Idealized tests of ALADIN-NH dynamical kernel at very high resolution (comparison of H and NH versions)

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Presentation outline

Part I – basic facts about ALADIN-NH

- brief overview of current ALADIN-NH configuration
- important steps making this configuration possible
- future challenges

Part II – idealized 2D simulations

- orographic flow $\Rightarrow$ robustness of ALADIN-NH dynamical kernel
- dry convection $\Rightarrow$ limitations of hydrostatic approximation

Part I – basic facts about ALADIN-NH

Current ALADIN-NH configuration (1)

- fully compressible system
- mass based hybrid eta coordinate
- two additional prognostic variables derived from NH pressure departure and vertical divergence:

$$\hat{q} = \ln\left(\frac{p}{\pi}\right) \qquad d_4 = d_3 + X$$

$$\pi - \text{hydrostatic pressure},\ d_3 = \frac{\partial w}{\partial z},\ X = -\frac{\partial \mathbf{v}}{\partial z} \cdot \nabla_\eta z$$

- representation of fields:

horizontal	spectral	(unstaggered grid)
vertical	finite difference	(Lorenz type staggering)

- 2TL timestepping with SL advection

Current ALADIN-NH configuration (2)

- ICI scheme (Iterated Centered Implicit) using SI model as preconditioner
- resting isothermal SI background leading to solver with constant coefficients
- recomputation of SL trajectories in each iteration
- possibility of truly 2TL scheme (i.e. non-extrapolating)

Steps towards current configuration (1)

Starting line for listed developments was first ALADIN-NH version, finished in 1994 (3TL SI scheme with iteration of X-term, Eulerian advection). Attempts to implement SL advection faced instability, which was particularly severe for 2TL scheme. Problem was solved in several steps during period 1999–2005:

- choice of NH prognostic variables $\widehat{q}, d_3$ based on linear stability analysis $\Rightarrow$ removal of some instabilities related to imperfect SI background
- relaxation of angular momentum conservation $\Rightarrow$ removed instability rising from inconsistent formulation of linear and non-linear models
- introduction of prognostic variable $d_4 = d_3 + X \Rightarrow$ reduced orographic instability in non-linear model
- ICI scheme $\Rightarrow$ further stabilisation of non-linear model, making it sufficiently robust for operational use

Steps towards current configuration (2)

- relaxation of SI operator by introducing concept of acoustic background temperature ⇒ removed thermal instability for SL2TL SI scheme

- advection of w ⇒ removal of SL chimney, clean bubble simulations

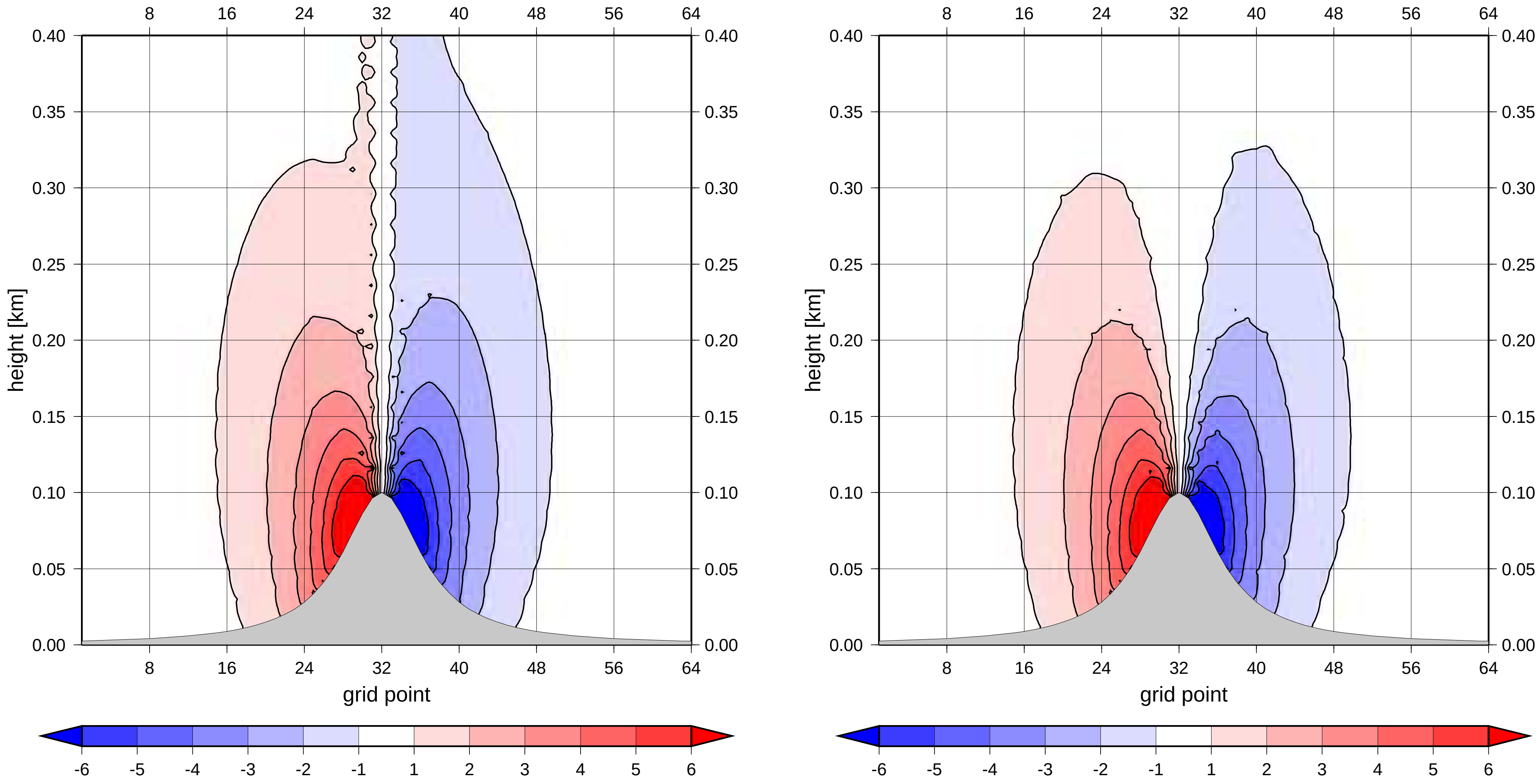
- diagnostic BBC ⇒ removal of SL chimney, achieved more consistently with ALADIN-NH code design

- SLHD scheme (Semi-Lagrangian Horizontal Diffusion) ⇒ removal of HD chimney by replacing spectral diffusion applied on $d_{3,4}$ with gridpoint one

All these steps led to final goal – sufficiently robust and accurate SL2TL ICI scheme with only one iteration needed.

ALADIN slang – SL chimney (1)

non-linear potential flow, vertical velocity w

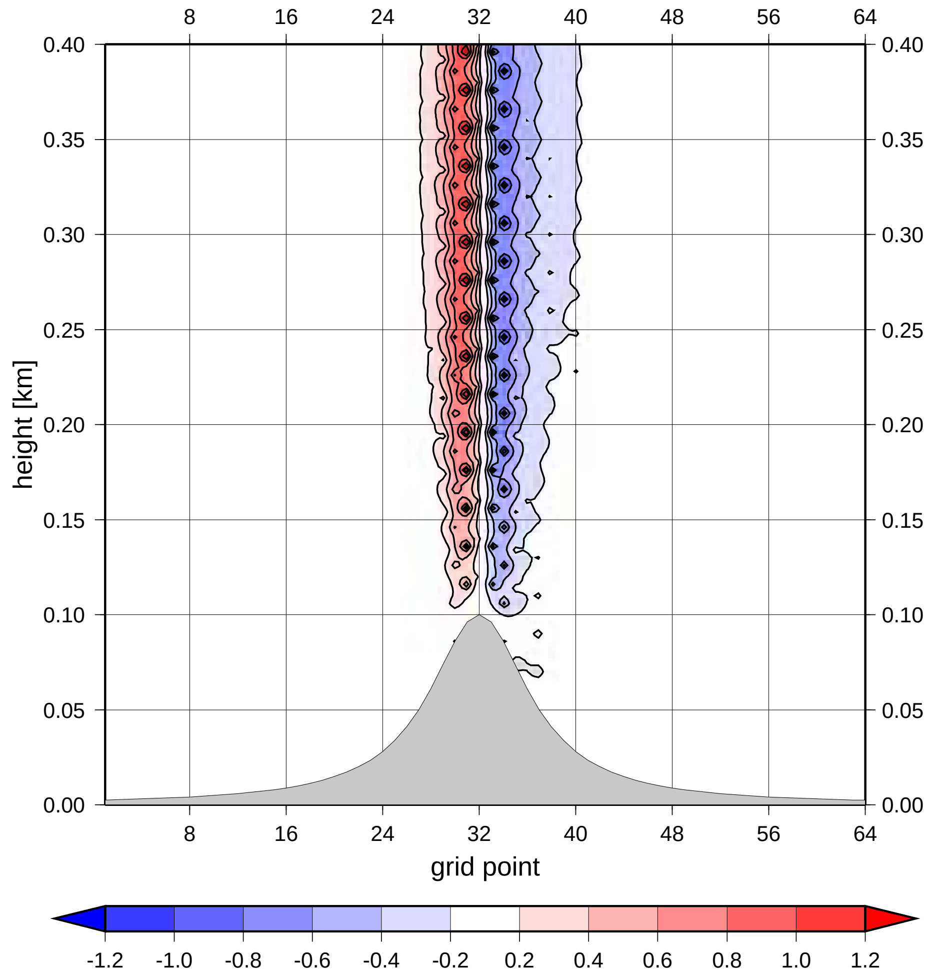


SL2TL

SL2TL, diagnostic BBC

ALADIN slang – SL chimney (2)

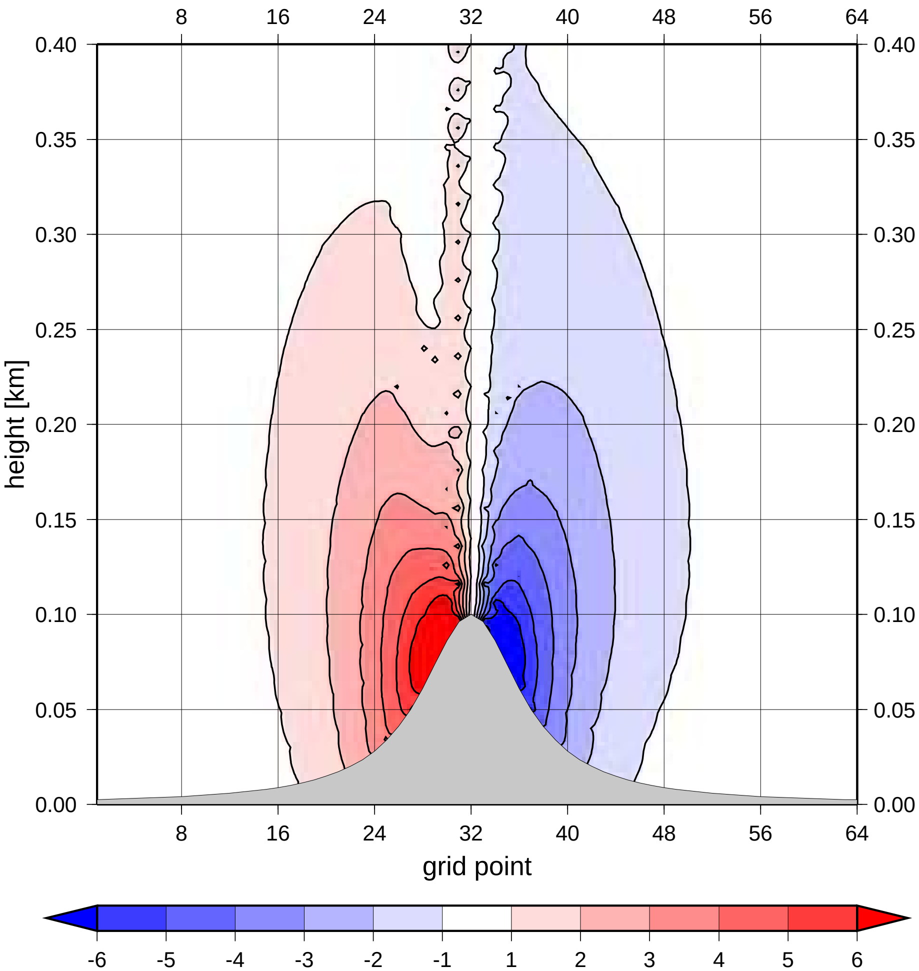
vertical velocity difference (left minus right)



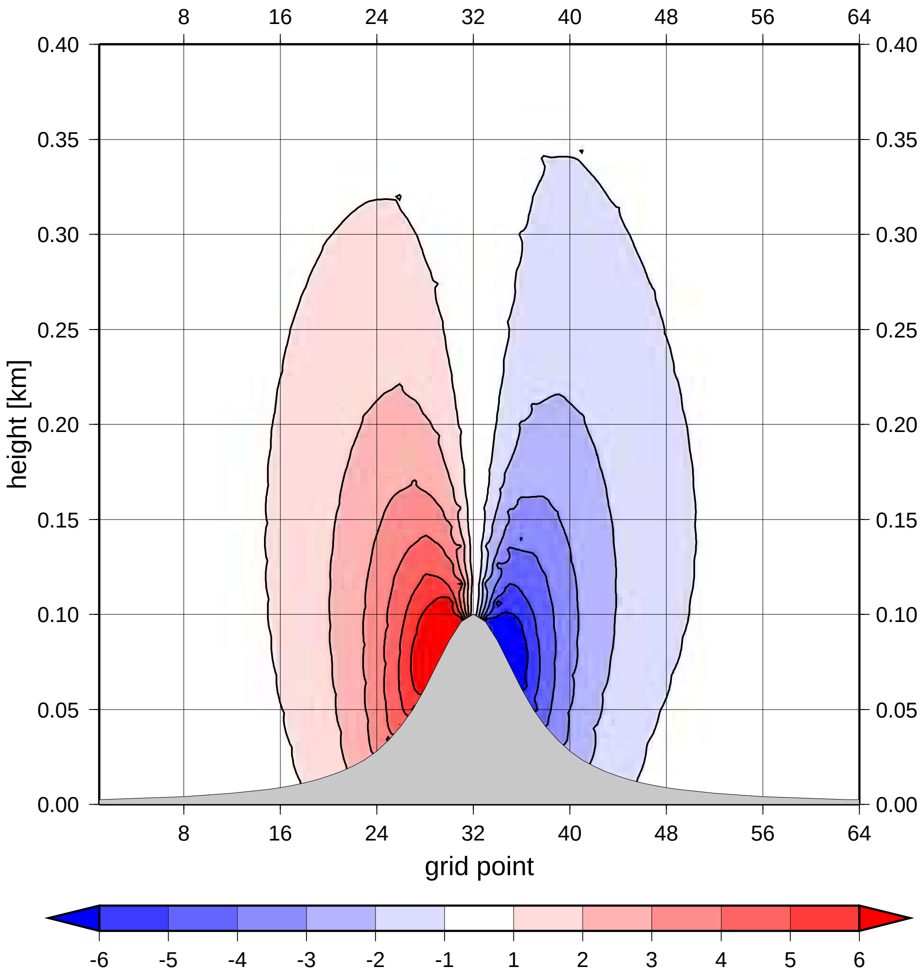
SL chimney unmasked

ALADIN slang – HD chimney (1)

non-linear potential flow, vertical velocity w



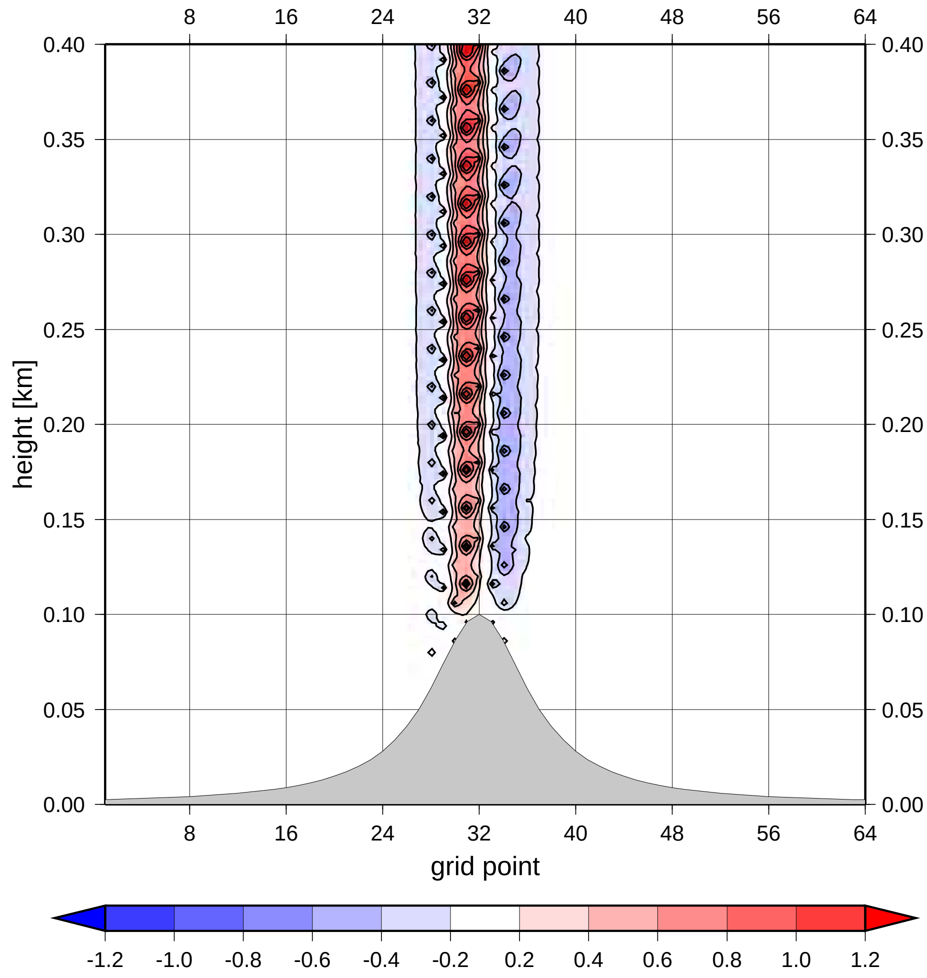
SL2TL, diagnostic BBC, HD



SL2TL, diagnostic BBC, HD*

ALADIN slang – HD chimney (2)

vertical velocity difference (left minus right)



HD chimney unmasked

Future challenges

- more transparent lateral boundary treatment – what can be achieved in spectral model? (not strictly NH problem)

- bottom boundary treatment consistent with diabatic tendencies – after SL and HD chimneys, will we face also Φ-sics one?

- non-reflective upper boundary condition – RUBC or something else?

- performance above steep orography – any bad surprises hidden? (common topic with HIRLAM)

- advection of w – yes or no? (currently implemented only for SL2TL non-extrapolating scheme)

- vertical finite element discretization – will it make ALADIN-NH dynamical kernel usable for ECMWF? (common topic with HIRLAM)

Part II – idealized 2D simulations

Case 1 – orographic flow

Model robustness will be demonstrated using non-linear potential flow. Reasons for this choice were following:

- purely NH regime (only trapped waves, excluded from H solution)
- strong orographic forcing, non-linear response
- analytical solution can be constructed iteratively
- simple enough solution, easier detection of model deficiencies
- little sensitivity to treatment of upper and lateral boundaries

Experimental setup

- background state: $$\begin{aligned} \bar{T} &= 239\,\text{K} \quad (\text{isothermal, } \bar{N} = 0.02\,\text{s}^{-1}) \\ \bar{\pi}_S &= 101\,325\,\text{Pa} \\ \bar{u} &= 15\,\text{m}\,\text{s}^{-1} \quad (\text{constant wind}) \end{aligned}$$

- bell shaped mountain: $$\begin{aligned} a &= 100\,\text{m (halfwidth)} \\ h &= 100\,\text{m (height)} \end{aligned}$$

- resolution: $$\begin{aligned} \Delta x &= 20\,\text{m, quadratic truncation} \\ \Delta z &= 20\,\text{m} \end{aligned}$$

- stationary final state obtained by short integration ($t = 200\,\text{s}$) with time constant LBC

Basic ALADIN-NH configuration

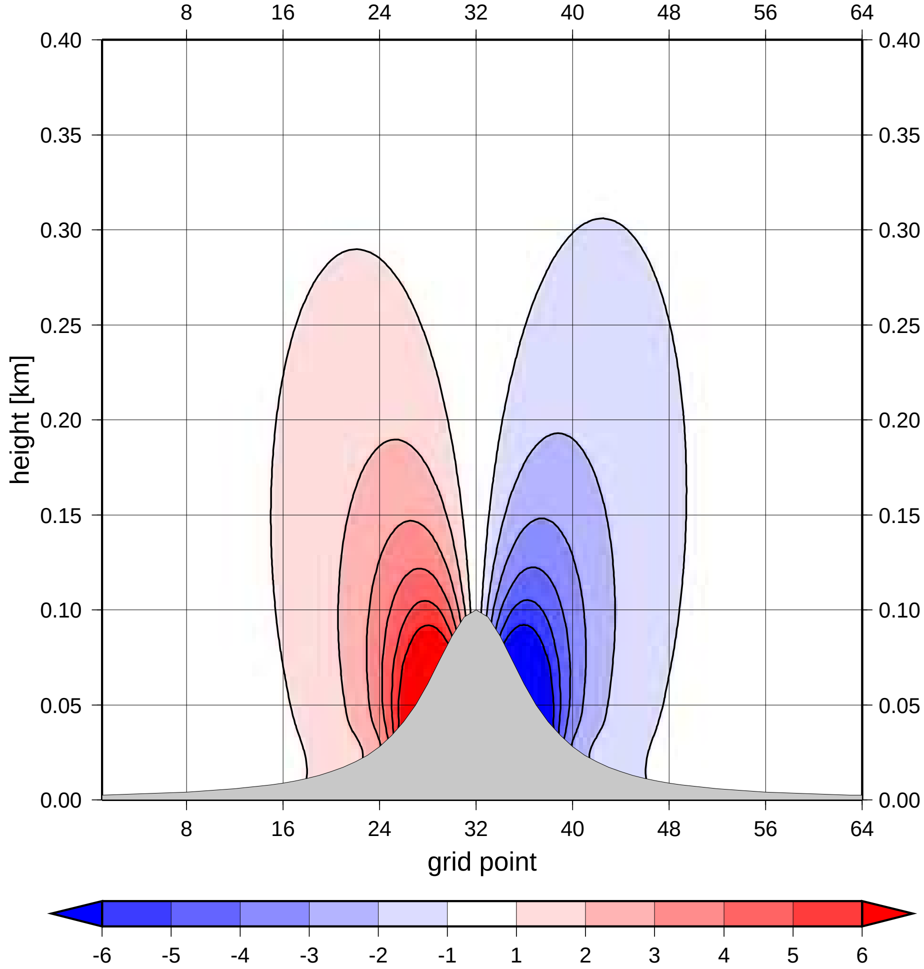
- non-extrapolating SL2TL ICI scheme with 1 iteration
- SI background: $\begin{aligned} T^* &= 300\,\mathrm{K} \\ T_a^* &= 100\,\mathrm{K} \\ \pi_S^* &= 90\,000\,\mathrm{Pa} \end{aligned}$
- timestep $\Delta t = 1.0\,\mathrm{s}$
- prognostic variable d_4
- diagnostic BBC
- diffusion of SLHD type
- lateral coupling with background state, sponge

Aspects to be tested

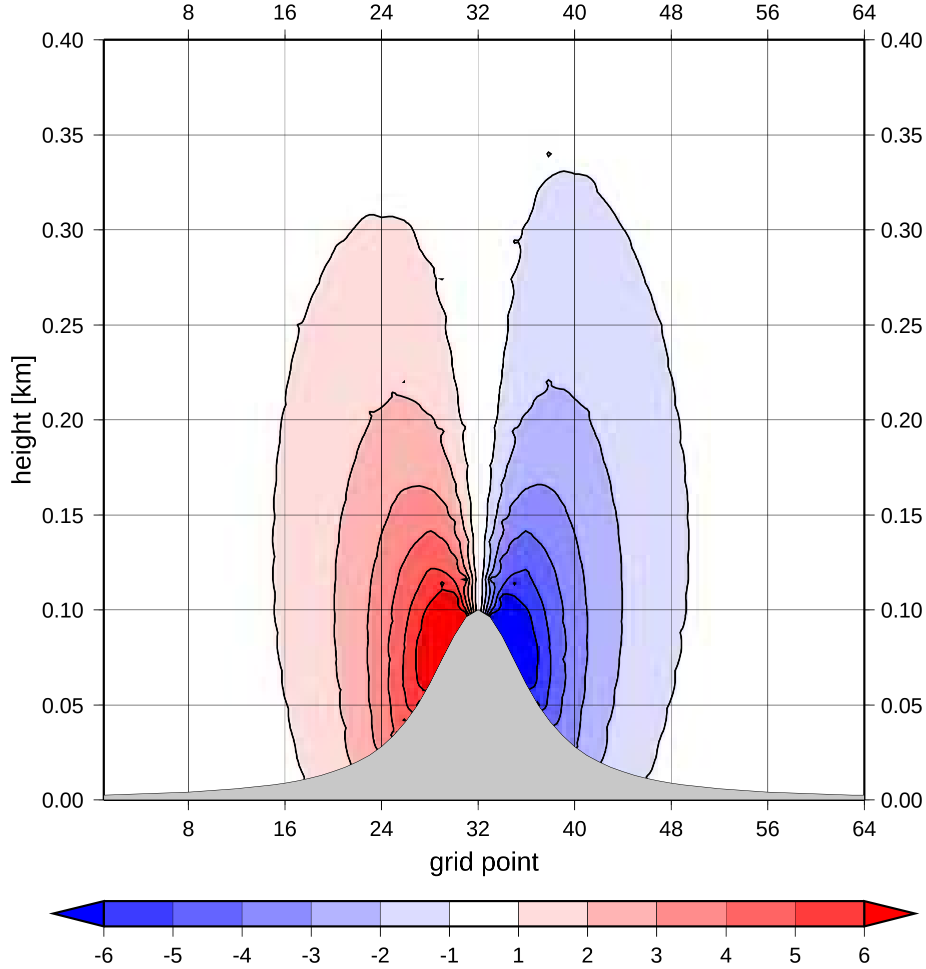
- stability and accuracy, behaviour for long timesteps
- impact of prognostic variable d_4
- impact of acoustic background temperature T_a^*

Stability and accuracy versus timestep (1)

vertical velocity w



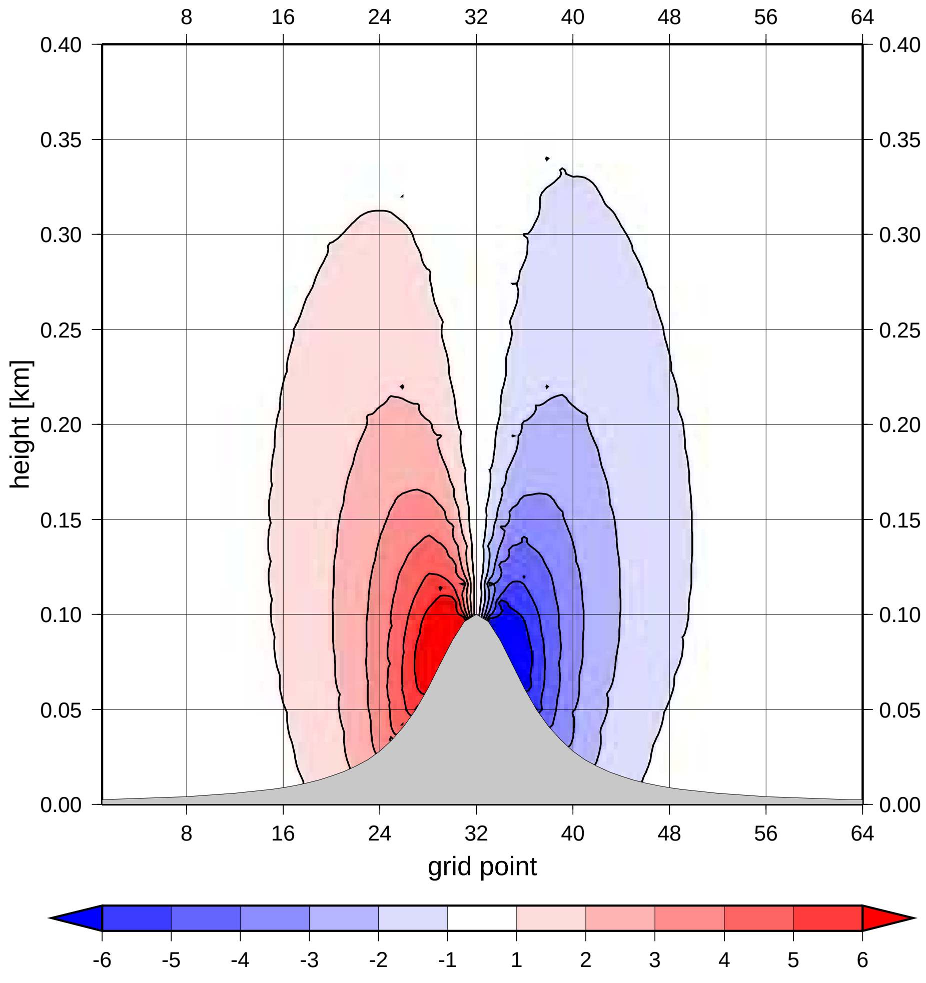
analytical solution



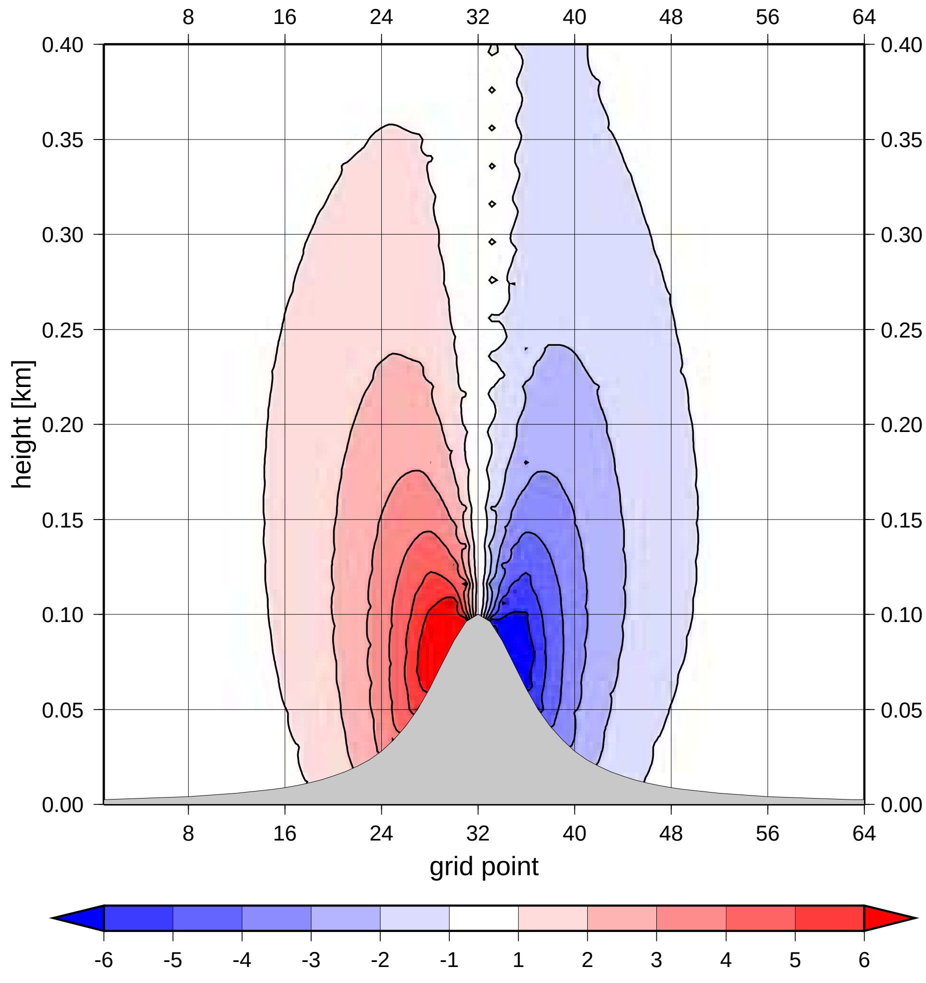
$\Delta t = 0.2\,\mathrm{s}$ (CFL $= 0.6$)

Stability and accuracy versus timestep (2)

vertical velocity w



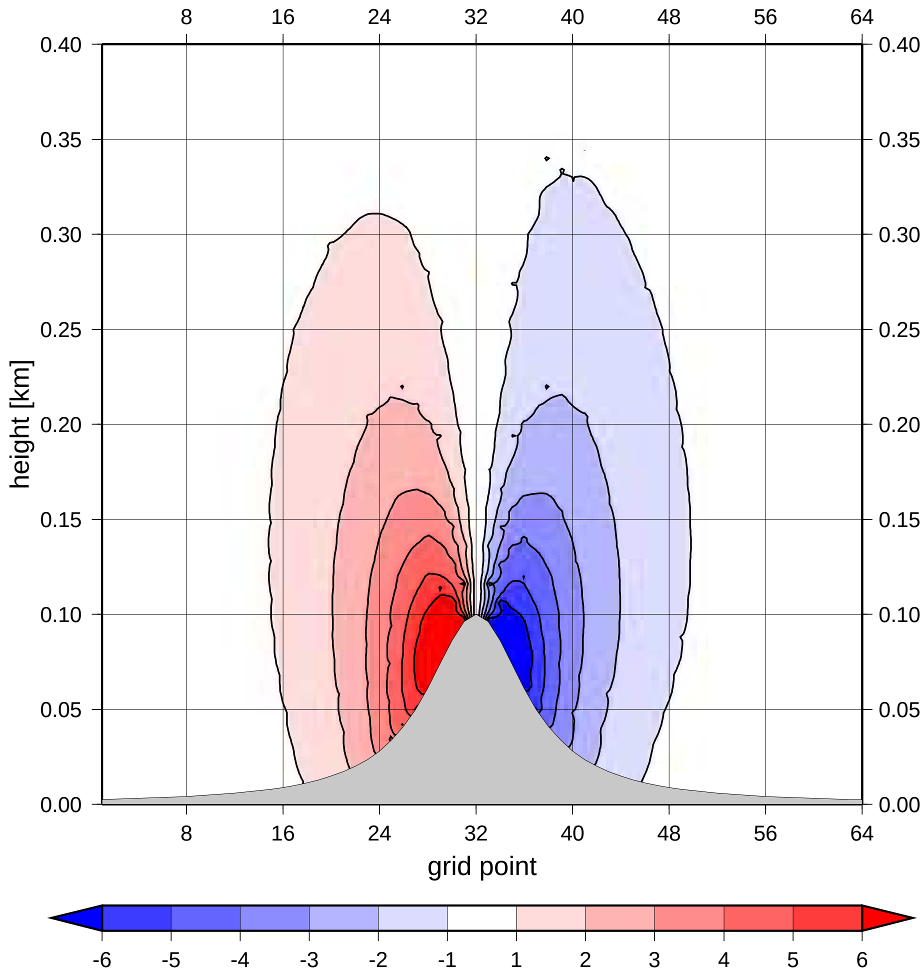
$\Delta t = 1.0\,\mathrm{s}$ (CFL = 3.0)



$\Delta t = 2.0\,\mathrm{s}$ (CFL = 5.6)

Impact of prognostic variable d_4

vertical velocity w

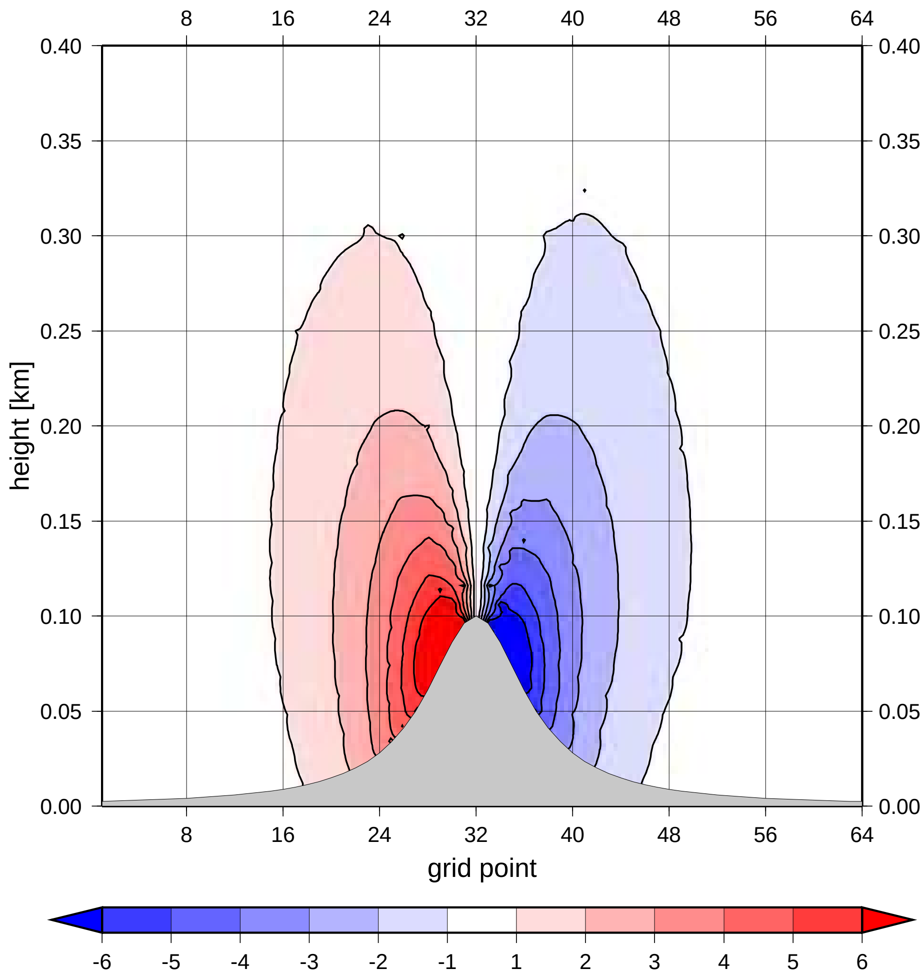


d_3, 3 iterations (CFL = 3.0)

variable d_3 requires 3 iterations to become stable

Impact of acoustic background temperature T_a^*

vertical velocity w



SL2TL SI (CFL = 3.0)

without T_a^*, SL2TL SI scheme blows after 9 timesteps

with T_a^*, SL2TL SI scheme is stable

Summary for the case 1

- tested ALADIN-NH configuration proved to be sufficiently accurate and stable
- there is little sensitivity to timestep length, response to orographic forcing is acceptable up to CFL ≈ 5
- for ICI scheme with 1 iteration, prognostic variable d_4 is necessary to remove orographic instability
- acoustic background temperature T_a^* removes thermal instability for SL2TL SI scheme, its importance diminishes for ICI scheme
- no detrimental effects of non-extrapolating scheme were detected

Case 2 – dry convection

Why convective case?

- convection is driven by local imbalance between buoyancy and gravity, which is non-hydrostatic effect
- comparison of H and NH simulations at different resolutions enables to limit validity of hydrostatic approximation
- explicit convection is very sensitive numerical test

Complications:

- analytical solution is not known
- advection of w had to be used to get clean solution

Common experimental setup

- resting initial state $(u, w = 0)$ with horizontally constant surface pressure $\pi_S = 101\,325\,\mathrm{Pa}$

- neutral background stratification with $\bar{\theta} = 300\,\mathrm{K}$

- cold bubble perturbation in initial θ field $(\theta = \bar{\theta} + \theta')$

- flat orography

- horizontally periodic domain, no coupling

Simulations at 10 m horizontal resolution

- domain 1.2×1.2 km, additional 30 layers at the top with isothermal stratification

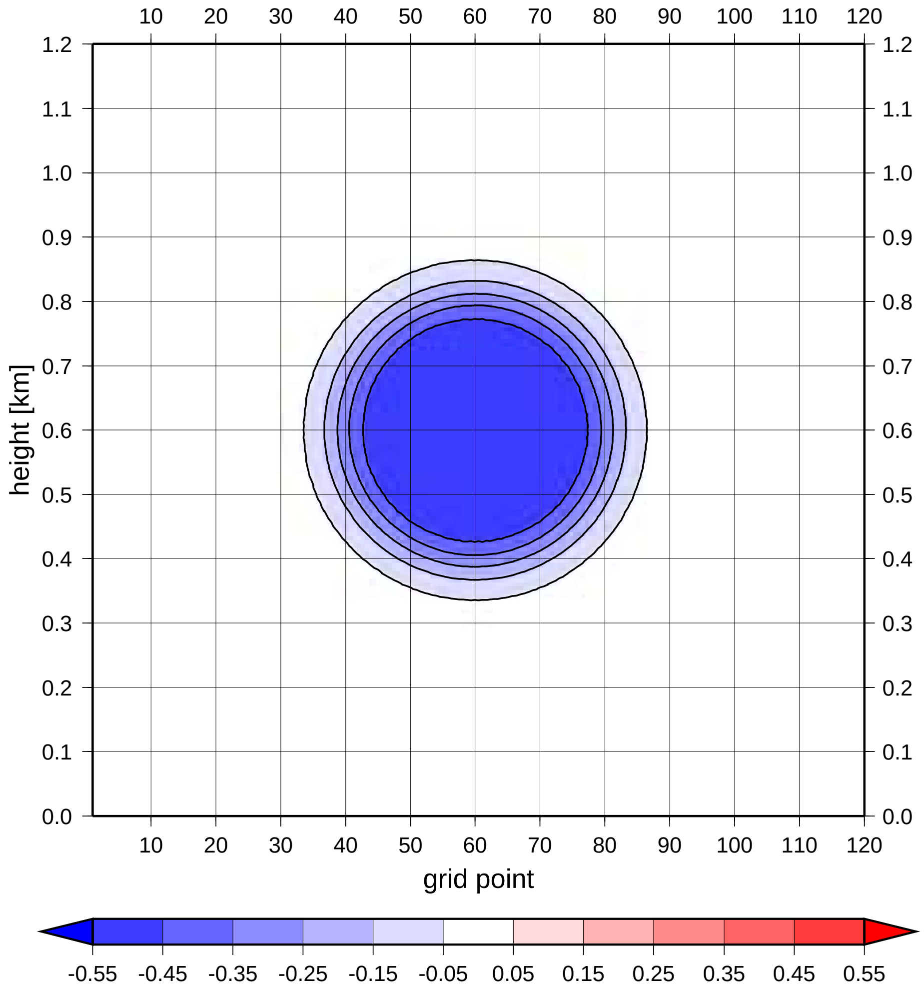
- resolution: $\Delta x = 10$ m, quadratic truncation
  $\Delta z = 10$ m

- circular bubble with $r = 150$ m and $\theta'_{\text{max}} = -0.5$ K placed 600 m above ground

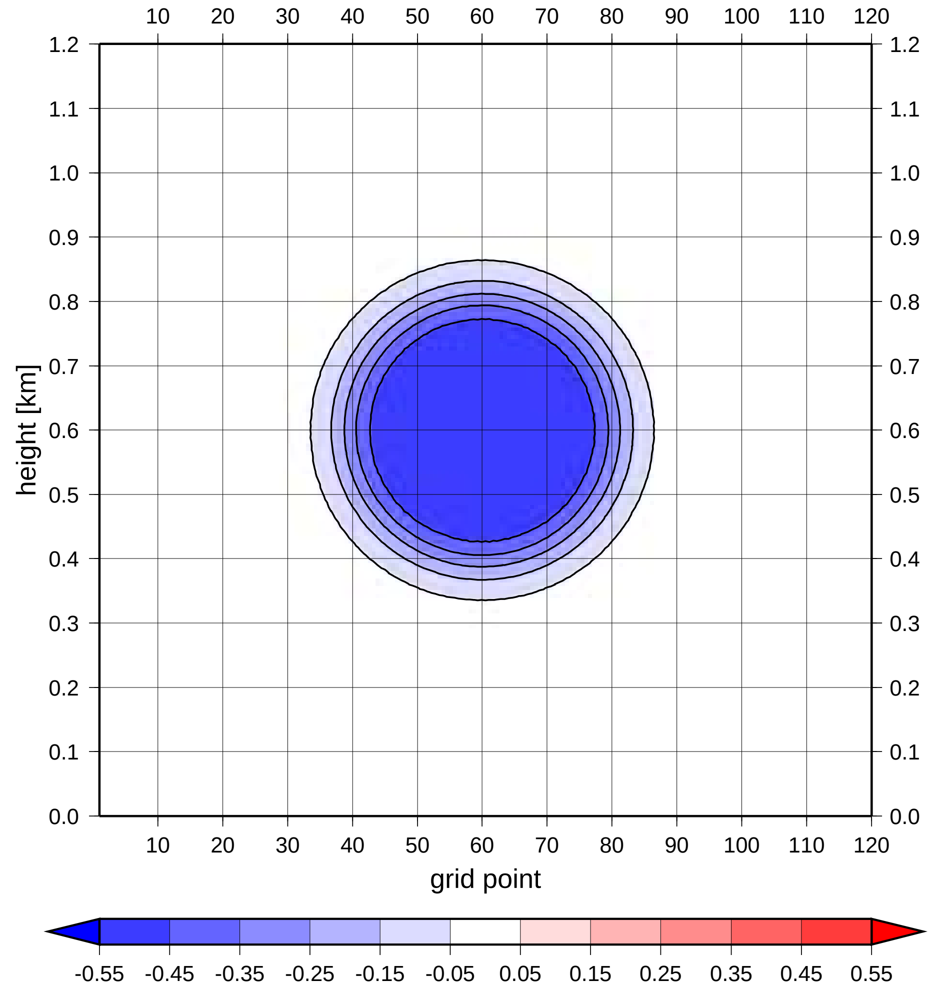
- ALADIN configuration as in case 1, except:
  - timestep $\Delta t = 0.4$ s
  - diagnostic BBC replaced by advection of w
  - hydrostatic simulations with extrapolating SL2TL SI scheme

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

hydrostatic

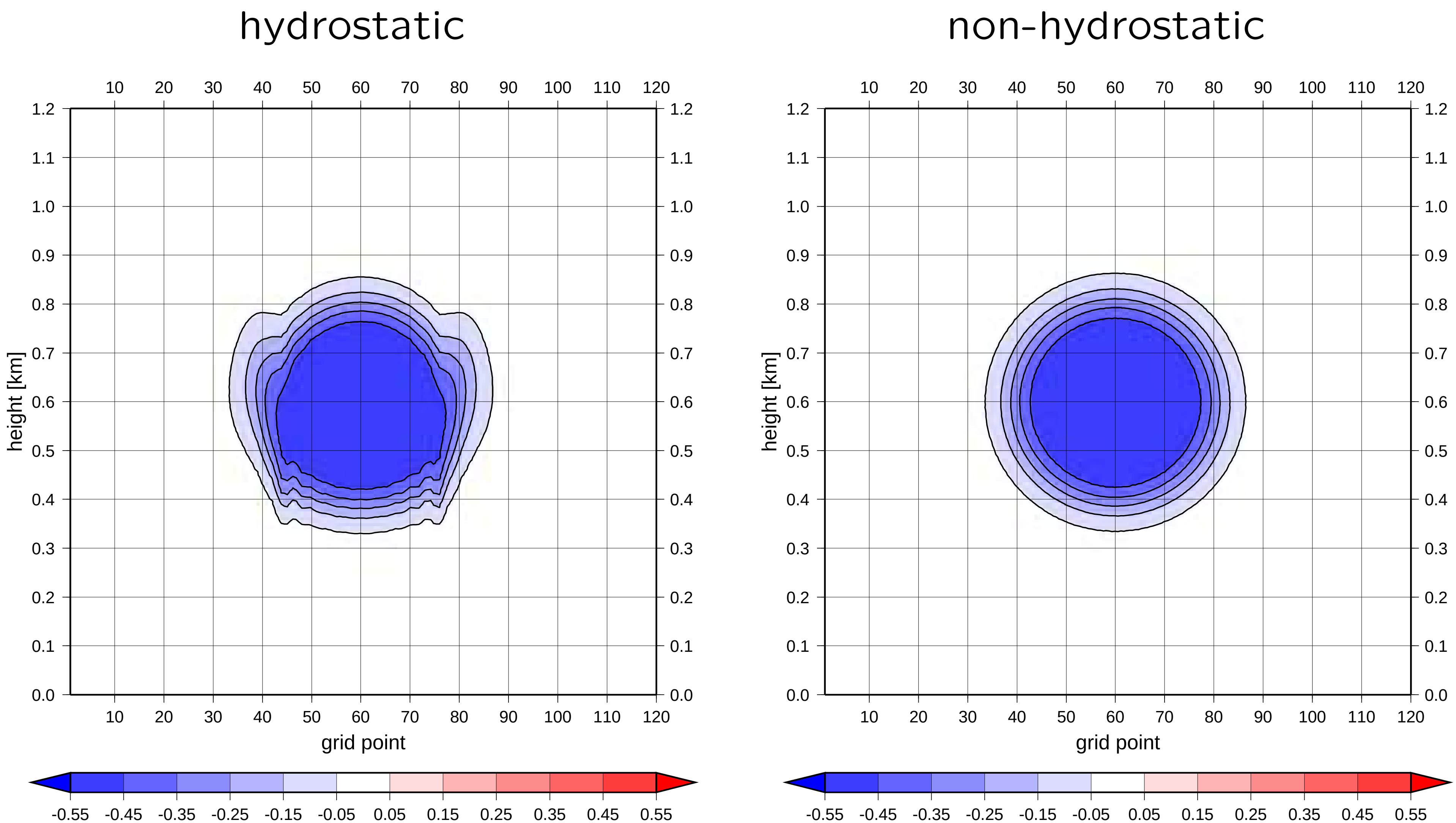


non-hydrostatic



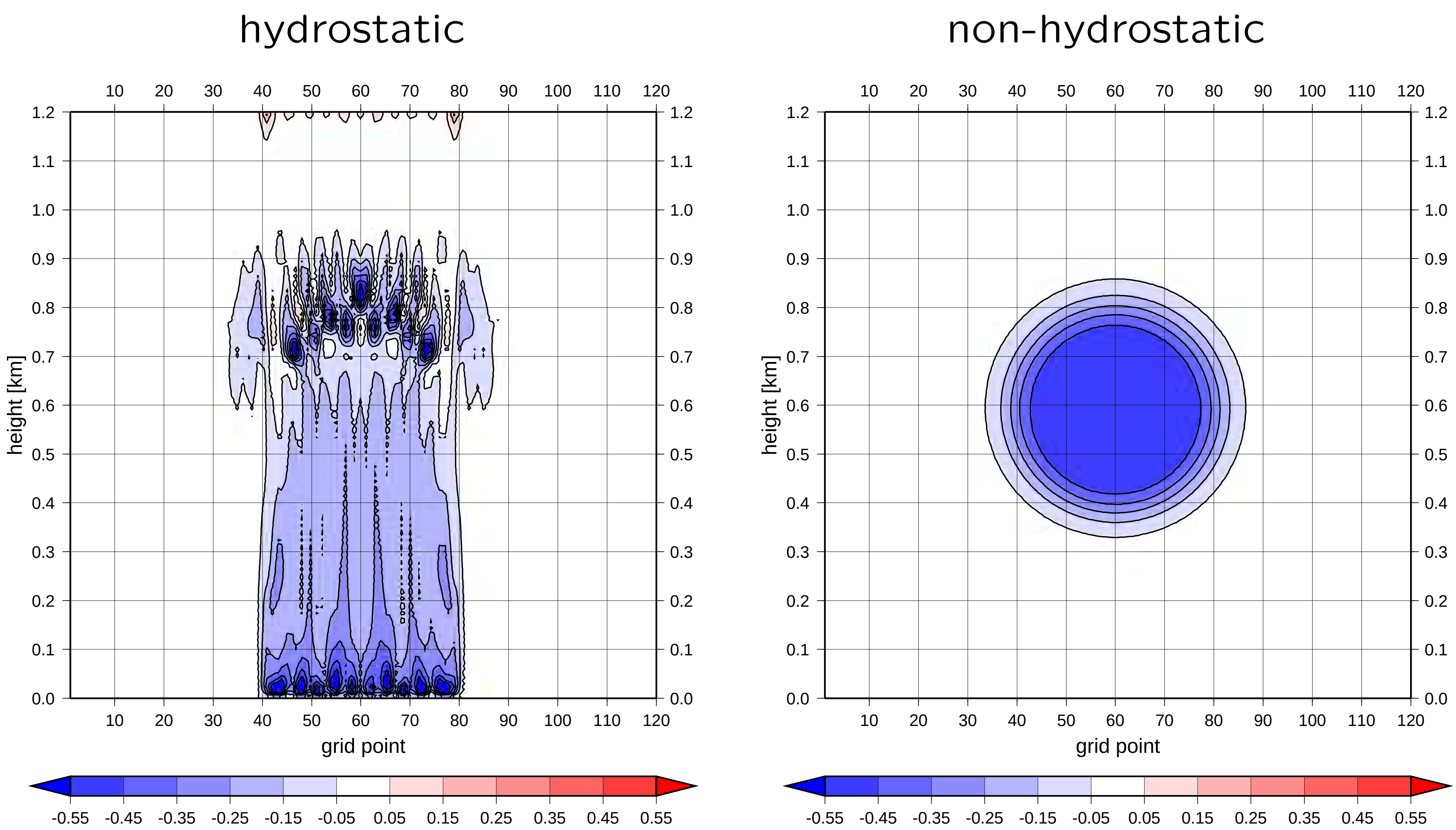
$\Delta x = 10\,\mathrm{m},\ t = 0\,\mathrm{s}$

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



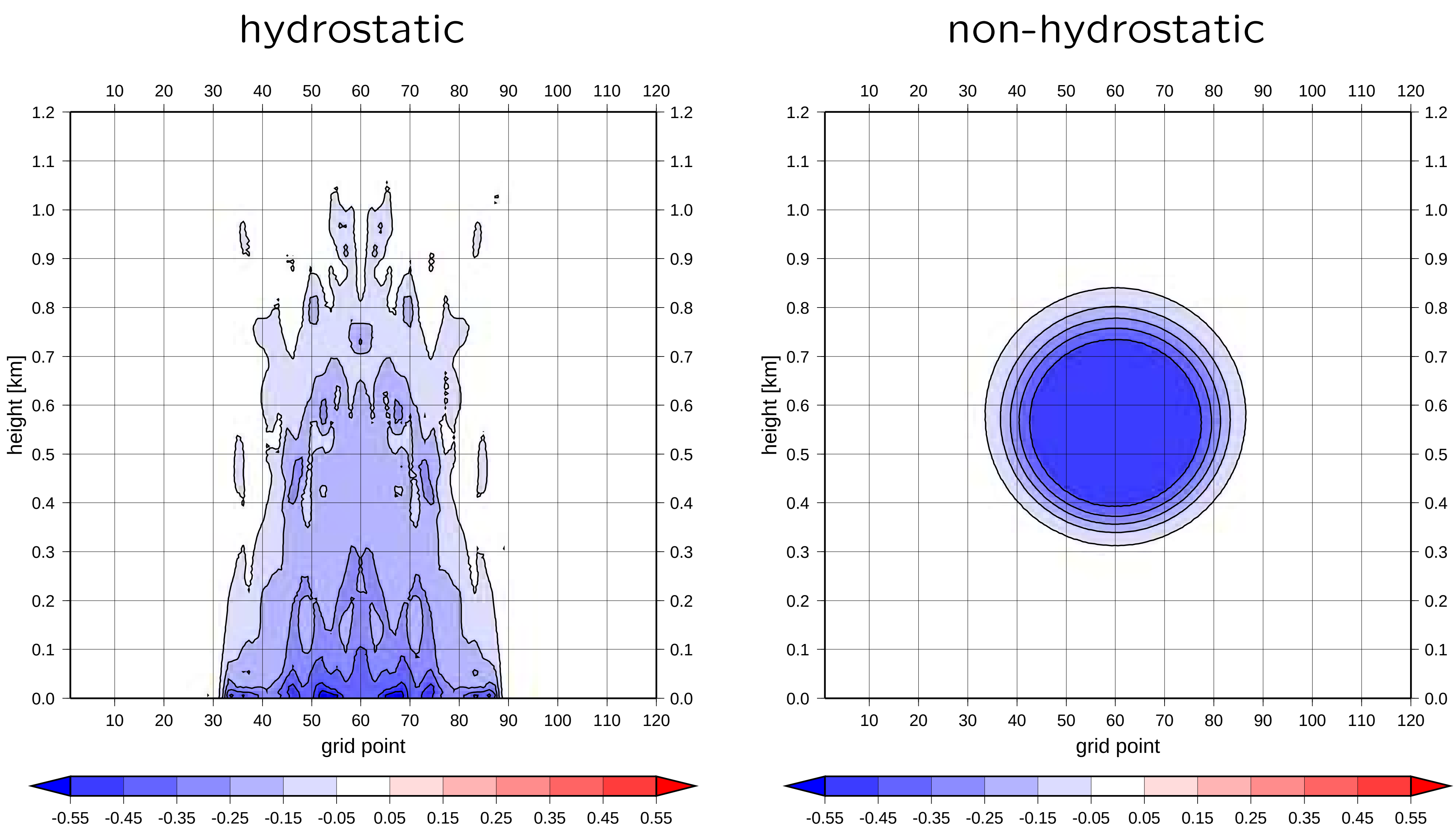
$\Delta x = 10\,\text{m},\ t = 20\,\text{s}$

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



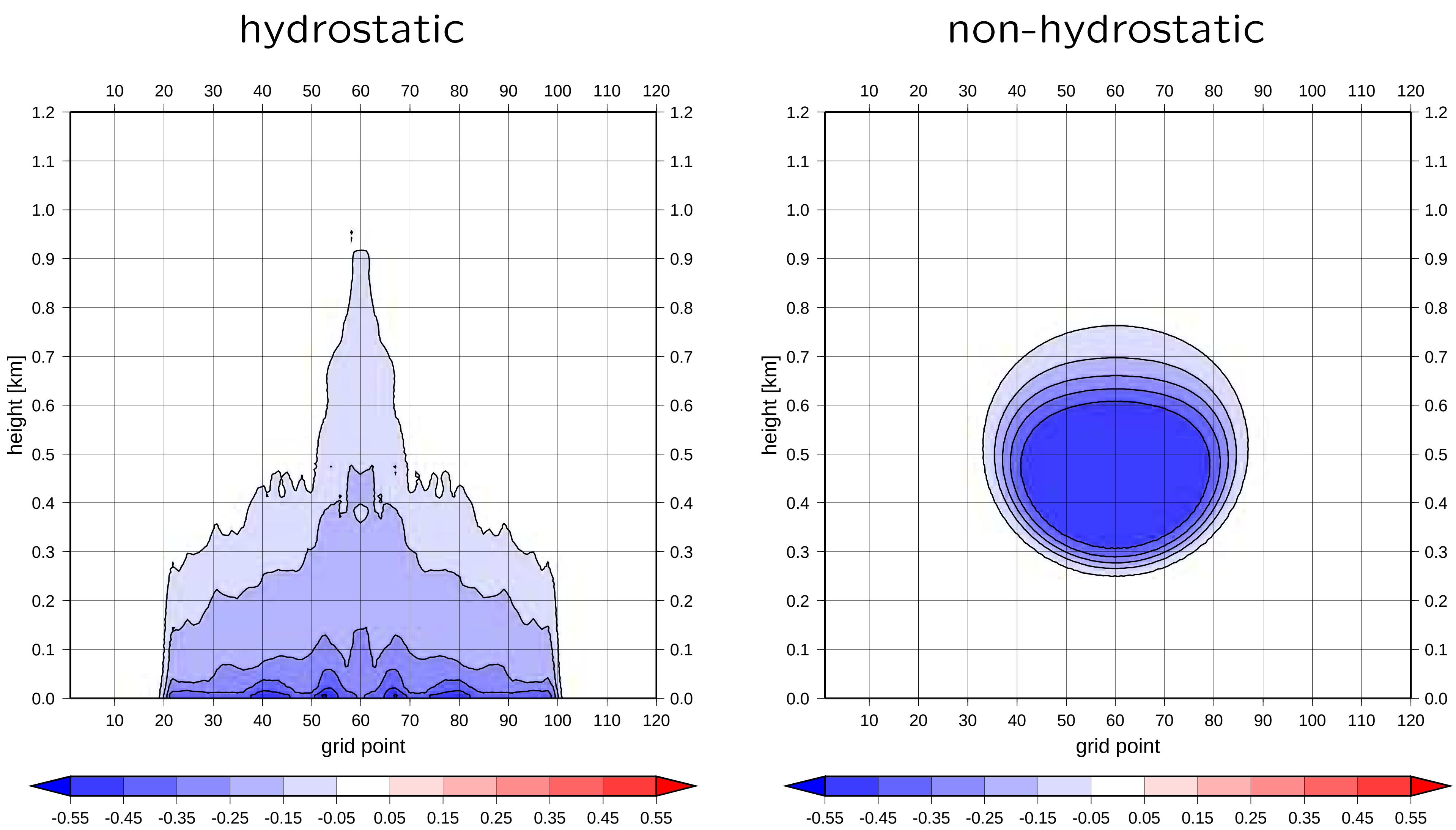
$\Delta x = 10\,\text{m},\ t = 50\,\text{s}$

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



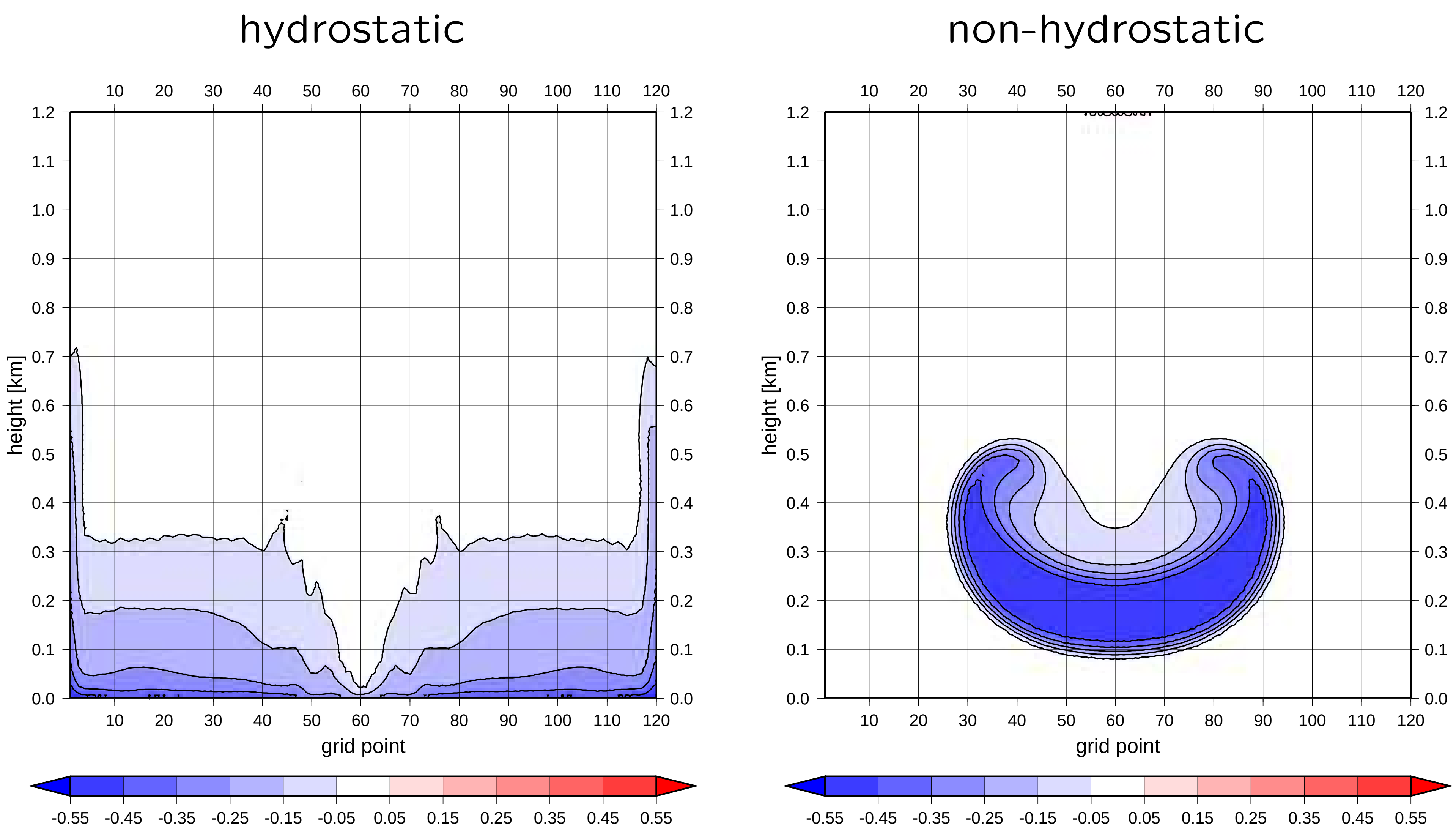
$\Delta x = 10\,\text{m},\ t = 100\,\text{s}$

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



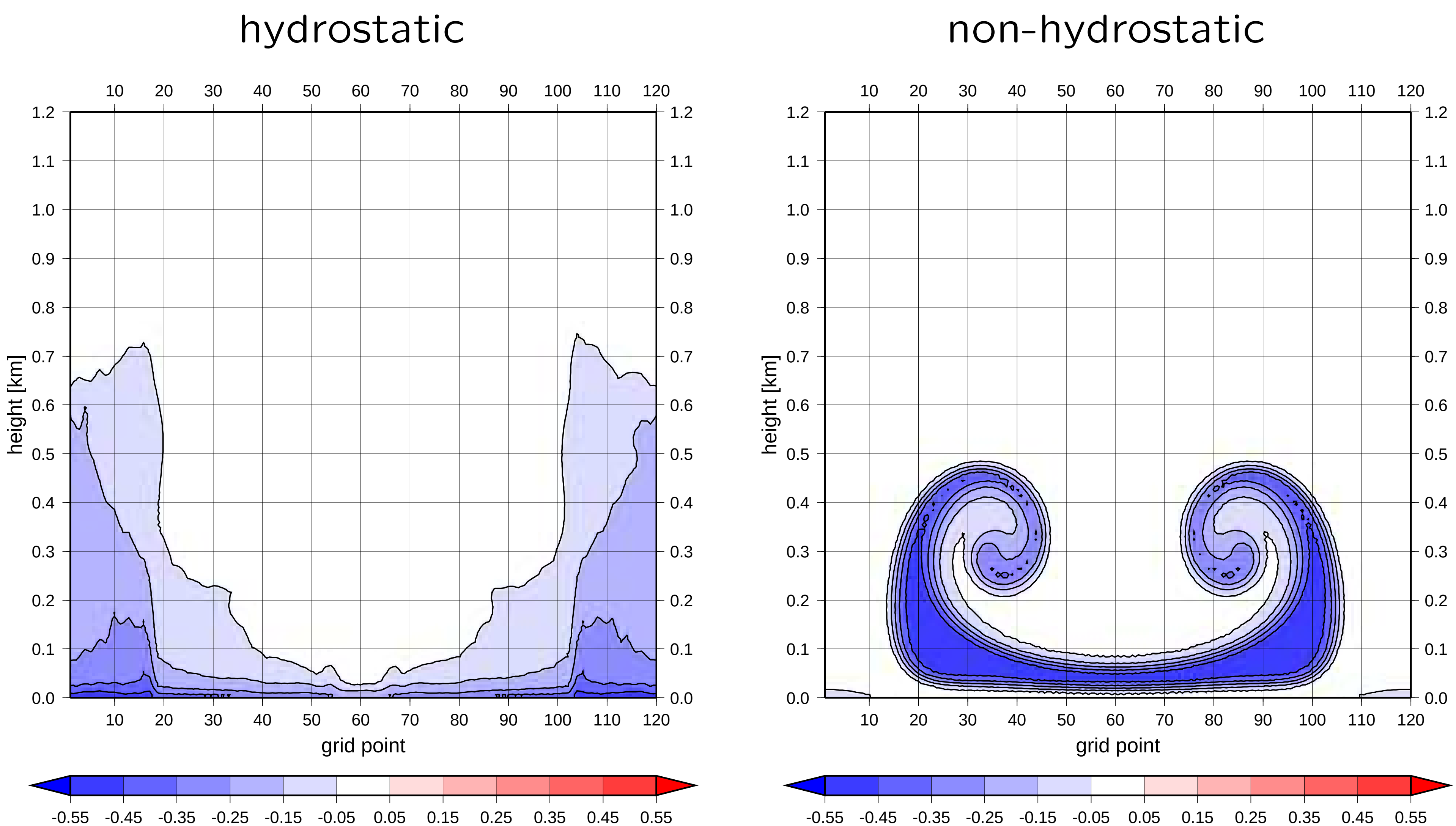
$\Delta x = 10\,\mathrm{m},\ t = 200\,\mathrm{s}$

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



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

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



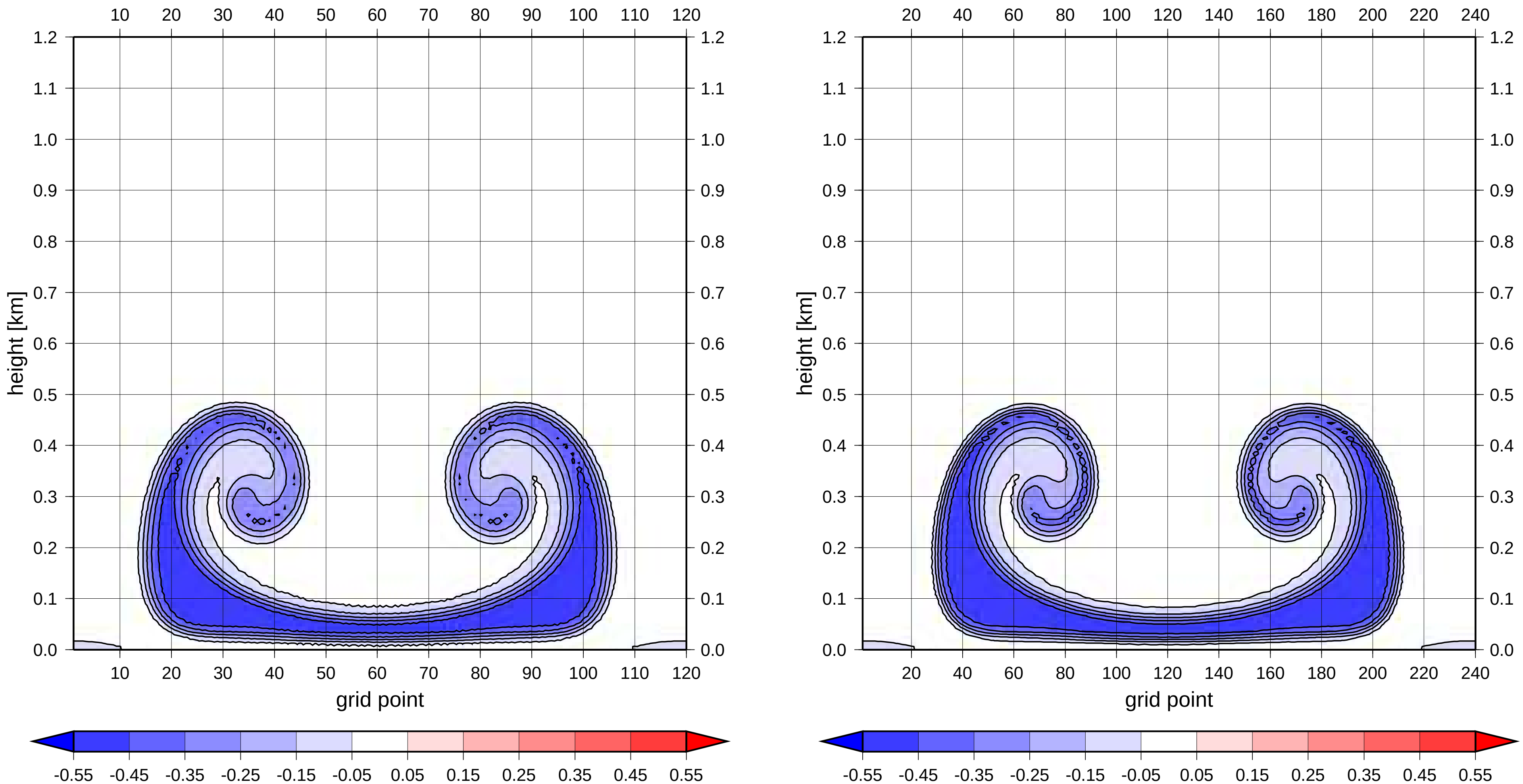
$\Delta x = 10\,\mathrm{m},\ t = 600\,\mathrm{s}$

Are the numerical results trustable?

- convection and turbulence are non-linear phenomena consisting of multiple interacting scales
- in reality, subgrid 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

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

$\Delta x = 10\,\mathrm{m}$ $\Delta x = 5\,\mathrm{m}$



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

Simulations at 1 km horizontal resolution

- domain 120 × 1.2 km, additional 30 layers at the top with isothermal stratification

- resolution: $\Delta x = \ 1$ km, quadratic truncation
  $\Delta z = 10$ m

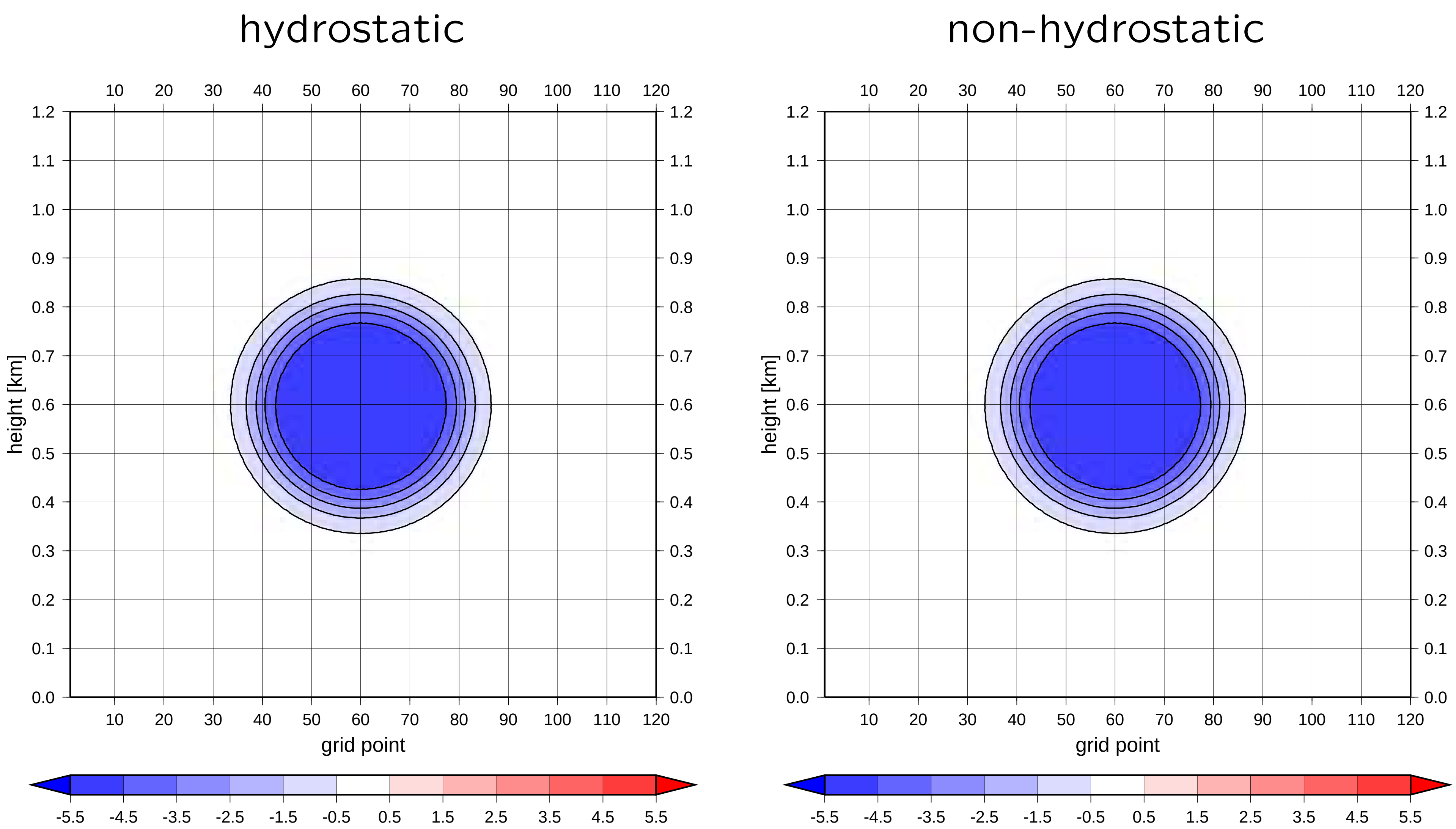
- initial bubble stretched to ellipse with $a = 15$ km and $b = 150$ m

- 10 times stronger initial perturbation ($\theta'_{\text{max}} = -5$ K)

- timestep $\Delta t = 40$ s

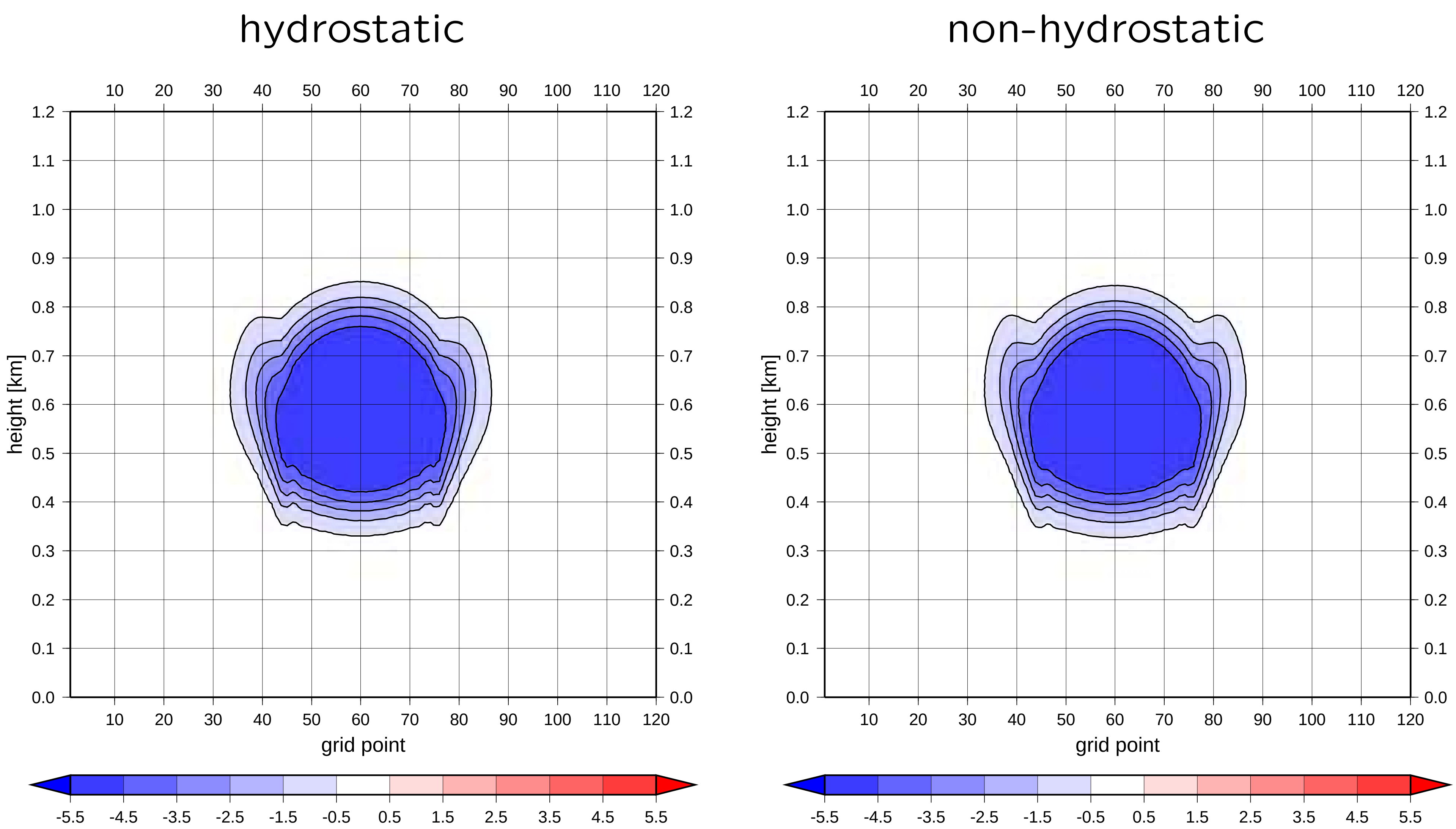
- other settings unchanged

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



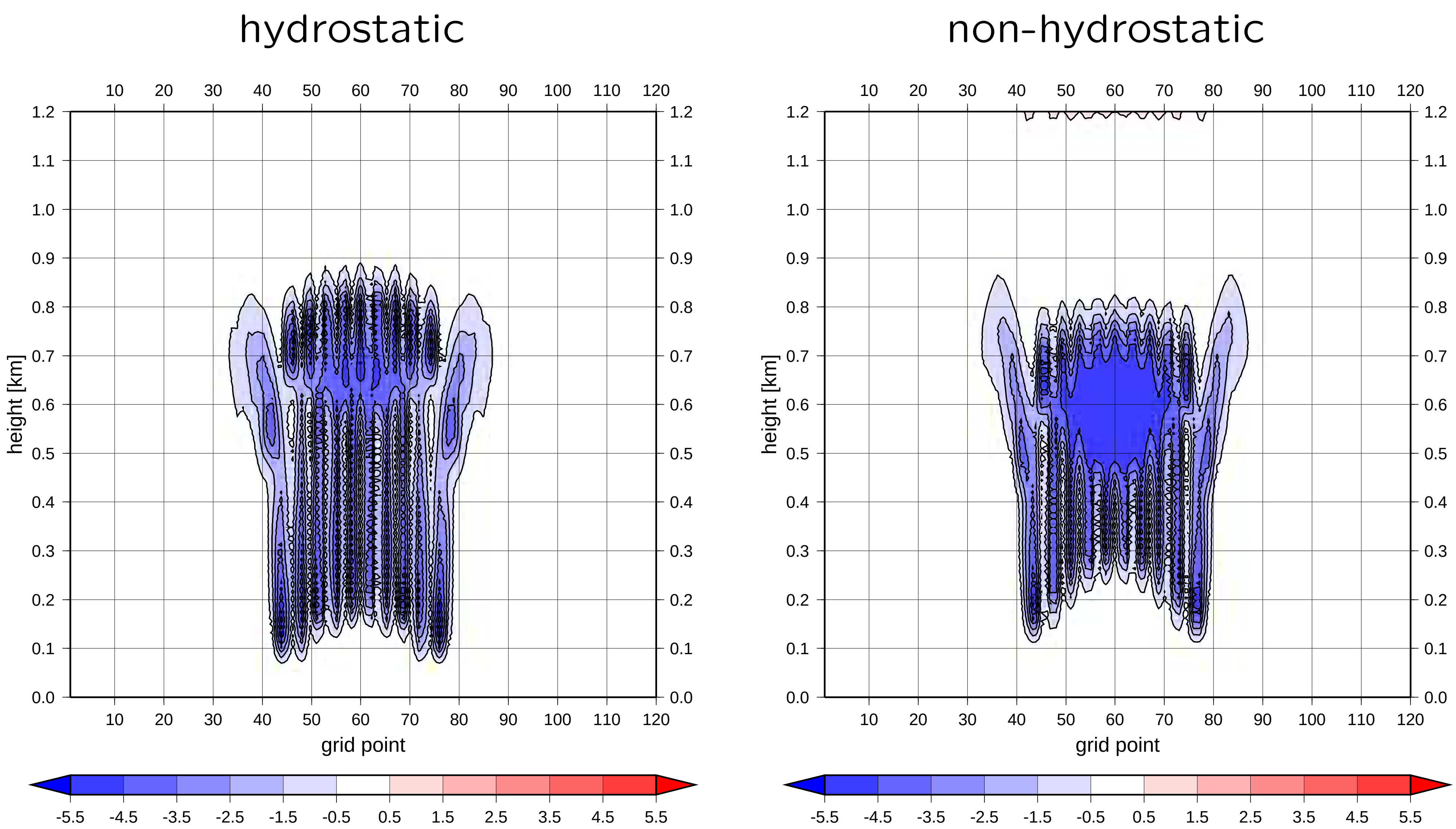
$\Delta x = 1\,\text{km},\ t = 0\,\text{min}$

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



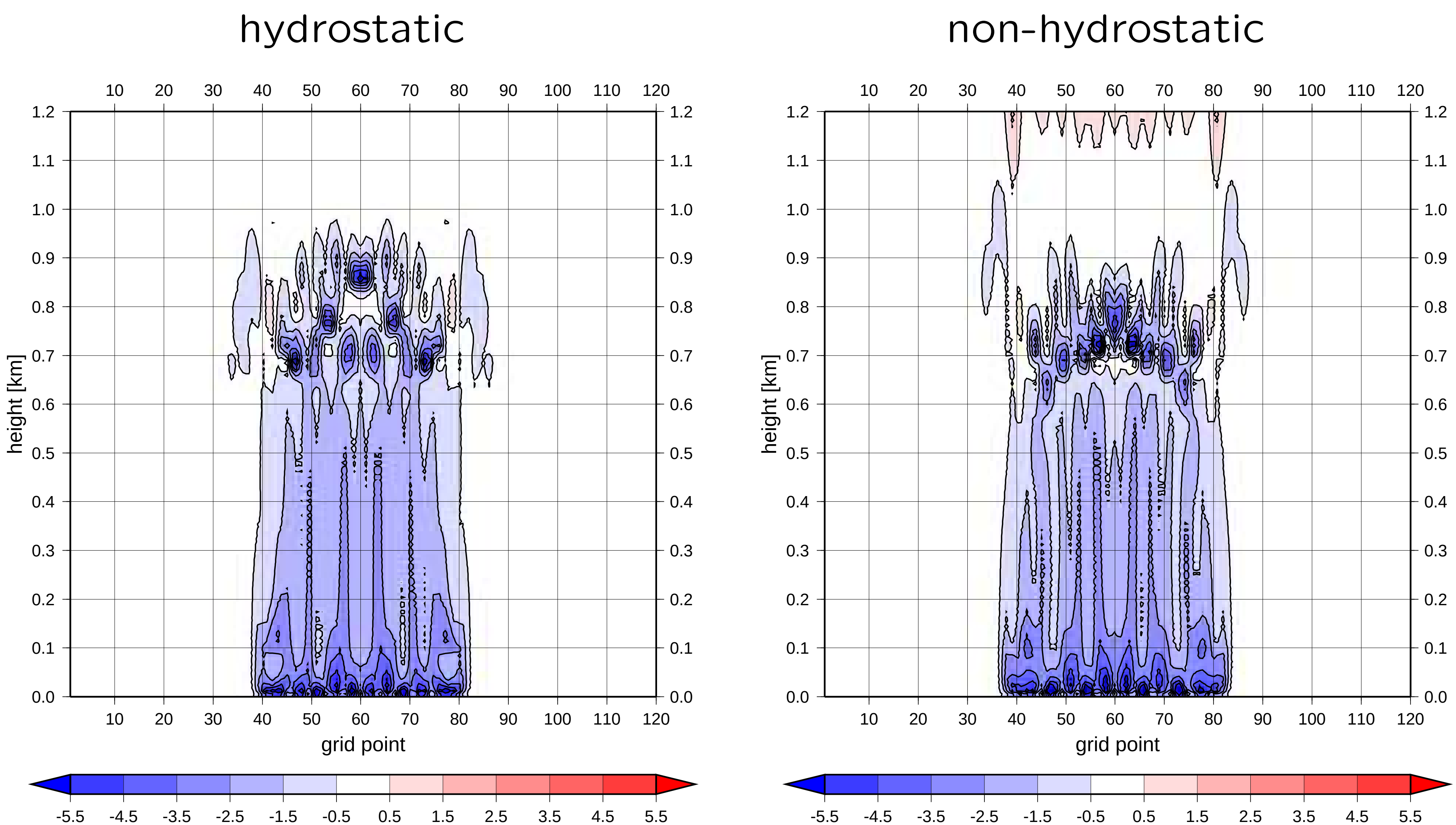
$\Delta x = 1\,\text{km},\ t = 10\,\text{min}$

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



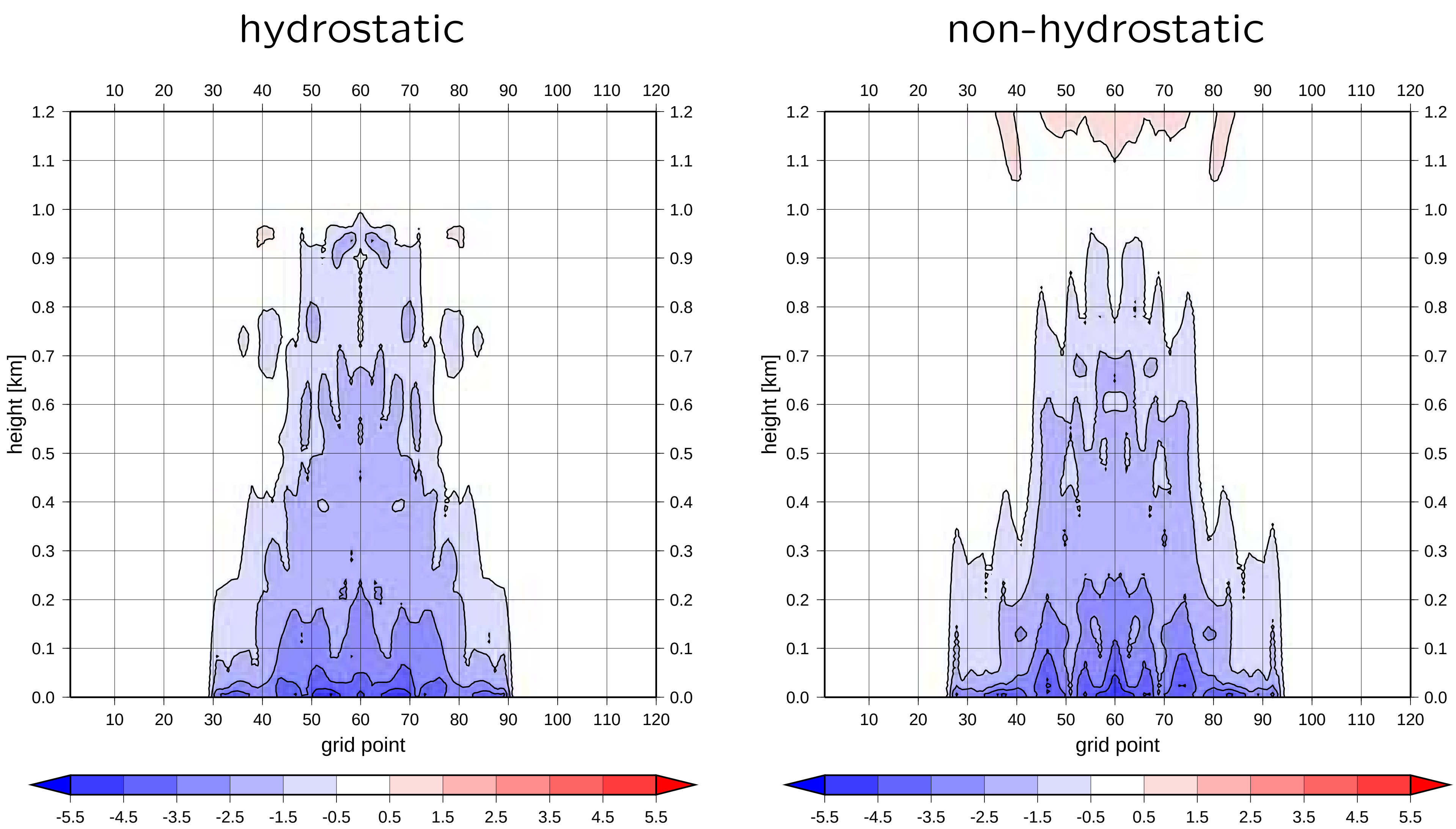
$\Delta x = 1\,\text{km},\ t = 20\,\text{min}$

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



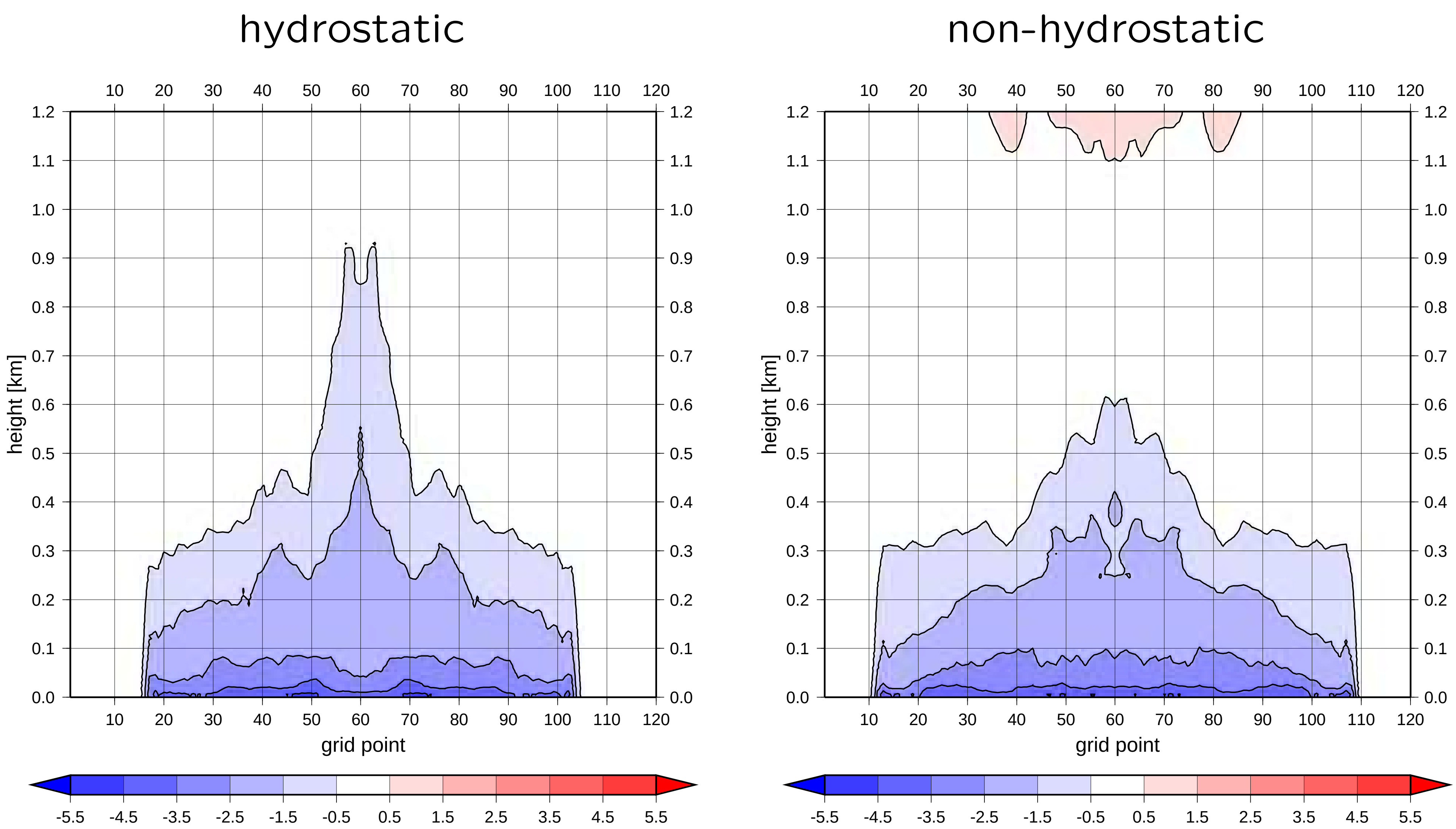
$\Delta x = 1\,\mathrm{km},\ t = 30\,\mathrm{min}$

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



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

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

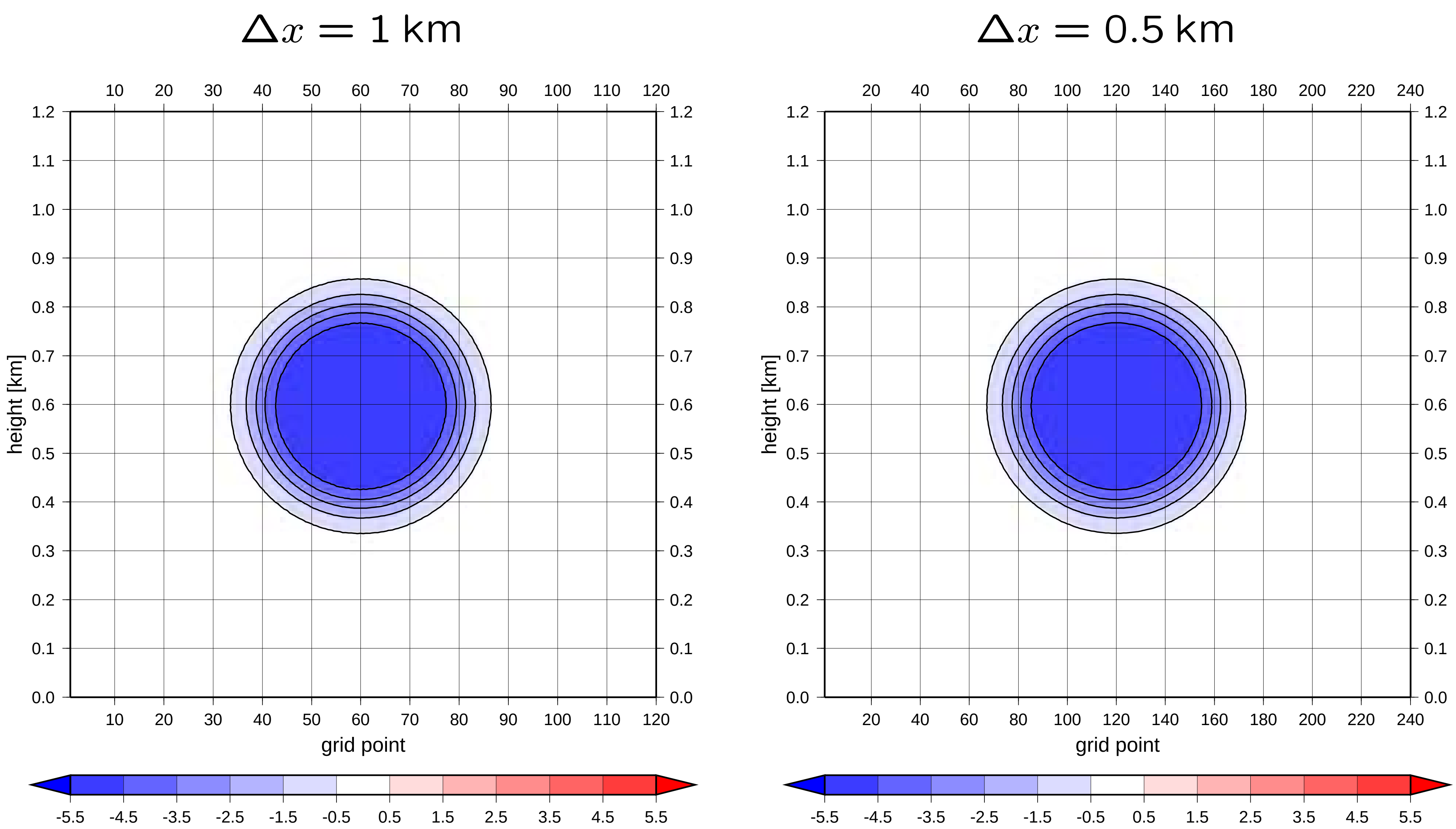


$\Delta x = 1\,\text{km},\ t = 2\,\text{h}$

How trustable are numerical results now?

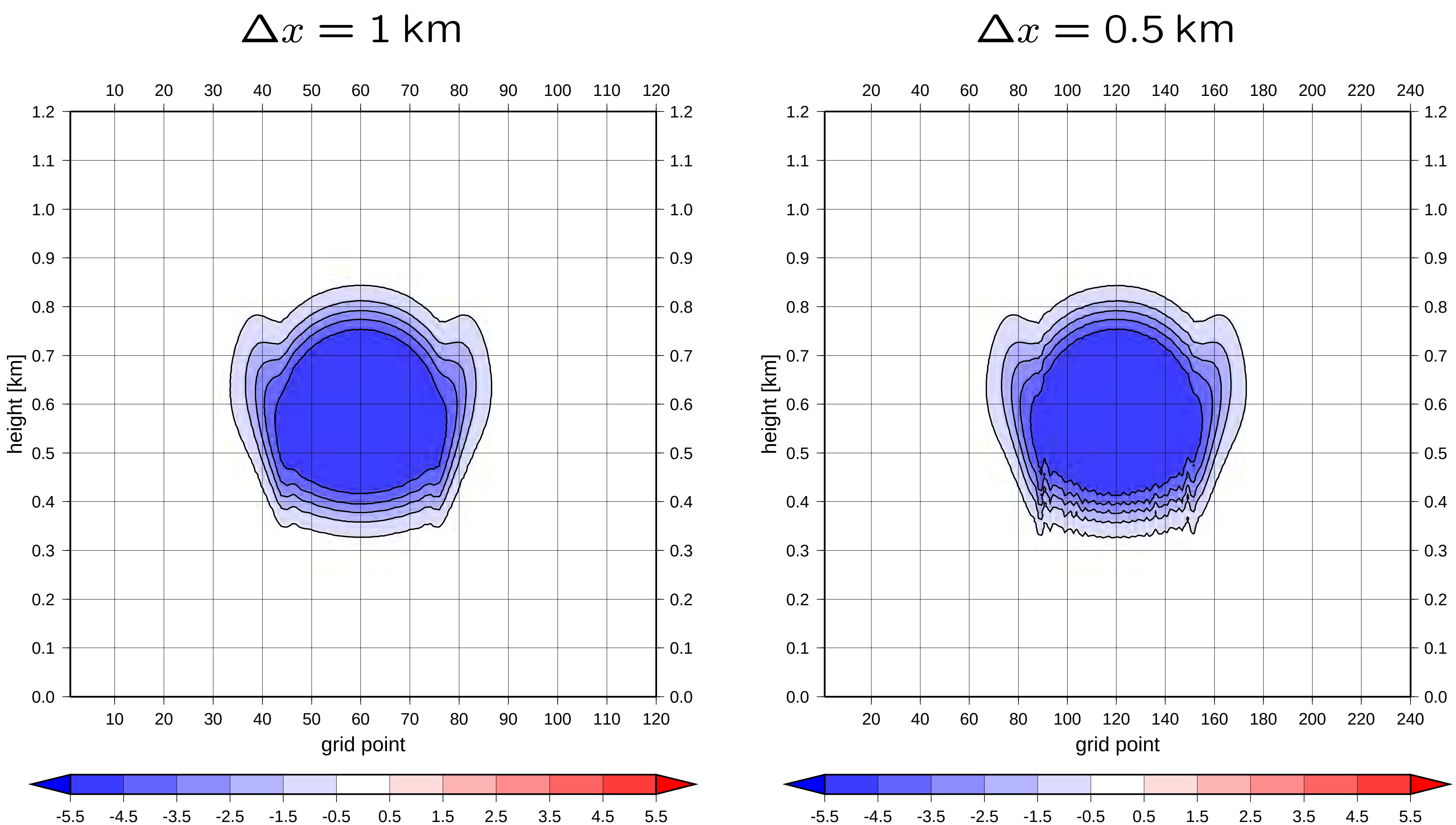
- with bigger Δx influence of subgrid scales might become stronger
- it is necessary to repeat the test with increased horizontal resolution

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



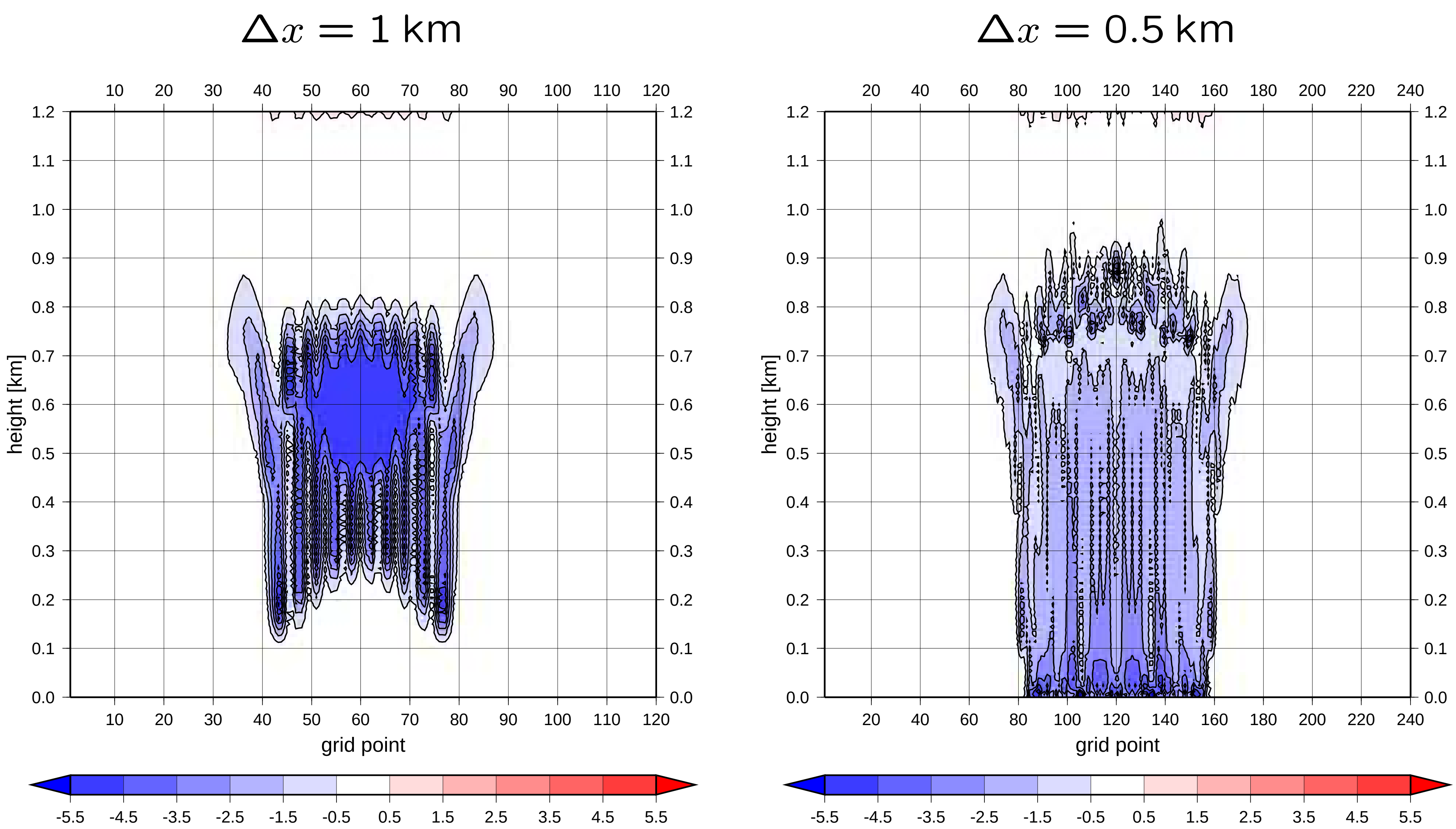
non-hydrostatic run, $t = 0\,\text{min}$

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



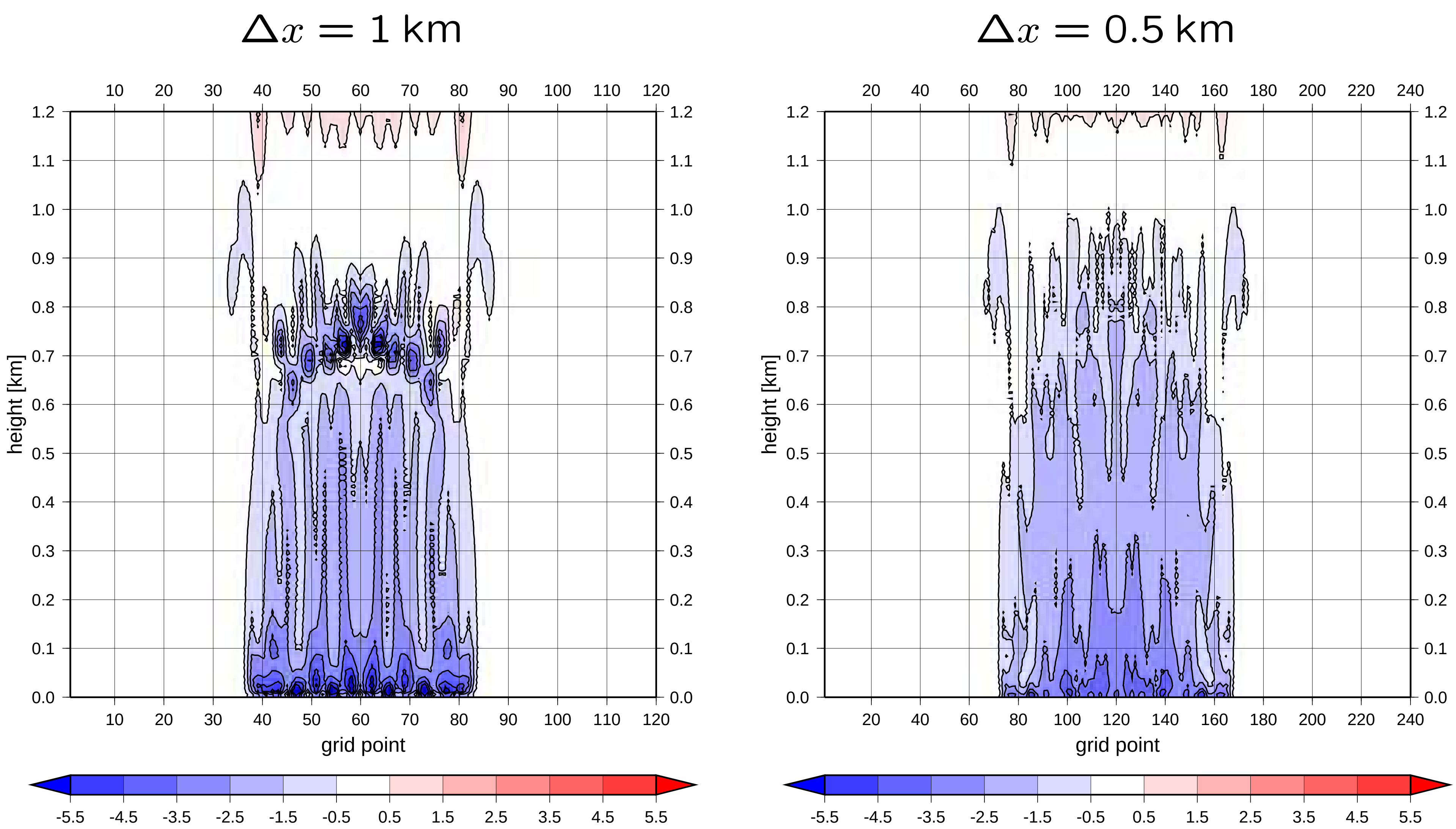
non-hydrostatic run, $t = 10\,\text{min}$

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



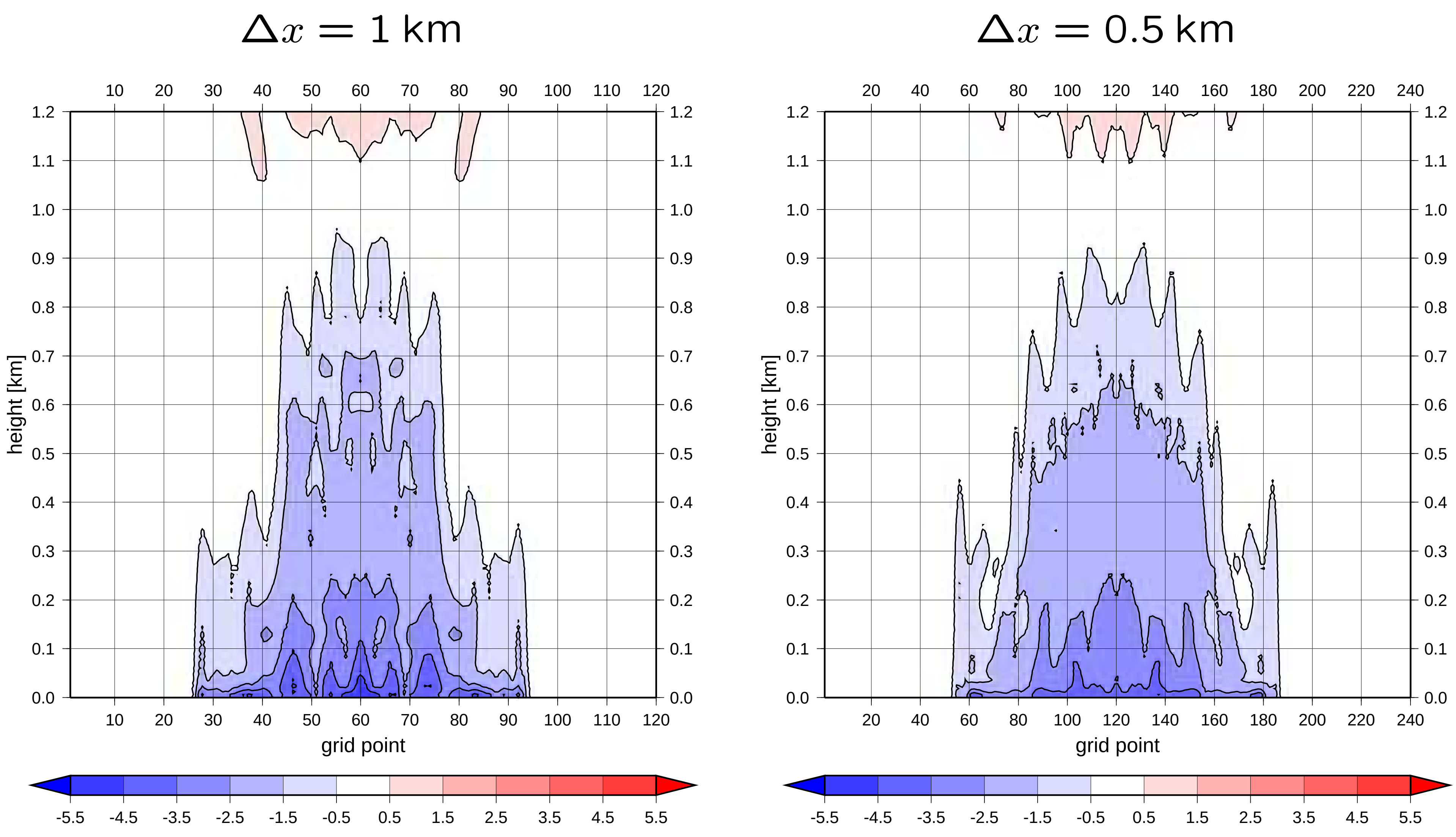
non-hydrostatic run, $t = 20\,\text{min}$

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



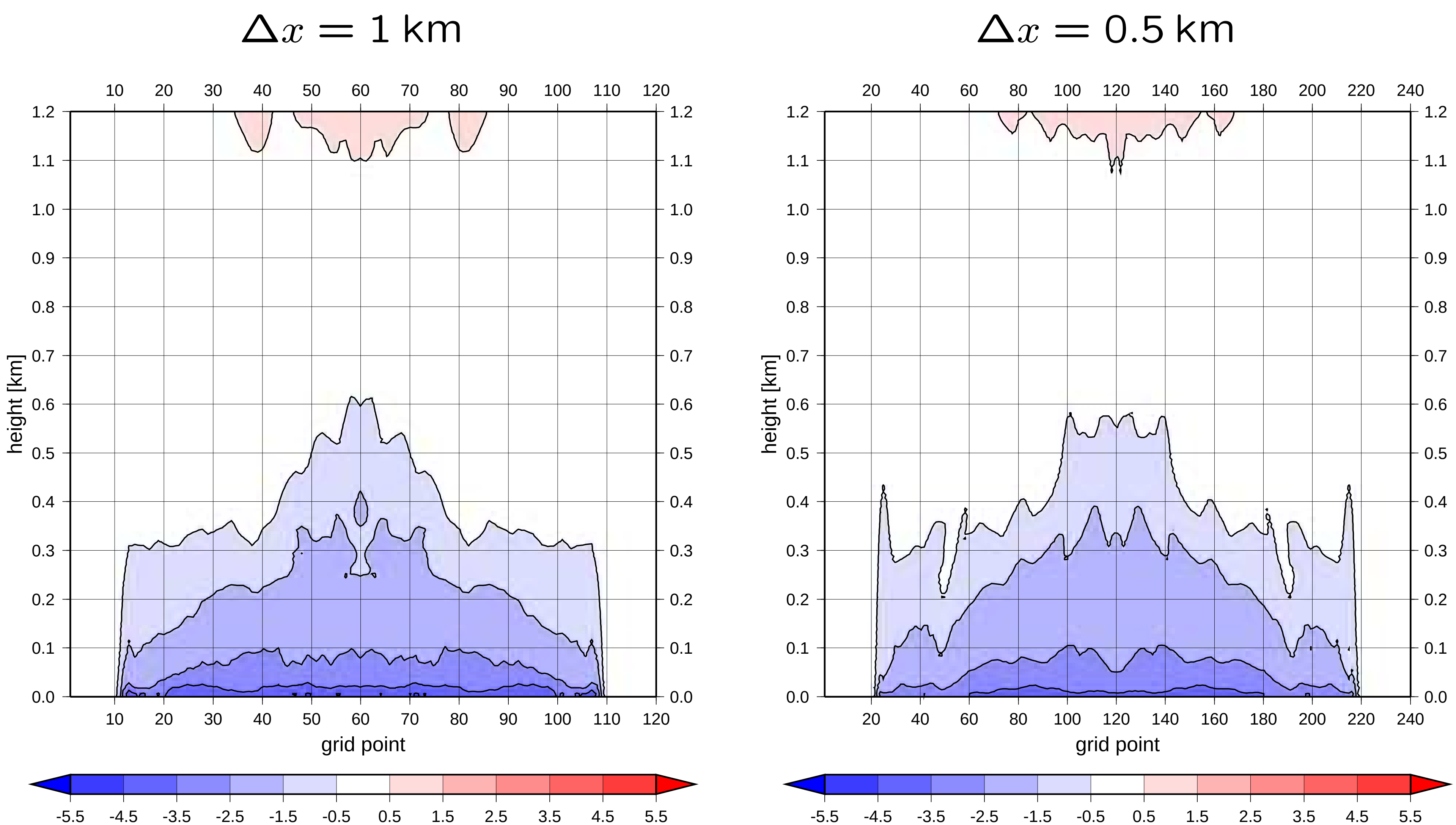
non-hydrostatic run, $t = 30\,\text{min}$

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



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

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



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

Summary for the case 2

- ALADIN-NH kernel (with advection of w) passed also cold bubble test

- at kilometric horizontal resolution, subgrid convective scales can still play an important role

- slight differences between H and NH simulations start to be visible

- it can be expected that these differences will become more pronounced for deep convective systems with diabatic forcing

- going to 10 m horizontal resolution, differences between H and NH simulations increase $\Rightarrow$ NH model becomes compulsory

- at the same time influence of subgrid scales diminishes, they can be satisfactorily represented by viscous dissipation

Conclusions

- ALADIN-NH dynamical kernel is now in stable state, ready for operational use
- there are still some details to be solved (advection of w, diabatic tendencies in BBC, non-reflective upper boundary treatment, ...)
- shape of the kernel can change with implementation of vertical finite elements, but its general concept will most likely remain untouched
- idealized bubble simulations show that non-hydrostatic effects start to be visible at kilometric horizontal resolution and they completely take over for 10 m horizontal resolution