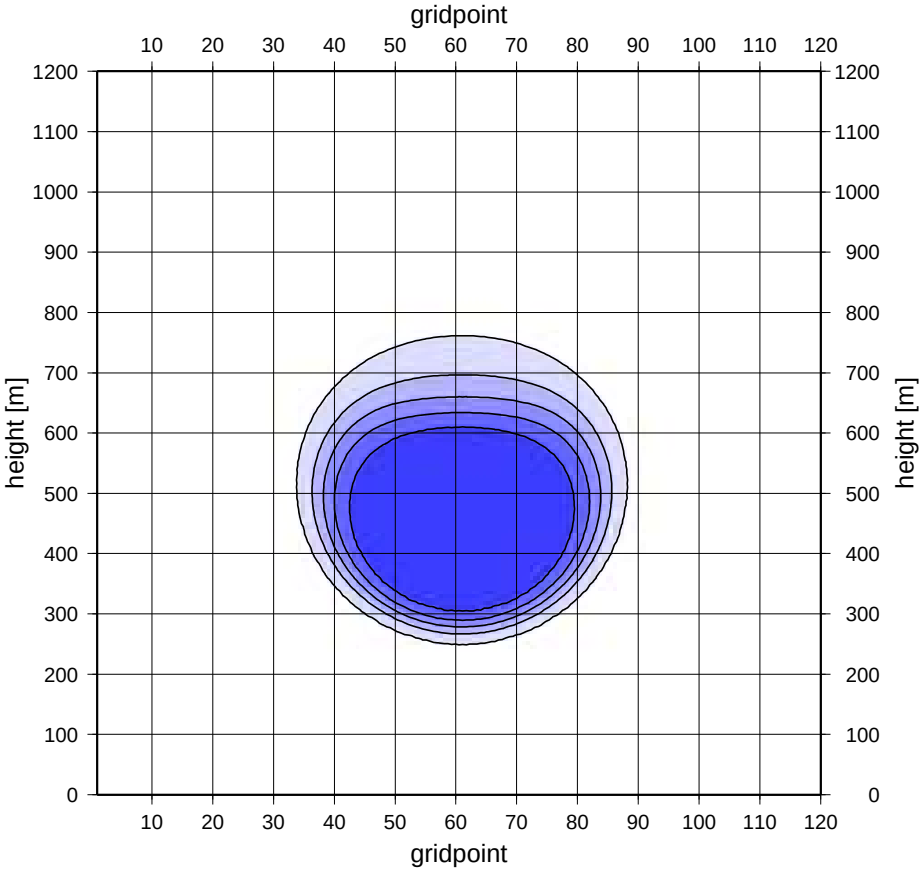
$\Delta x = 5\,\mathrm{m}$



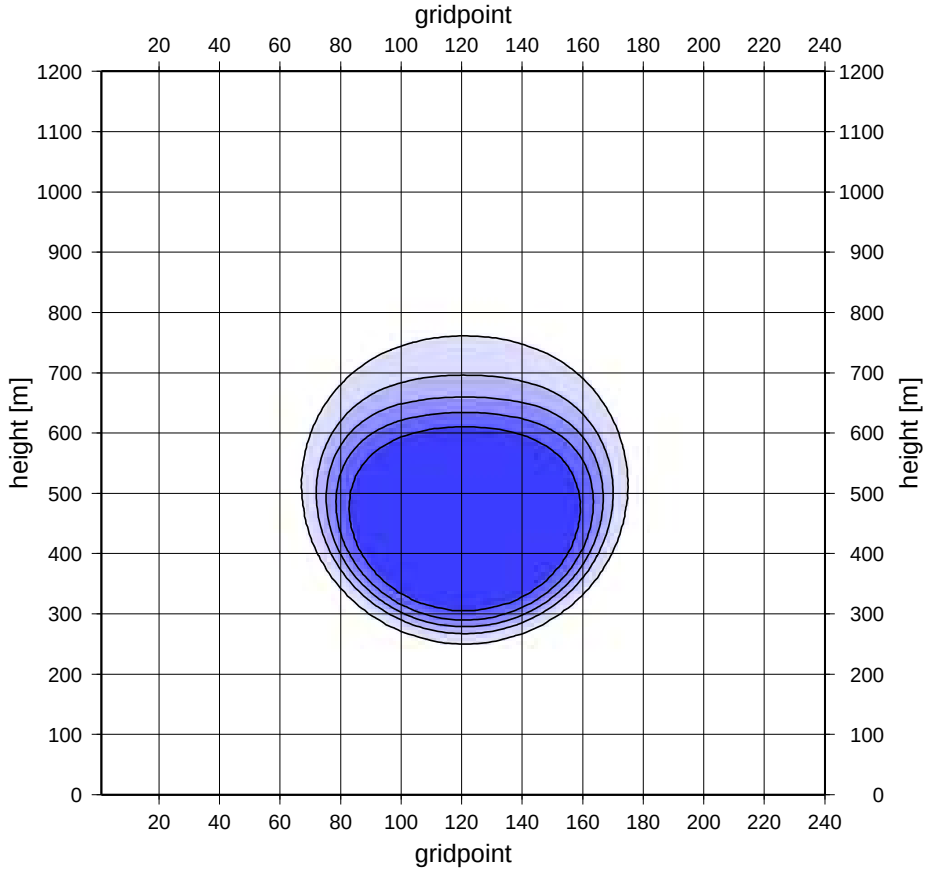
non-hydrostatic run, $t = 100\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

$\Delta x = 10\,\mathrm{m}$



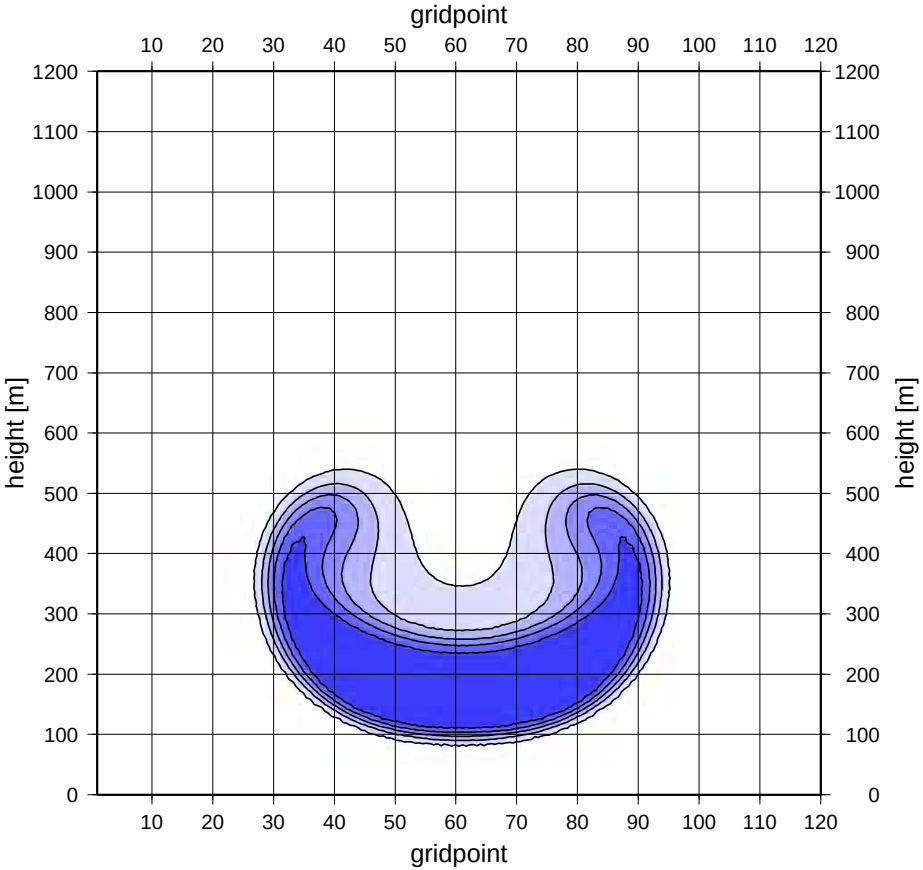
$\Delta x = 5\,\mathrm{m}$



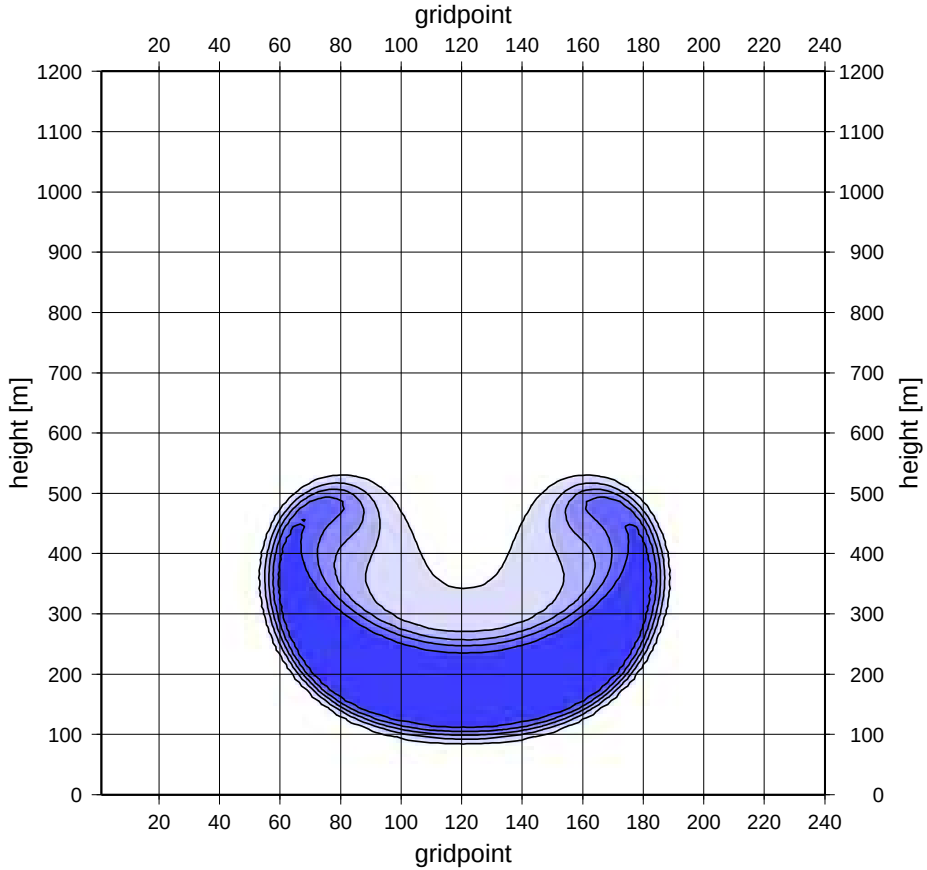
non-hydrostatic run, $t = 200\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

$\Delta x = 10\,\mathrm{m}$



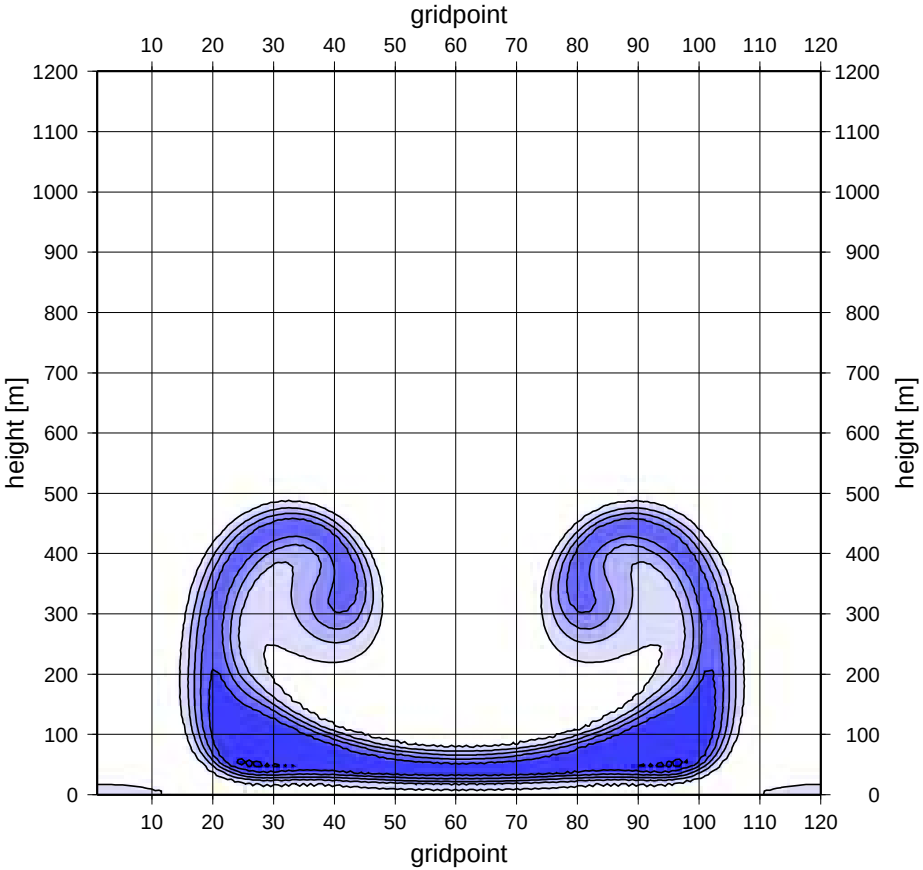
$\Delta x = 5\,\mathrm{m}$



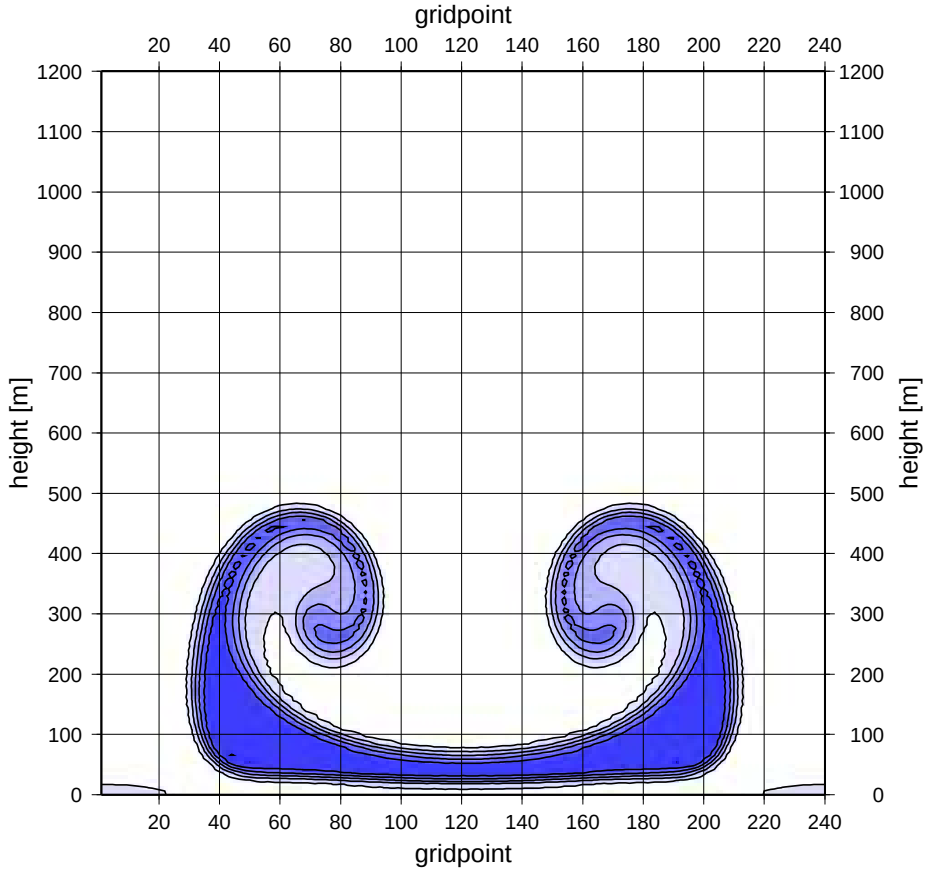
non-hydrostatic run, $t = 400\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

$\Delta x = 10\,\mathrm{m}$



$\Delta x = 5\,\mathrm{m}$



non-hydrostatic run, $t = 600\,\mathrm{s}$

Results for 10 versus 5 m horizontal resolution

- NH simulation with halved horizontal mesh size gives qualitatively the same results, horizontal gradients in final state being sharper

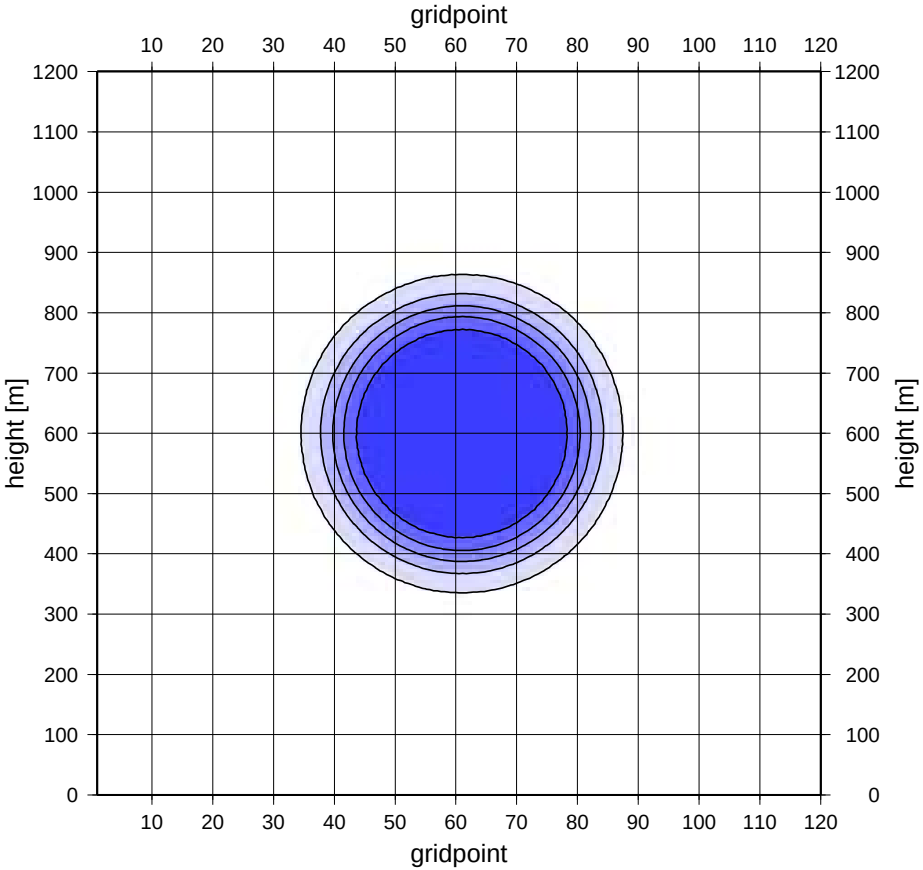
- it means that with 10 m horizontal resolution explicit simulation of convection is sufficient, at least for short evolution times

Simulations at 100 m horizontal resolution

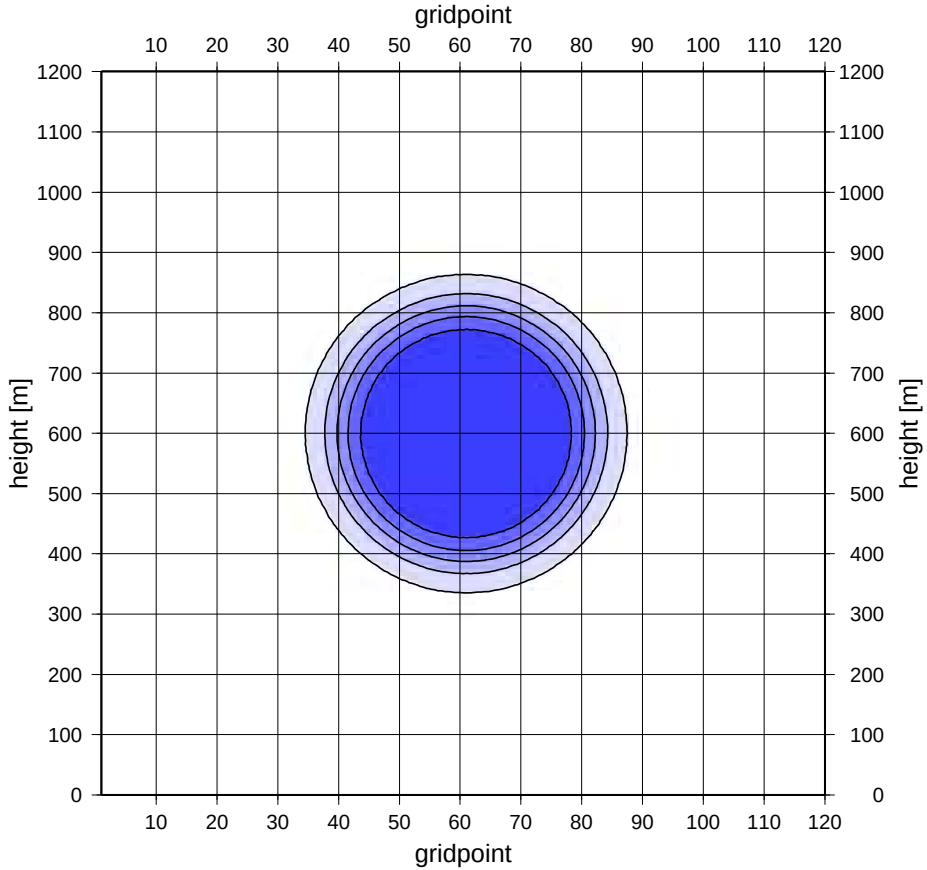
- what happens when Δx is increased to 100 m?
- initial bubble stretched to ellipse with $a = 1.5$ km and $b = 150$ m
- timestep prolongated to $\Delta t = 4$ s
- 10 times weaker horizontal diffusion (and sponge in H case)
- other settings unchanged

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



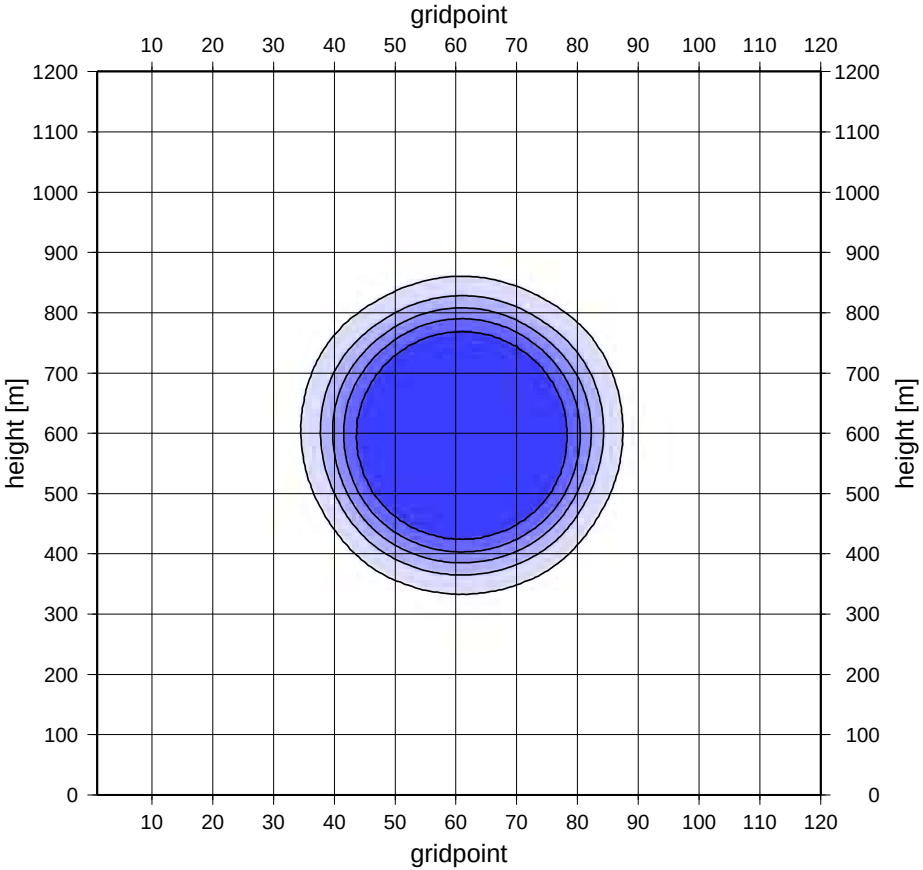
hydrostatic



$\Delta x = 100\,\mathrm{m},\ t = 0\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



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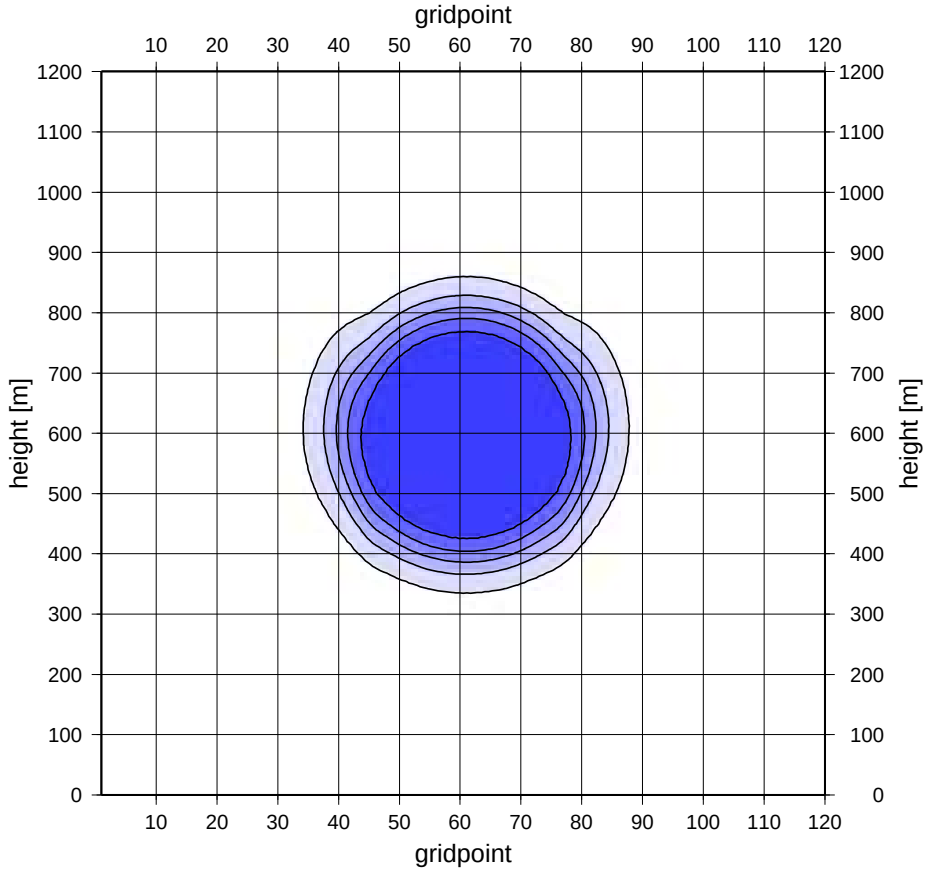
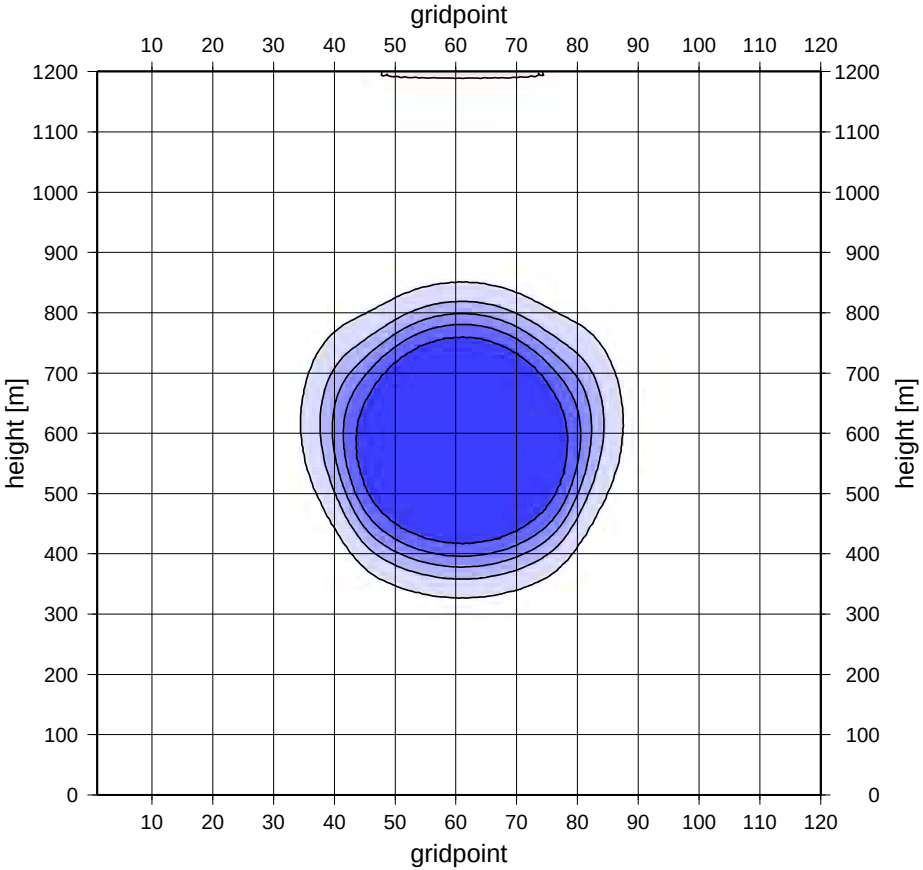


$\Delta x = 100\,\mathrm{m},\ t = 100\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



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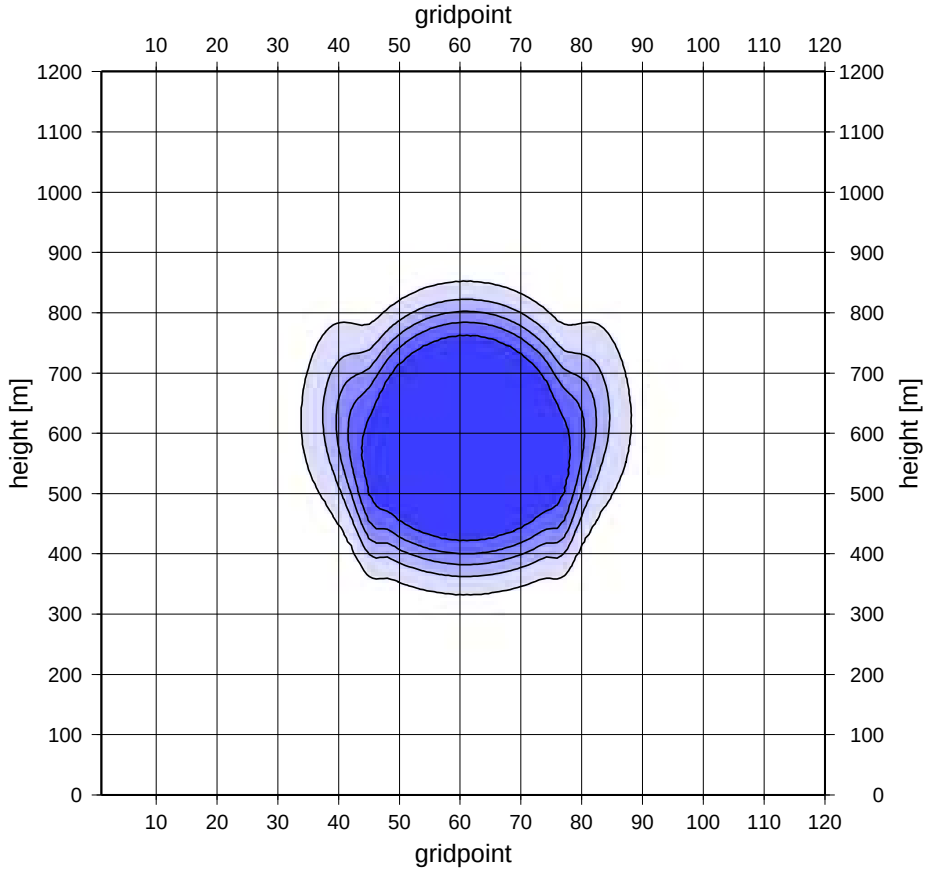
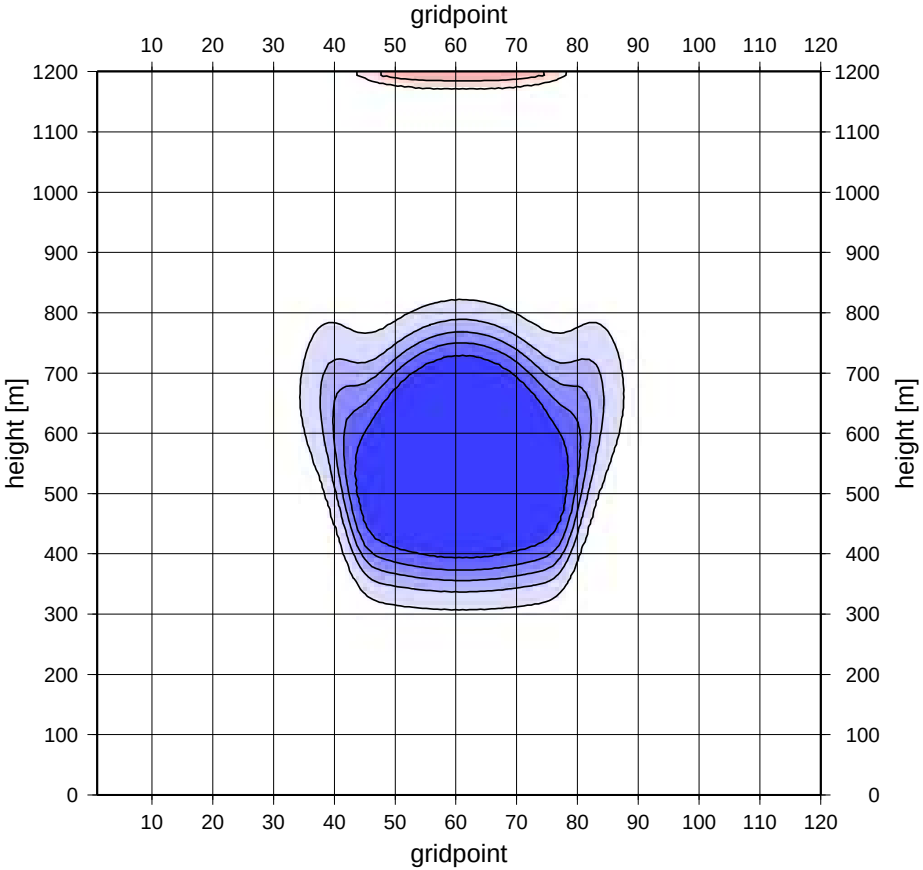


$\Delta x = 100\,\mathrm{m},\ t = 200\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



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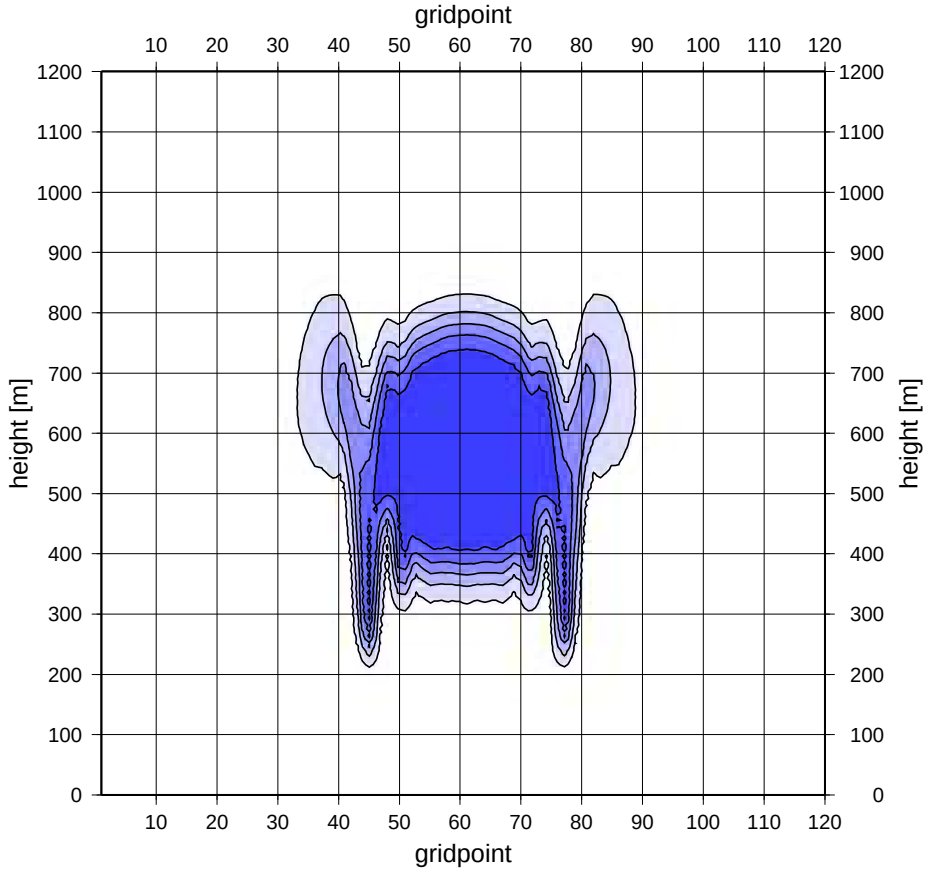
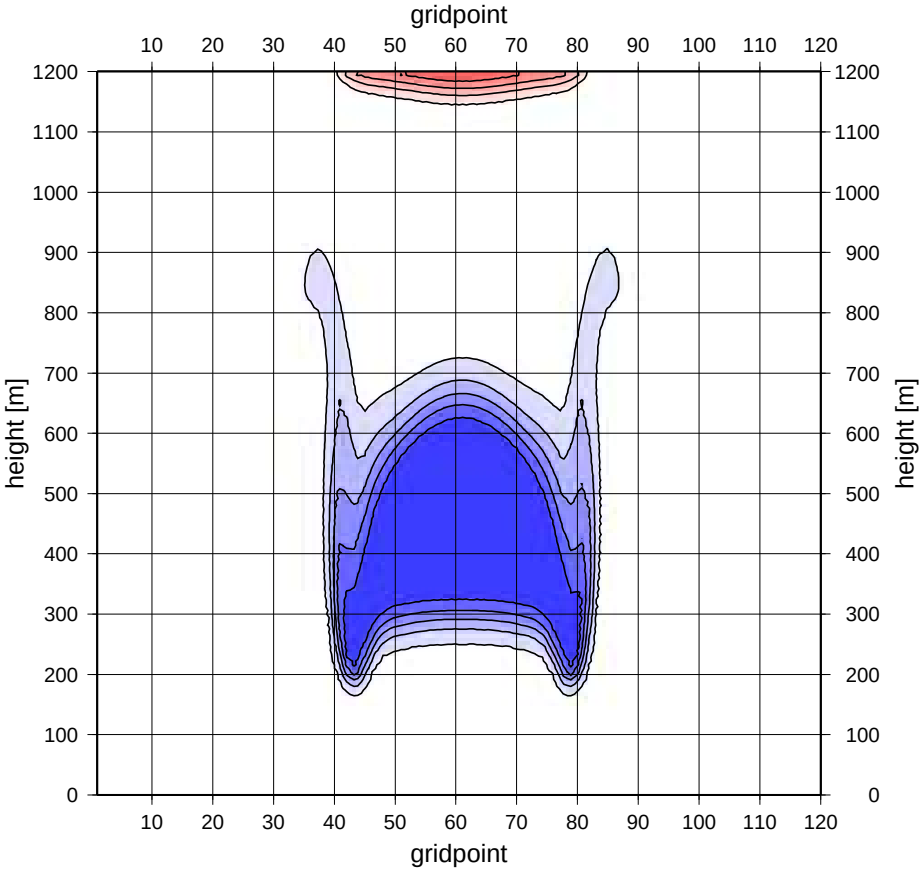


$\Delta x = 100\,\mathrm{m},\ t = 400\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



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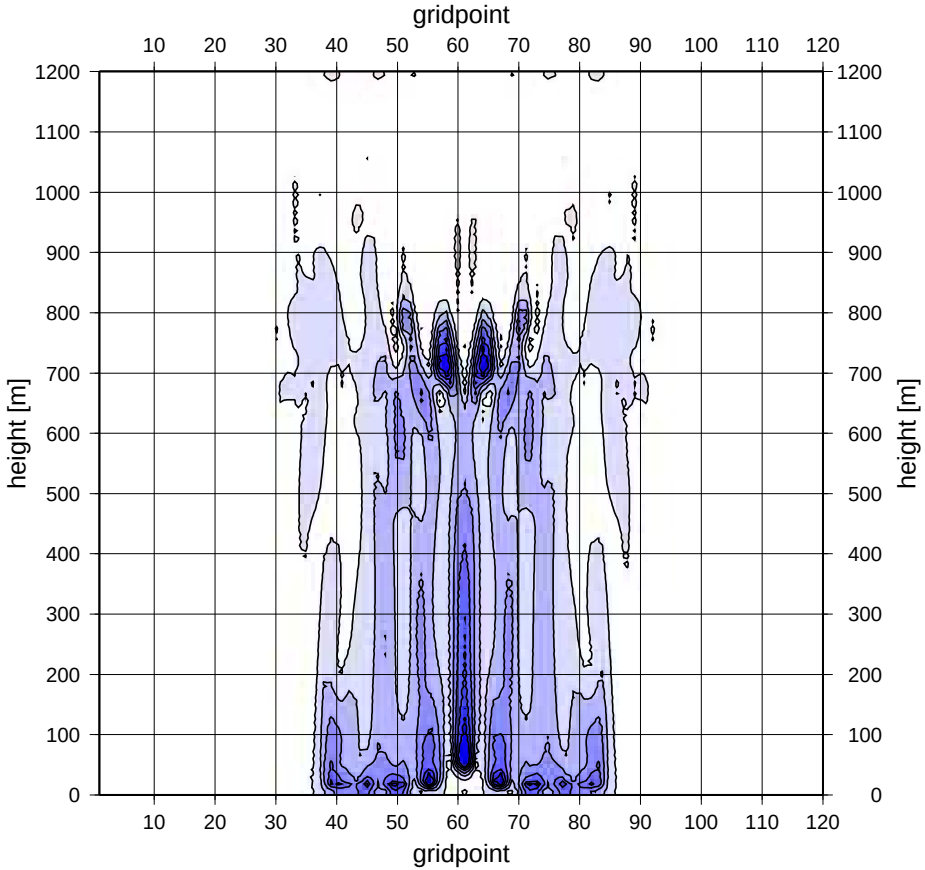
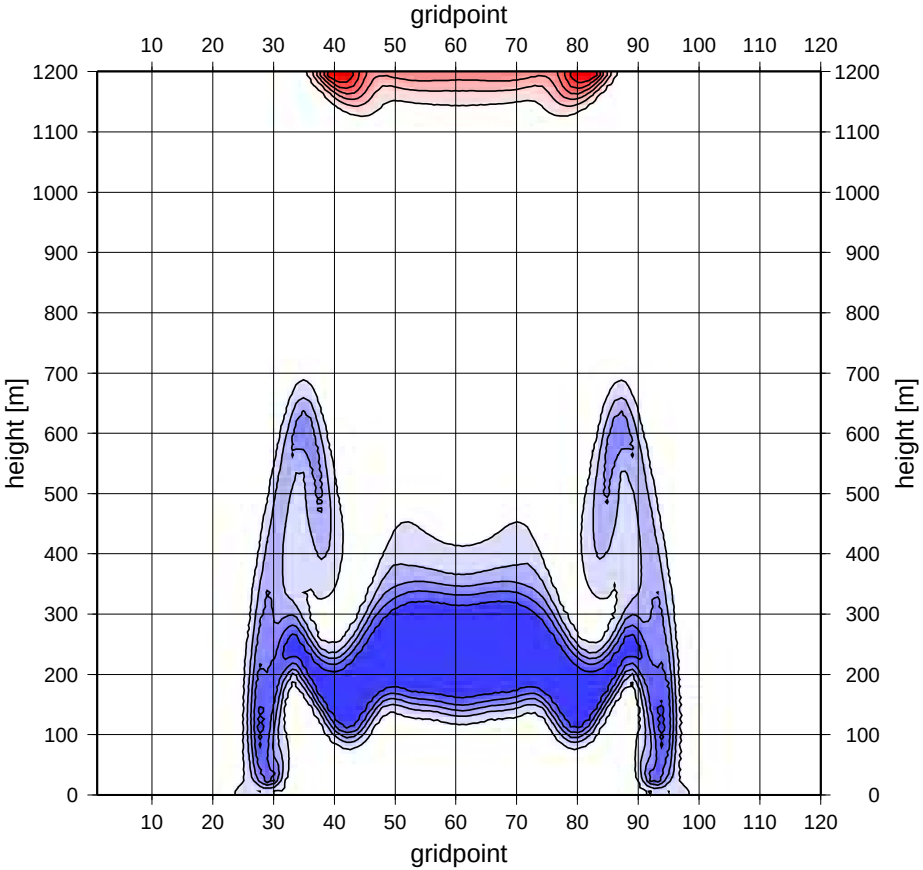


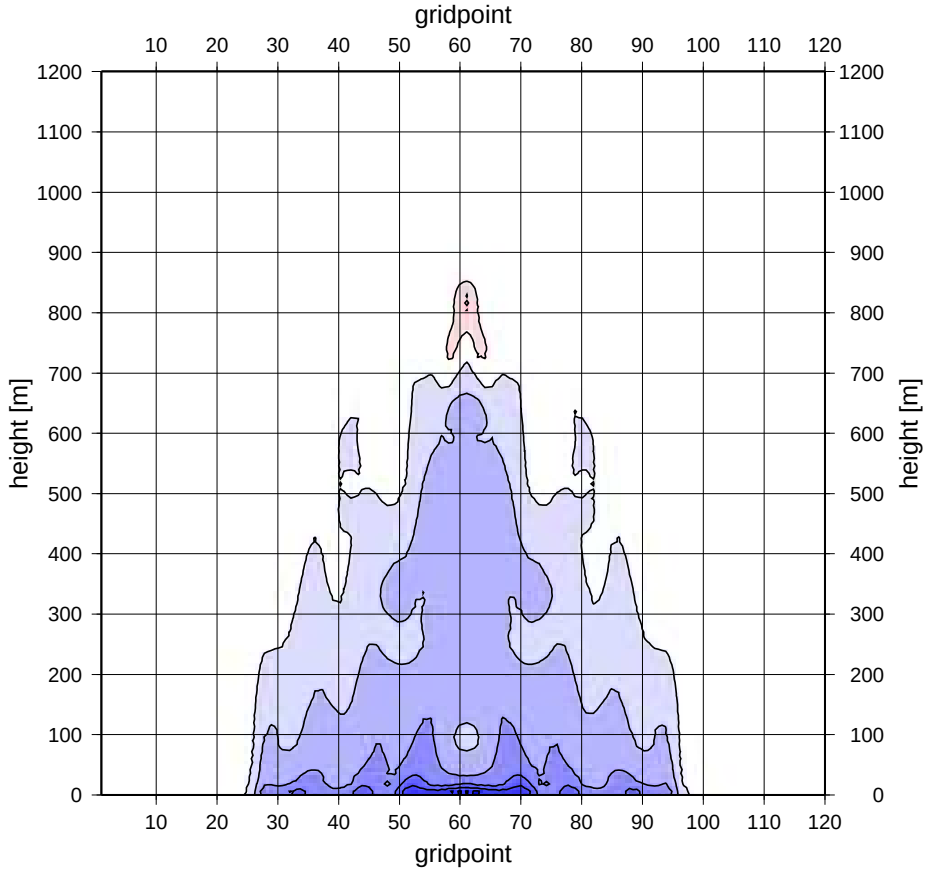
$\Delta x = 100\,\mathrm{m},\ t = 800\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



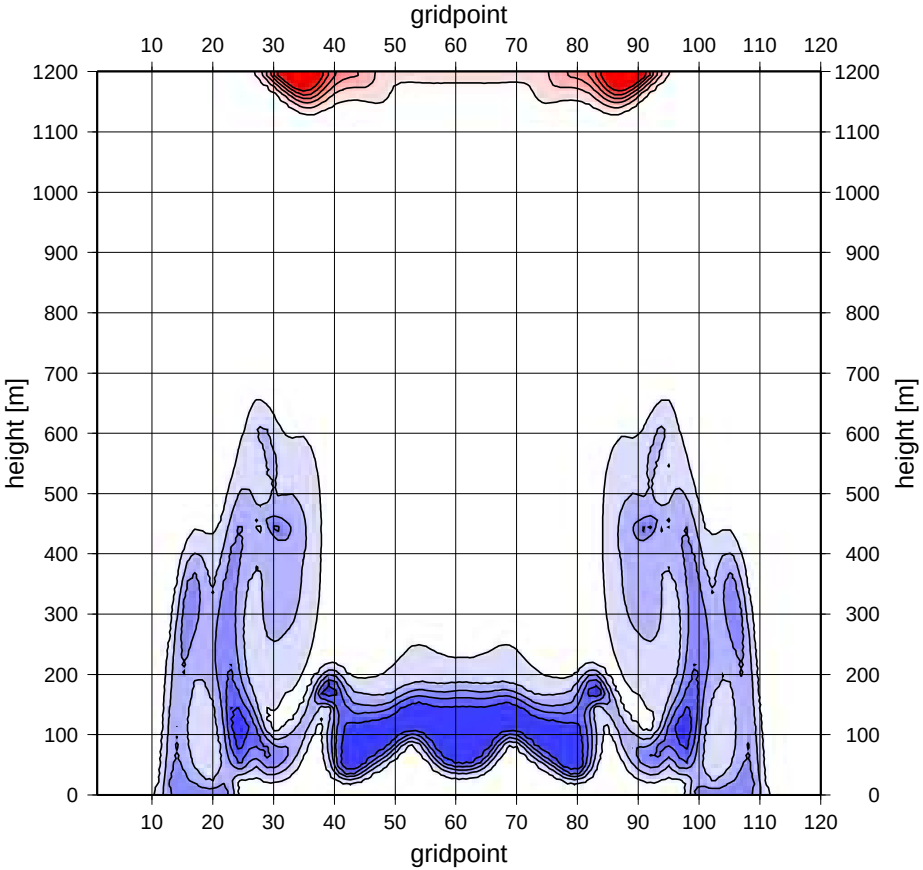
hydrostatic



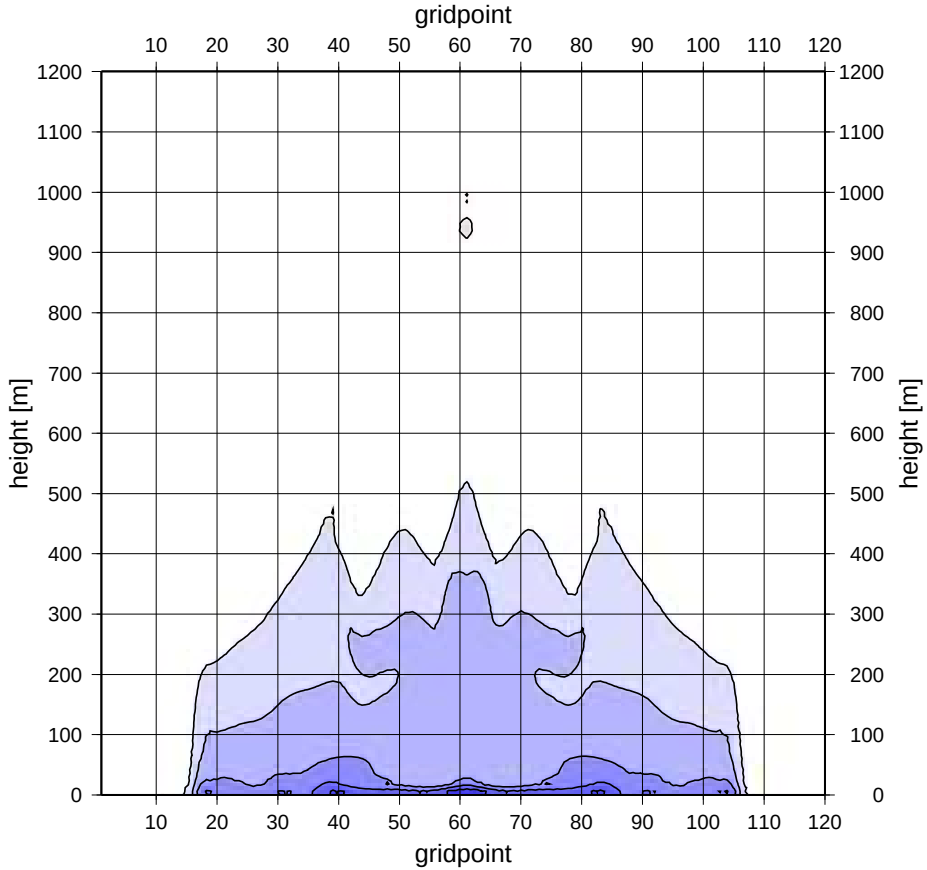
$\Delta x = 100\,\mathrm{m},\ t = 1600\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



hydrostatic



$\Delta x = 100\,\mathrm{m},\ t = 2400\,\mathrm{s}$

Results for 100 m horizontal resolution

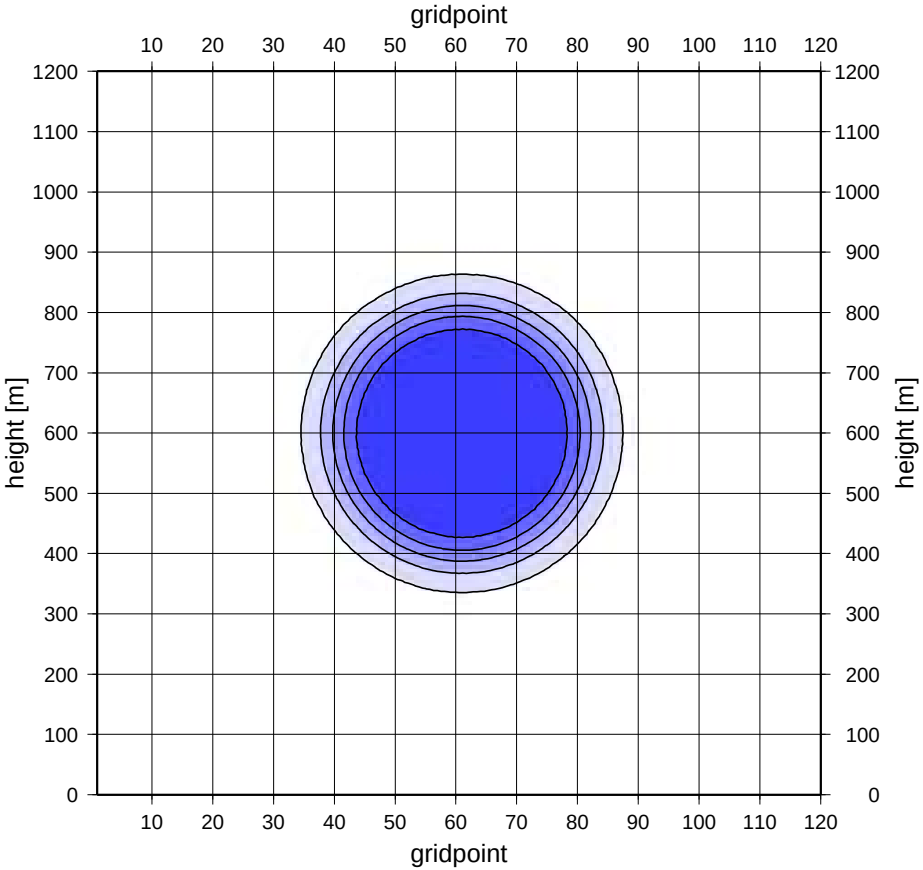
- evolution has slowed down, it takes longer for the bubble to reach the surface
- there is still significant difference between H and NH simulations
- some similarity of bubble shape can be seen at initial stages
- in H case bubble decays into smaller cells which descend too quickly

Simulations at 1 km horizontal resolution

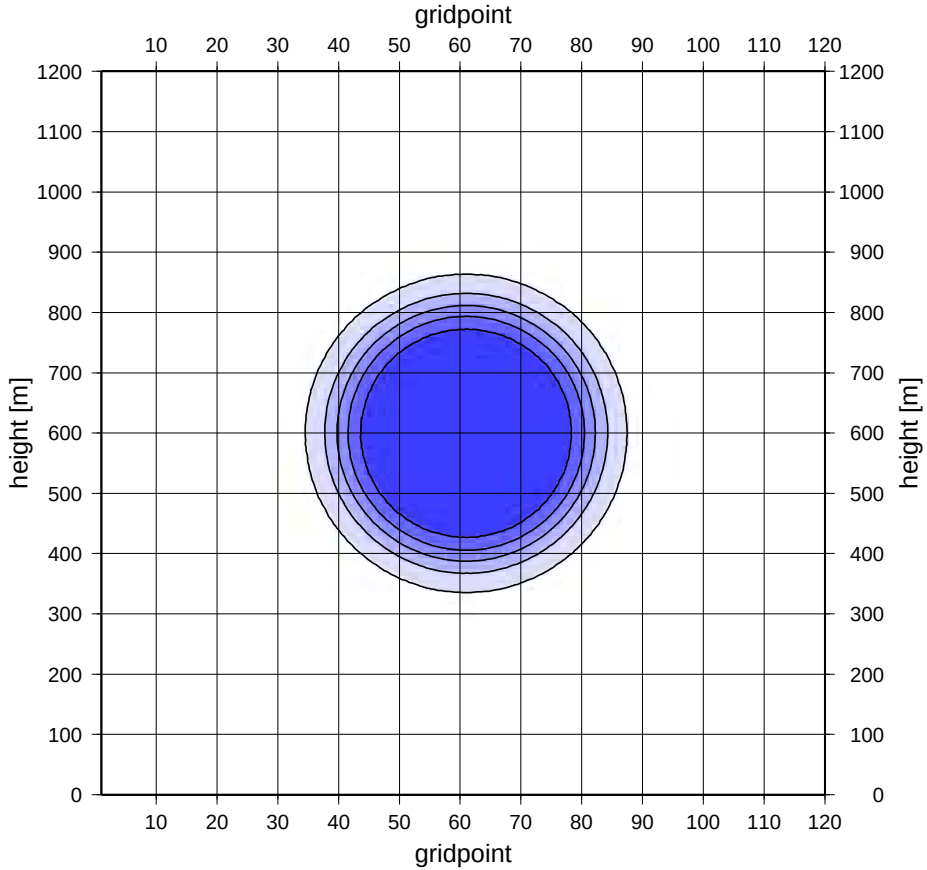
- what happens when Δx is further increased to 1 km?
- initial bubble stretched to ellipse with $a = 15$ km and $b = 150$ m
- timestep prolongated to $\Delta t = 40$ s
- 10 times weaker horizontal diffusion (and sponge in H case)
- other settings unchanged

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



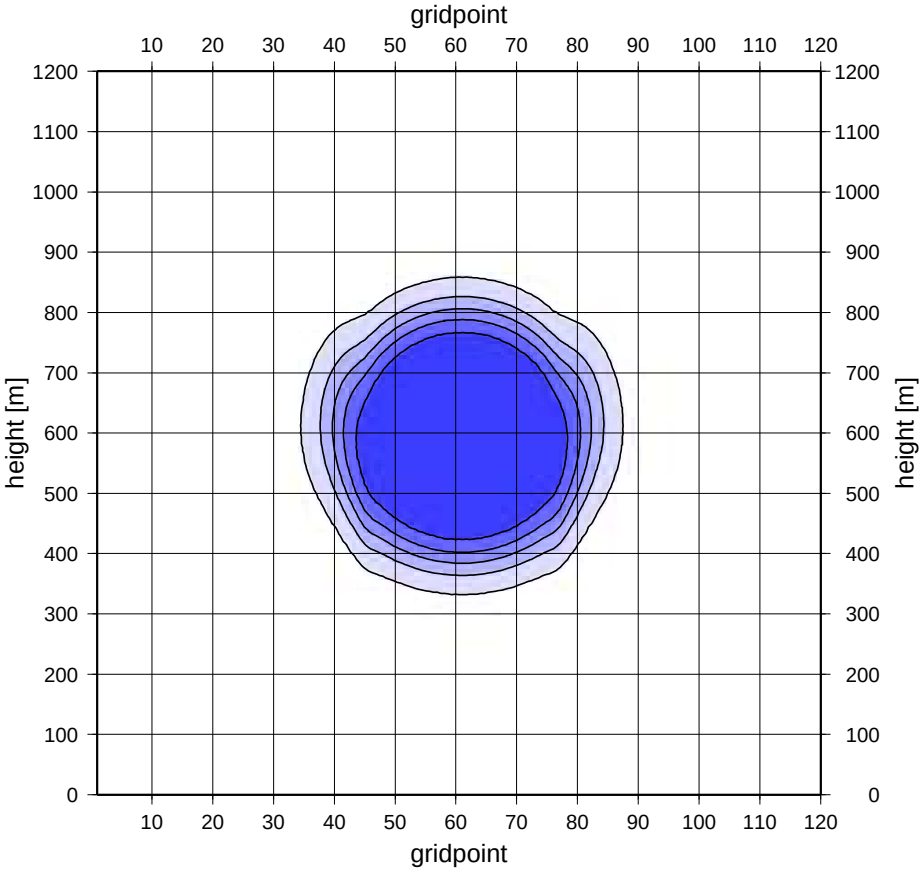
hydrostatic



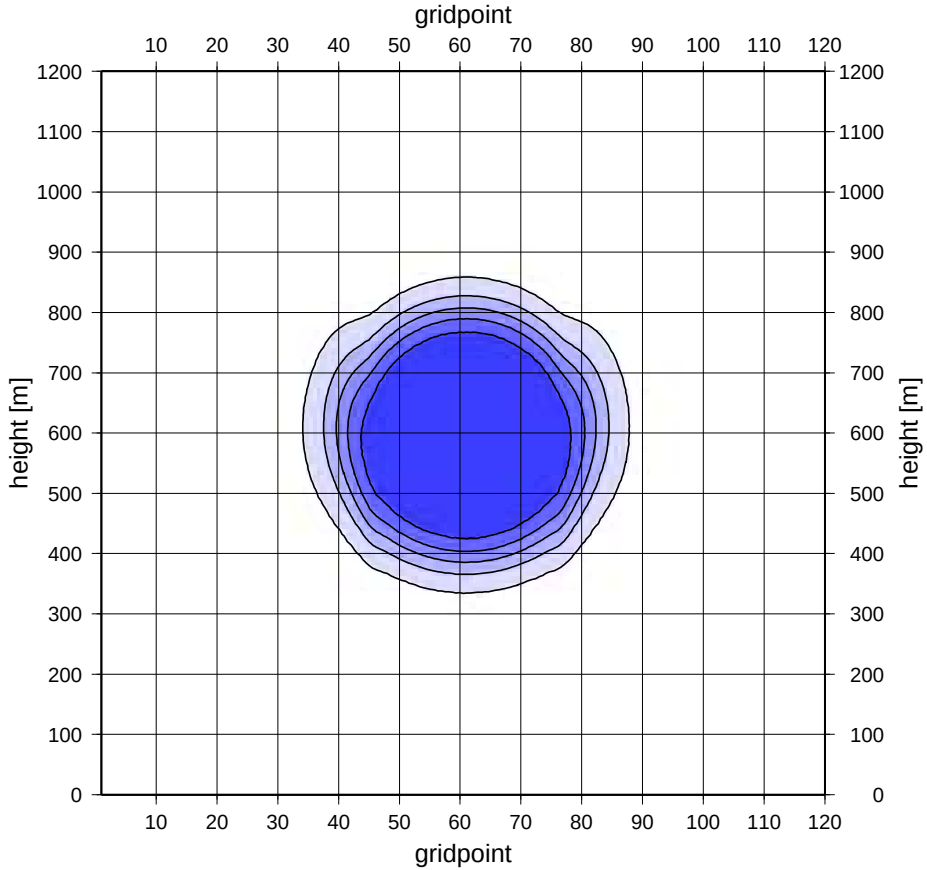
$\Delta x = 1\,\mathrm{km},\ t = 0\,\mathrm{min}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



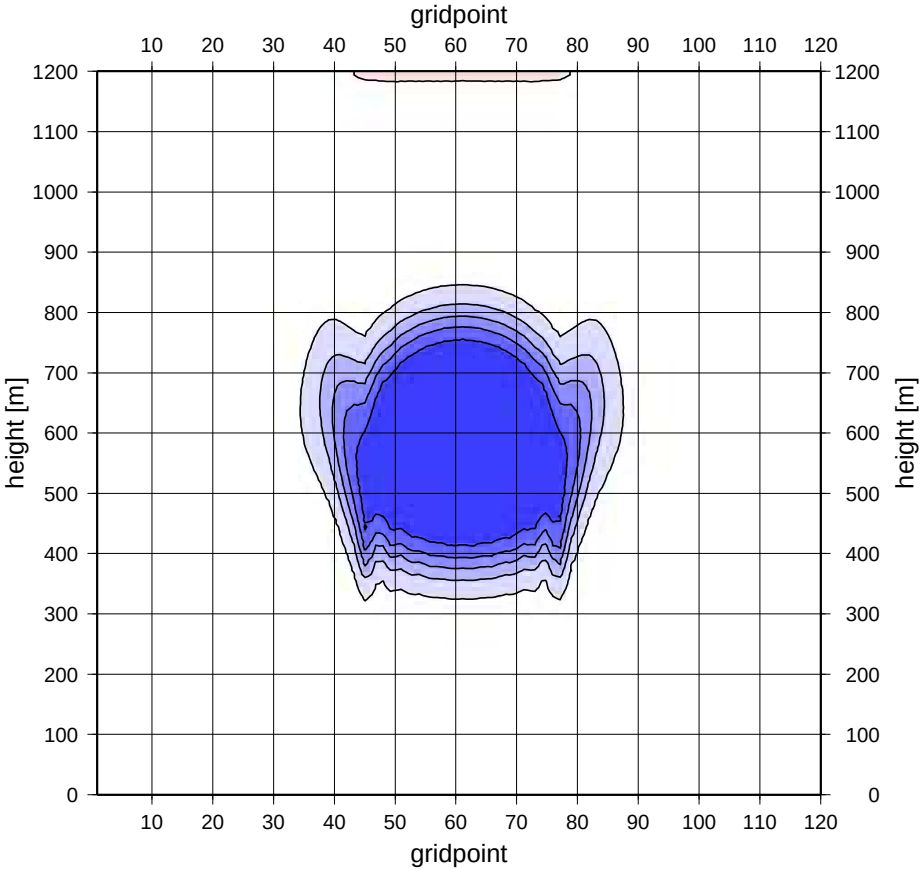
hydrostatic



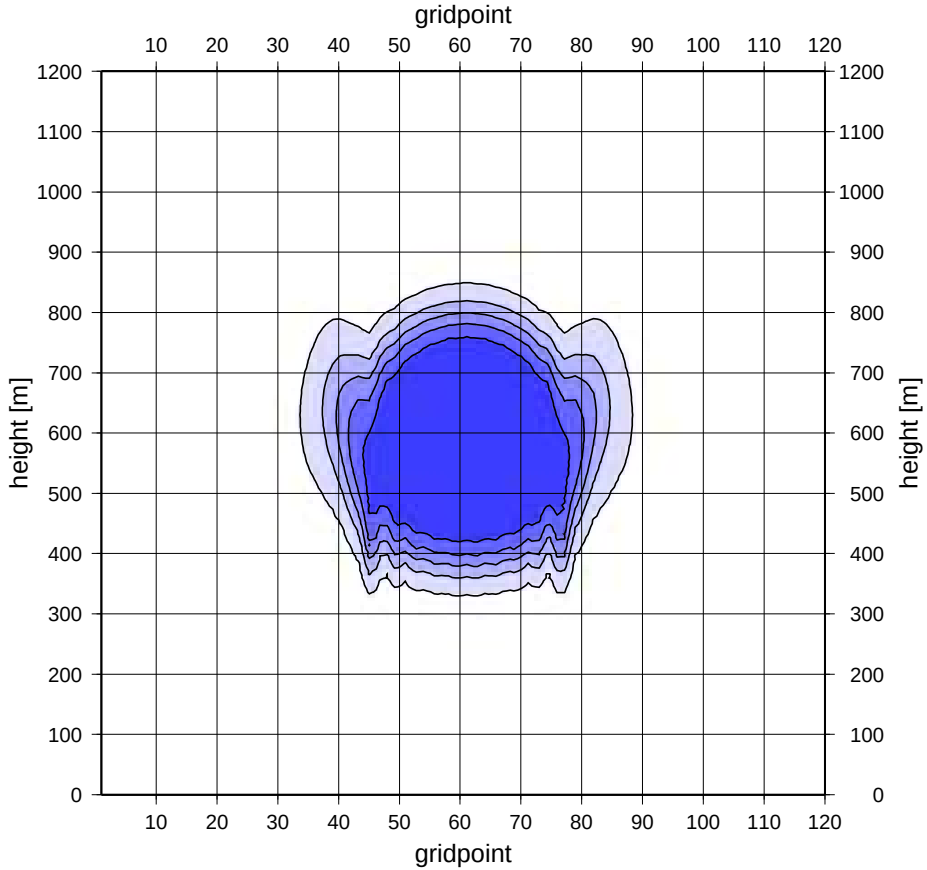
$\Delta x = 1\,\mathrm{km},\ t = 20\,\mathrm{min}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



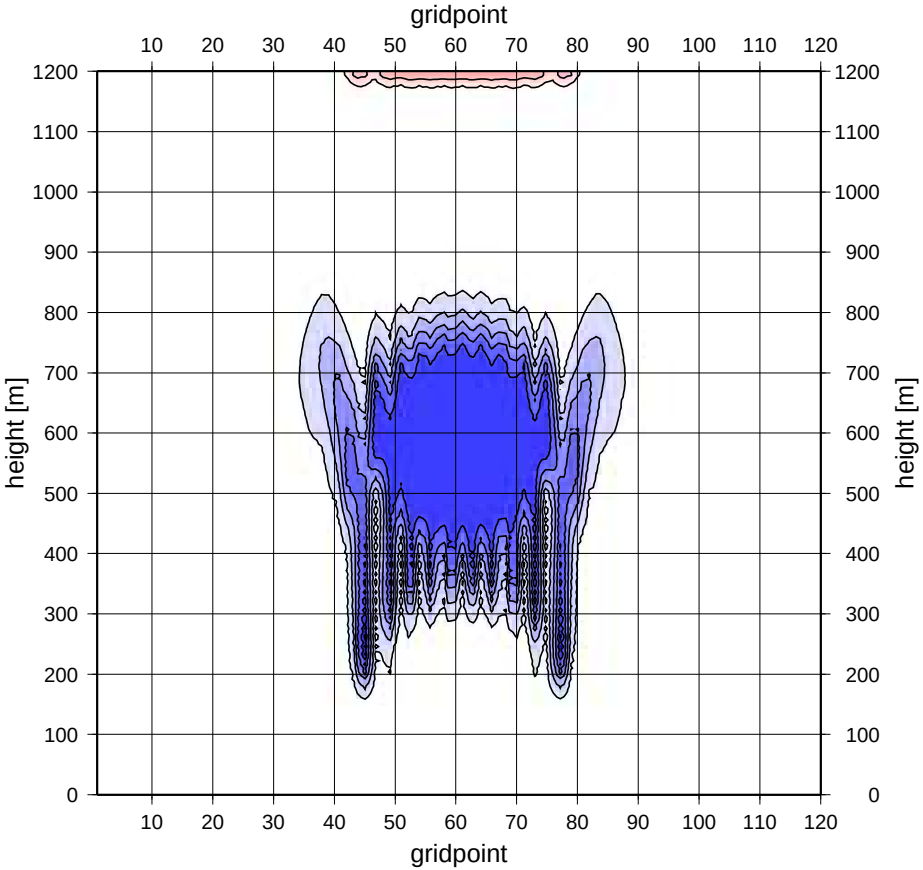
hydrostatic



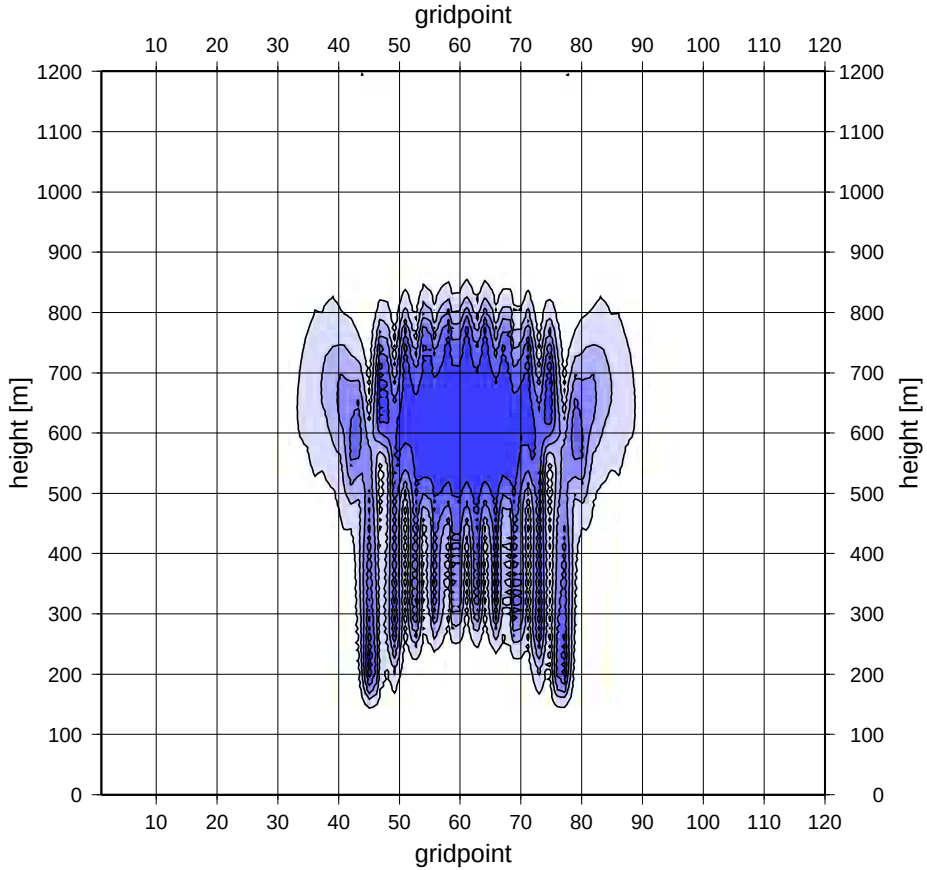
$\Delta x = 1\,\mathrm{km},\ t = 40\,\mathrm{min}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



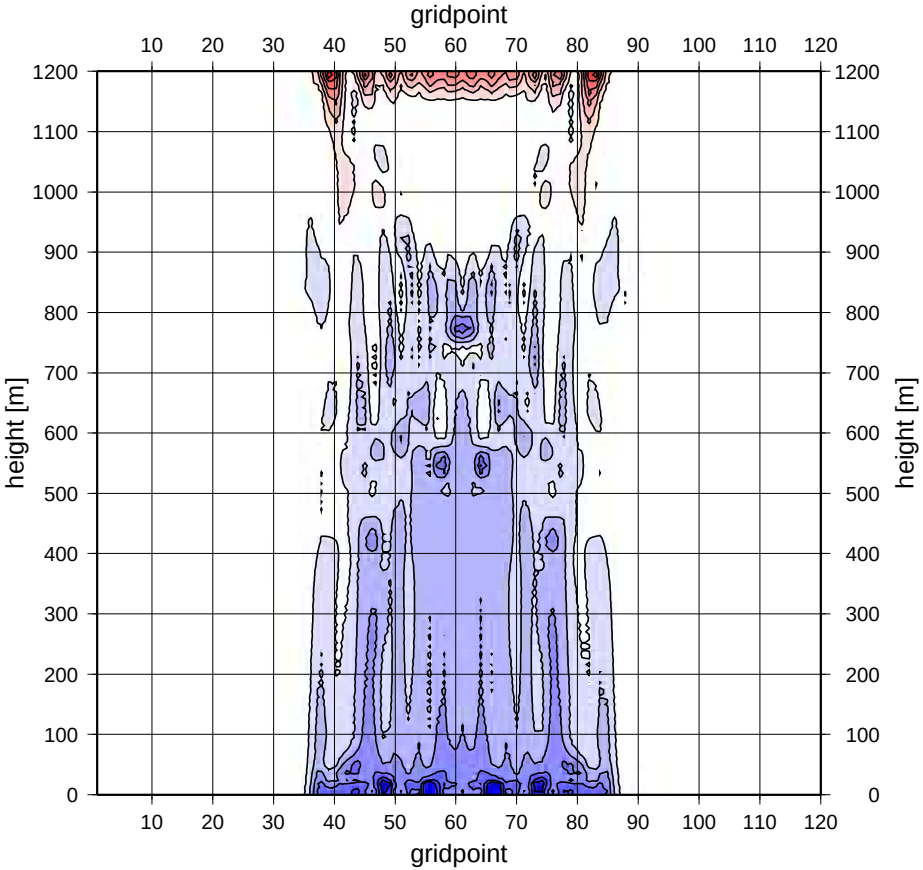
hydrostatic



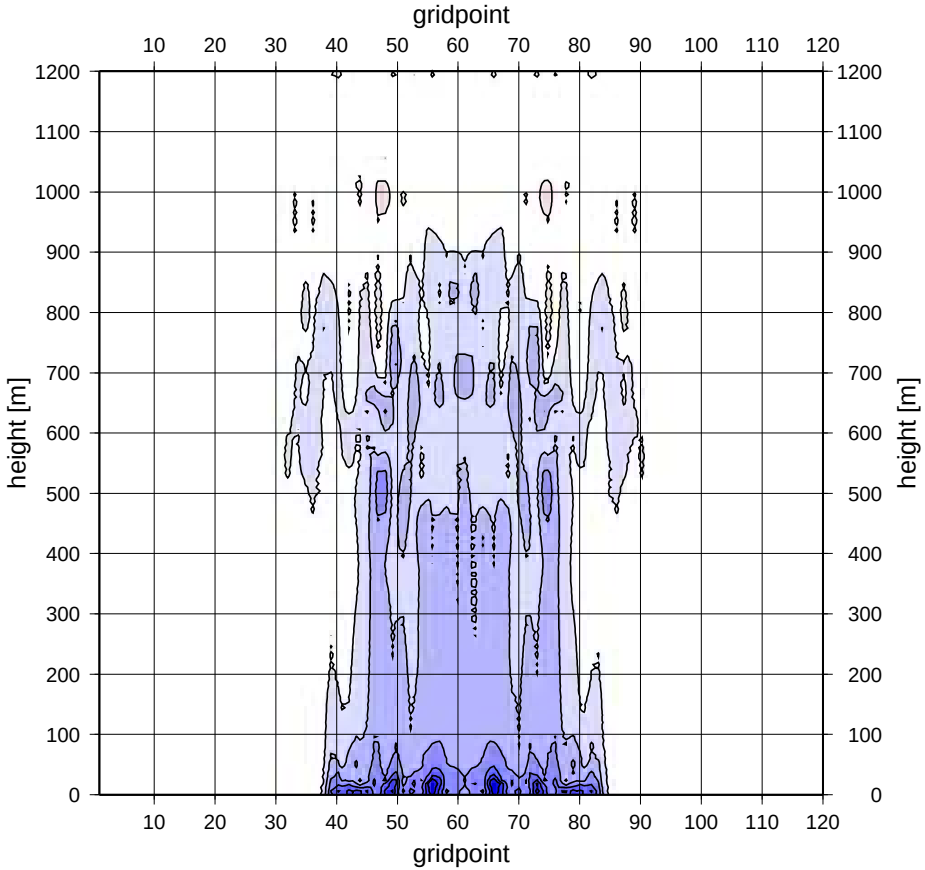
$\Delta x = 1\,\mathrm{km},\ t = 1\,\mathrm{h}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



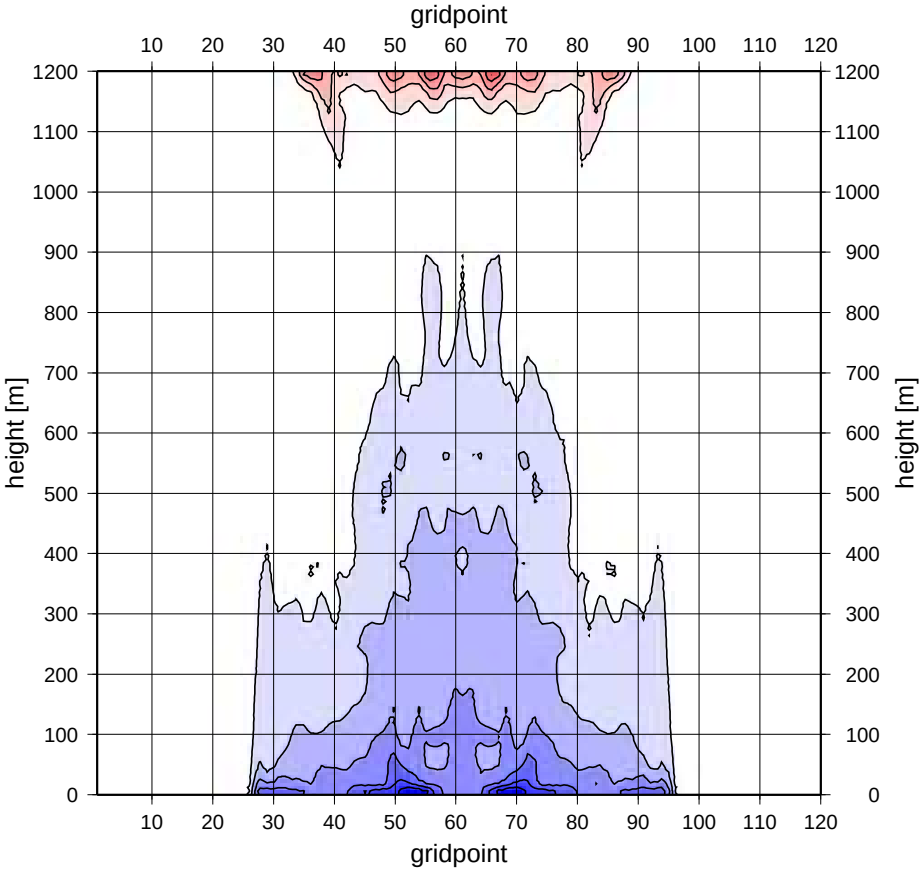
hydrostatic



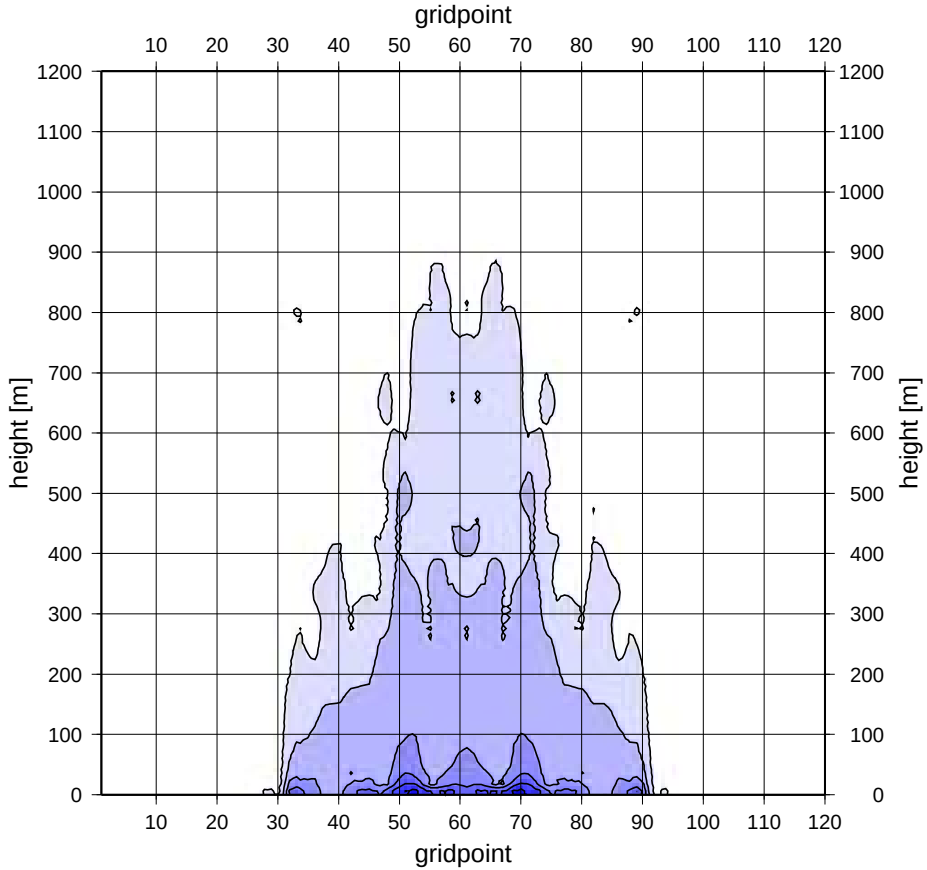
$\Delta x = 1\,\mathrm{km},\ t = 2\,\mathrm{h}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



hydrostatic



$\Delta x = 1\,\mathrm{km},\ t = 4\,\mathrm{h}$

Results for 1 km horizontal resolution

- evolution has further slowed down
- now there is quite good agreement between H and NH results
- in both cases bubble decays into smaller cells

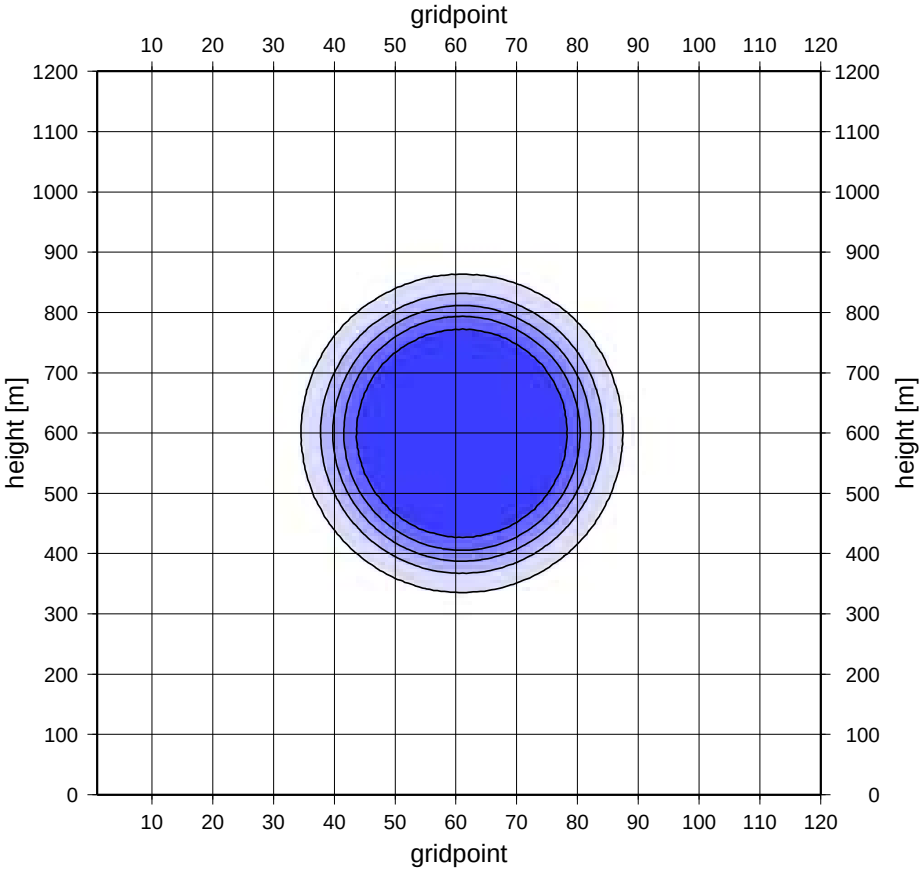
How trustable are numerical results now?

- with bigger Δx influence of subgrid convective scales might become stronger

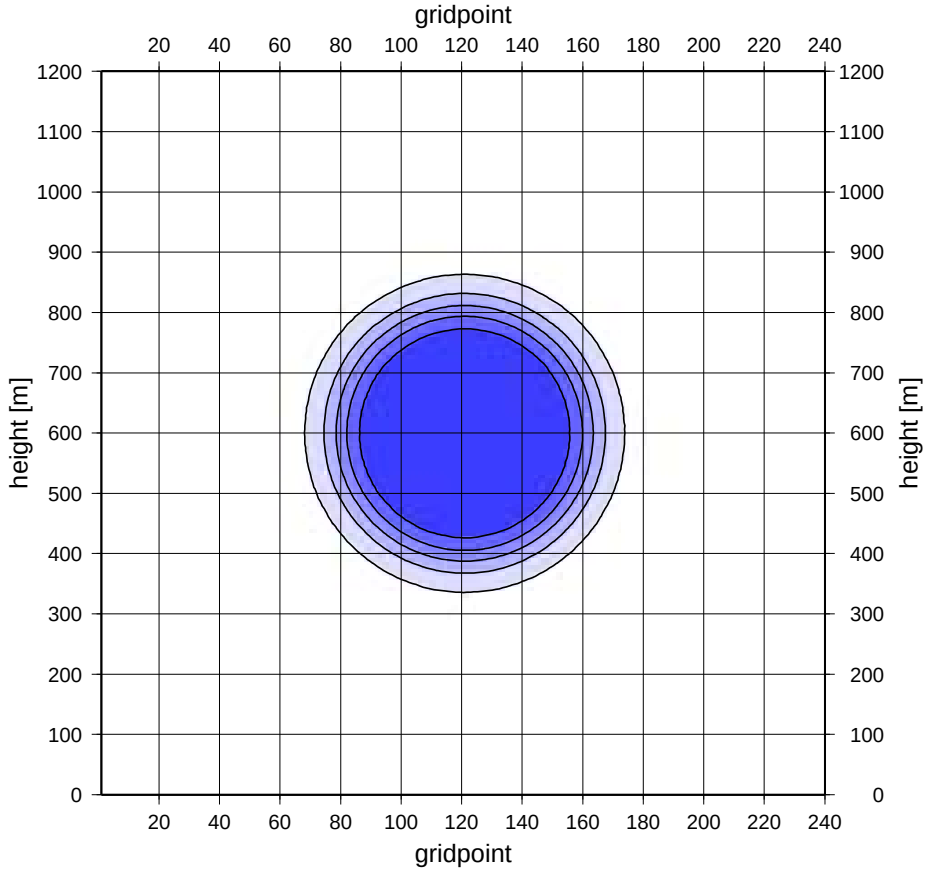
- it is necessary to repeat the test with increased horizontal resolution

perturbation of potential temperature $\theta - \overline{\theta}$

$\Delta x = 1\,\mathrm{km}$



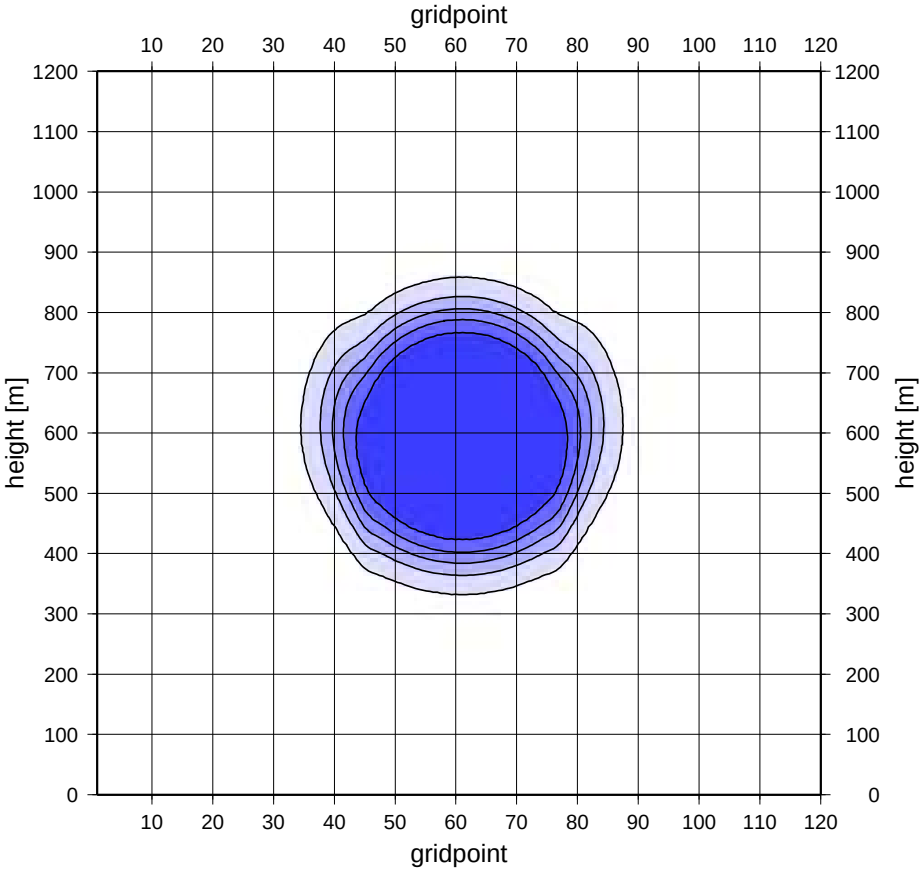
$\Delta x = 0.5\,\mathrm{km}$



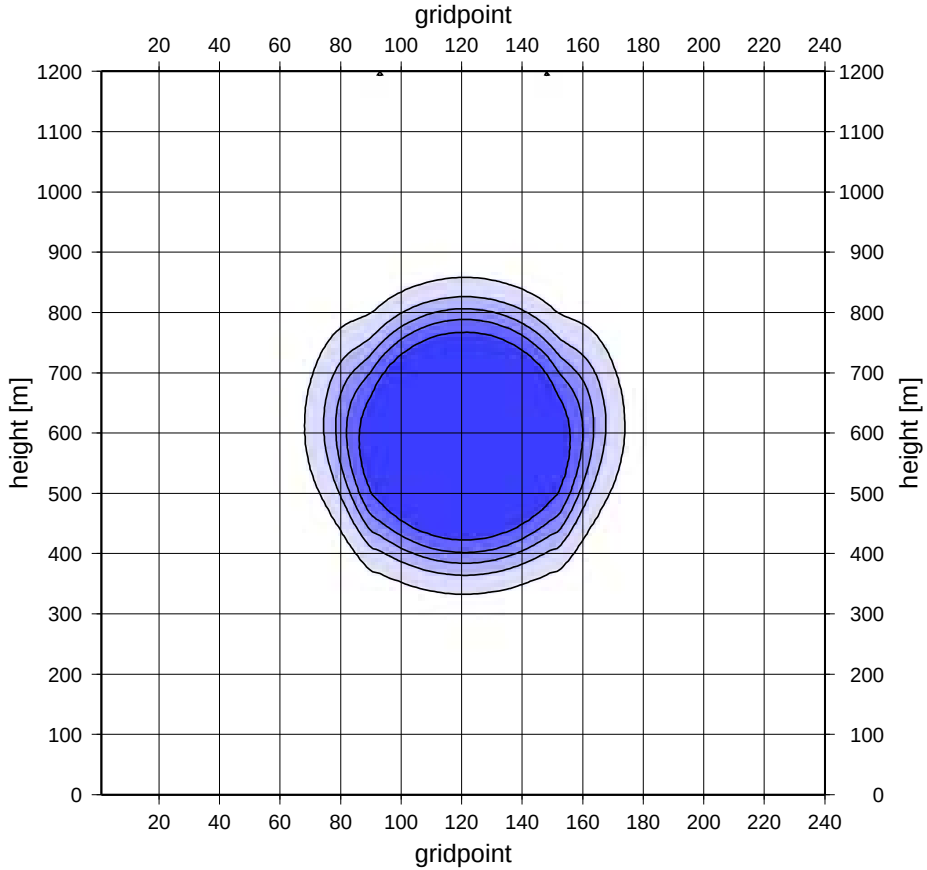
non-hydrostatic run, $t = 0\,\mathrm{min}$

perturbation of potential temperature $\theta - \overline{\theta}$

$\Delta x = 1\,\mathrm{km}$



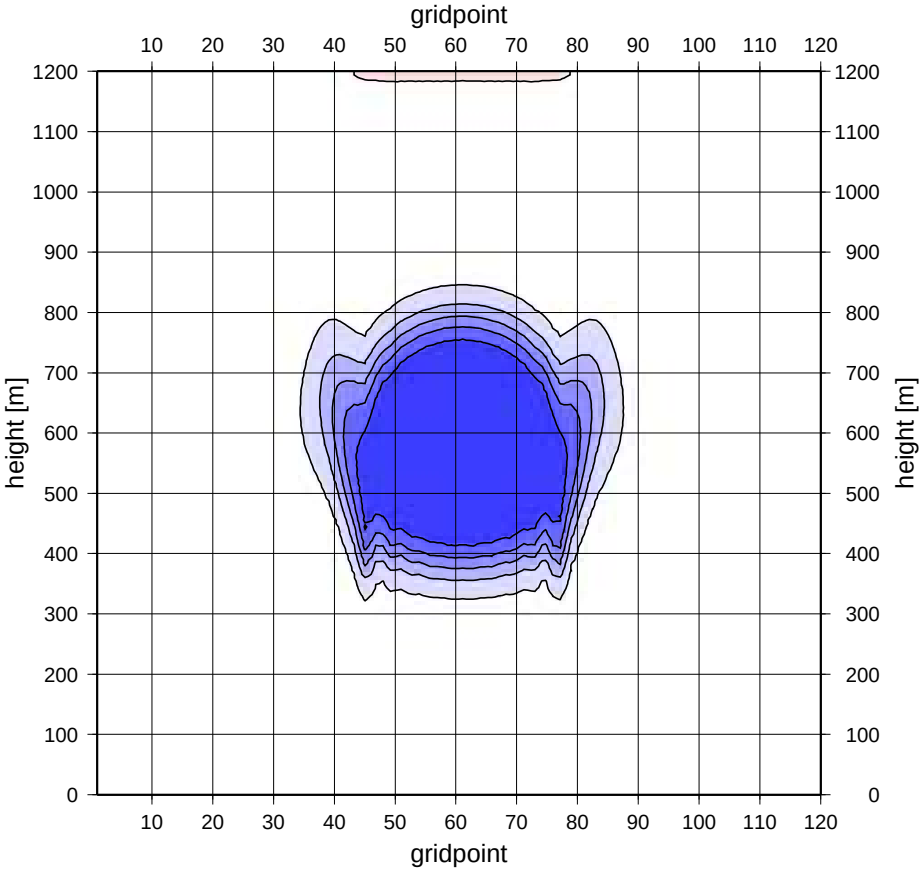
$\Delta x = 0.5\,\mathrm{km}$



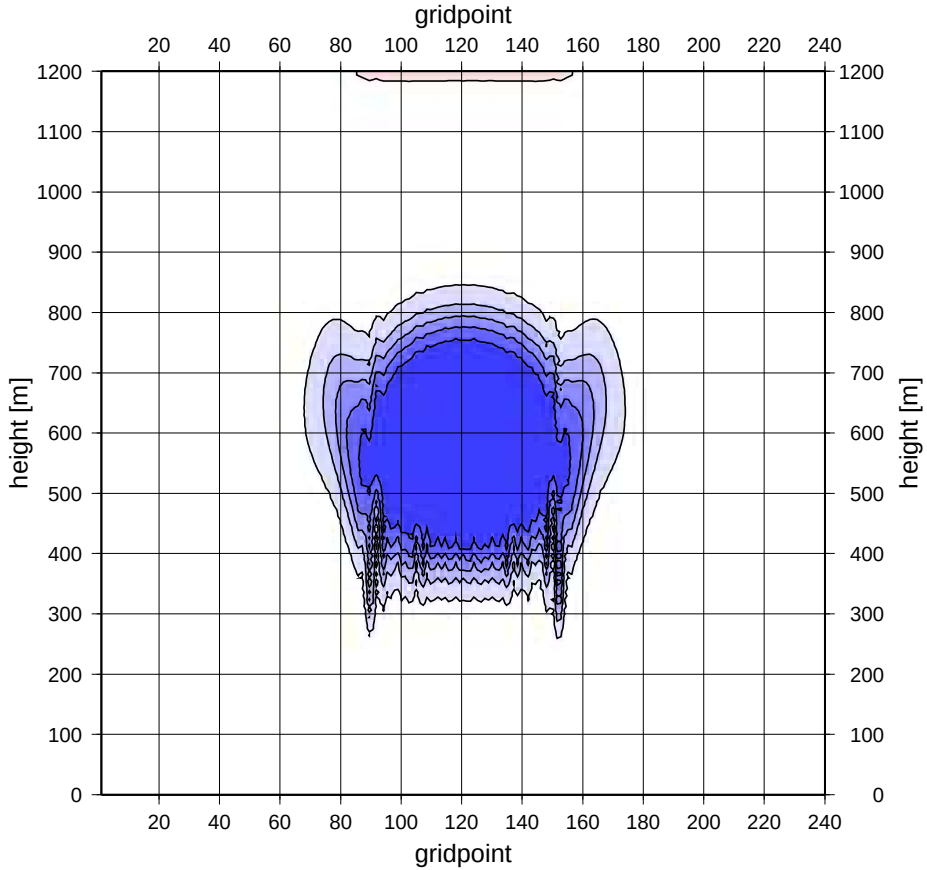
non-hydrostatic run, $t = 20\,\mathrm{min}$

perturbation of potential temperature $\theta - \overline{\theta}$

$\Delta x = 1\,\mathrm{km}$



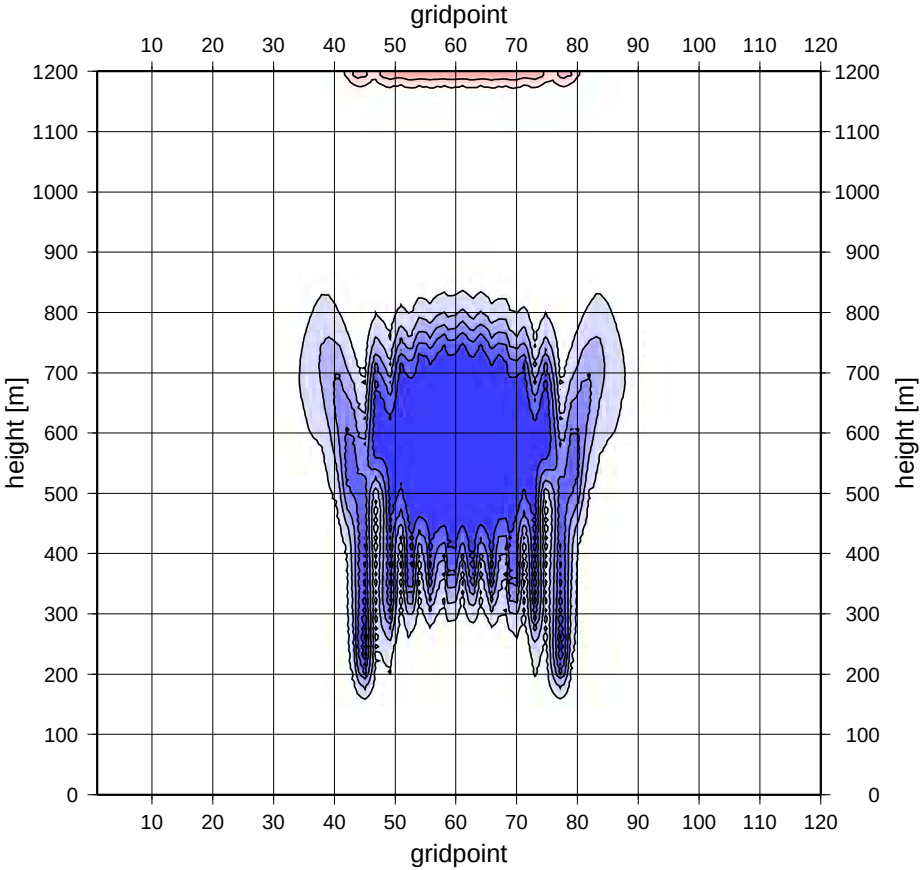
$\Delta x = 0.5\,\mathrm{km}$



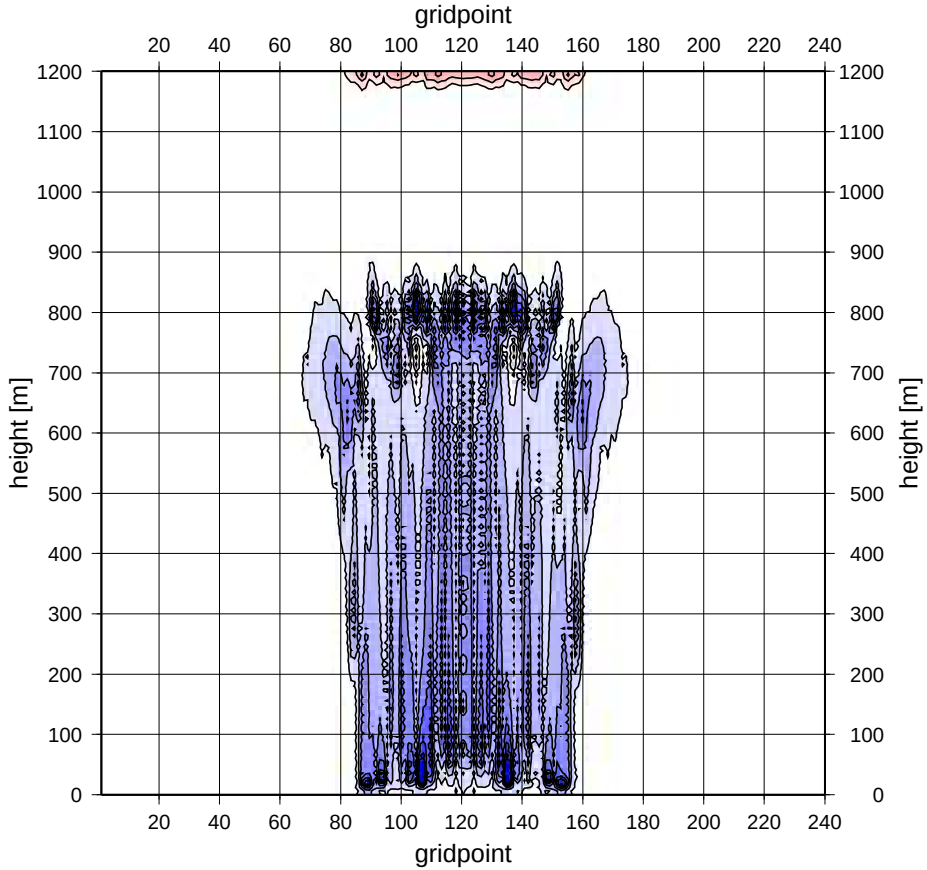
non-hydrostatic run, $t = 40\,\mathrm{min}$

perturbation of potential temperature $\theta - \overline{\theta}$

$\Delta x = 1\,\mathrm{km}$



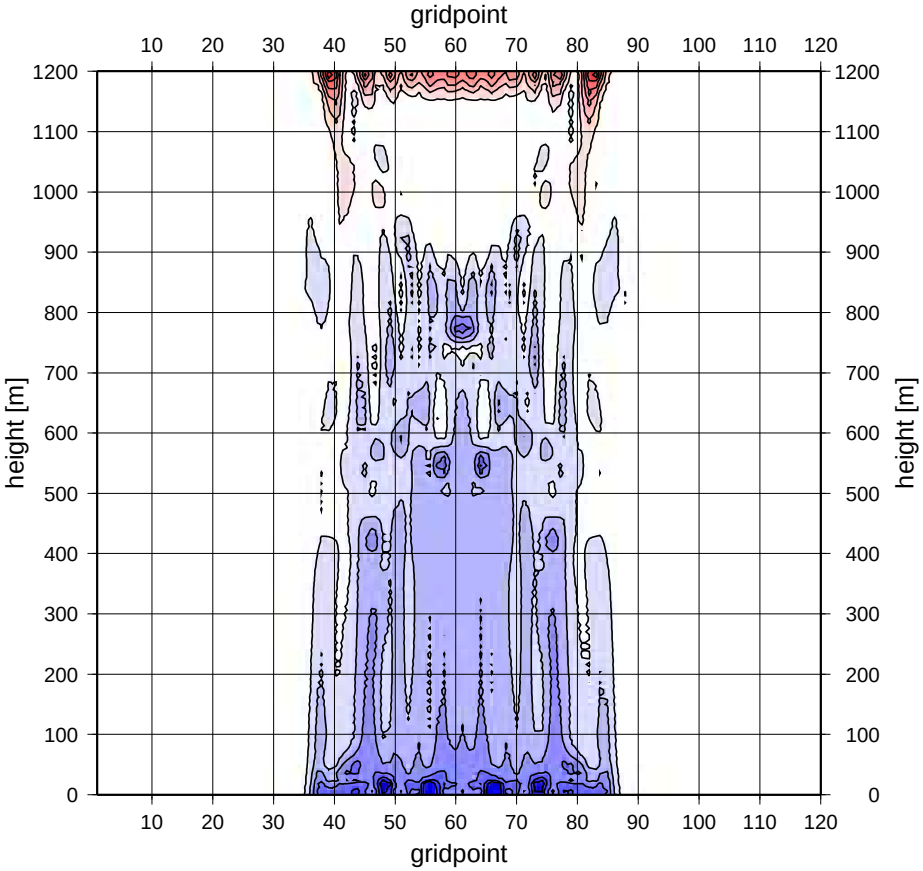
$\Delta x = 0.5\,\mathrm{km}$



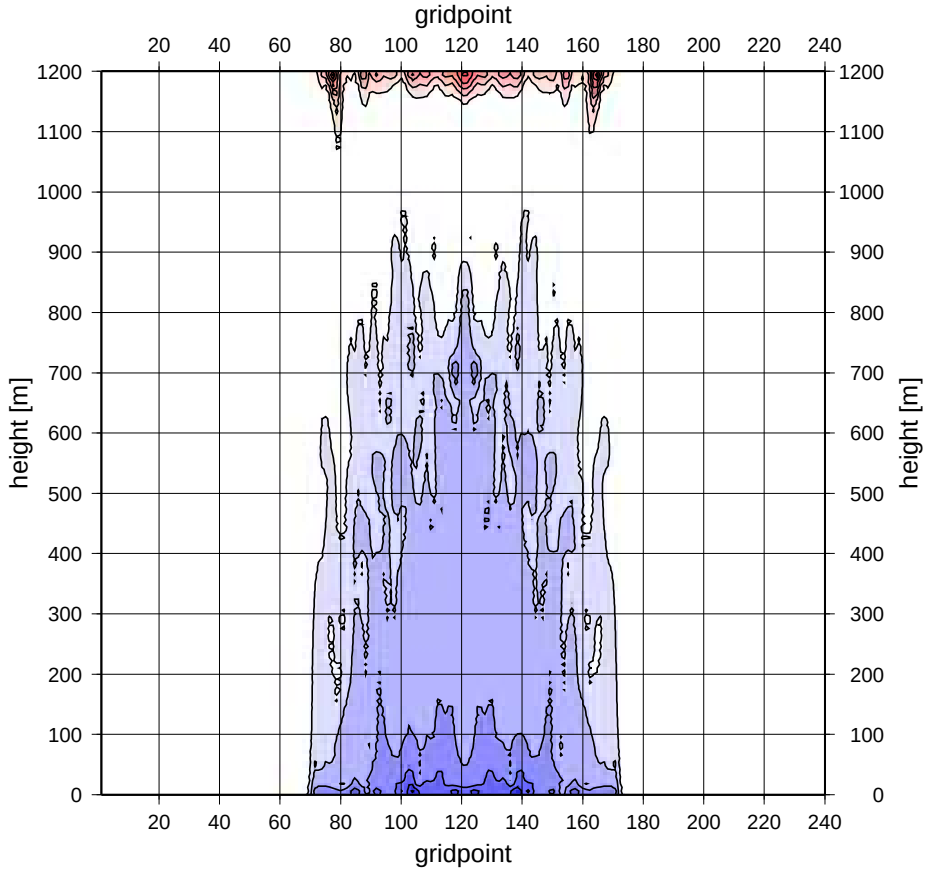
non-hydrostatic run, $t = 1\,\mathrm{h}$

perturbation of potential temperature $\theta - \overline{\theta}$

$\Delta x = 1\,\mathrm{km}$



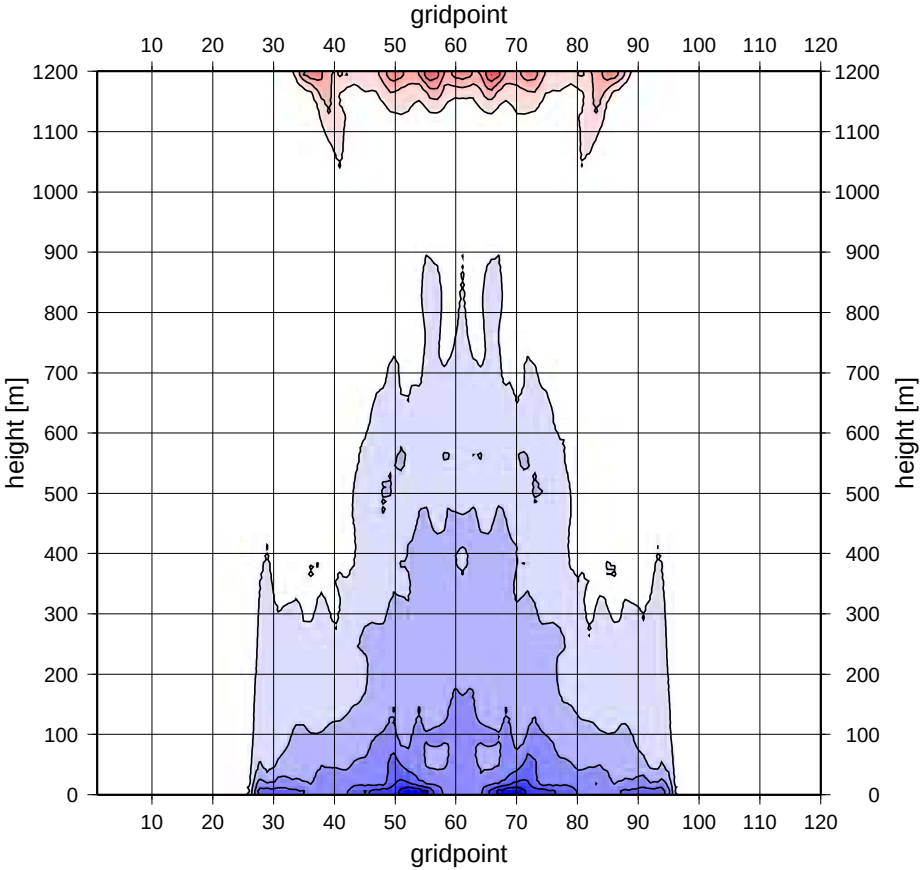
$\Delta x = 0.5\,\mathrm{km}$



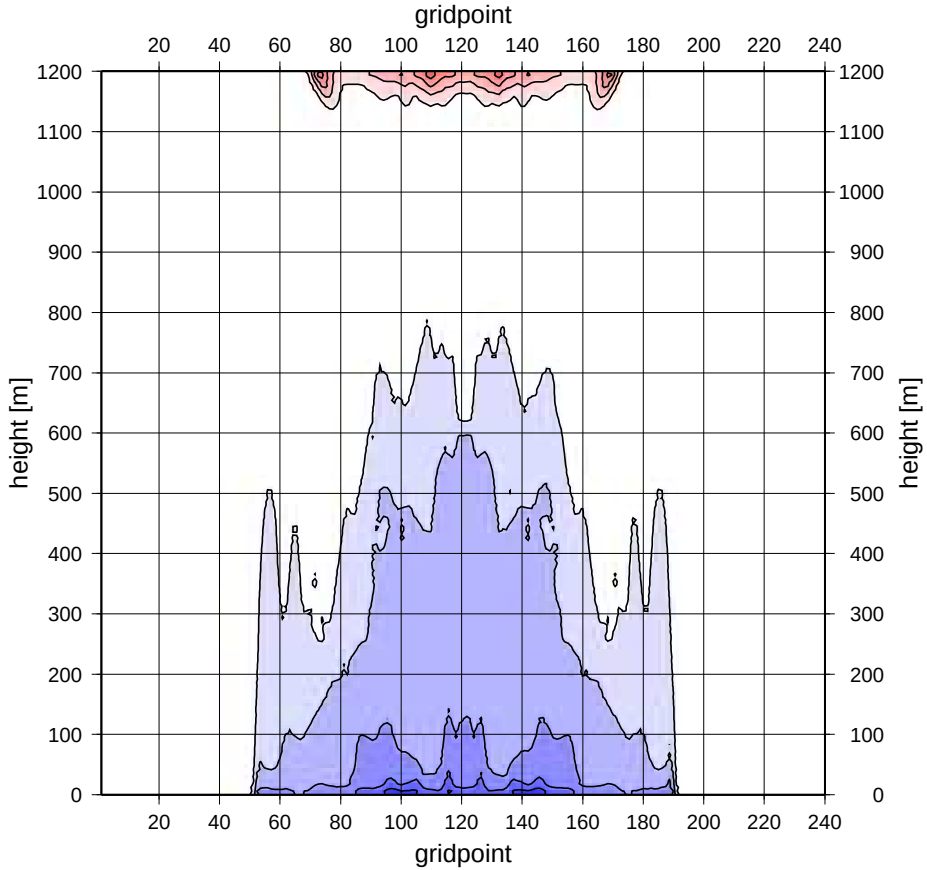
non-hydrostatic run, $t = 2\,\mathrm{h}$

perturbation of potential temperature $\theta - \overline{\theta}$

$\Delta x = 1\,\mathrm{km}$



$\Delta x = 0.5\,\mathrm{km}$



non-hydrostatic run, $t = 4\,\mathrm{h}$

Results for 1 versus 0.5 km horizontal resolution

- in NH simulation with halved horizontal mesh size cold bubble has stronger tendency to decay and speed up the descent

- it indicates that subgrid convective scales start to play important role at 1 km horizontal resolutions

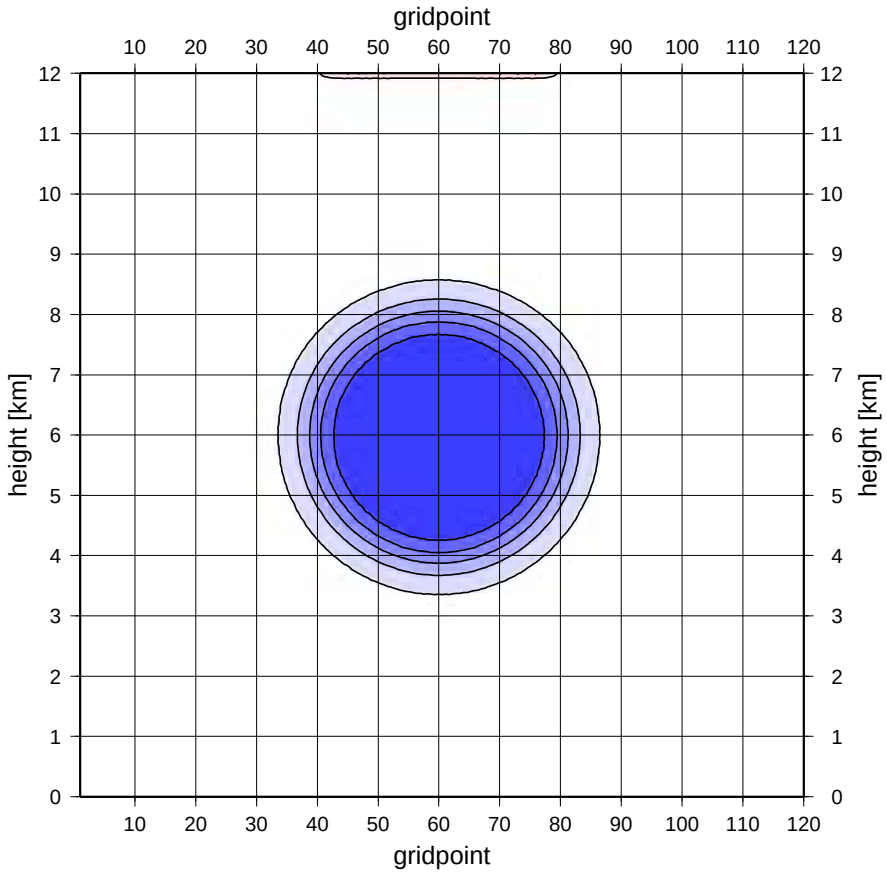
- explicit description of resolved convective scales becomes insufficient, it should be complemented with parameterization of subgrid convective scales

Does this all mean that NH model is not needed for convection at kilometric horizontal resolutions?

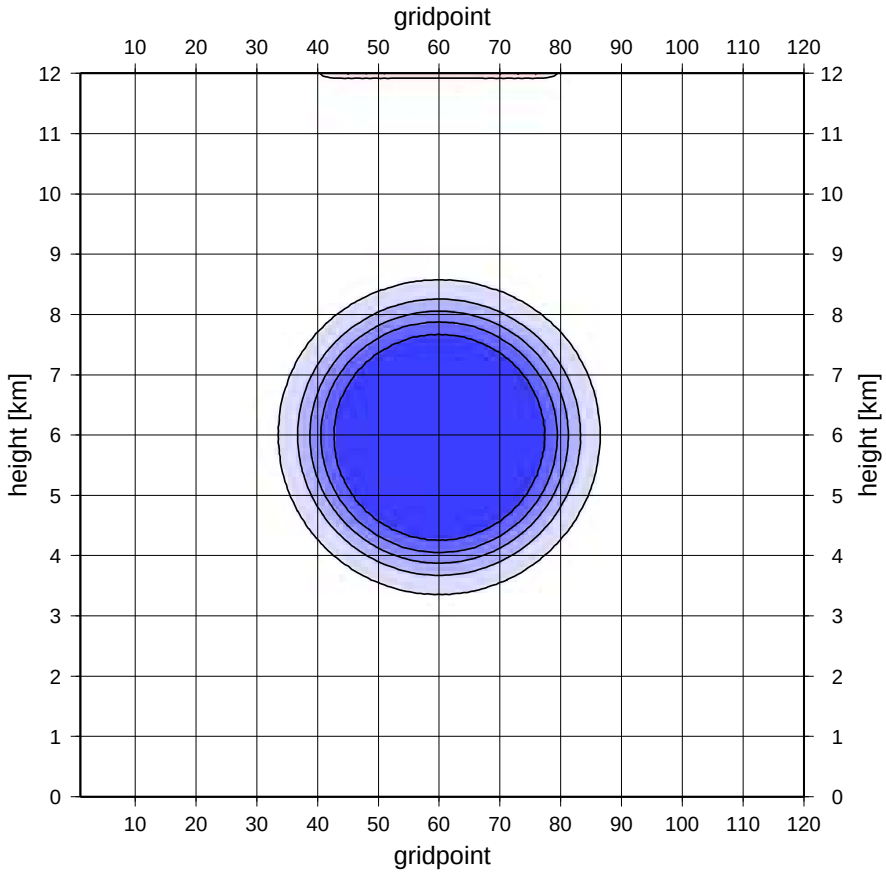
- it would be dangerous to base such strong statement on just few experiments
- other cases might exist where difference between H and NH simulations appears even at 1 km horizontal resolution
- one such case can be obtained by increasing vertical scale and using stronger perturbation in θ field:
  - domain extended vertically to 12 km, vertical mesh size increased to $\Delta z = 100\,\mathrm{m}$
  - elliptical initial bubble with $a = 15\,\mathrm{km}$ and $b = 1.5\,\mathrm{km}$ placed 6 km above ground
  - 10 times stronger perturbation in θ field ($\theta'_{\mathrm{max}} = -5\,\mathrm{K}$)
  - other settings unchanged

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



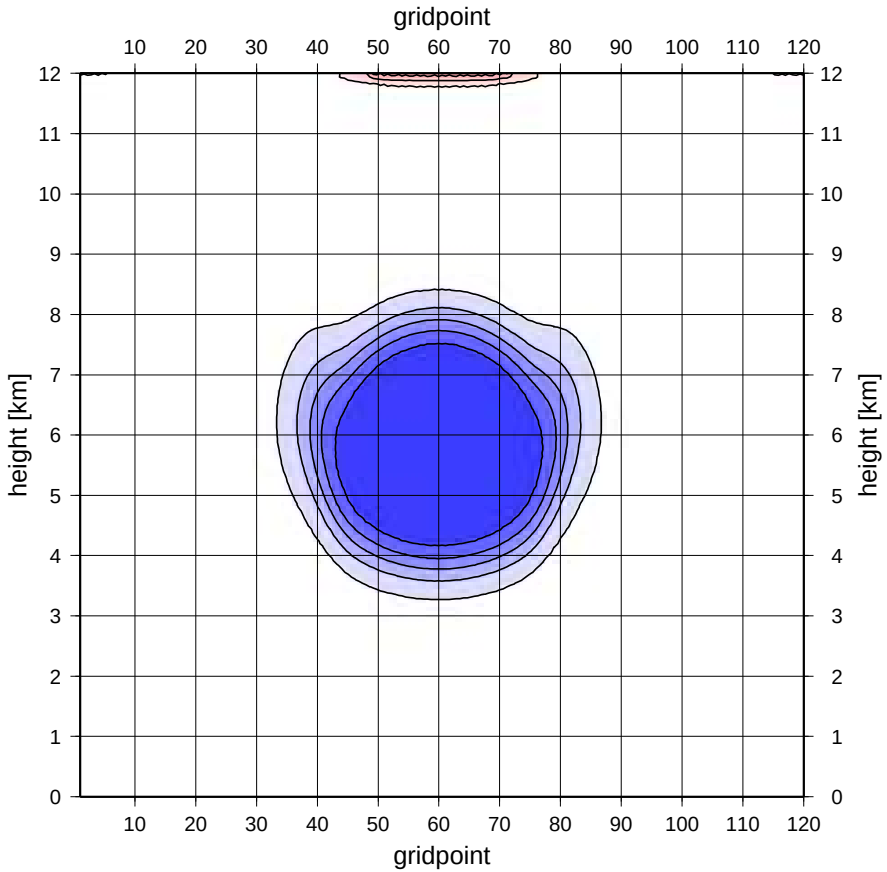
hydrostatic



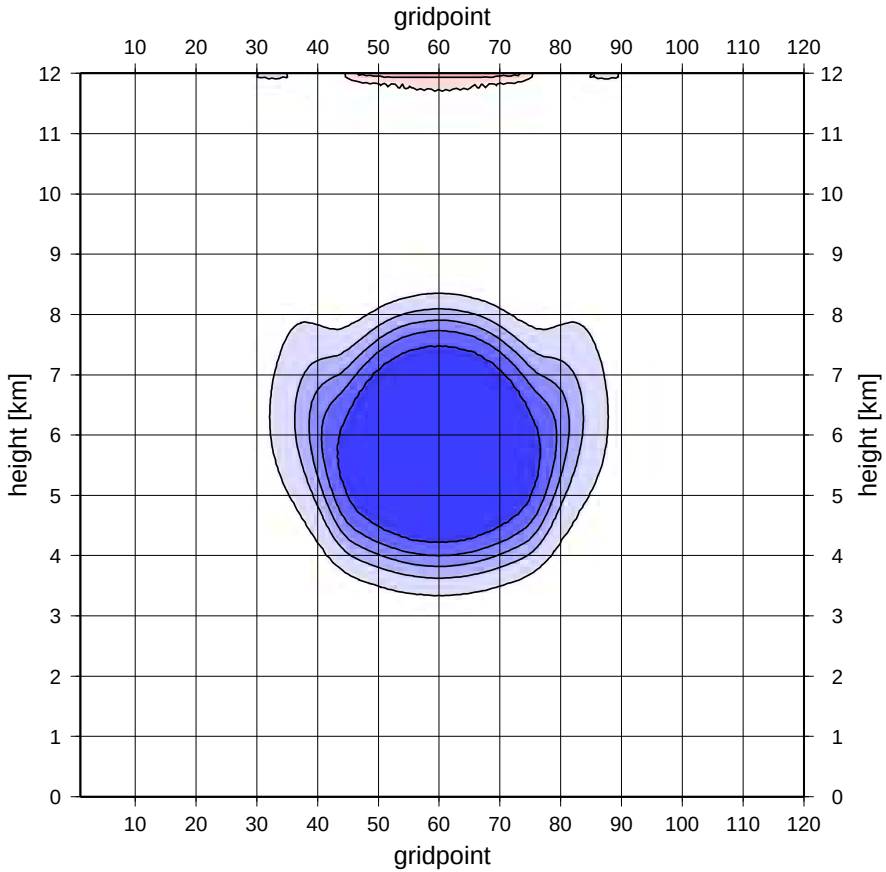
$\Delta x = 1\,\mathrm{km},\ t = 0\,\mathrm{min}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



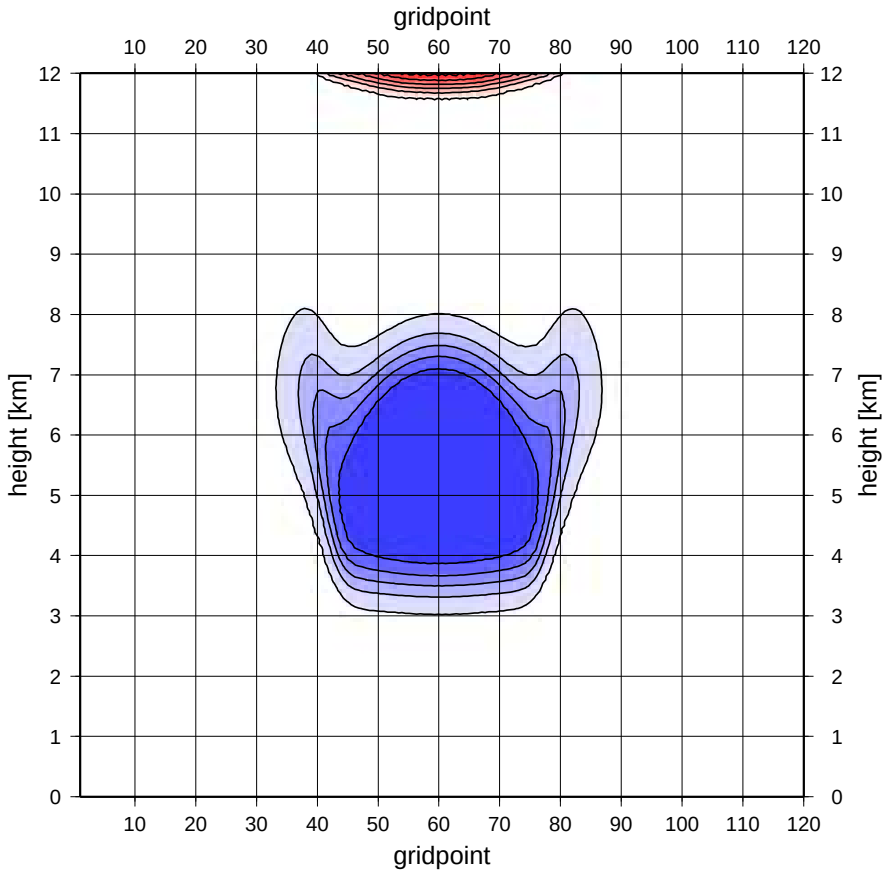
hydrostatic



$\Delta x = 1\,\mathrm{km},\ t = 4\,\mathrm{min}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



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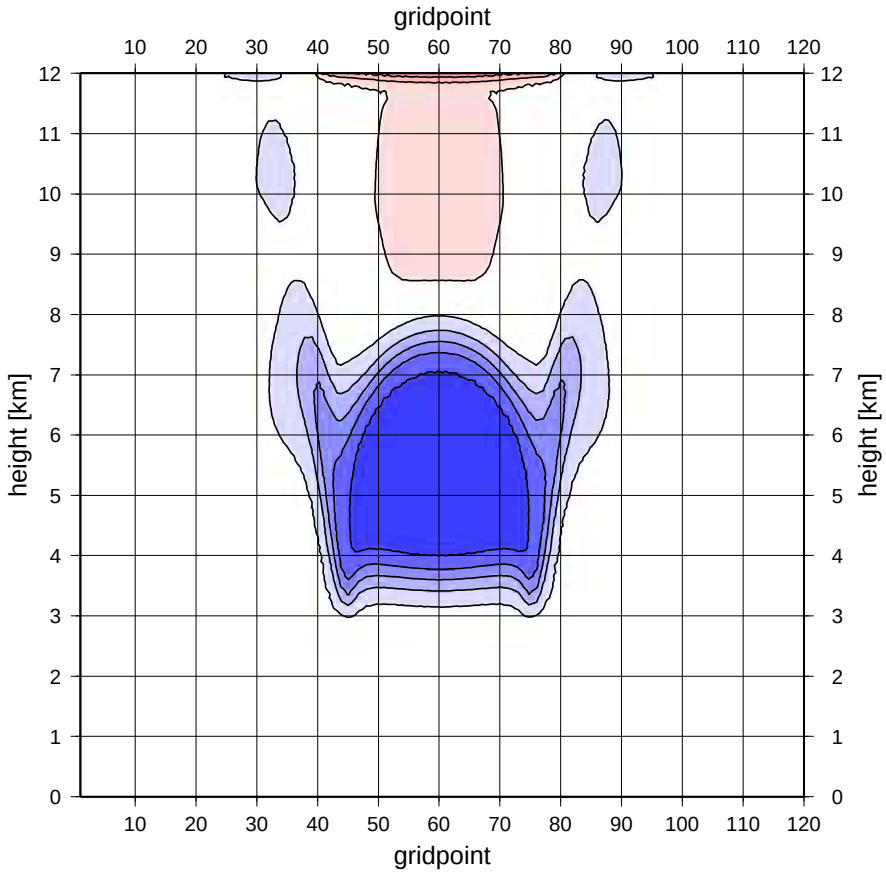
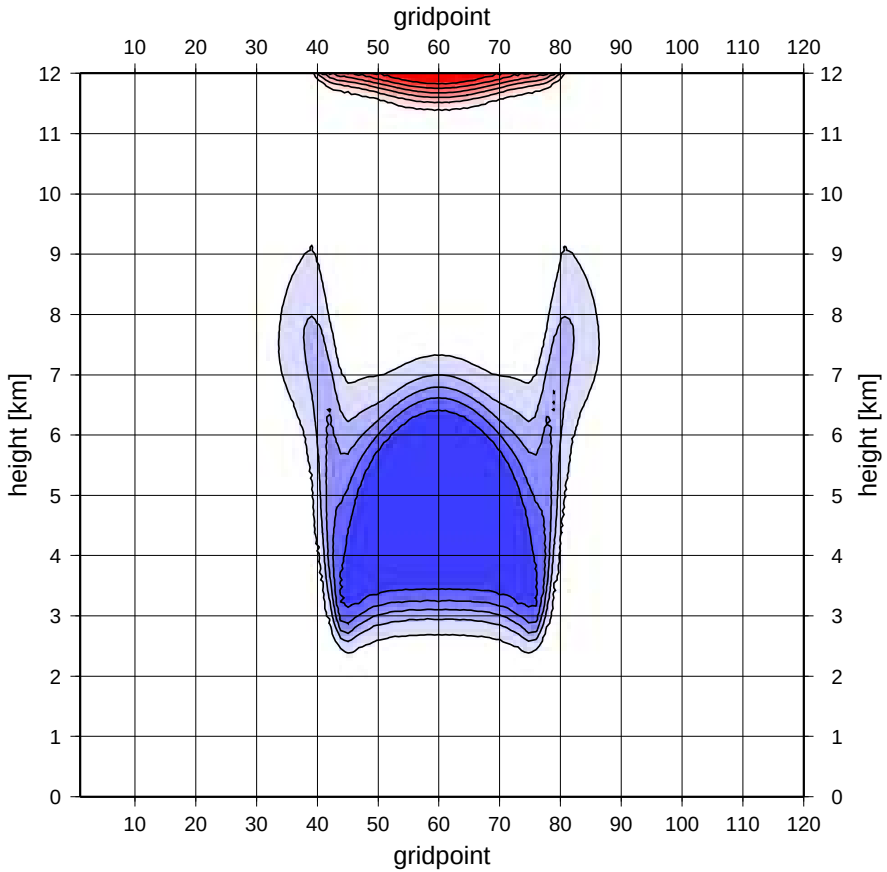


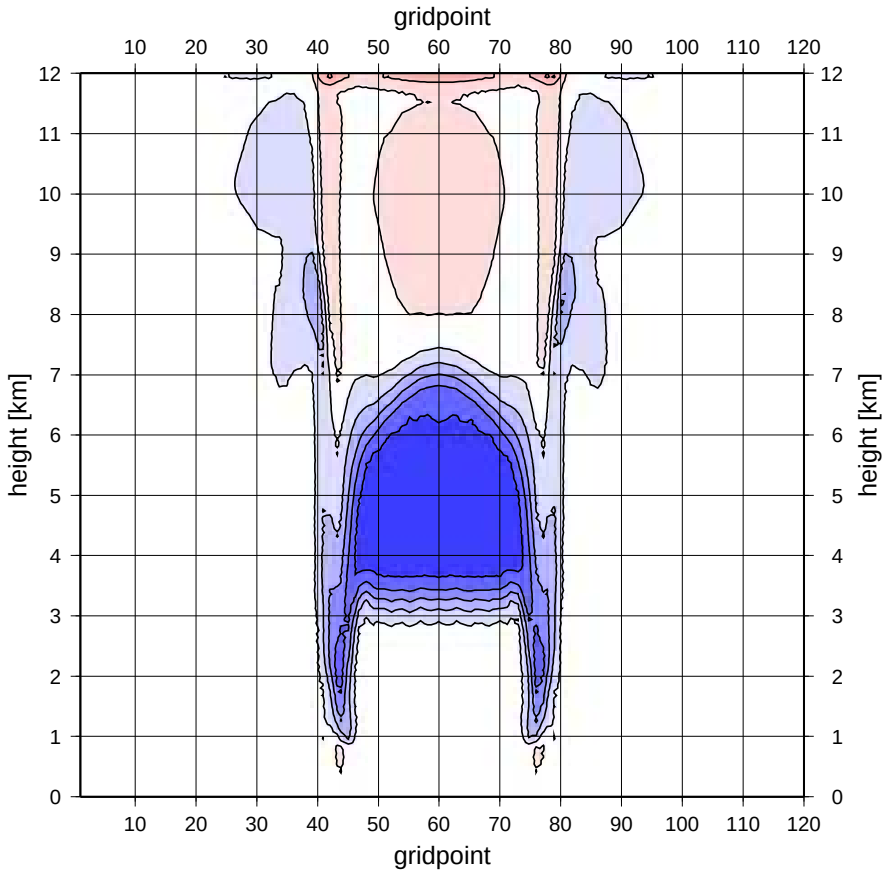
$\Delta x = 1\,\mathrm{km},\ t = 8\,\mathrm{min}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



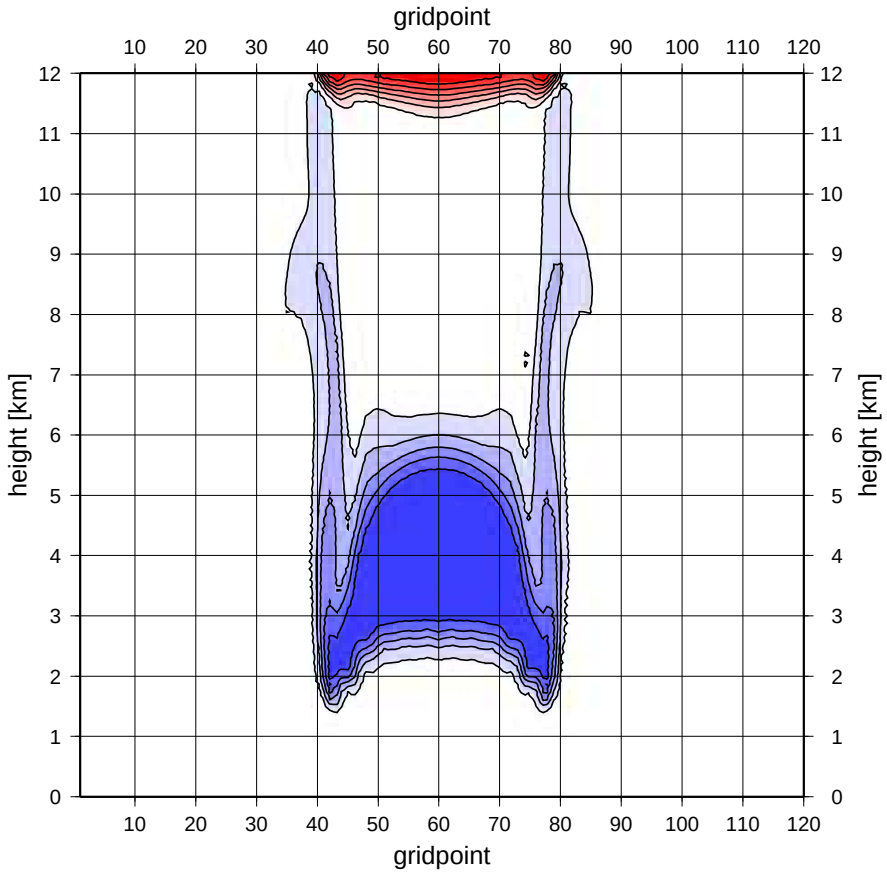
hydrostatic



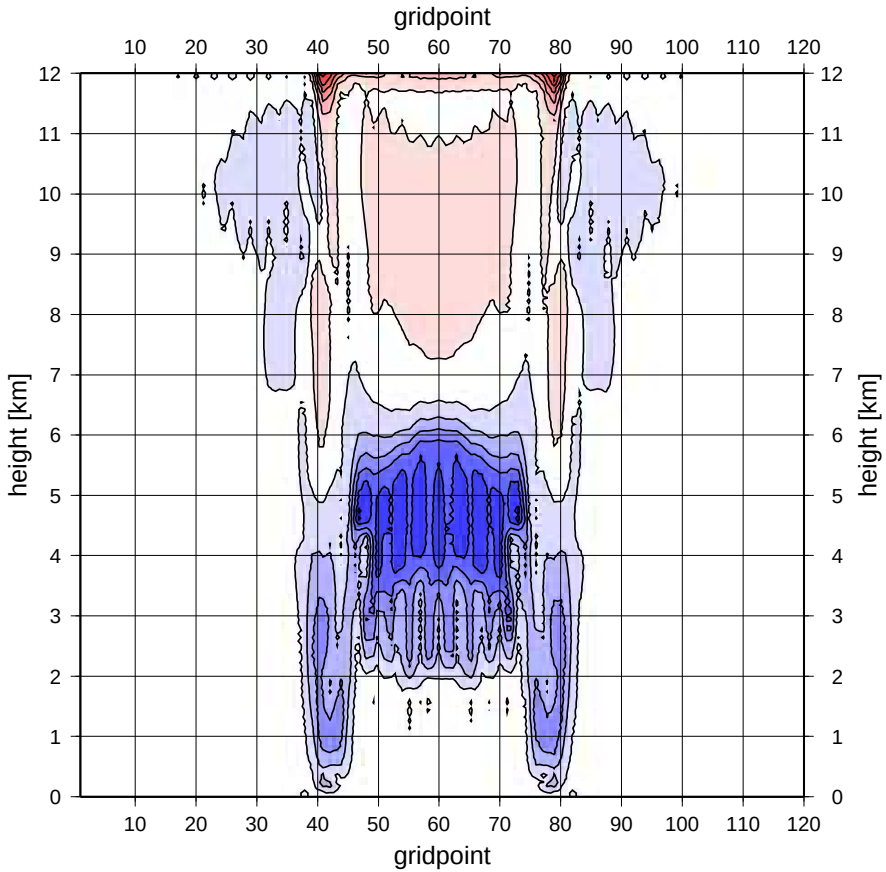
$\Delta x = 1\,\mathrm{km},\ t = 12\,\mathrm{min}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



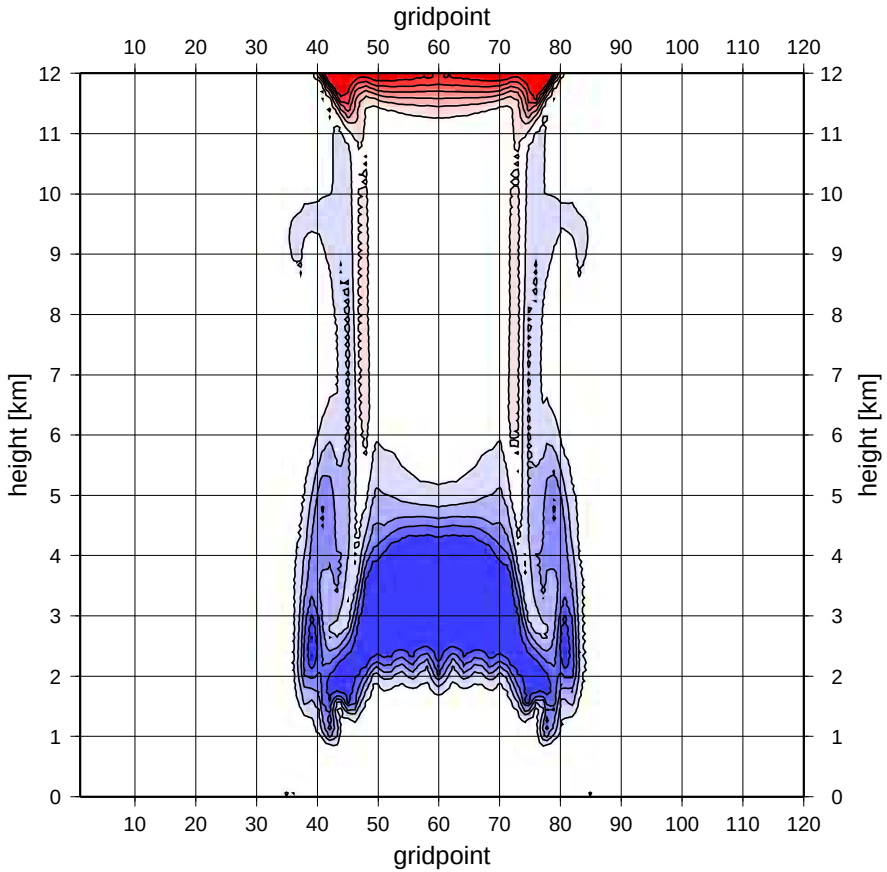
hydrostatic



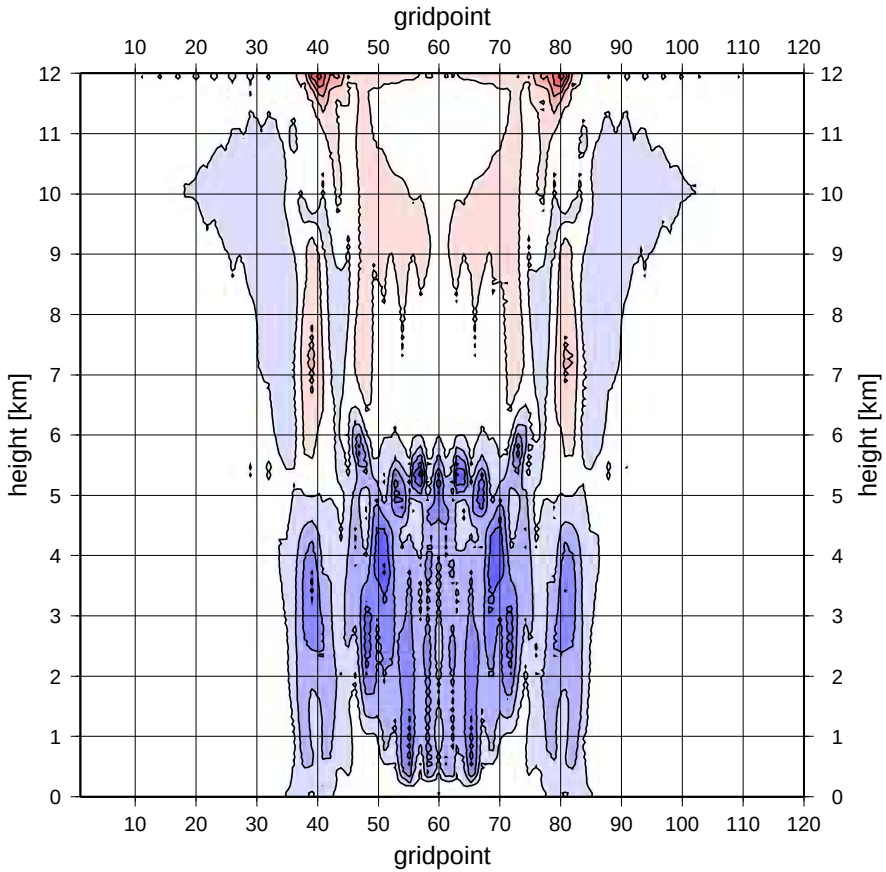
$\Delta x = 1\,\mathrm{km},\ t = 16\,\mathrm{min}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



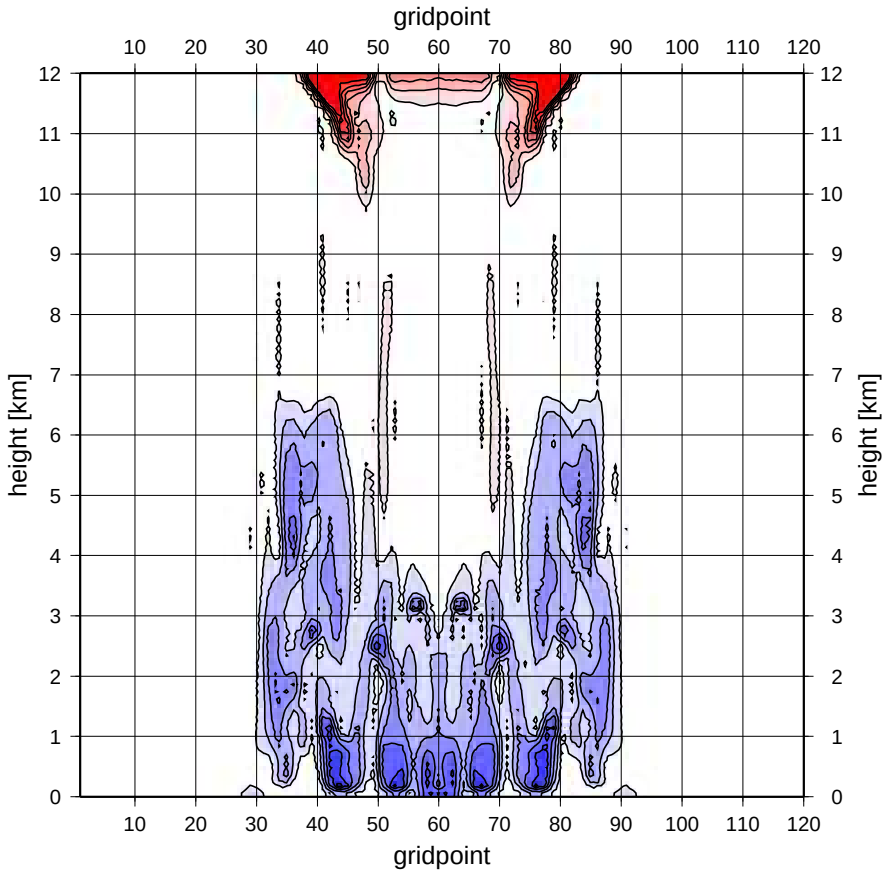
hydrostatic



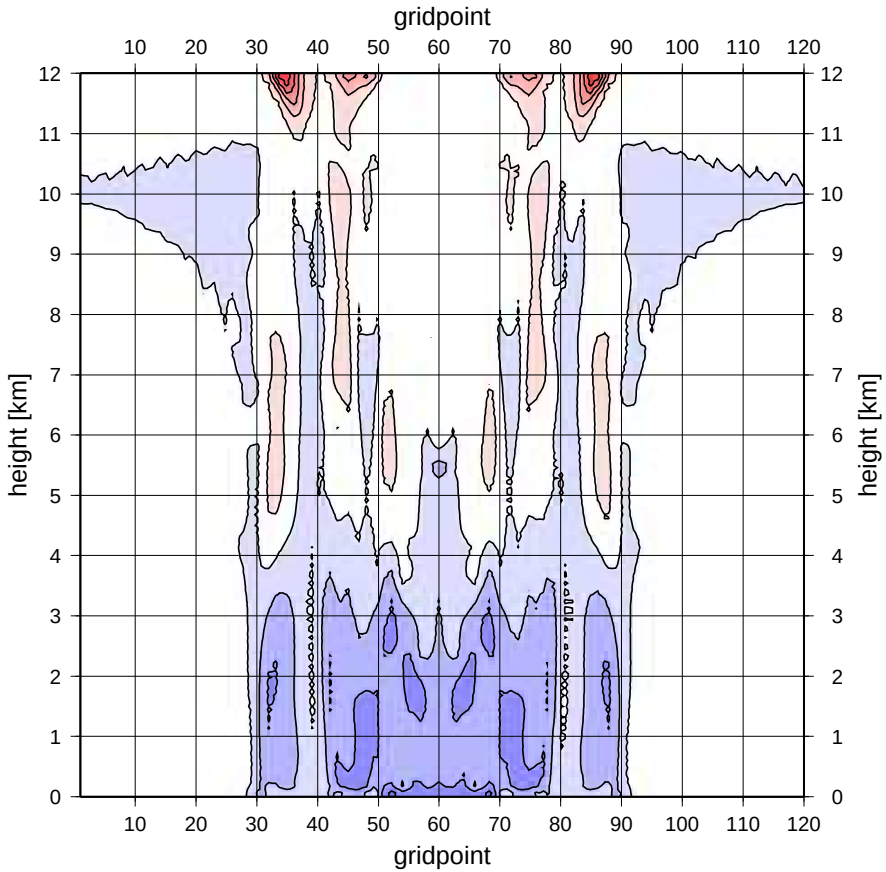
$\Delta x = 1\,\mathrm{km},\ t = 20\,\mathrm{min}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



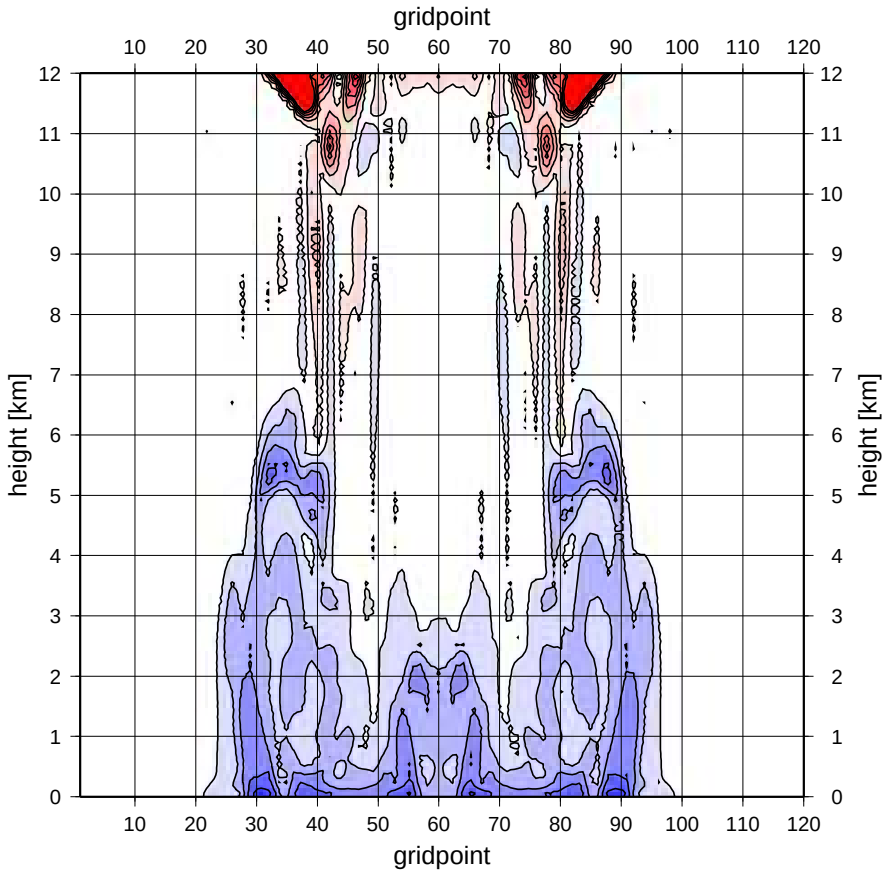
hydrostatic



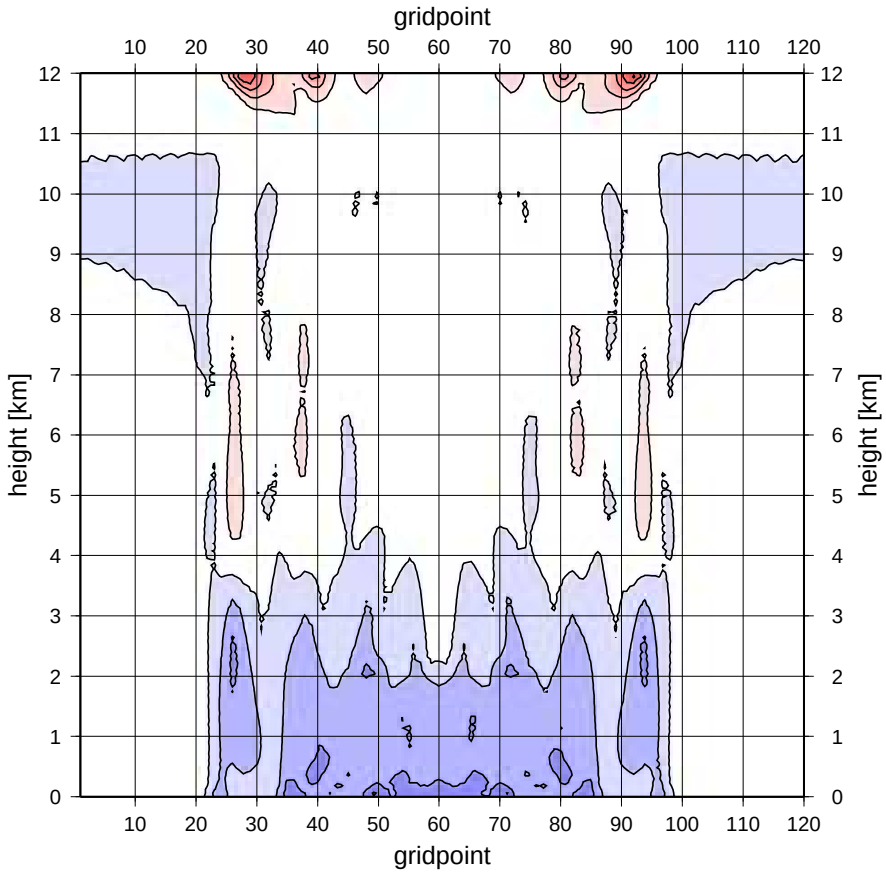
$\Delta x = 1\,\mathrm{km},\ t = 30\,\mathrm{min}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



hydrostatic



$\Delta x = 1\,\text{km},\ t = 40\,\text{min}$

Results for 1 km horizontal resolution with increased vertical scale

- in H simulation cold bubble descents faster, distorts and decays into smaller cells too early
- it seems that at kilometric resolutions correct description of convection still requires NH model
- however, it must be remembered that in both H and NH simulations interaction with subgrid convective scales was ignored
- in reality, cold bubble evolution would be strongly influenced by these scales
- one might argue that used initial state was too artificial, it would probably never evolve with convective parameterization turned on
- this fact reduces significance of the test for NWP

Conclusions

- results from restricted set of numerical experiments enable to draw only qualitative conclusions
- at lower horizontal resolutions, H and NH simulations give comparable results for explicit convection $\Rightarrow$ no need of NH model
- these results are sensitive to horizontal resolution increase, therefore it is necessary to parameterize effects of subgrid convective scales
- going to higher horizontal resolutions, difference between H and NH results increases $\Rightarrow$ NH model becomes compulsory
- at the same time, influence of subgrid convective scales becomes less important
- at very high resolutions, fully explicit description of convection should be possible with NH model