Bottom boundary condition treatment

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Introduction

- evolution of atmosphere is driven by set of PDE
- in order to get unique solution, proper initial and boundary conditions must be specified
- treatment of initial and lateral boundary conditions is the task for data assimilation, initialization and coupling procedures
- top boundary condition is artificial, it comes from the requirement to have vertically bounded atmosphere
- this talk will be about bottom boundary condition (BBC) in ALADIN-NH, which is the only physical boundary condition in model

Simplifications

- in order to make analysis more transparent, two simplifications are used troughout the lecture:

  1. flat geometry (map factor = 1, no curvature terms)
  2. dry atmosphere (as a consequence, pseudovertical divergence d_3 equals to true vertical divergence $d \equiv \partial w / \partial z$)

Bottom boundary condition - continuous case (1)

- prognostic equations for momentum in η coordinate have the form ($\tilde{p} \equiv p - \pi$ is unscaled NH pressure departure):

$$\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = -\frac{RT}{p}\nabla p - \left(\frac{\partial \tilde{p}}{\partial \pi} + 1\right)\nabla \phi + \boldsymbol{\mathcal{V}}$$
$$\frac{\mathrm{d}}{\mathrm{d}t}(gw) = g^2 \frac{\partial \tilde{p}}{\partial \pi} + g\mathcal{W}$$

- in ALADIN-NH, free slip BBC is imposed:

$$gw_S = \mathbf{v}_S \cdot \nabla \phi_S$$

- it means that air velocity at the surface is parallel to it (surface is a material boundary, so the air cannot cross it)

- as a consequence, air being initially at the surface remains attached there forever (it can only slip along)

Bottom boundary condition - continuous case (2)

- requirement that prognostic equations are fulfilled also at bottom boundary imposes constraint on dynamical fields:

$$gw_S = \mathbf{v}_S \cdot \nabla\phi_S \quad \Rightarrow \quad \frac{\mathrm{d}}{\mathrm{d}t}(gw_S) = \frac{\mathrm{d}\mathbf{v}_S}{\mathrm{d}t} \cdot \nabla\phi_S + \mathbf{v}_S \cdot \frac{\mathrm{d}}{\mathrm{d}t}\nabla\phi_S$$

$$\left(\frac{\mathrm{d}}{\mathrm{d}t}(gw)\right)_S = \left(\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t}\right)_S \cdot \nabla\phi_S + \mathbf{v}_S \cdot \frac{\mathrm{d}}{\mathrm{d}t}\nabla\phi_S$$

$$\mathbf{v}_S \cdot \frac{\mathrm{d}}{\mathrm{d}t}\nabla\phi_S = \mathbf{v}_S \cdot [(\mathbf{v}_S \cdot \nabla)\nabla\phi_S] = \underbrace{\frac{\partial^2\phi_S}{\partial x^2}{u_S}^2 + 2\frac{\partial^2\phi_S}{\partial x \partial y}u_S v_S + \frac{\partial^2\phi_S}{\partial y^2}{v_S}^2}_{J_S}$$

$$\Downarrow$$

$$\left[g^2 + (\nabla\phi_S)^2\right]\left(\frac{\partial\tilde{p}}{\partial\pi}\right)_S = \left[-\frac{RT}{p}\nabla p - \nabla\phi + \boldsymbol{\mathcal{V}}\right]_S \cdot \nabla\phi_S + J_S - g\mathcal{W}_S$$

- term $(\partial\tilde{p}/\partial\pi)_S$ cannot be specified arbitrarily, it is fully determined by surface fields $\mathbf{v}_S$, T_S, p_S, ϕ_S, $\boldsymbol{\mathcal{V}}_S$ and $\mathcal{W}_S$

Bottom boundary condition - continuous case (2)

- requirement that prognostic equations are fulfilled also at bottom boundary imposes constraint on dynamical fields:

$$g w_S = \mathbf{v}_S \cdot \nabla \phi_S \quad \Rightarrow \quad \frac{\mathrm{d}}{\mathrm{d}t}(g w_S) = \frac{\mathrm{d}\mathbf{v}_S}{\mathrm{d}t} \cdot \nabla \phi_S + \mathbf{v}_S \cdot \frac{\mathrm{d}}{\mathrm{d}t} \nabla \phi_S$$

$$\left(\frac{\mathrm{d}}{\mathrm{d}t}(g w) \right)_S = \left(\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} \right)_S \cdot \nabla \phi_S + \mathbf{v}_S \cdot \frac{\mathrm{d}}{\mathrm{d}t} \nabla \phi_S$$

$$\mathbf{v}_S \cdot \frac{\mathrm{d}}{\mathrm{d}t} \nabla \phi_S = \mathbf{v}_S \cdot [(\mathbf{v}_S \cdot \nabla) \nabla \phi_S] = \underbrace{\frac{\partial^2 \phi_S}{\partial x^2} {u_S}^2 + 2 \frac{\partial^2 \phi_S}{\partial x \partial y} u_S v_S + \frac{\partial^2 \phi_S}{\partial y^2} {v_S}^2}_{J_S}$$

$$\Downarrow$$

$$\left[g^2 + (\nabla \phi_S)^2 \right] \left(\frac{\partial \tilde{p}}{\partial \pi} \right)_S = \left[-\frac{RT}{p} \nabla p - \nabla \phi + \boldsymbol{\mathcal{V}} \right]_S \cdot \nabla \phi_S + J_S - g \mathcal{W}_S$$

- term $(\partial \tilde{p} / \partial \pi)_S$ cannot be specified arbitrarily, it is fully determined by surface fields $\mathbf{v}_S$, T_S, p_S, ϕ_S, $\boldsymbol{\mathcal{V}}_S$ and $\mathcal{W}_S$ $\Rightarrow$ force acting on air parcel at surface must deflect its trajectory by the right amount so that it does not detach from surface

Going from vertical velocity w to vertical divergence d

- in ALADIN-NH, prognostic equation for vertical velocity w is replaced by prognostic equation for vertical divergence $d \equiv \partial(gw)/\partial\phi$:

$$\frac{\mathrm{d}d}{\mathrm{d}t} = \frac{\partial}{\partial\phi}\left[g^2\frac{\partial\tilde{p}}{\partial\pi} + g\mathcal{W}\right] - d(d+X) + Z$$

$$X \equiv -\frac{\partial\mathbf{v}}{\partial\phi}\cdot\nabla\phi \qquad Z \equiv -\frac{\partial\mathbf{v}}{\partial\phi}\cdot\nabla(gw)$$

- vertical velocity w present in Z-term can be diagnosed as:

$$gw = gw_S + \int_{\phi_S}^{\phi} d\,\mathrm{d}\phi' = gw_S + \int_{\eta}^{1}\frac{mRT}{p}d\,\mathrm{d}\eta'$$

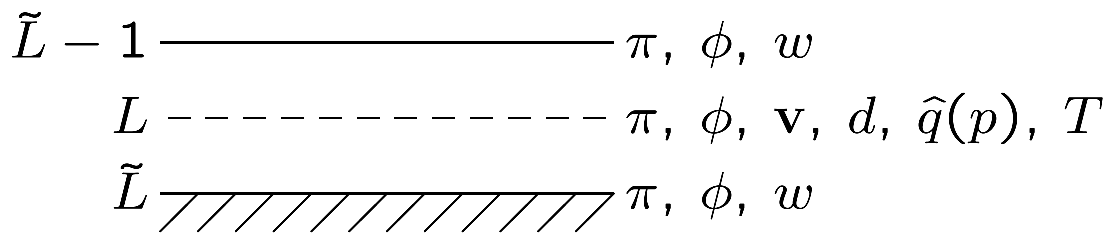
$$gw_S = \mathbf{v}_S\cdot\nabla\phi_S \qquad m \equiv \frac{\partial\pi}{\partial\eta}$$

- source of future troubles is the vertical laplacian term:

$$\frac{\partial}{\partial\phi}\left[g^2\frac{\partial\tilde{p}}{\partial\pi}\right] = -\rho g^2\frac{\partial^2\tilde{p}}{\partial\pi^2}$$

Bottom boundary condition - vertically discretized case (1)

- in vertically discretized case situation becomes more complicated, since some model variables are not available at the surface:



- at bottom full level L, vertically discretized equation for vertical divergence d reads:

$$\left(\frac{\mathrm{d}d}{\mathrm{d}t}\right)_L = \frac{1}{\delta\phi_L}\left[g^2\left(\frac{\partial\tilde{p}}{\partial\pi}\right)_{\tilde{L}} + g\mathcal{W}_{\tilde{L}} - g^2\left(\frac{\partial\tilde{p}}{\partial\pi}\right)_{\tilde{L}-1} - g\mathcal{W}_{\tilde{L}-1}\right] - \\ - d_L(d_L + X_L) + Z_L$$

- as in continuous case, term $(\partial\tilde{p}/\partial\pi)_{\tilde{L}}$ must be evaluated consistently with free slip boundary condition and dynamical equations

Bottom boundary condition - vertically discretized case (2)

- horizontal momentum equation is evaluated only at full levels $\Rightarrow$ hypothesis $\mathbf{v}_{\tilde{L}} = \mathbf{v}_L$ is used in free slip BBC

- using this hypothesis following diagnostic formula can be derived:

$$g^2 \left(\frac{\partial \tilde{p}}{\partial \pi} \right)_{\tilde{L}} = \left[-\frac{RT}{p} \nabla p - \left(\frac{\partial \tilde{p}}{\partial \pi} + 1 \right) \nabla \phi + \boldsymbol{\mathcal{V}} \right]_L \cdot \nabla \phi_{\tilde{L}} + J_L - g \mathcal{W}_{\tilde{L}}$$

- to be usable, term $(\partial \tilde{p} / \partial \pi)_L$ appearing on RHS must be evaluated, but it requires NH pressure departure $\tilde{p}$ at half levels:

$$\left(\frac{\partial \tilde{p}}{\partial \pi} \right)_l = \frac{\tilde{p}_{\tilde{l}} - \tilde{p}_{\tilde{l}-1}}{\pi_{\tilde{l}} - \pi_{\tilde{l}-1}} \qquad \tilde{p}_{\tilde{l}} = [\pi(\exp \hat{q} - 1)]_{\tilde{l}}$$

- prognostic variable $\hat{q}$ at half levels is determined simply as:

$$\hat{q}_{\tilde{l}} = \frac{1}{2}(\hat{q}_{l+1} + \hat{q}_l) \qquad \tilde{l} = \tilde{1}, \ldots, \tilde{L} - 1$$

$$\hat{q}_{\tilde{0}} = \hat{q}_1 \qquad \hat{q}_{\tilde{L}} = \hat{q}_L$$

2D tests - NLNH case

- suitable test cases for evaluation of BBC treatment are orographic flows

- any inconsistency in BBC treatment should be seen in wrong model response

- crucial test turned to be non-linear non-hydrostatic (NLNH) regime:
  - uniform background flow with horizontal wind speed $10\,\mathrm{ms}^{-1}$ over bell shaped mountain with half width $a = 1\,\mathrm{km}$ and height $h = 1\,\mathrm{km}$
  - background stratification with surface temperature $293\,\mathrm{K}$ and constant Brunt-Väisälä frequency $N = 0.01\,\mathrm{s}^{-1}$ up to tropopause at $20\,\mathrm{km}$, isothermal above
  - background surface pressure $101\,325\,\mathrm{Pa}$

NLNH case - model specific settings

- periodic domain with 128 gridpoints (8 points in coupling zone), horizontal resolution $\Delta x = 200\,\mathrm{m}$

- 100 vertical levels with $\Delta z \approx 300\,\mathrm{m}$, sponge layer between 20 and 29.5 km

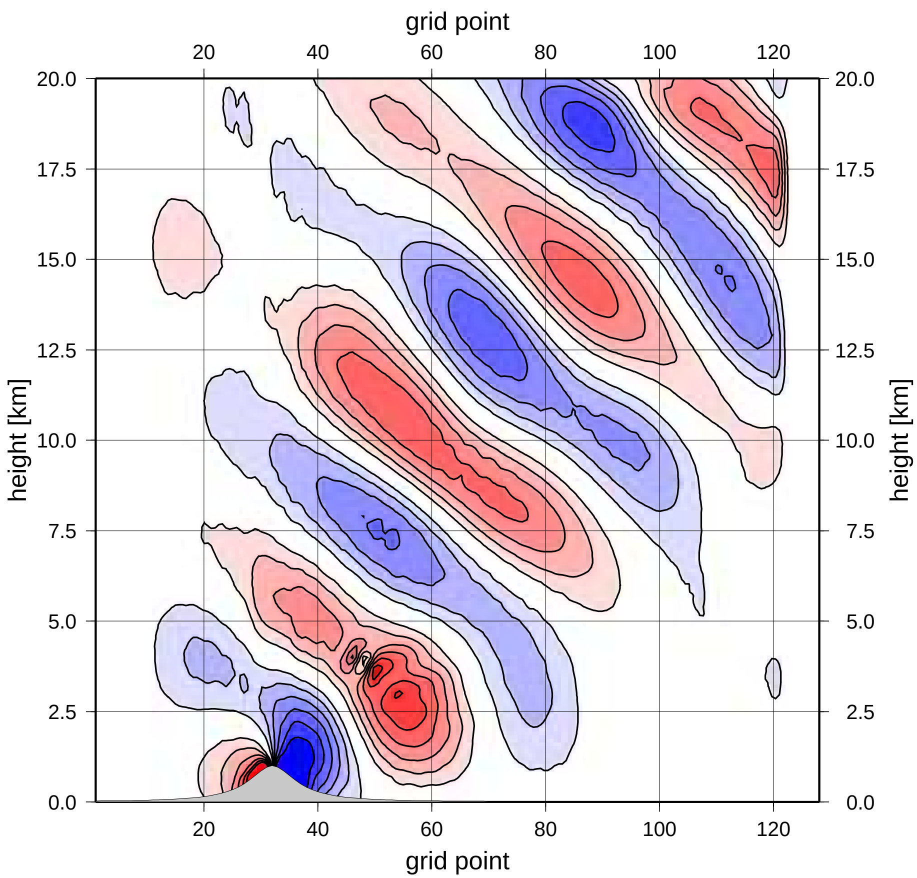
- time constant LBC (coupling files identical to init file)

- no horizontal diffusion, no decentering

Appearance of SL chimney

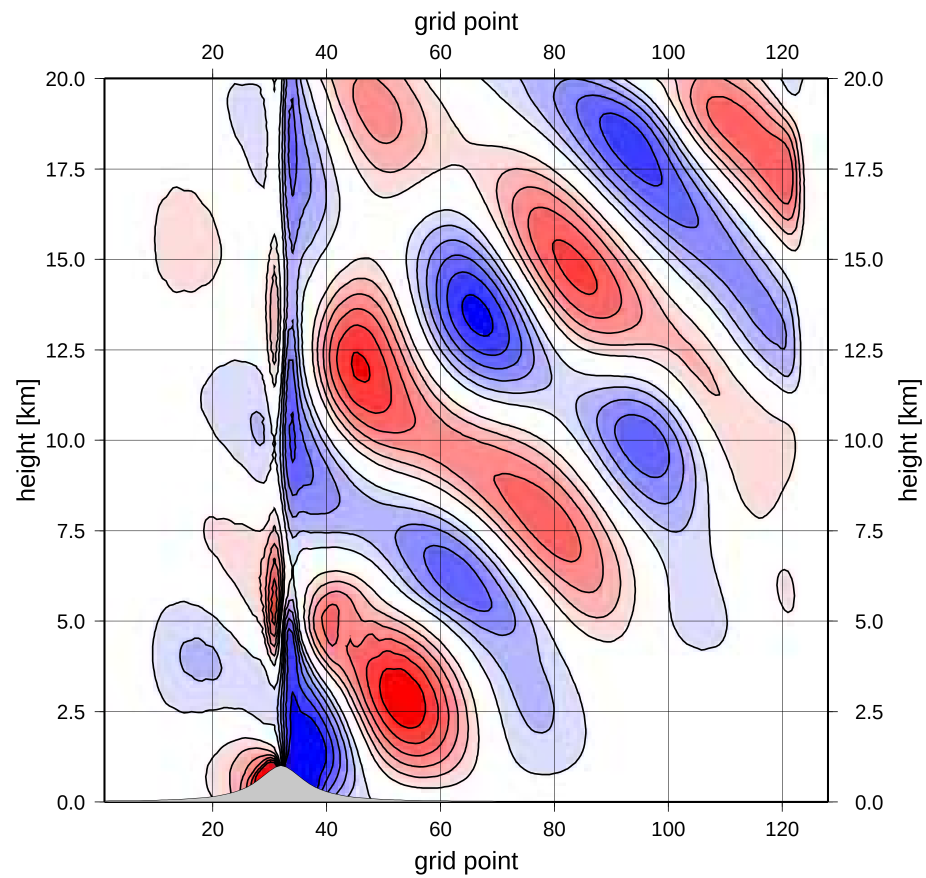
vertical velocity w

euler



$\Delta t = 1\,\mathrm{s},\ N_{\mathrm{step}} = +5000$

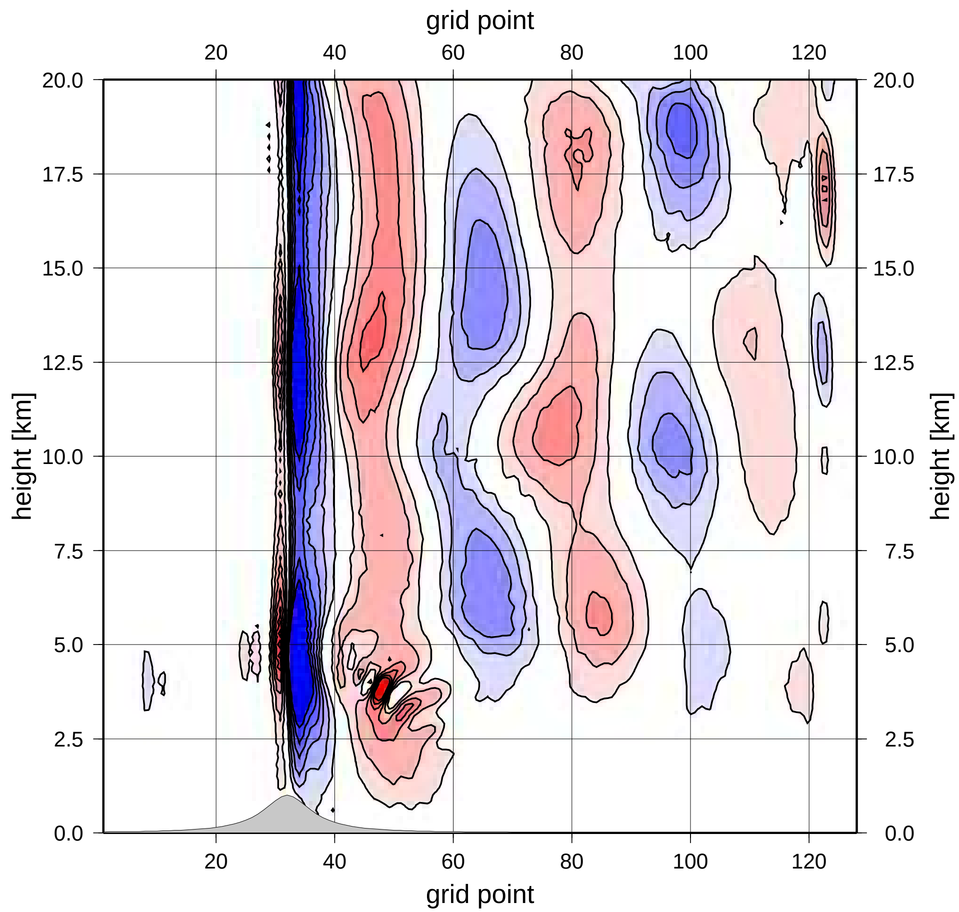
SL3TL



$\Delta t = 5\,\mathrm{s},\ N_{\mathrm{step}} = +1000$

Why chimney?

vertical velocity difference $w_{\mathsf{SL3TL}} - w_{\mathsf{euler}}$

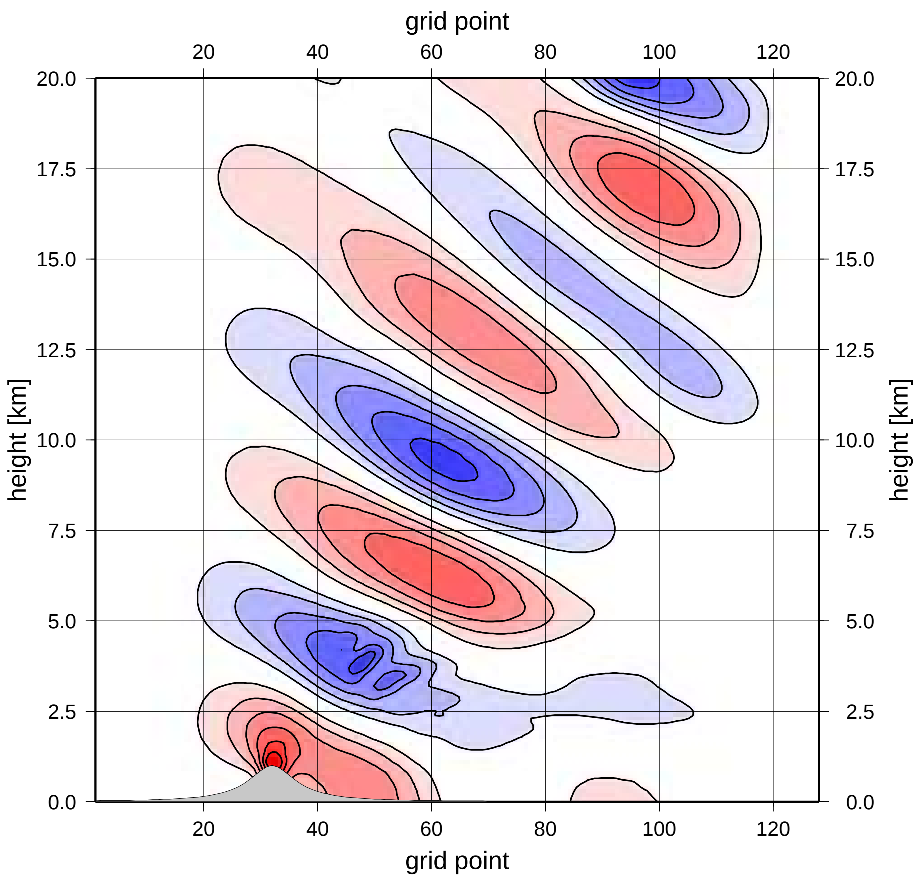


$t = 5000\,\mathsf{s}$

What about other fields?

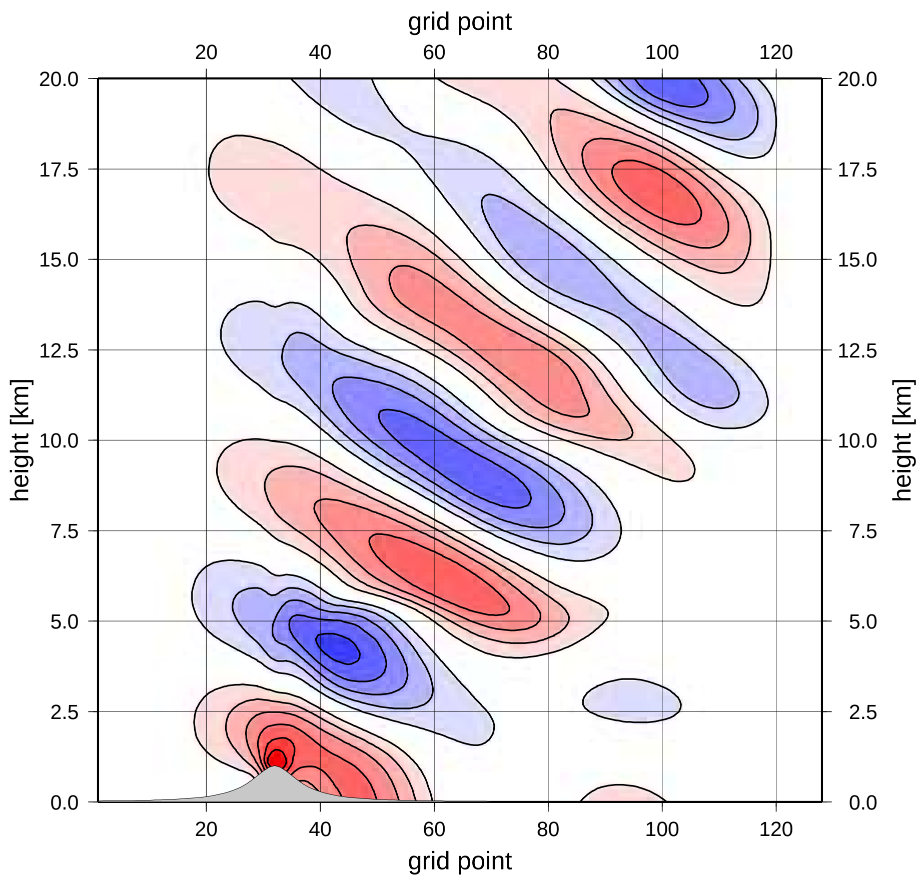
perturbation of horizontal velocity v'

euler



$\Delta t = 1\,\mathrm{s},\ N_{\mathrm{step}} = +5000$

SL3TL

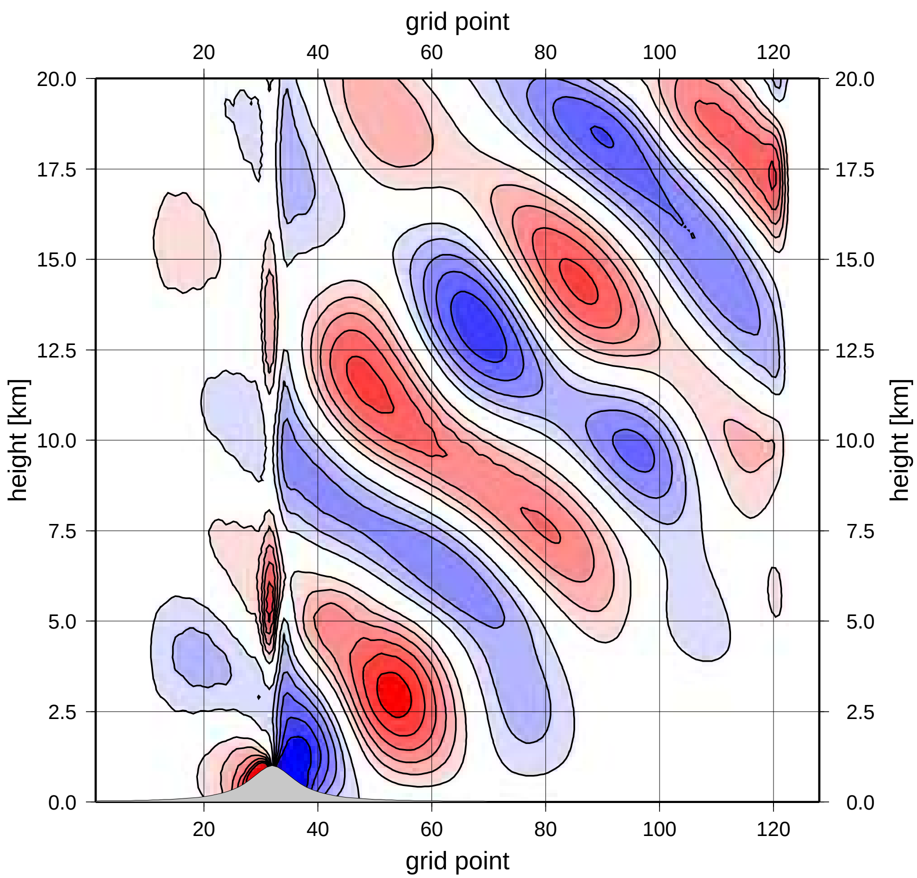


$\Delta t = 5\,\mathrm{s},\ N_{\mathrm{step}} = +1000$

Sensitivity to timestep - SL3TL scheme

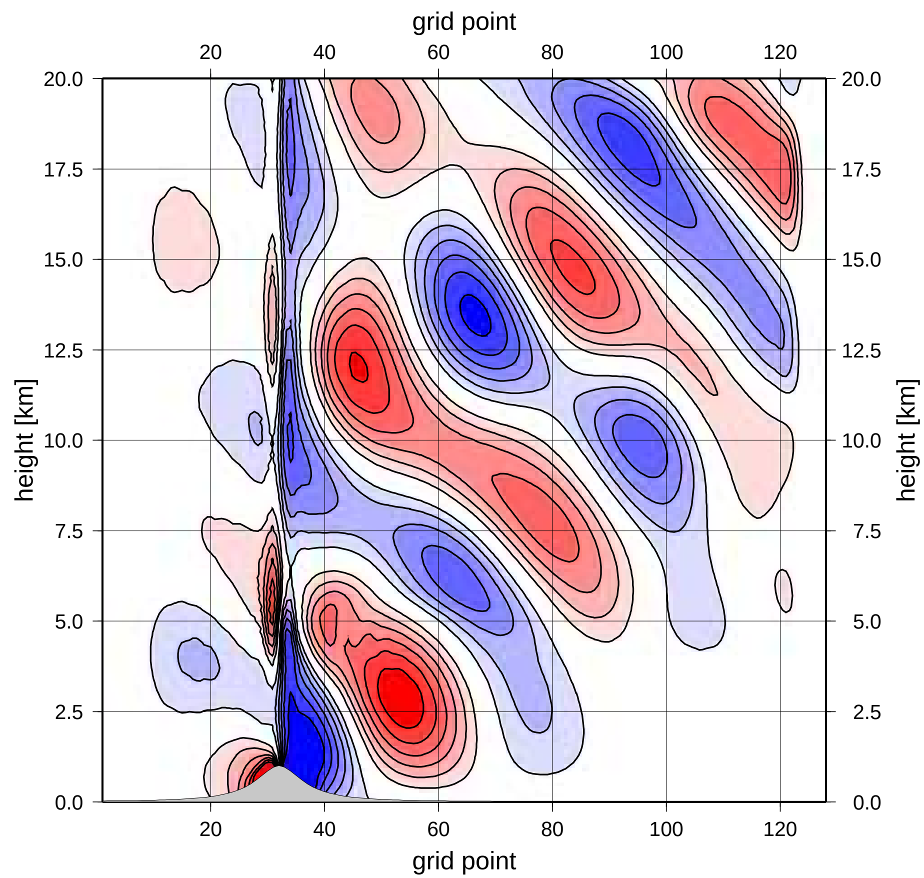
vertical velocity w

eulerian timestep



$\Delta t = 1\,\mathrm{s},\ N_{\mathrm{step}} = +5000$

SL timestep

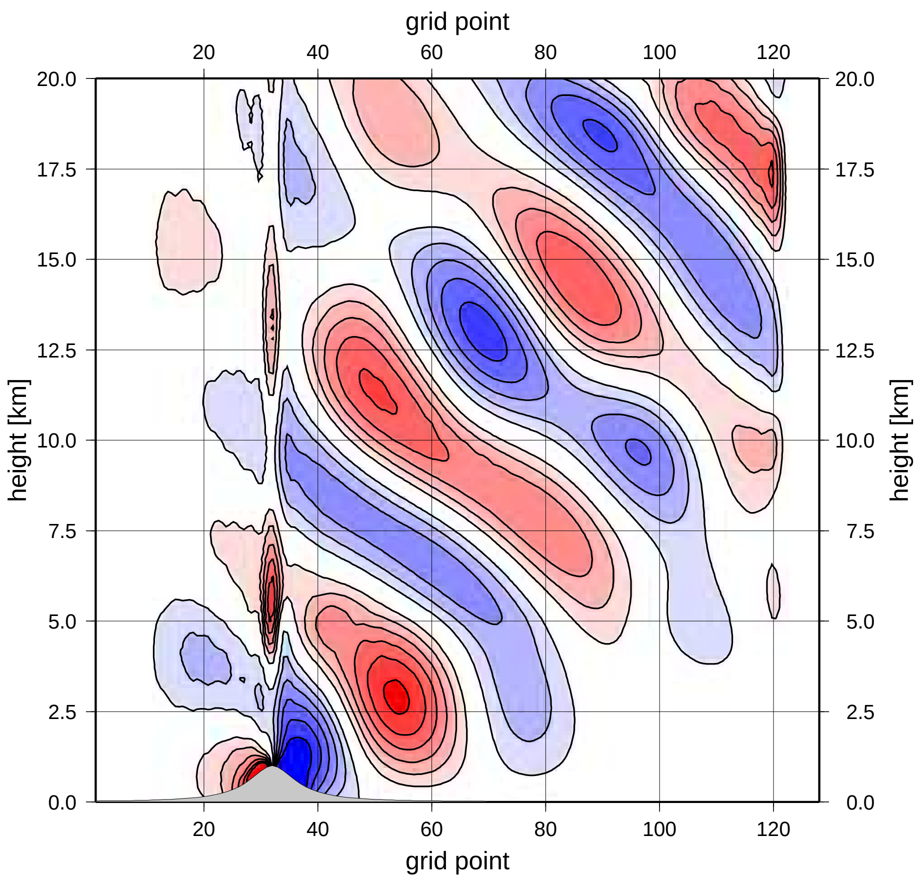


$\Delta t = 5\,\mathrm{s},\ N_{\mathrm{step}} = +1000$

Sensitivity to timestep - SL2TL scheme

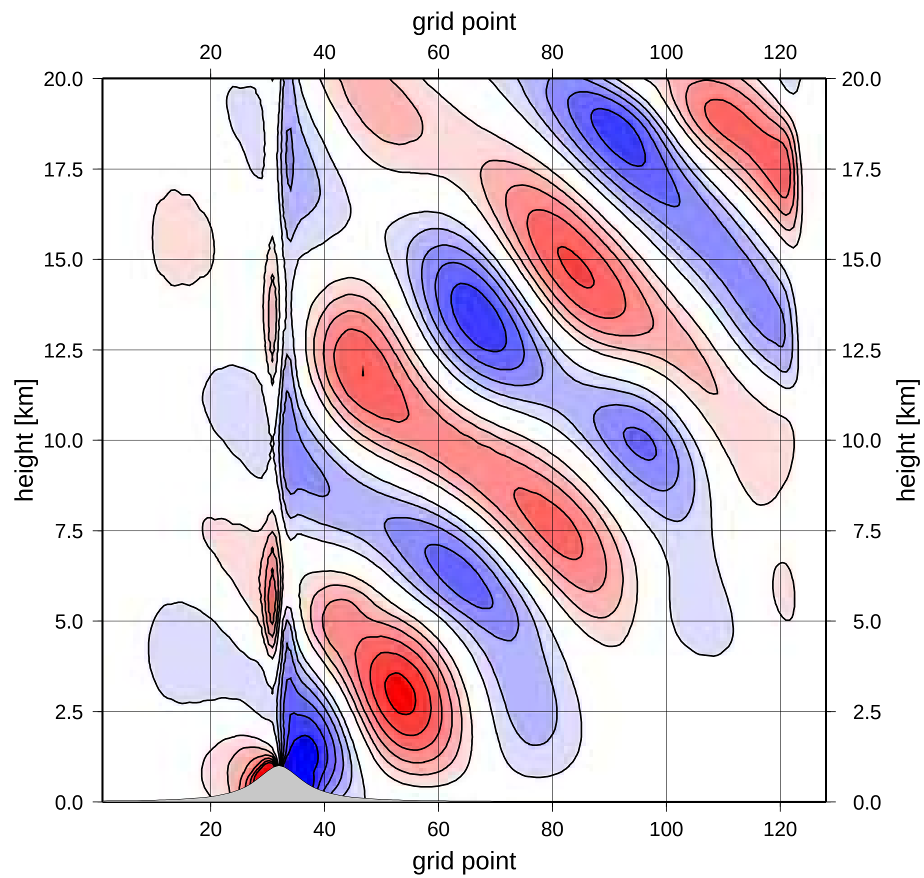
vertical velocity w

eulerian timestep



$\Delta t = 1\,\mathrm{s},\ N_{\mathrm{step}} = +5000$

SL timestep



$\Delta t = 10\,\mathrm{s},\ N_{\mathrm{step}} = +0500$

Summary of NLNH results

- eulerian scheme gives correct response, but the fields are noisy
- with semi-lagrangian scheme fields are less noisy, but chimney pattern appears in w field
- SL chimney does not disappear even with eulerian timesteps
- other fields seem to be unaffected in SL case

Explanation of SL chimney

- every evolution of vertical divergence d implicitly evolves also surface vertical velocity $w_{\tilde{L}}$, since:

$$d_L = \frac{g w_{\tilde{L}} - g w_{\tilde{L}-1}}{\delta \phi_L}$$

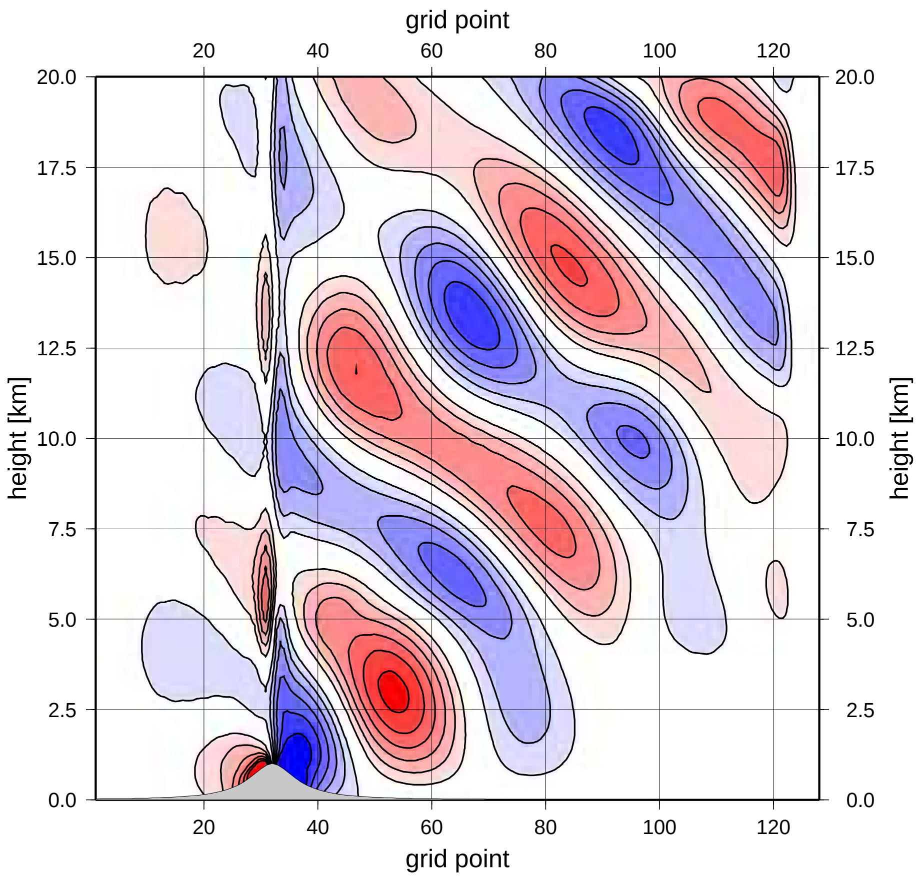
- due to free slip BBC, this implicit evolution of $w_{\tilde{L}}$ must be consistent with evolution of $\mathbf{v}_{\tilde{L}}$

- in SL case consistency was violated, because term d/d$t(\mathbf{v}_{\tilde{L}} \cdot \nabla \phi_{\tilde{L}})$ used in derivation of BBC for $(\partial \tilde{p} / \partial \pi)_{\tilde{L}}$ was expressed in eulerian way, i.e. inconsistently with semi-lagrangian evolution of $\mathbf{v}_{\tilde{L}}$

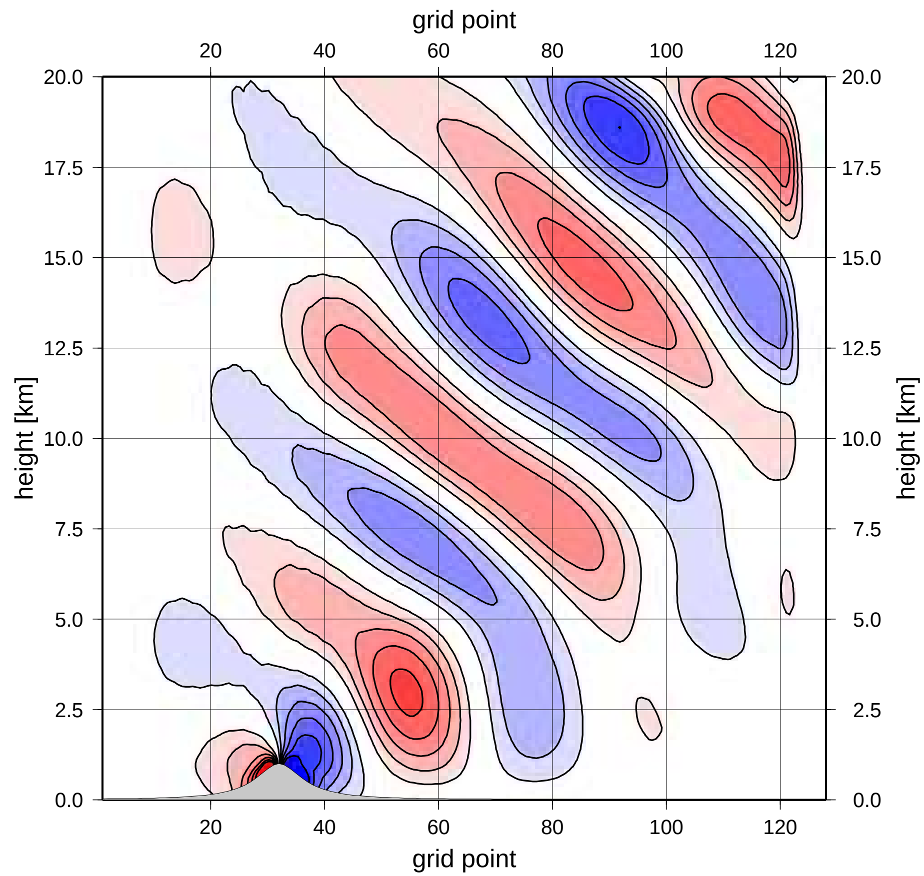
First chimney treatment - advection of w

vertical velocity w

SL2TL



SL2TL, `LGWADV`

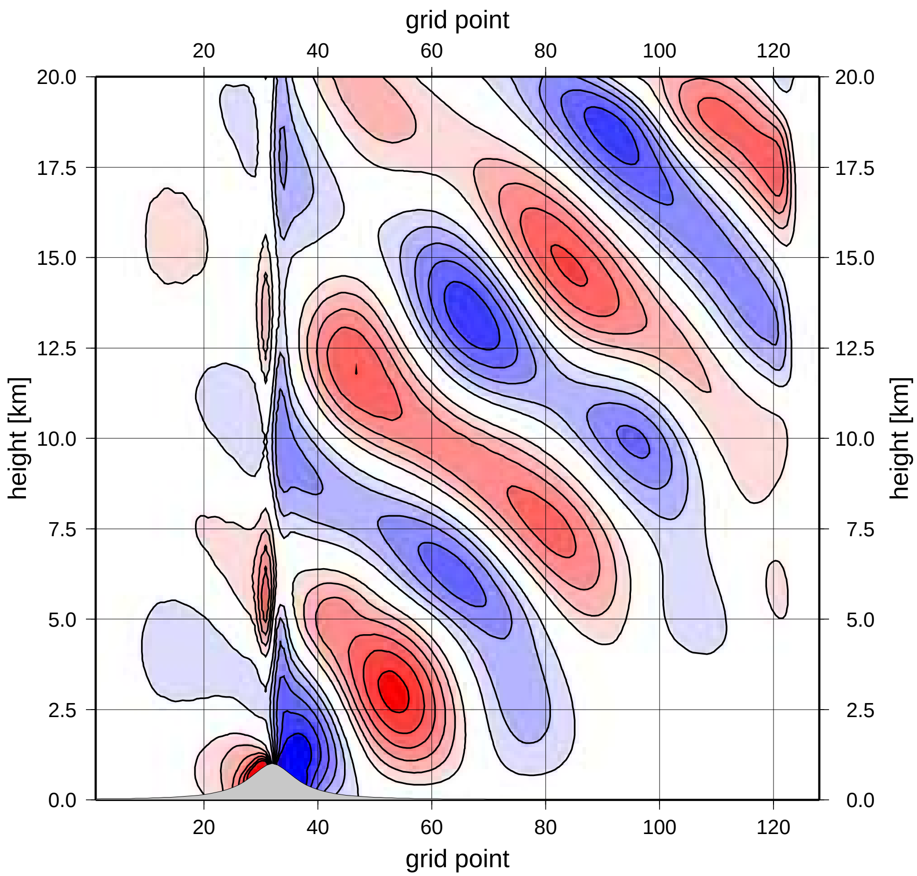


$\Delta t = 10\,\text{s},\ N_{\text{step}} = +0500$

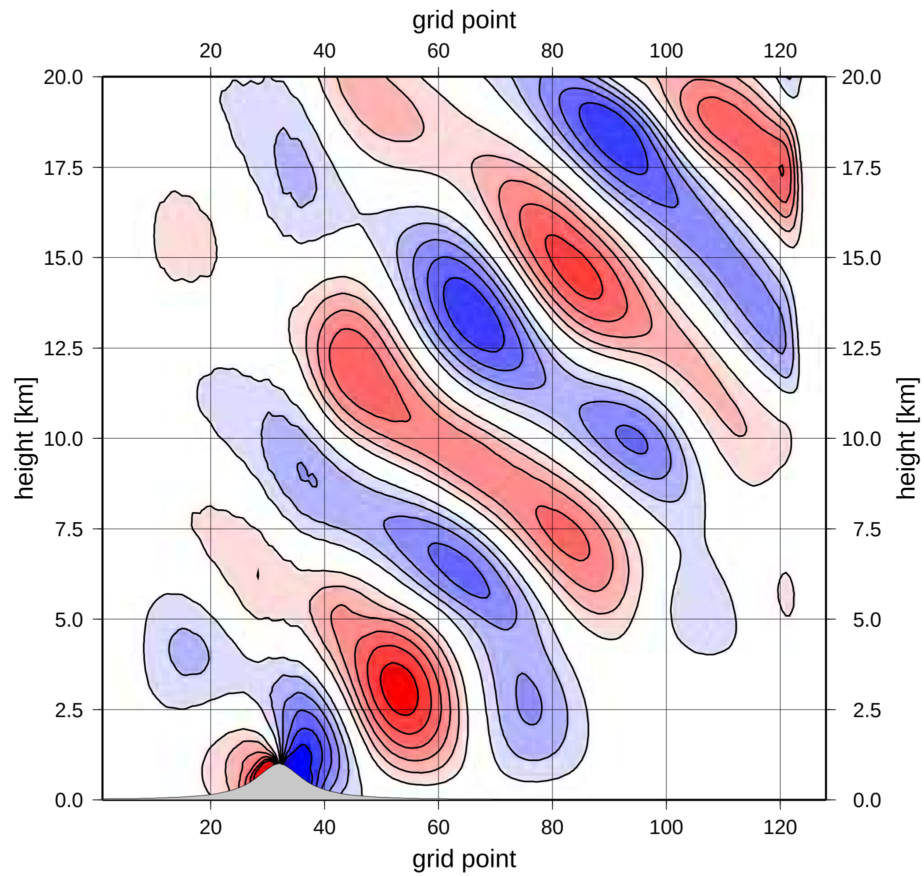
Second chimney treatment - diagnostic BBC

vertical velocity w

SL2TL



SL2TL, `LRDBBC`



$$\Delta t = 10\,\mathrm{s},\ N_{\mathrm{step}} = +0500$$

Advection of w – outline of the scheme (1)

- central idea is to use vertical velocity w instead of vertical divergence d in gridpoint computations $\Rightarrow$ no need to evaluate BBC for the term $(\partial\tilde{p}/\partial\pi)_{\tilde{L}}$

- however, for stability reasons variable d must be kept in spectral part of SI computations

- non-trivial part of the job is preparation of RHS for Helmholtz solver, because operators acting on w must be transformed into operators acting on d (transformation is non-linear)

- problem is solved by using the fact that transformation between explicit guesses $\tilde{w}^{+}$ and $\tilde{d}^{+}$ is very close to transformation between final quantities w^{+} and d^{+}

Advection of w – outline of the scheme (2)

- in gridpoint computations prognostic equation for vertical momentum is used:

$$\left[\frac{\mathrm{d}(gw)}{\mathrm{d}t}\right]_{\tilde{l}} = g^2\left(\frac{\partial \tilde{p}}{\partial \pi}\right)_{\tilde{l}} + g\mathcal{W}_{\tilde{l}}$$

- surface tendency $[\mathrm{d}(gw)/\mathrm{d}t]_{\tilde{L}}$ is not needed for evolution of $w_{\tilde{L}}$, since it can be diagnosed from free slip BBC

- but since SL advection is used, surface tendency $[\mathrm{d}(gw)/\mathrm{d}t]_{\tilde{L}}$ might be needed for evolution of $w_{\tilde{l}}$ at higher levels

- before performing SL interpolations, surface tendency $[\mathrm{d}(gw)/\mathrm{d}t]_{\tilde{L}}$ must be initialized with provisional value diagnosed in eulerian way

- this residual inconsistency seems to be harmless for the performance of the scheme

Diagnostic BBC – outline of the scheme

- main idea of diagnostic BBC is to express problematic surface term in semi-lagrangian way

- in case of SL3TL scheme this gives (subscript $\tilde{L}$ is omitted):

$$\left[\frac{\mathrm{d}}{\mathrm{d}t}(\mathbf{v}\cdot\nabla\phi)\right]_M^0 = \frac{\tilde{\mathbf{v}}_F^+\cdot\nabla\phi_F - \mathbf{v}_O^-\cdot\nabla\phi_O}{2\Delta t}$$

- explicit guess $\tilde{\mathbf{v}}_F^+$ is known only after performing SL interpolations $\Rightarrow$ before going to SL interpolations term $(\partial\tilde{p}/\partial\pi)_{\tilde{L}}$ must be provisionally diagnosed in eulerian way

- afterwards tendency $(\mathrm{d}d/\mathrm{d}t)_L$ is rediagnosed using SL approach, but tendencies at higher levels might remain affected by provisional BBC diagnostics

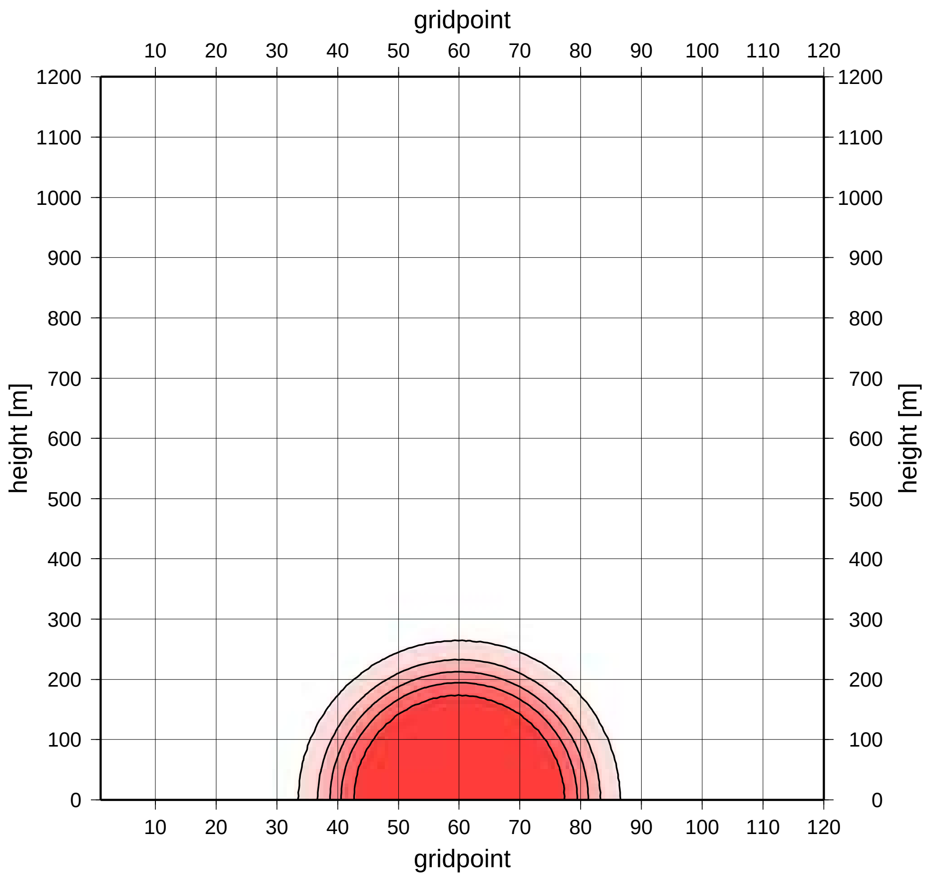
- but again, this residual inconsistency seems to be harmless

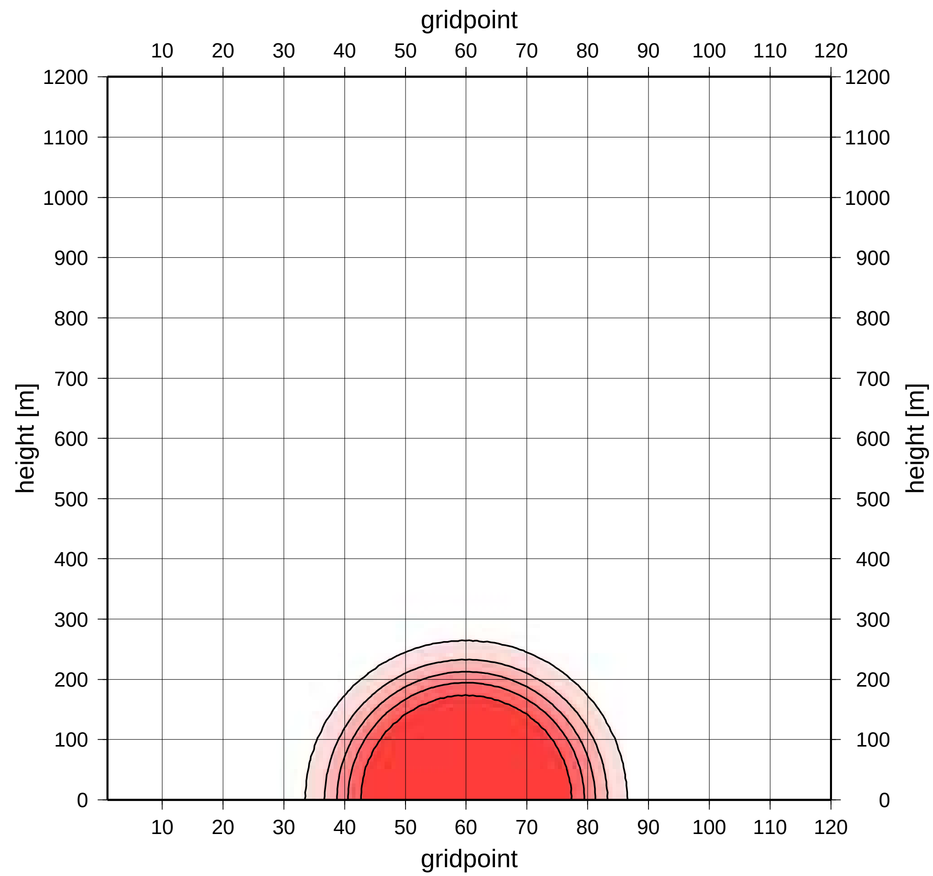
Surprise from bubble experiment

perturbation of potential temperature θ'

SL2TL, advection of w

SL2TL, advection of d



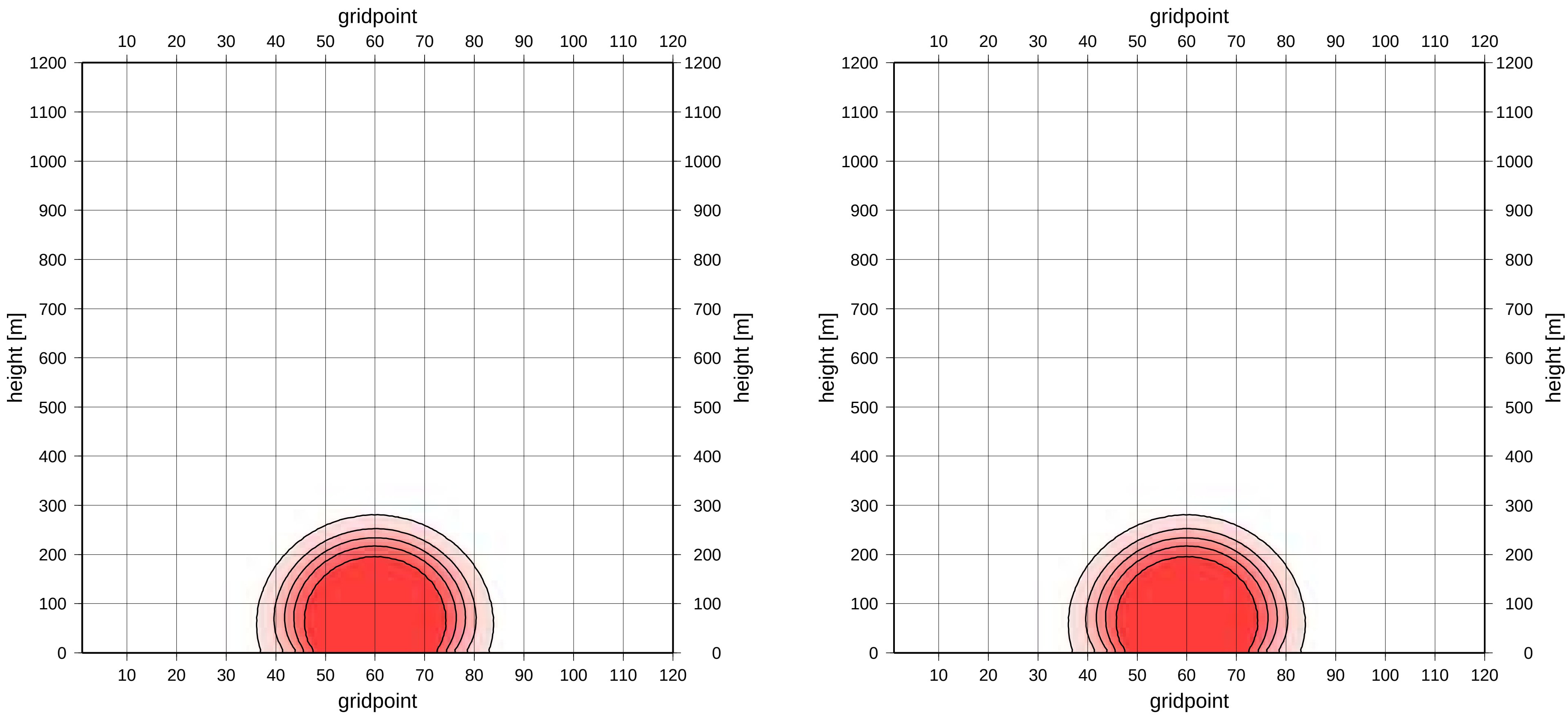


$\Delta t = 1\,\mathrm{s},\ N_{\mathrm{step}} = +0000$

Surprise from bubble experiment

perturbation of potential temperature θ'

SL2TL, advection of w SL2TL, advection of d



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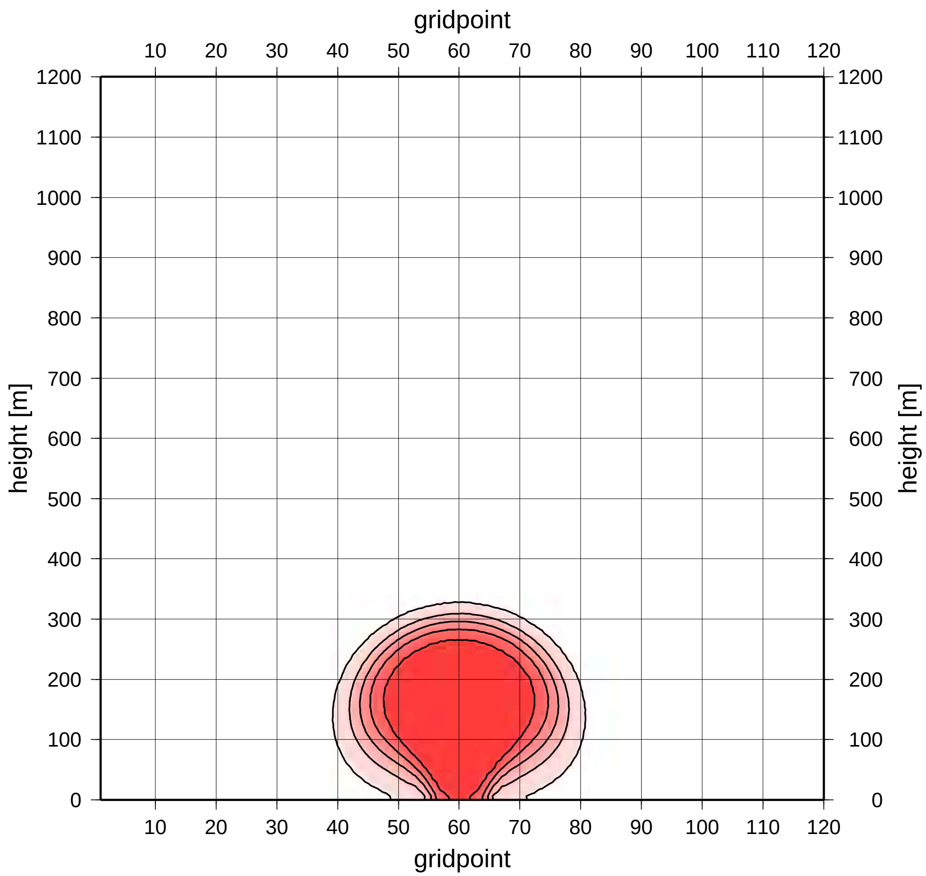
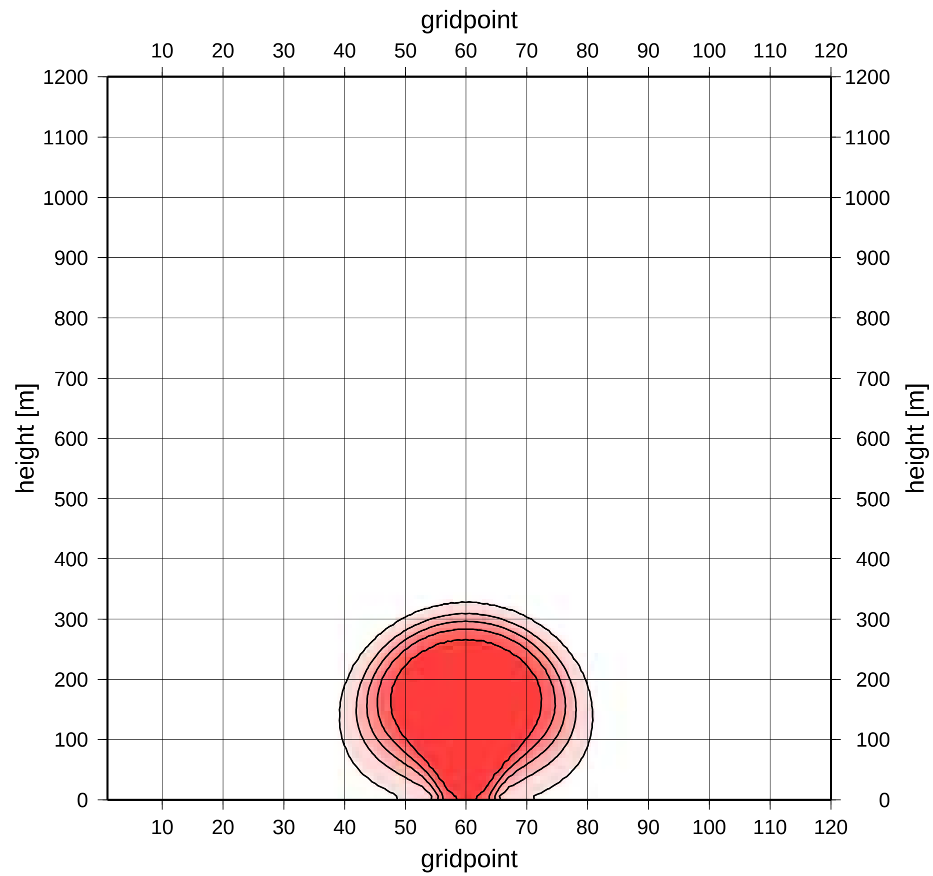
Surprise from bubble experiment

perturbation of potential temperature θ'

SL2TL, advection of w



SL2TL, advection of d



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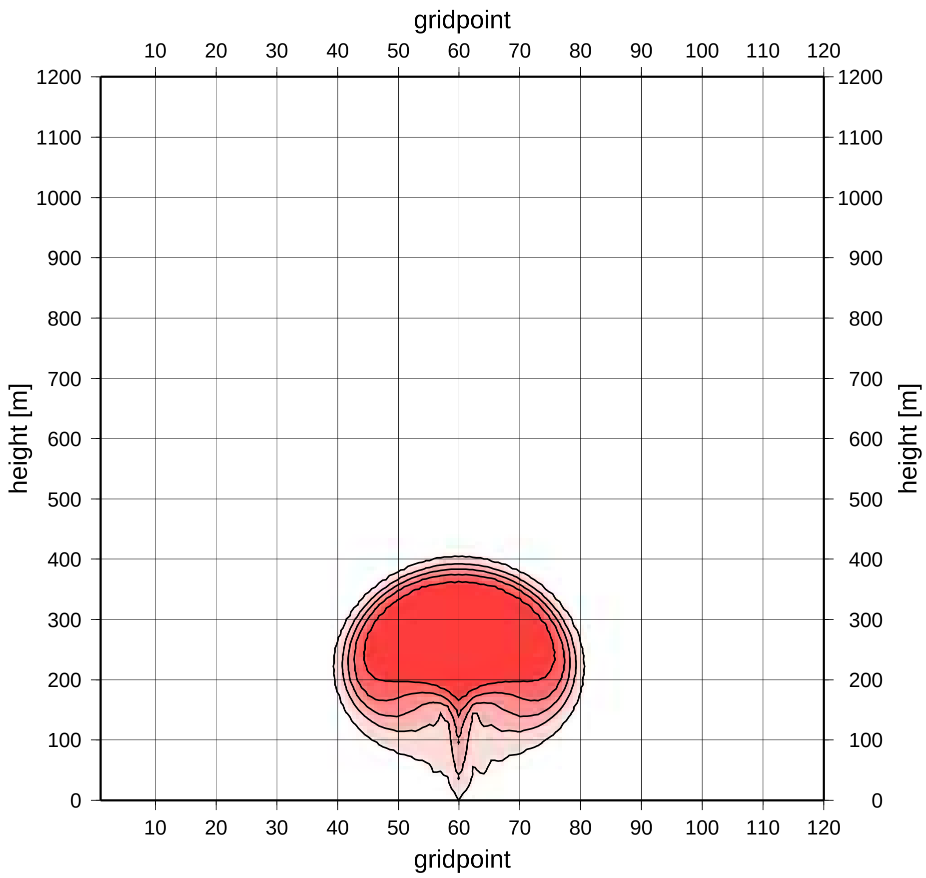
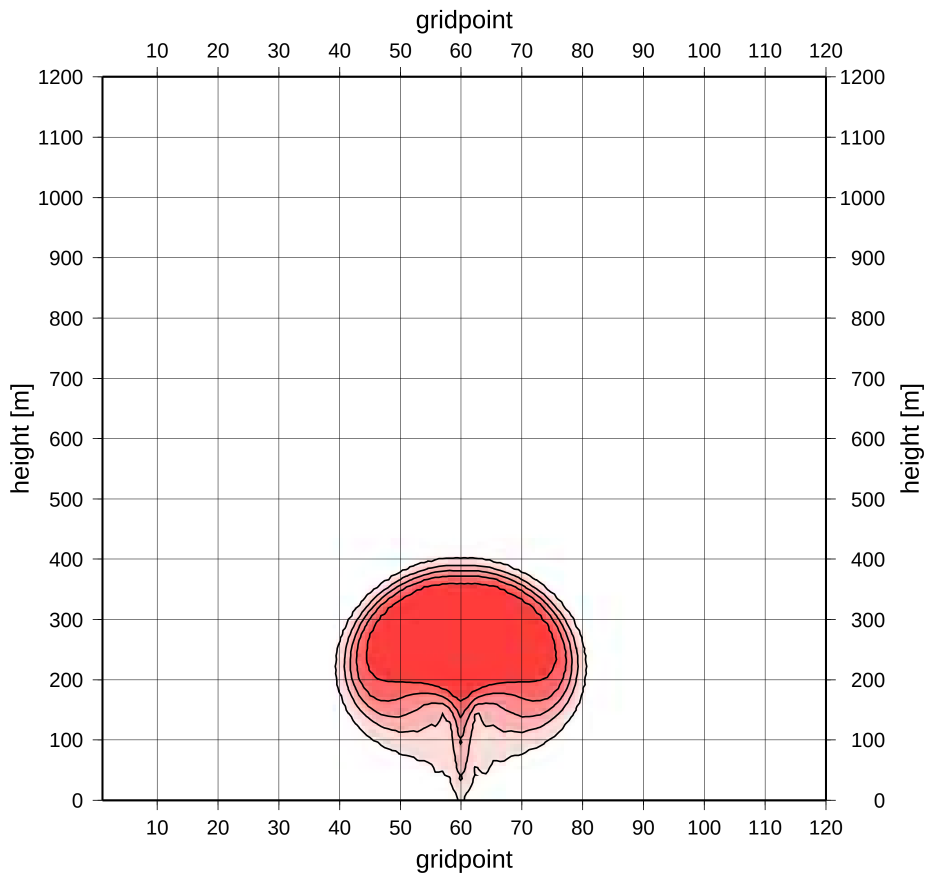
Surprise from bubble experiment

perturbation of potential temperature θ'

SL2TL, advection of w



SL2TL, advection of d

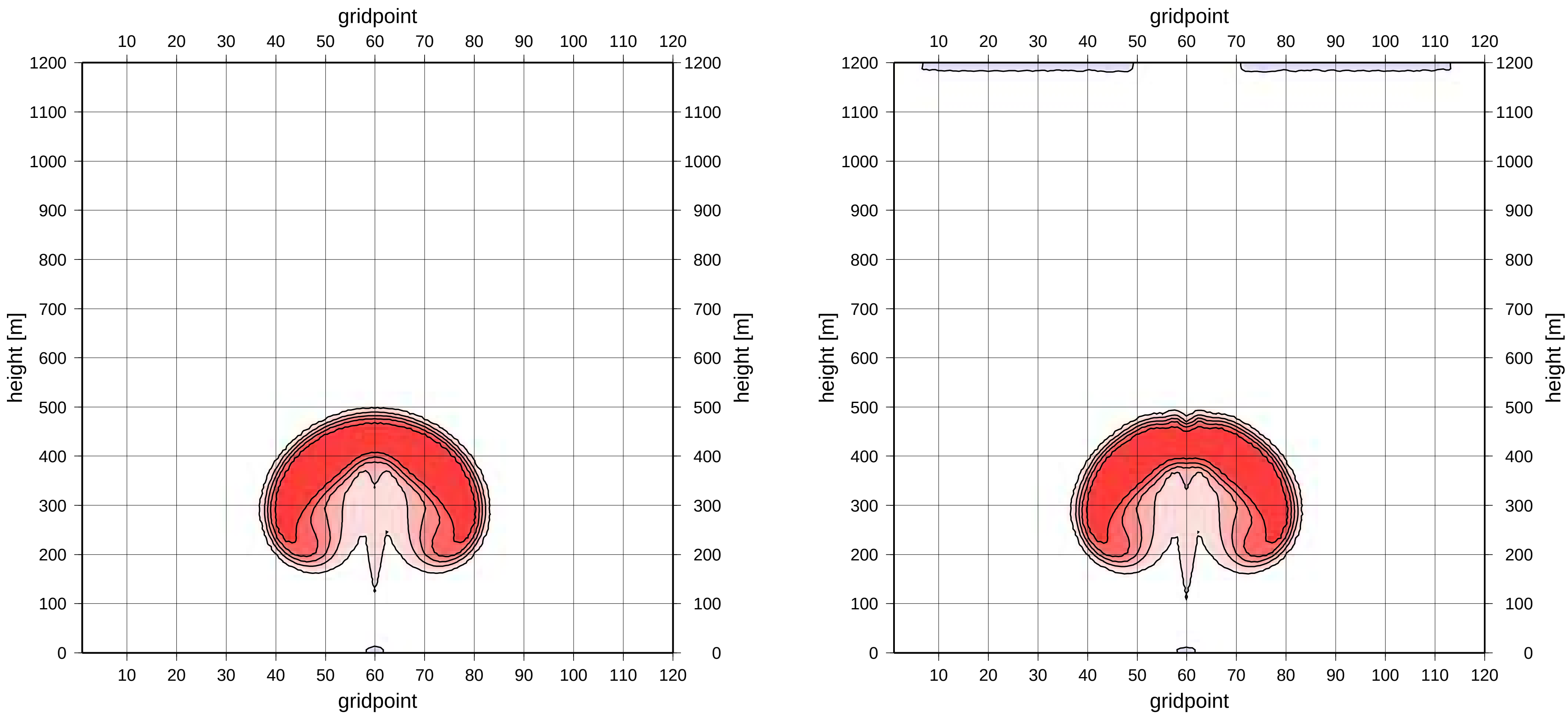


$$\Delta t = 1\,\text{s},\ N_{\text{step}} = +0300$$

Surprise from bubble experiment

perturbation of potential temperature θ'

SL2TL, advection of w — SL2TL, advection of d

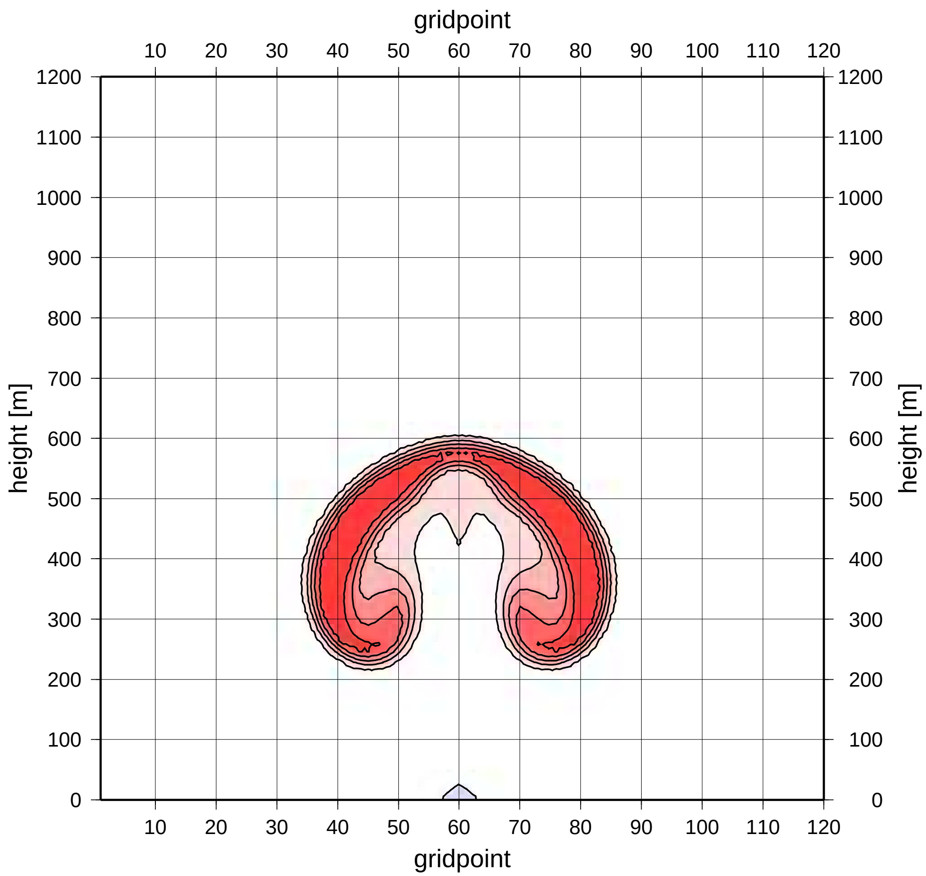


$\Delta t = 1\,\text{s},\ N_{\text{step}} = +0400$

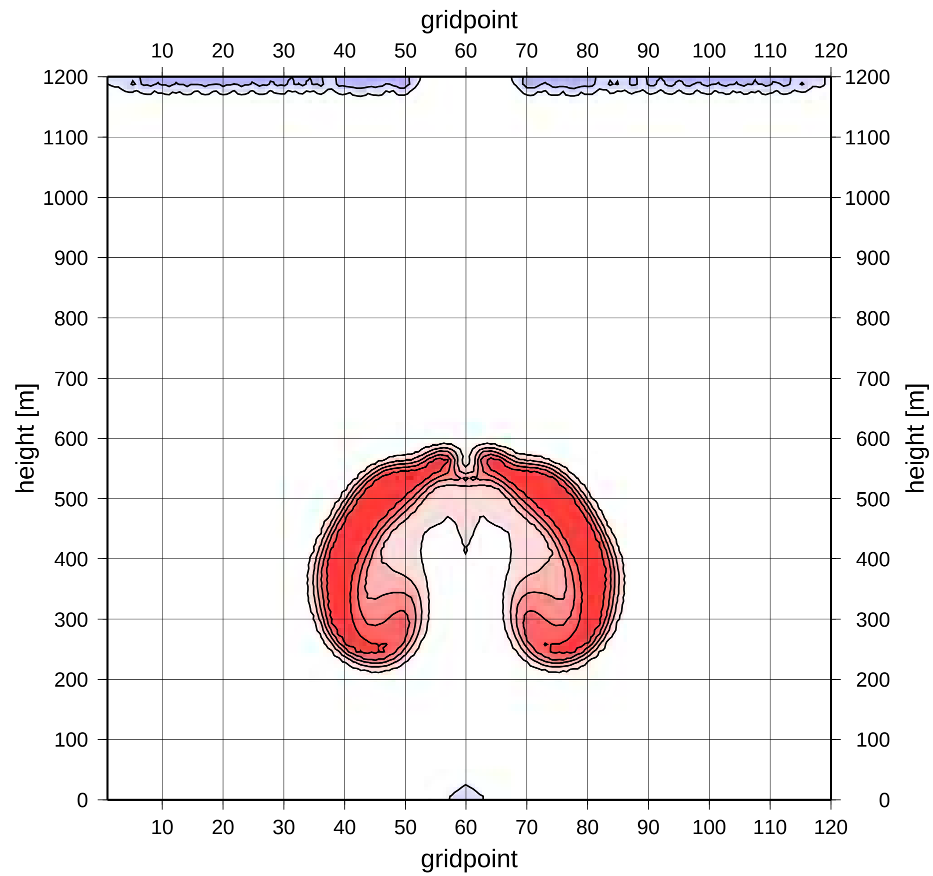
Surprise from bubble experiment

perturbation of potential temperature θ'

SL2TL, advection of w



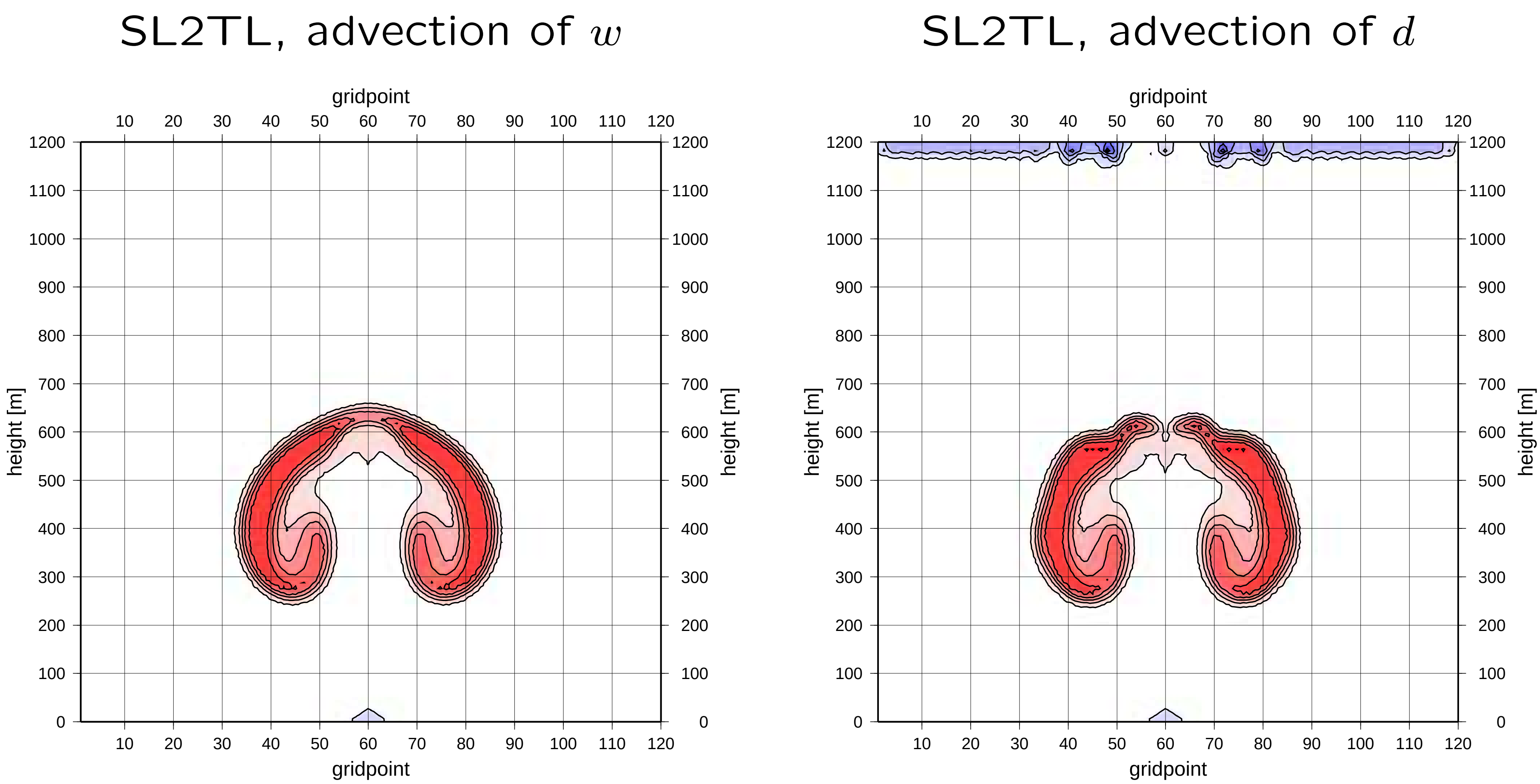
SL2TL, advection of d



$$\Delta t = 1\,\mathrm{s},\ N_{\mathrm{step}} = +0500$$

Surprise from bubble experiment

perturbation of potential temperature θ'

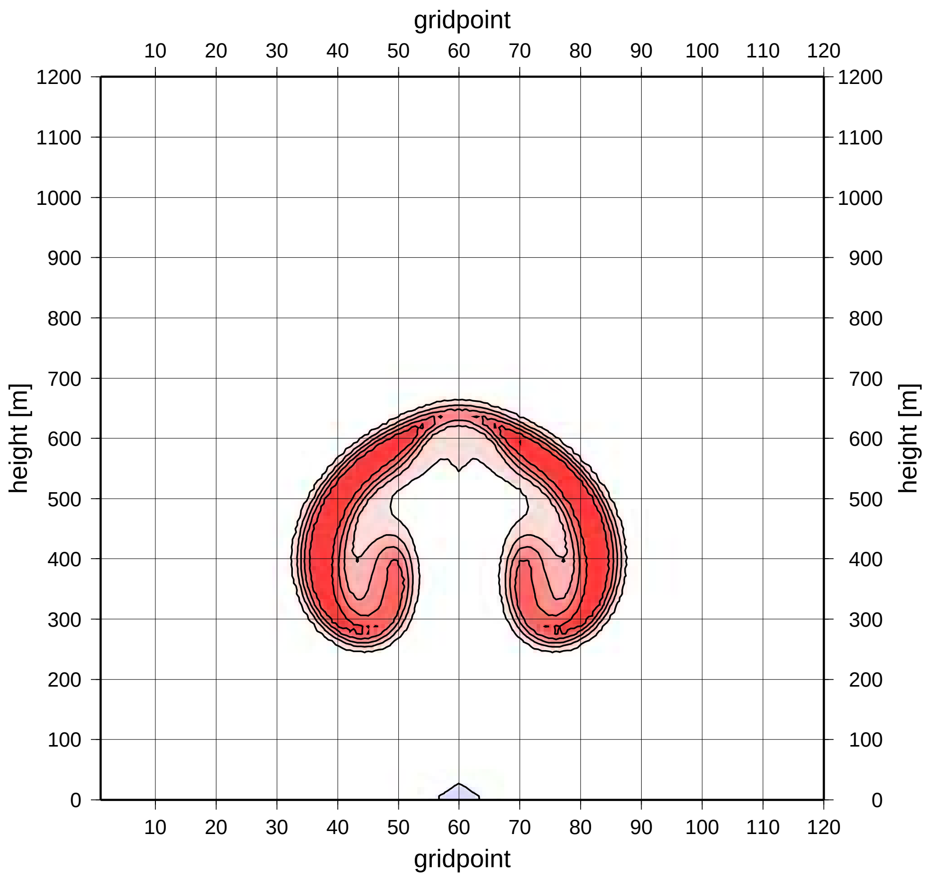


$\Delta t = 1\,\mathrm{s},\ N_{\mathrm{step}} = +0550$

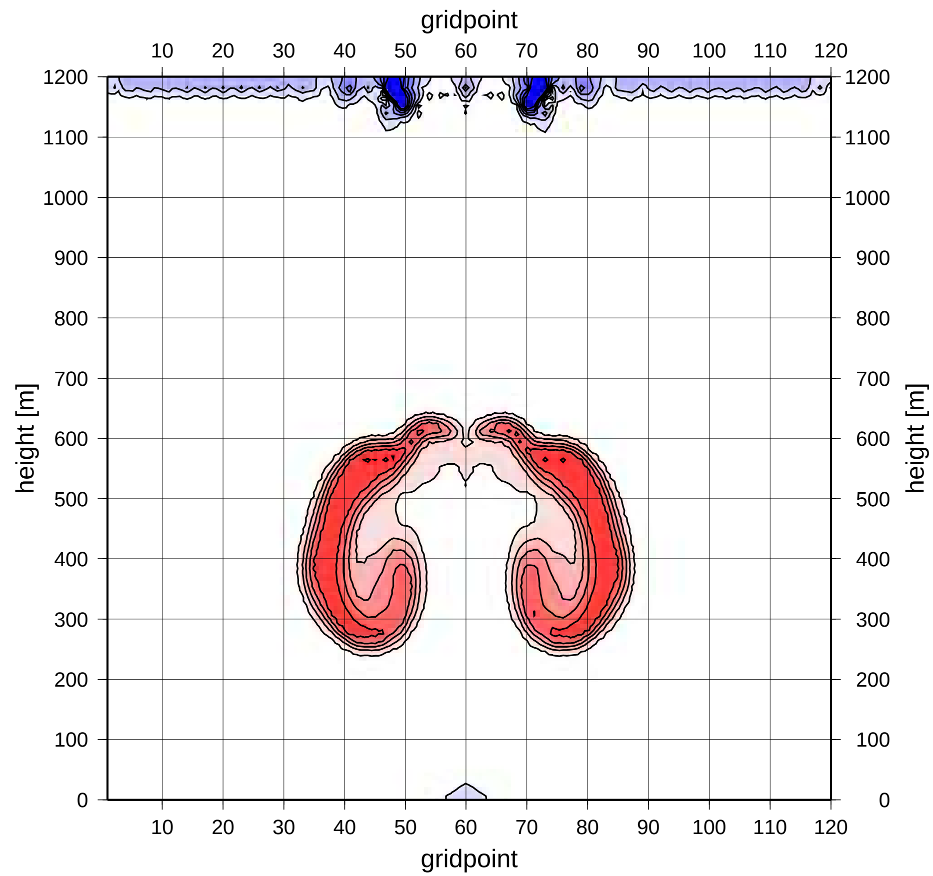
Surprise from bubble experiment

perturbation of potential temperature θ'

SL2TL, advection of w



SL2TL, advection of d

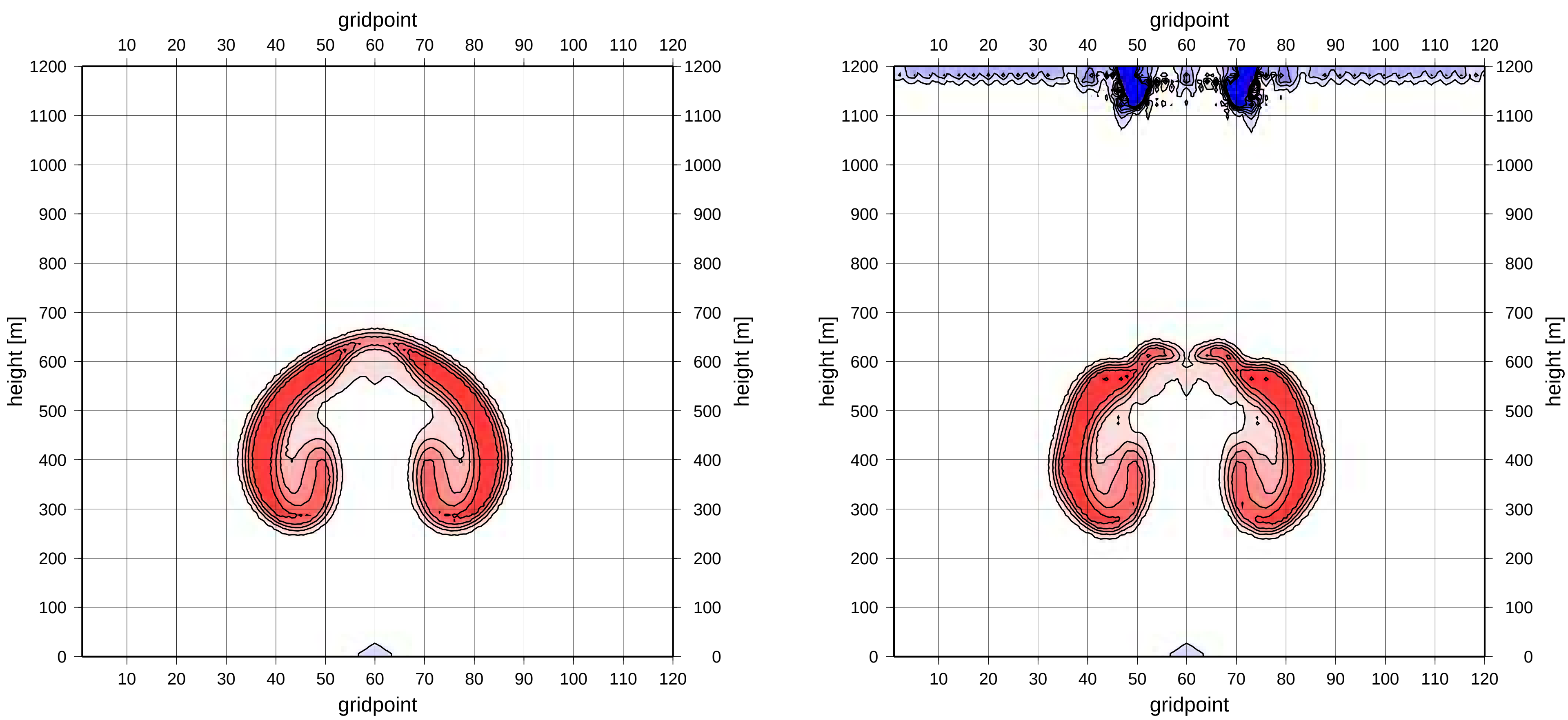


$\Delta t = 1\,\text{s},\ N_{\text{step}} = +0555$

Surprise from bubble experiment

perturbation of potential temperature θ'

SL2TL, advection of w | SL2TL, advection of d

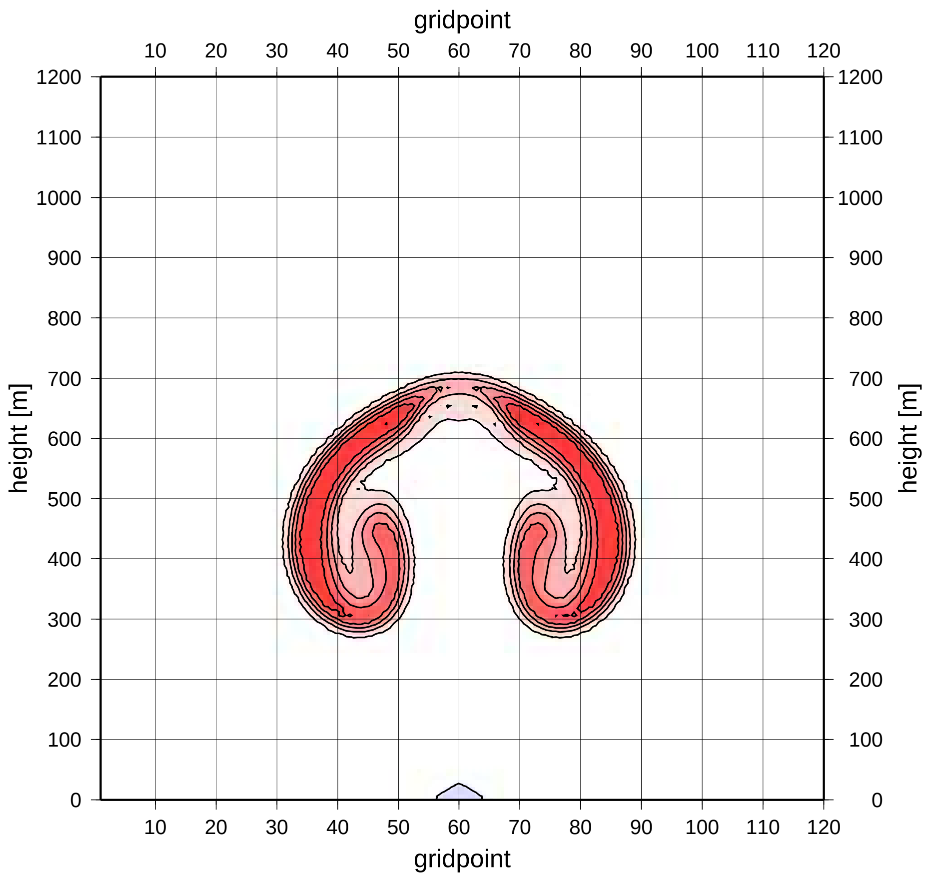


$$\Delta t = 1\,\text{s},\ N_{\text{step}} = +0558$$

Surprise from bubble experiment

perturbation of potential temperature θ'

SL2TL, advection of w



SL2TL, advection of d

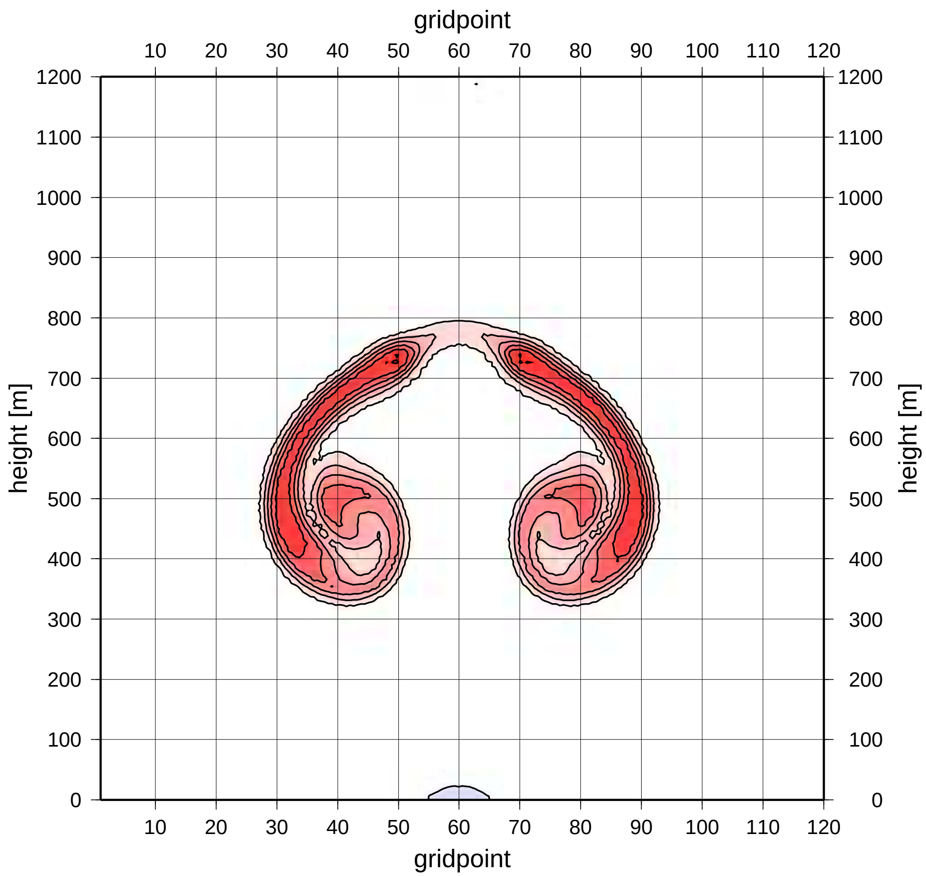
exploded at $N_{\text{step}} = +0560$

$\Delta t = 1\,\text{s}$, $N_{\text{step}} = +0600$

Surprise from bubble experiment

perturbation of potential temperature θ'

SL2TL, advection of w



SL2TL, advection of d

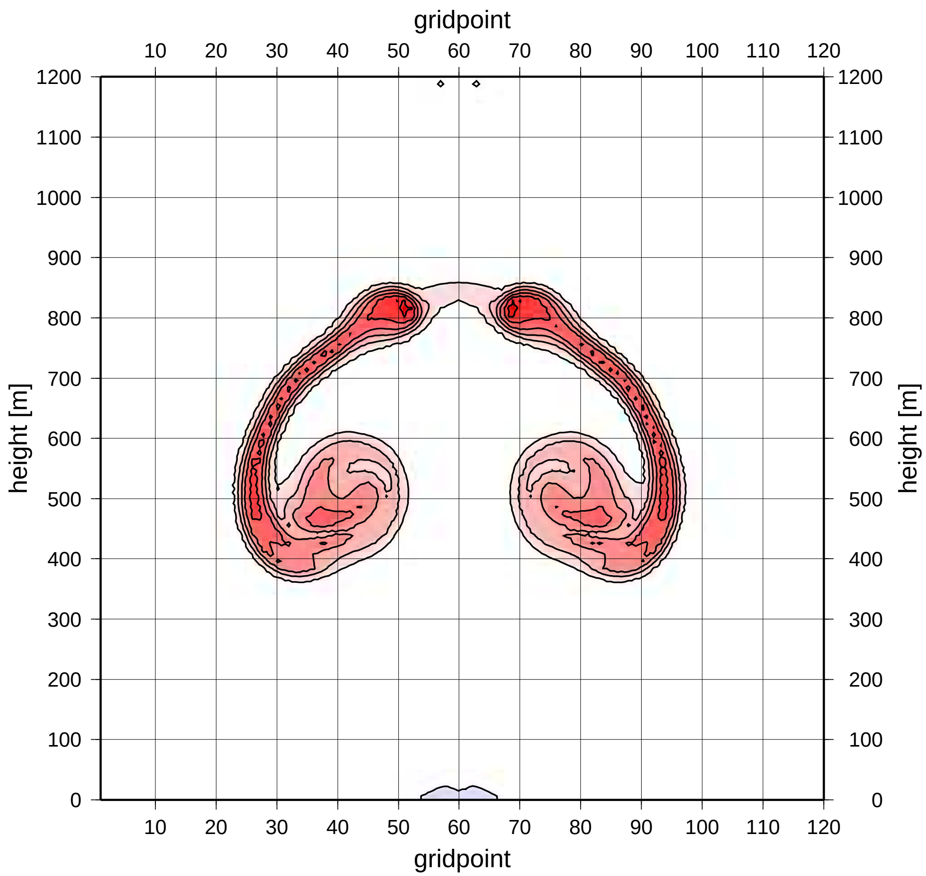
exploded at $N_{\text{step}} = +0560$

$\Delta t = 1\,\text{s},\ N_{\text{step}} = +0700$

Surprise from bubble experiment

perturbation of potential temperature θ'

SL2TL, advection of w



SL2TL, advection of d

exploded at $N_{\text{step}} = +0560$

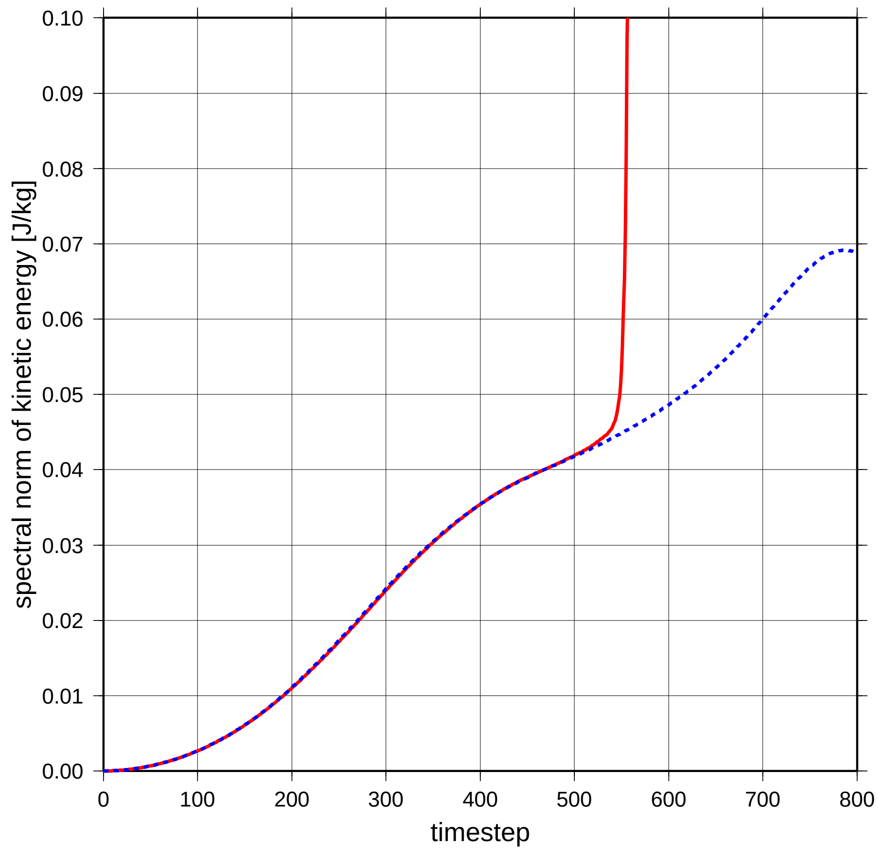
$\Delta t = 1\,\text{s},\ N_{\text{step}} = +0800$

Quick look at explosion

spectral norms of kinetic energy

SL2TL, advection of w

SL2TL, advection of d



SL chimney treatment – summary

- currently two SL chimney treatments are coded:
  - advection of w (available only for SL2TL NESC scheme):

```
&NAMDYNA
  LGWADV=.T.,
```

  - diagnostic BBC:

```
&NAMDYNA
  LRDBBC=.T.,
```

- diagnostic BBC is better suited for traditional ALADIN-NH choices
- advection of w requires extra SL interpolations of half level quantities, but on the other hand it reduces spurious noise in bubble experiments (problem still to be understood)
- for the time being both treatments are kept in the code

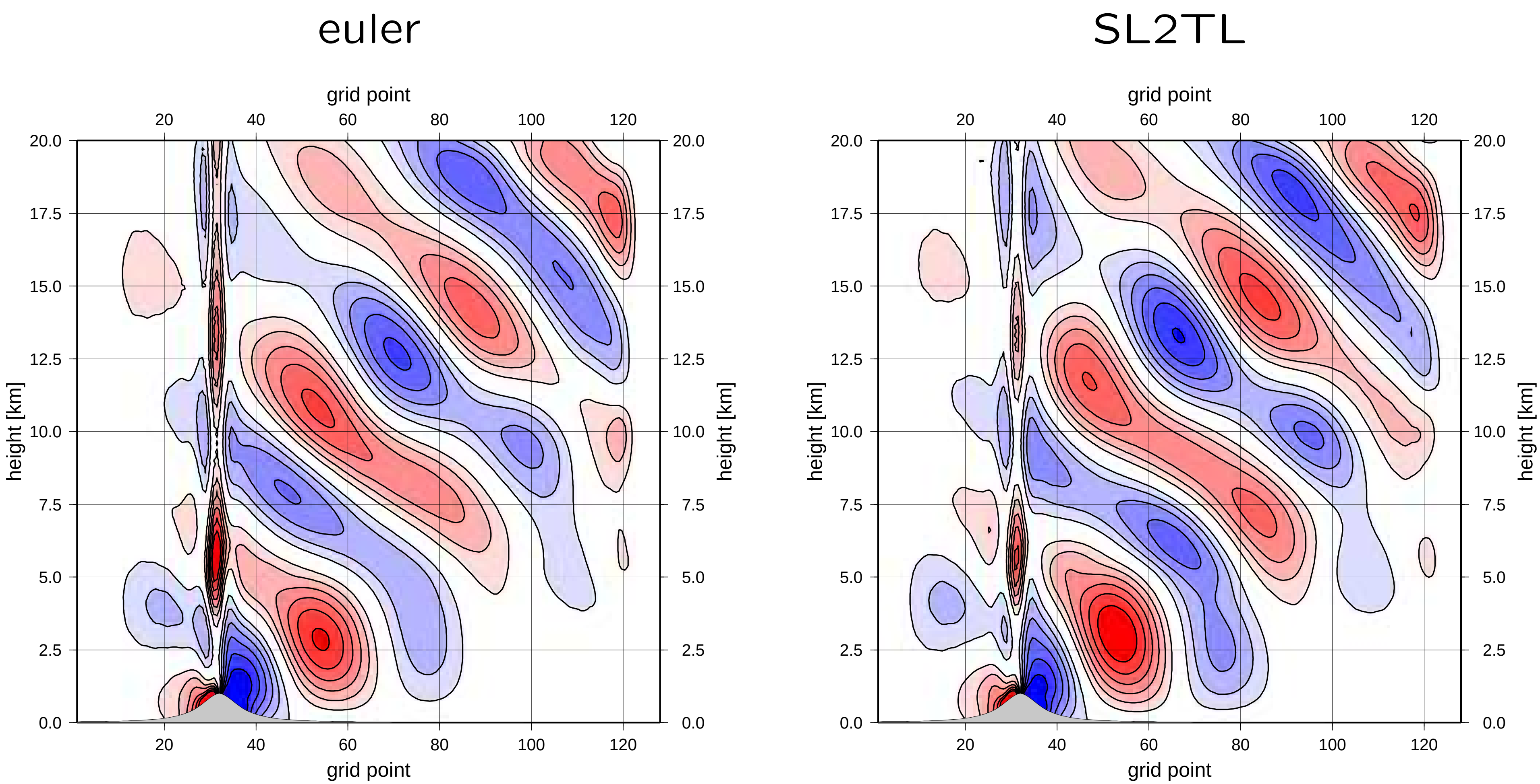
Now when safe from chimneys, what about reducing the noise in NLNH regime?

- noise usually appears due to non-linearity of the flow
- in order to suppress it, horizontal diffusion (HD) can be activated:

```
&NAMDYN
  REXPDH=4.,       ... order of diffusion
  RRDXTAU=200.,    ... strength of diffusion [s^-1]
  RDAMPDIV=1.,     ... damping factor for D
  RDAMPVD=1.,      ... damping factor for d
  RDAMPVOR=5.,     ... damping factor for ξ
  RDAMPPD=5.,      ... damping factor for q̂
  RDAMPT=5.,       ... damping factor for T
  RDAMPSP=0.,      ... no HD on π_S
```

- diagnostic BBC is used to suppress SL chimney, other experimental settings remain unchanged

Chimney again – even with eulerian advection!



$\Delta t = 1.0\,\mathrm{s},\ N_{\mathrm{step}} = +5000$ $\qquad$ $\Delta t = 10.0\,\mathrm{s},\ N_{\mathrm{step}} = +0500$

What is the source of chimney now?

- apparently it is horizontal diffusion, but why?
- once again, the problem is caused by inconsistent BBC treatment
- in order to see the reason, it is enough to look at continuous equations for momentum:

$$\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = -\frac{RT}{p}\nabla p - \left(\frac{\partial \tilde{p}}{\partial \pi} + 1\right)\nabla\phi + \mathcal{V}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}(gw) = g^2\frac{\partial \tilde{p}}{\partial \pi} + g\mathcal{W}$$

- source terms $\mathcal{V}$ and $\mathcal{W}$ contain also HD tendencies
- but since HD is applied in spectral space while BBC is evaluated in gridpoint space, these terms are simply ignored in BBC treatment

Academic treatment of HD chimney (1)

- inclusion of HD source terms into BBC is not tractable in ALADIN-NH, since diffusion is applied in spectral space at the very end of timestep:

$$\frac{X^{+} - X^{(+)}}{\Delta t} = -K\nabla^4 X^{+}$$
$$X^{+} = [1 + \Delta t K \nabla^4]^{-1} X^{(+)}$$

$X^{(+)}$ – undiffused value coming from Helmholtz solver

- it is not easy to get HD tendencies into gridpoint space

- complementary approach is to leave BBC as it is, but in order to make it consistent with model dynamics not to diffuse $w_{\tilde{L}}$

Academic treatment of HD chimney (2)

- practically it means not to diffuse part of d_L containing $w_{\tilde{L}}$, i.e. apply HD on quantity $d_L - gw_{\tilde{L}}/\delta\phi_L$:

$$d_L^{+} = [1 + \Delta t K \nabla^4]^{-1} \left[d_L^{(+)} - \left(\frac{gw_{\tilde{L}}}{\delta\phi_L} \right)^{(+)} \right] + \left(\frac{gw_{\tilde{L}}}{\delta\phi_L} \right)^{+}$$

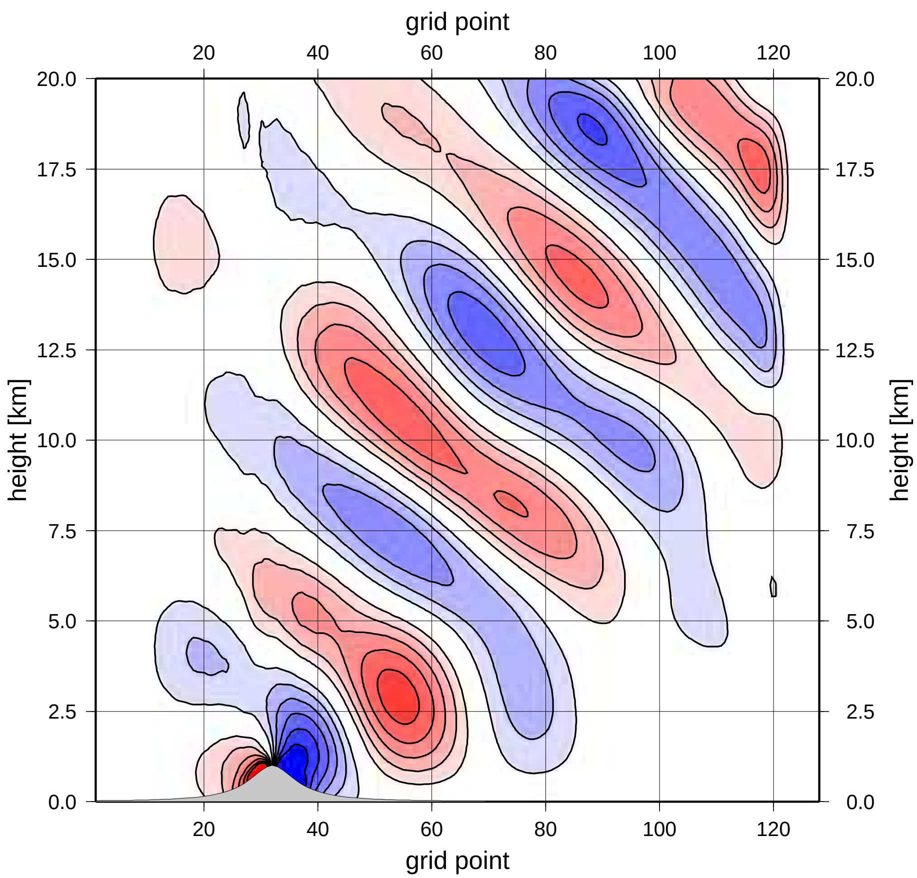
$$gw_{\tilde{L}}^{(+)} = \mathbf{v}_{\tilde{L}}^{(+)} \cdot \nabla\phi_{\tilde{L}} \qquad gw_{\tilde{L}}^{+} = \mathbf{v}_{\tilde{L}}^{+} \cdot \nabla\phi_{\tilde{L}}$$

- this treatment is unusable in 3D model, since it diagnoses non-linear terms in spectral space

- it can be easily implemented and tested in vertical plane 2D model, where it is not a problem to call extra spectral transforms

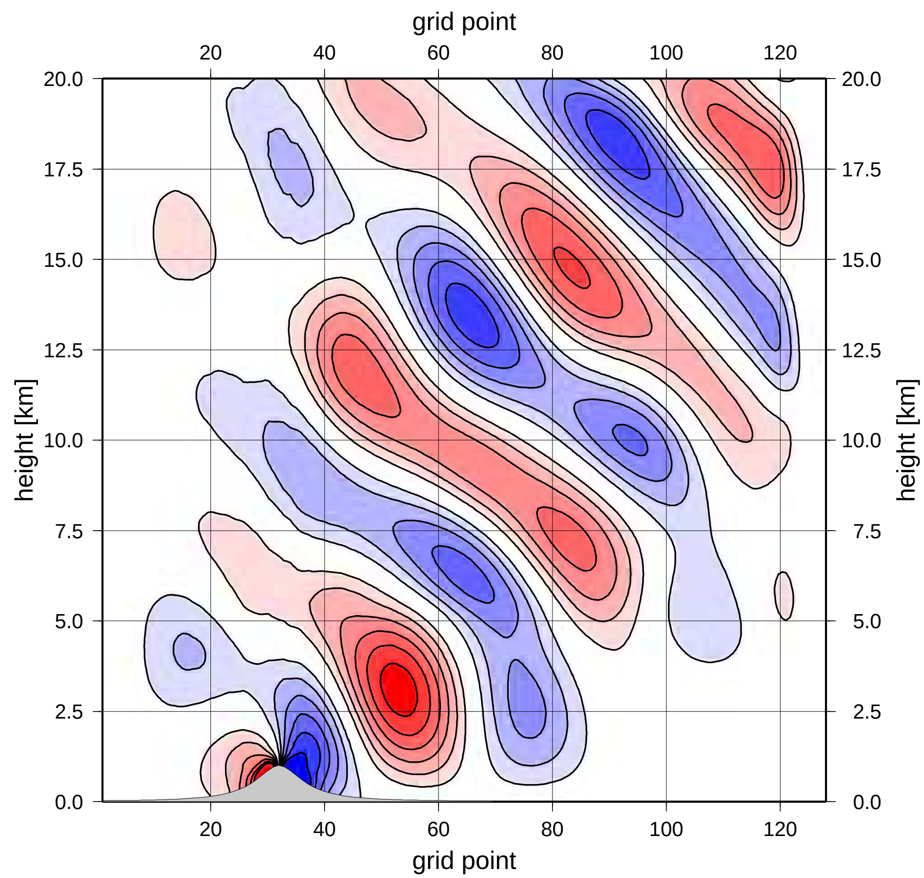
Results for academic HD chimney treatment

euler



$\Delta t = 1.0\,\text{s},\ N_{\text{step}} = +5000$

SL2TL



$\Delta t = 10.0\,\text{s},\ N_{\text{step}} = +0500$

Is there no treatment suitable for 3D model?

- there is, thanks to semi-lagrangian horizontal diffusion (SLHD) appearing at the right time

- it is based on diffusive properties of semi-lagrangian interpolators modulated by horizontal deformation of the flow

- SLHD enables to reduce significantly strength of spectral diffusion, especially in boundary layer

- in 3D real cases some residual spectral diffusion is needed to control small scale noise generated by orography, as well as to control noise generated at the top of model domain

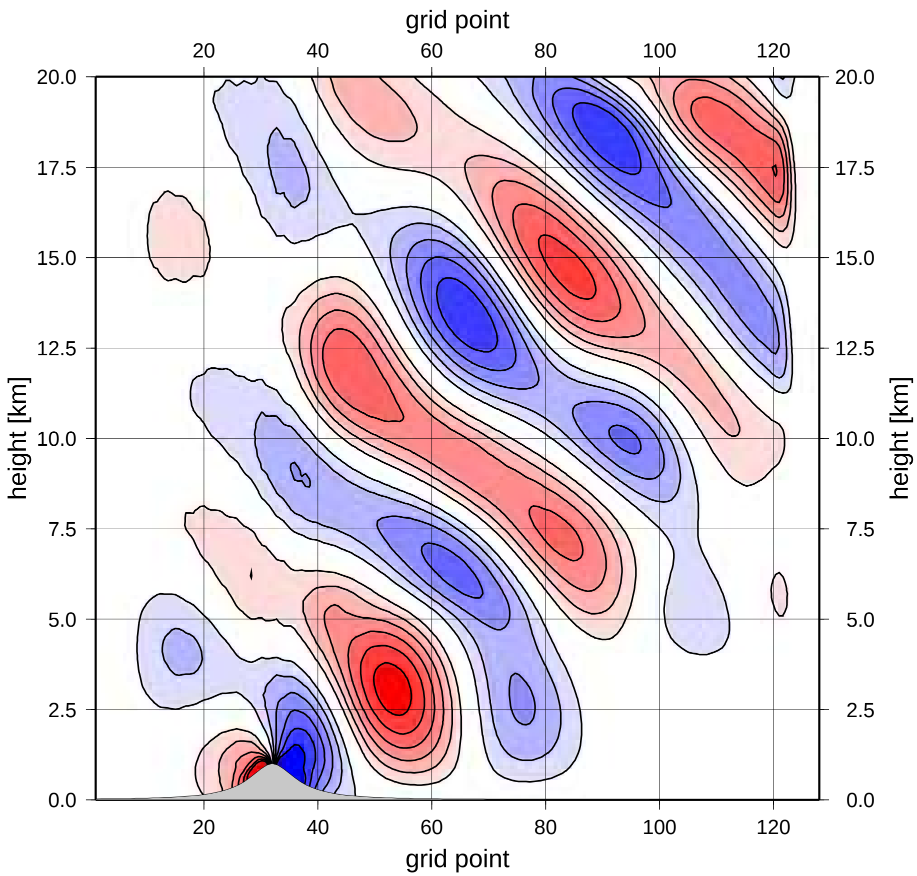
- in 2D orographic flows with smooth terrain SLHD can be used completely without spectral diffusion

- the only problem is that SLHD cannot work with eulerian advection (which is not used operationally, however)

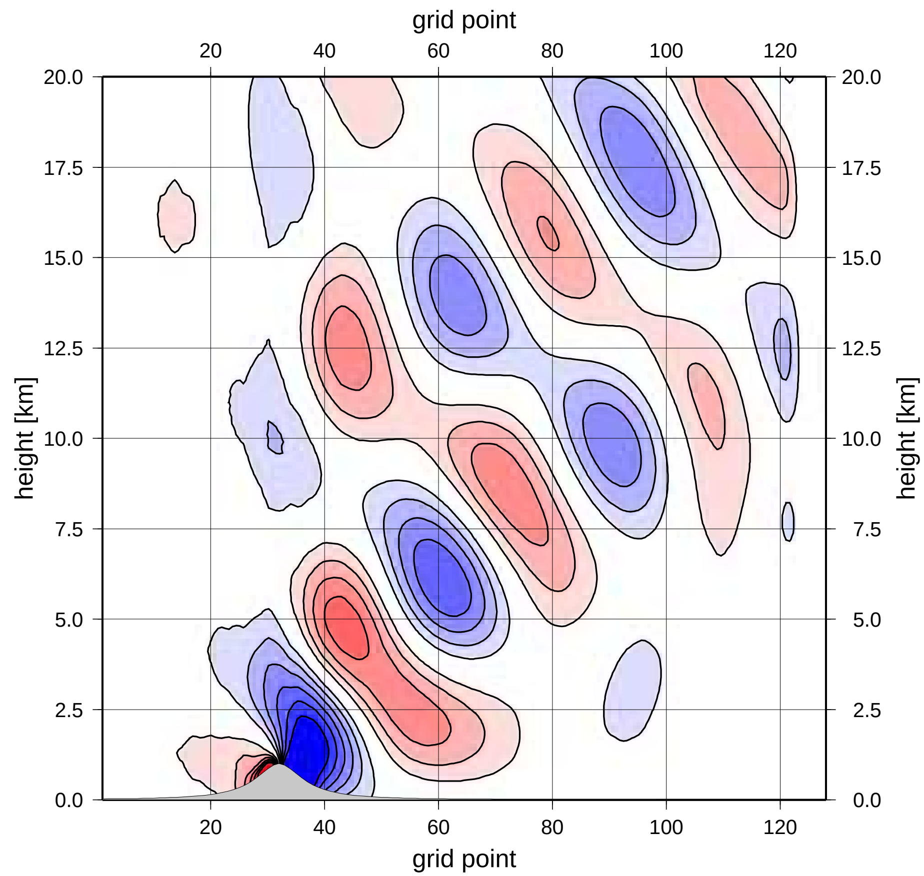
Results obtained with SLHD

SL2TL scheme, diagnostic BBC

no HD



gridpoint part of SLHD



$$\Delta t = 10.0\,\mathrm{s},\ N_{\mathrm{step}} = +0500$$

HD chimney treatment – summary

- use of spectral HD with inconsistently treated BBC leads to chimney problem both for SL and eulerian advection
- there is an academic treatment of HD chimney, but it is usable only for vertical plane 2D model
- clean solution for 3D model is to use SLHD with spectral diffusion at the surface reduced as much as possible
- 3D case with eulerian advection remains unsolved

Conclusions

- BBC treatment must be done consistently with model dynamics, otherwise problems as bizarre as chimney may appear

- it is very easy to overlook some inconsistencies in time and space discretized equations

- on the other hand it is very hard to say a priori which discretization details are innocent and which are harmful

- correct BBC treatment in spectral model can be technically difficult