NH ALADIN dynamics development

Presented by: Jozef Vivoda

- “Chimney” problem

Radmila Brožková, Filip Váňa, Miklós Voros, Yan Seity, JF Geleyn, J. Vivoda

- Vertical finite element scheme

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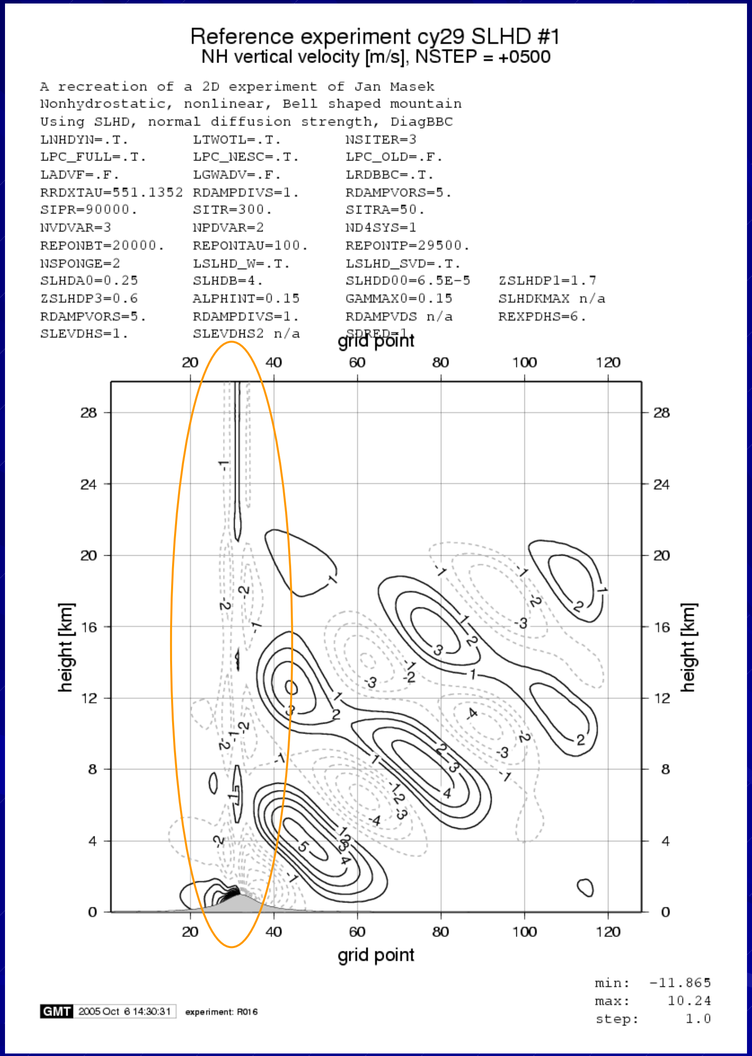
SHMÚ, METEO France, CHMI, HMI, DMI

"Chimney" problem

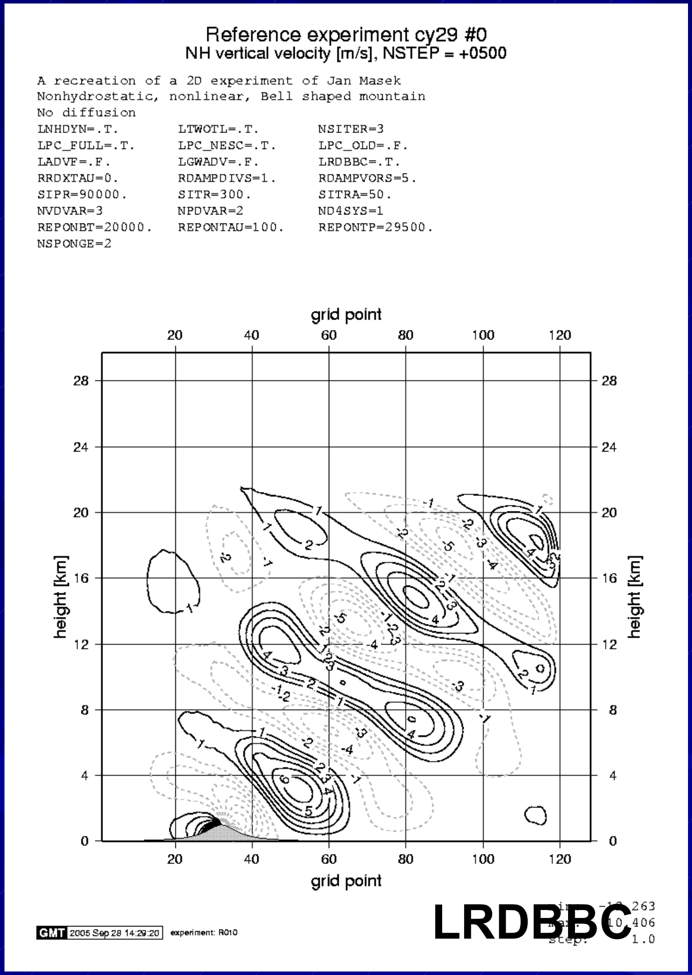
- "chimney" – unrealistic pattern in w field above the range of mountains
- We recognized the 2 kinds:
  1. SL "chimneys" – consequence of interactions between kinematic BBC, "d" prognostic variable and SL algorithm
  2. HD "chimneys" – HD diffusion on "d" implicitly diffuses w_s but inconsistently with w_s computed from diffused wind.



SL “Chimney”- solutions

Two independent solutions were found:

1. Brožková, Smolíková – diagnostic kinematic BBC with consistent SL treatment (LRDBBC)
2. Smith, Brožková, Vivoda – SL computations performed with half –level prognostic variable “w”, SI part with “d” (LGWADV, works only with 2TL ICI NESC)

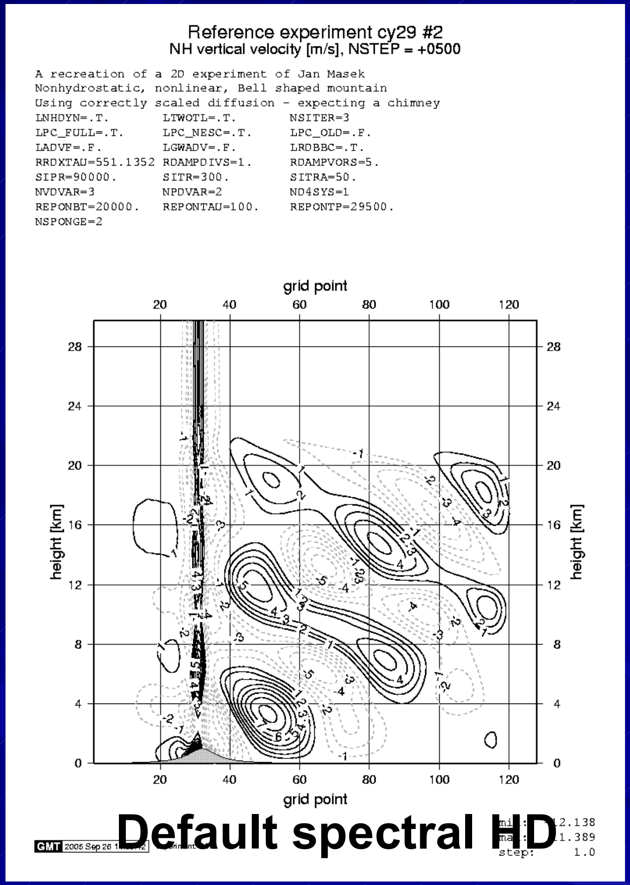


$$\frac{dw_s}{dt} = \frac{1}{g}\frac{d}{dt}\left(\frac{d\Phi_s}{dt}\right) \longrightarrow \frac{dw_s}{dt} = \frac{w_{sF}^{t+dt} - w_{sO}^{t}}{\Delta t}$$

HD “Chimney”

HD “chimneys” possible solutions

1. Replace “d” prognostic variable by “w” also in spectral space (this would lead to unstable model)
2. To call extra transforms inside spectral computations, to diagnose new BBC and to correct “d” (code revolution)
3. To replace spectral diffusion by grid-point diffusion
   - fortunately this happens, SLHD was implemented (Vana).



SLHD and HD “Chimney”

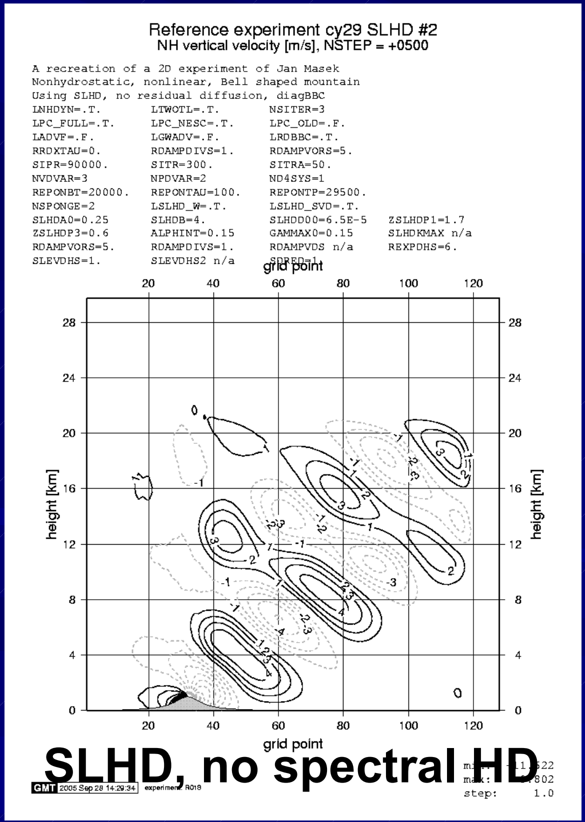
- SLHD is an alternative to spectral linear diffusion at high horizontal resolutions. SLHD exploits diffusivity of SL interpolators. Intensity of diffusion is determined by flow deformation field.

- Compatibility of SLHD with advection of half-level “w” (LGWADV):
  – SLHD works on full levels only and other R&D is required to combine it with LGWADV

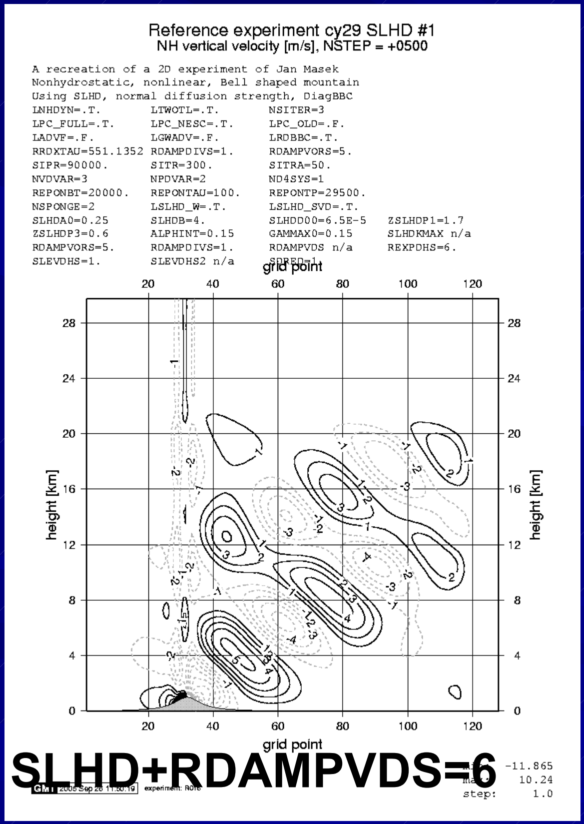
- Interaction of SLHD with averaging along trajectories:
  – SLHD does not act on arrival point quantities (no interpolations)
  – Solution 1: To abandon averaging and to interpolate all terms in middle point
  – Solution 2: To apply weak “supporting” diffusion in spectral space on variables with orographic forcing (u,v,d)

SLHD and HD “Chimney” in 2D

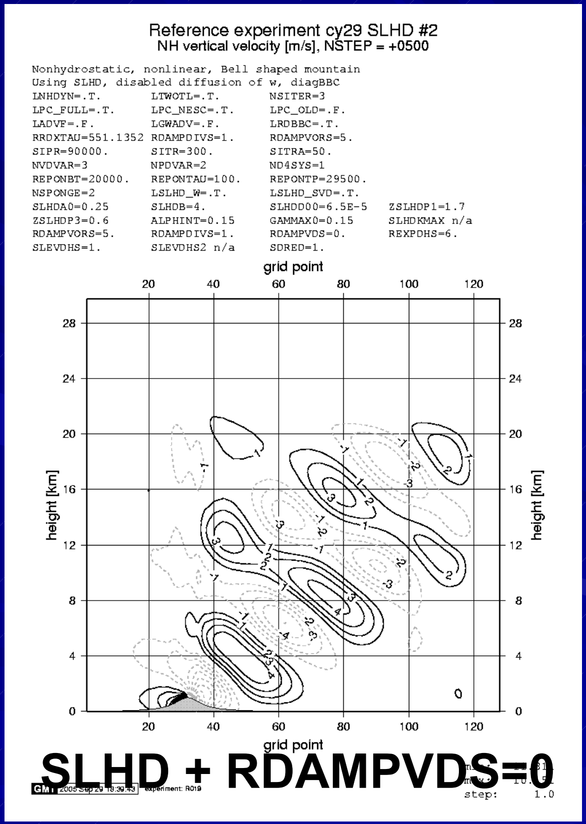
- Potential of solving HD “chimneys” by SLHD was studied by Voros and Brožková
- Conclusion from experiments in 2D framework:
  SLHD is capable to supress HD “chimney” problem, but supporting spectral HD on „d“ variable must be turned off



SLHD, no spectral HD



SLHD+RDAMPVDS=6

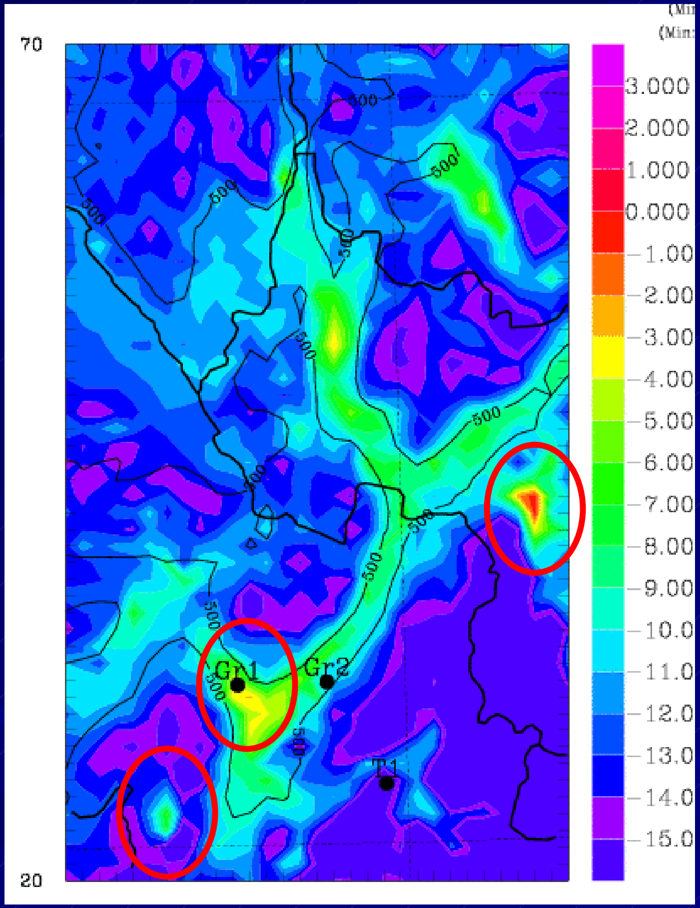


SLHD + RDAMPVDS=0

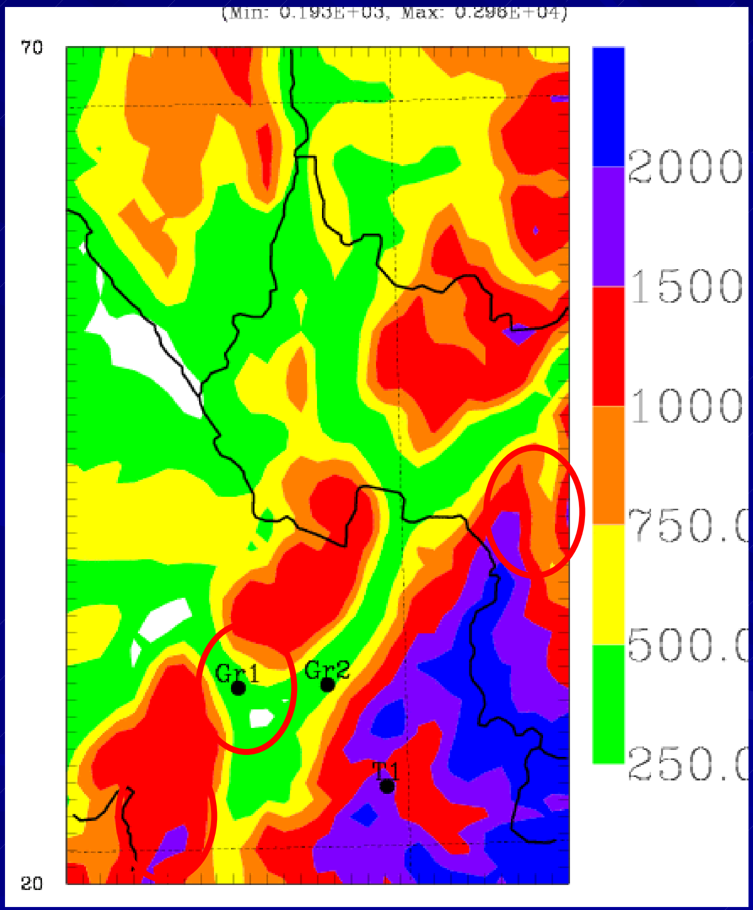
SLHD in 3D real case

AROME prototype run at 6TU: T2m field (Yan Seity results, 30.12.2005 – too warm in Grenoble)

SLHD=T (daily run) dt=60s :



Orography (in m)



Areas with problems in SLHD 60s run

SLHD in 3D real case

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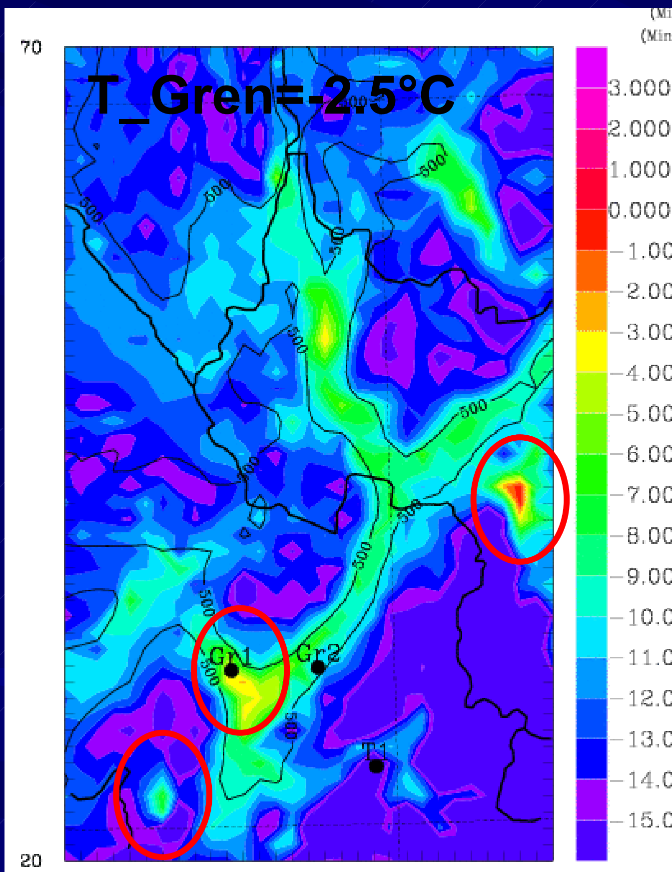
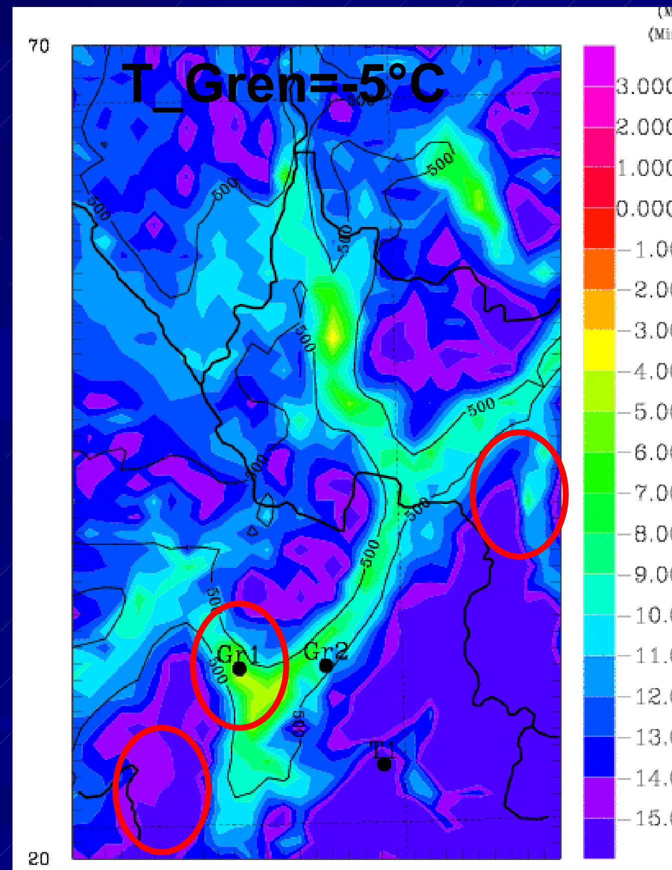
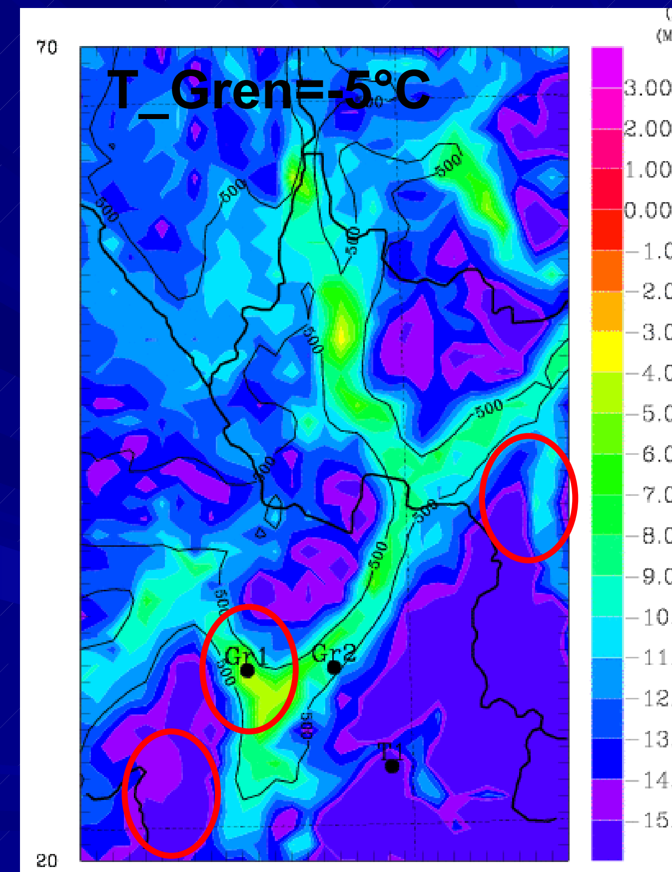


SLHD=T dt=60s SDRED=0.9



SLHD=F

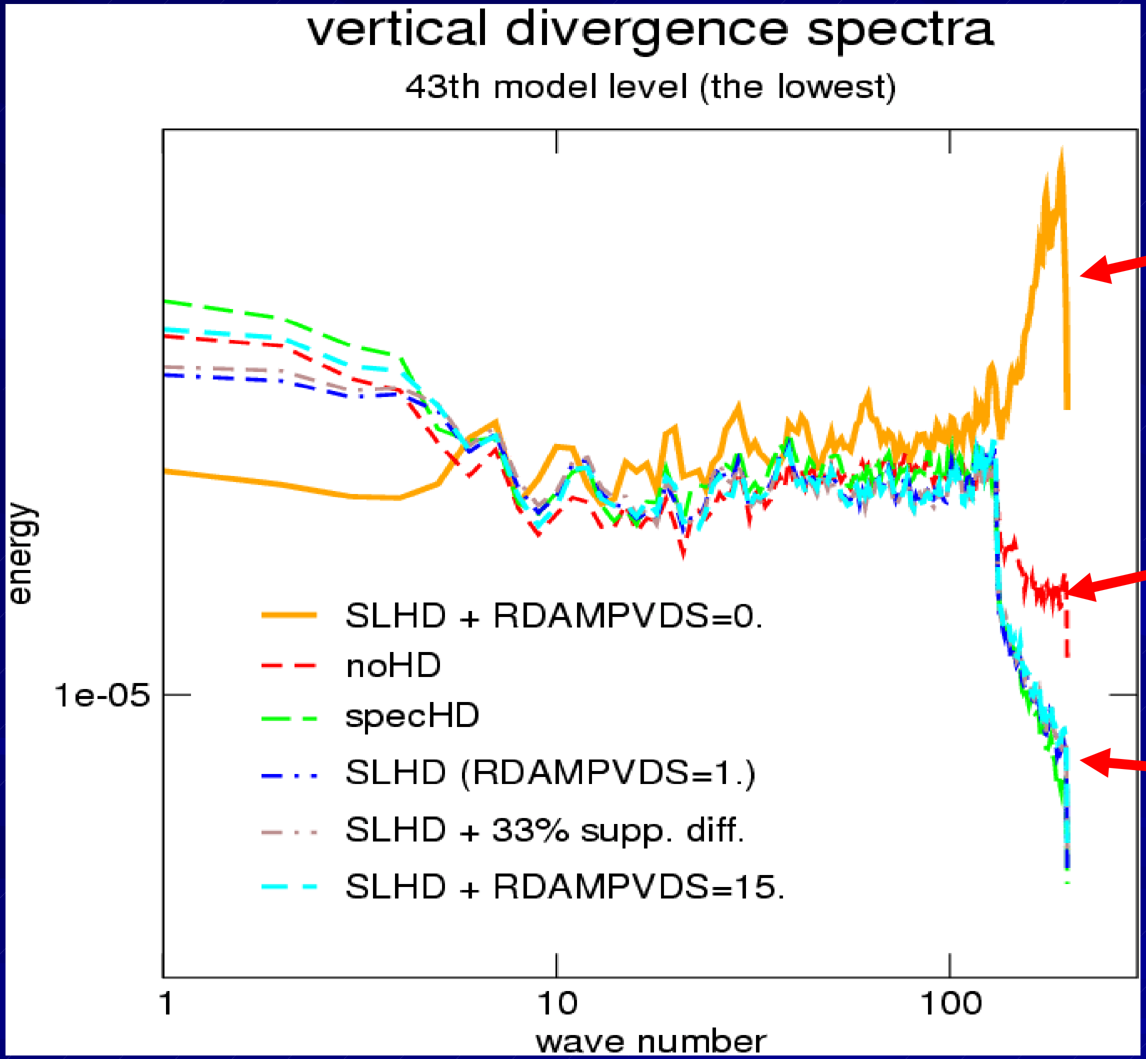


Areas with problems in SLHD 60s run

SLHD and HD "Chimney"- again 2D

- Result from 3D real case (Vana & Seity):

When supporting HD of "d" is off -> "d" array is noisy -> supporting diffusion on "d" is neccessary



SLHD, no supp. Diffusion on "d"

No diffusion

- **Full spectral HD**
- **SLHD + supp. diffusion**

SLHD+RDAMPVDS=15

SLHD and HD “Chimney”- again 2D

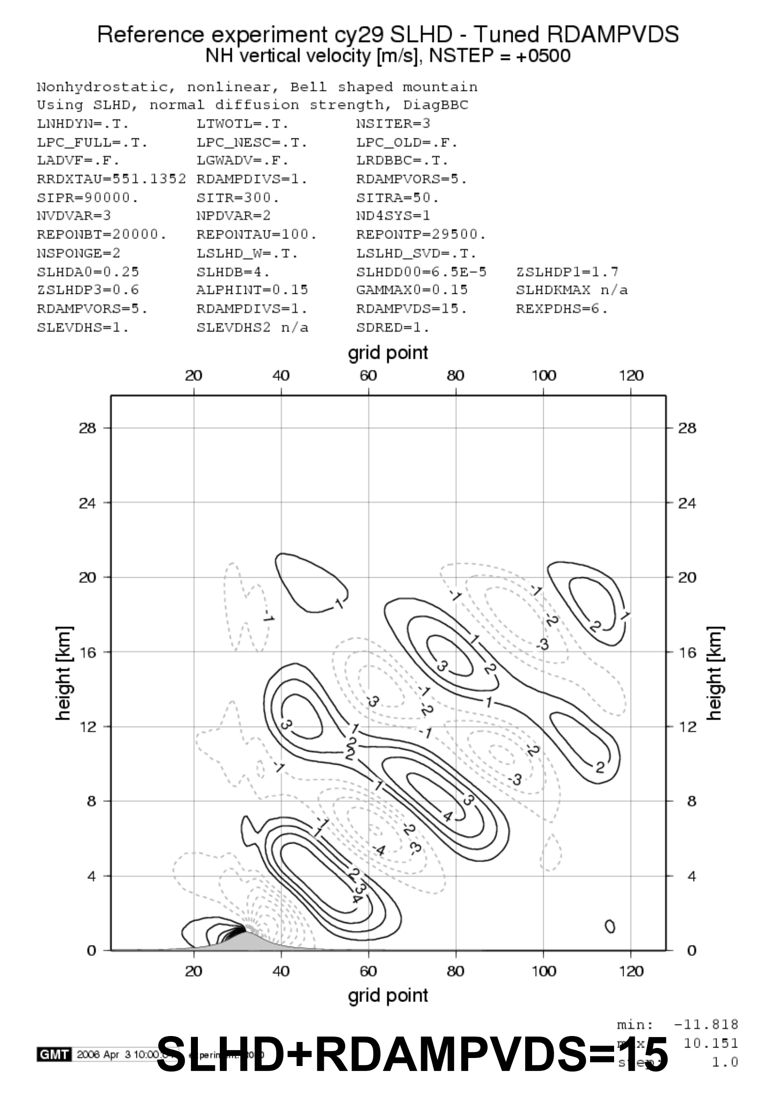
- Re-tested in 2D by Voros

- Conclusions:

LRDBBC combined with SLHD and very weak spectral HD on “d” cures satisfatory both SL and HD “chimneys”.

LGWADV will be still kept in the code because it is the only scheme capable to simulate density currents at metric scales (10-100m).

15x weaker HD on “d” than default



VFE scheme in NH model

Motivation:

- VFE scheme successfully implemented into HY model (ECMWF operational scheme, Untch and Hortal)
- If we succeed the NH VFE ALADIN dynamical core could become the basis for future ECMWF NH dynamics
- VFE with cubic functions is eight order of accuracy (two times higher accuracy than FD method on the same stencil)
- More accurate vertical velocities for SL scheme
- Is it possible to extend easily existing VFE for NH model ?

Work done so far:

- Benard – study of accuracy of vertical integral operators and of compatibility of VFE with existing model choices
- Vivoda – linear analysis of stability of VFE scheme

VFE scheme basic features

- Basis functions – cubic B-splines with compact support
- No staggering – all variables are defined on model full levels, including pressure
- Only integration/derivation is performed in FE space, the products of variables are done in physical space
- In SL version of HY model (ECMWF or ARPEGE) only non-local operations in the vertical are integrations. In NH version derivatives plays crucial role (structure equation contains vertical laplacian).

VFE scheme – redefinition of A and B

- In current ALADIN the functions A and B are determined on half levels
- VFE requires definition of derivatives of A and B function on full levels

$$\frac{\partial \pi}{\partial \eta_l} = \frac{dA}{d\eta_l} + \frac{dB}{d\eta_l}\pi_s$$

  - Starting from half level A and B we correct ΔA_l and ΔB_l in a manner that for VFE integral operator the mass is conserved

$$\int_0^1 \frac{\Delta A_l}{\Delta \eta_l} d\eta' = 0 \qquad \int_0^1 \frac{\Delta B_l}{\Delta \eta_l} d\eta' = 1$$

  - Than using VFE integral operator we get full level A and B

$$\int_0^{\eta} \frac{\Delta A_l}{\Delta \eta_l} d\eta' = A_l \qquad \int_0^{\eta} \frac{\Delta B_l}{\Delta \eta_l} d\eta' = B_l$$

FE derivative operator

We expand F and f in terms of chosen set of functions:

$$F(x,\eta) = \frac{\partial f(x,\eta)}{\partial \eta} \Rightarrow \sum_i \hat{F}(x)_i \, d(\eta)_i - \sum_i \hat{f}(x)_i \frac{\partial e(\eta)_i}{\partial \eta} = R$$

Truncation error R is orthogonalized (required to vanish in weighted integral sense) on interval (0,1):

$$\int_0^1 R \, \Psi j = 0 \Rightarrow \sum_i \hat{F}_i \int_0^1 d_i \Psi_j d\eta = \sum_i \hat{f}_i \int_0^1 \frac{de_i}{d\eta} \Psi_j d\eta$$

$$\mathbf{A\hat{F} = B\hat{f}}$$

Finally we incorporate the transforms from physical to FE space and back:

$$\mathbf{F = T\hat{F}}$$
$$\mathbf{\hat{f} = C^{-1}f} \Rightarrow \mathbf{F = TA^{-1}BC^{-1}f = Df}$$

FE integration operator

We expand F and f in terms of chosen set of functions:

$$F(x,\eta) = \int_0^{\eta} f(x,\eta')\,d\eta' \quad \Rightarrow \quad \sum_i \hat{F}(x)_i\, d(\eta)_i - \sum_i \hat{f}(x)_i \int_0^{\eta} e(\eta')_i\, d\eta' = R$$

Truncation error R is orthogonalized (required to vanish in weighted integral sense) on interval (0,1):

$$\int_0^1 R\,\Psi j = 0 \quad \Rightarrow \quad \sum_i \hat{F}_i \int_0^1 d_i \Psi_j\, d\eta = \sum_i \hat{f}_i \int_0^1 \left(\int_0^{\eta} e_i\, d\eta' \right) \Psi_j\, d\eta$$

$$\mathbf{A}_I \hat{\mathbf{F}} = \mathbf{B}_I \hat{\mathbf{f}}$$

Finally we incorporate the transforms from physical to FE space and back:

$$\mathbf{F} = \mathbf{T}\hat{\mathbf{F}}$$

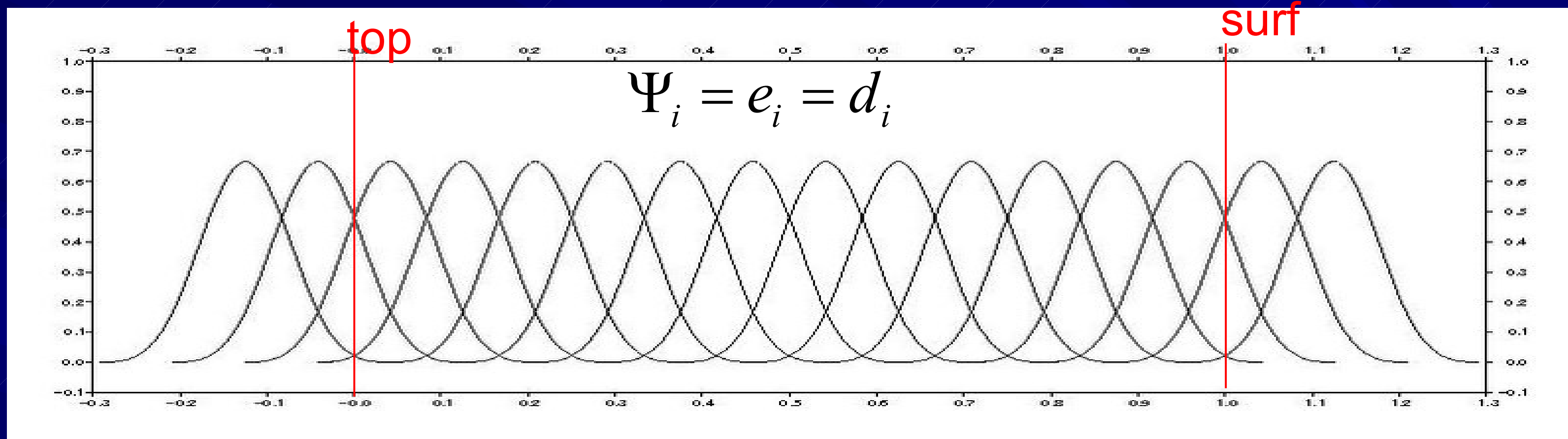
$$\hat{\mathbf{f}} = \mathbf{C}^{-1}\mathbf{f}$$

$$\Rightarrow \quad \mathbf{F} = \mathbf{T}\mathbf{A}_I^{-1}\mathbf{B}_I\mathbf{C}^{-1}\mathbf{f} = \mathbf{J}\mathbf{f}$$

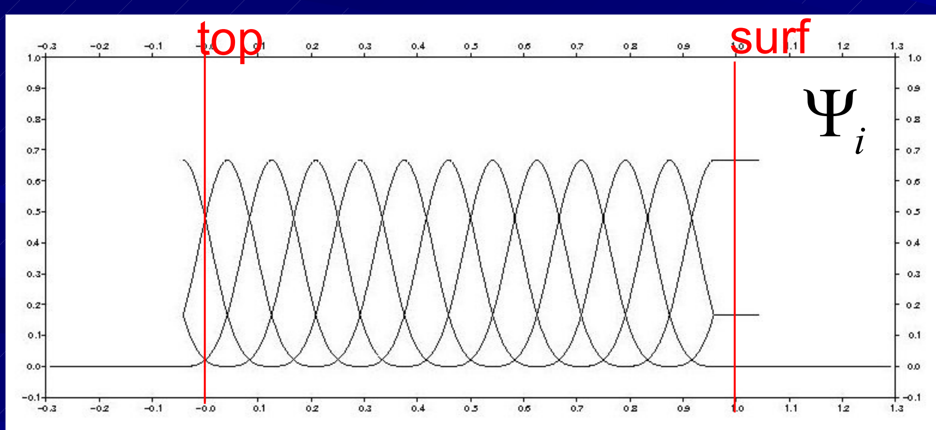
In: N values of f
Out: N values of integral
On full levels + integral from
Model top to surface

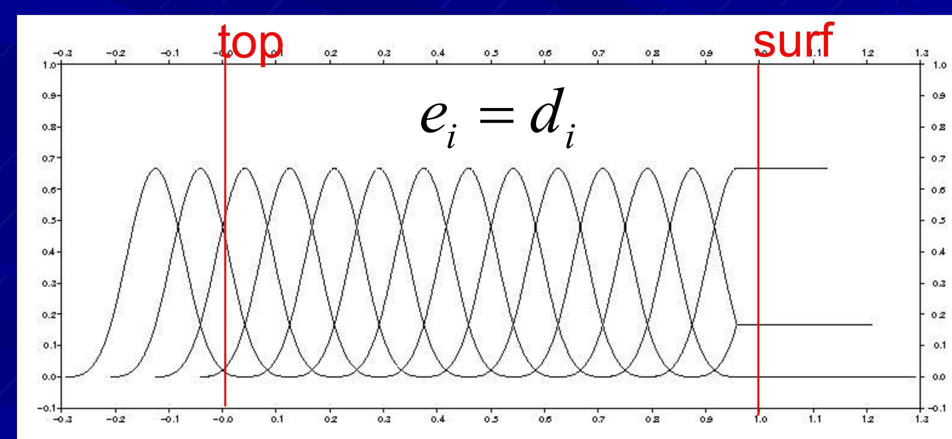
VFE scheme – basis functions

- **cubic B-splines (piecewise polynomials, preferred to interpolation avoiding oscillatory behaviour of polynomial of higher degrees)**
- **To cover the whole model domain with the full base L+4 functions is needed**



Basis functions for derivatives for model with 12 levels





Basis functions for integrals for model with 12 levels

VFE scheme – overdimensioning

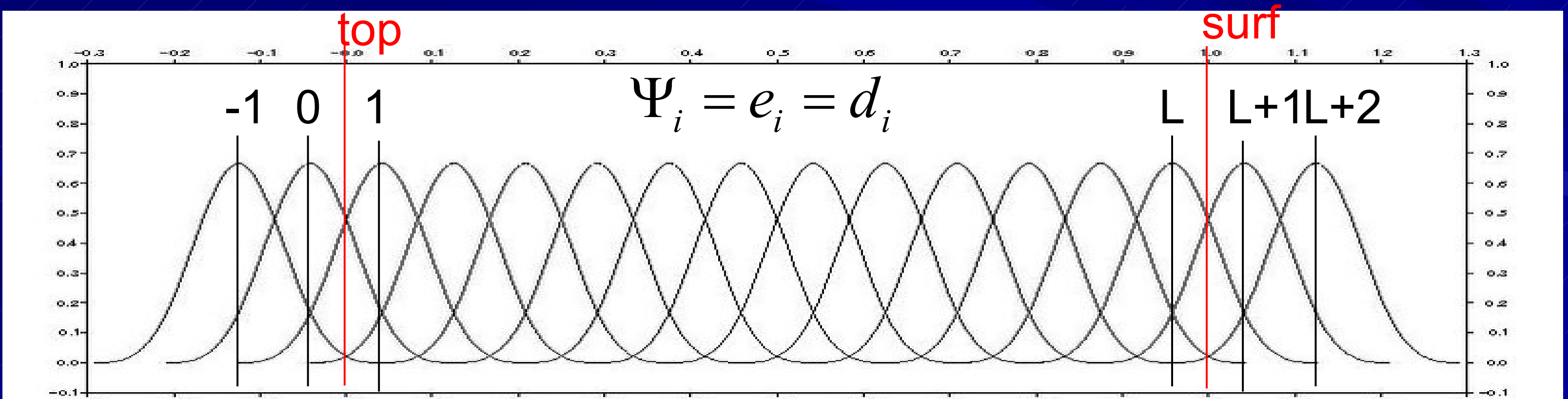
- To determine L+4 coefficients (one for each basis function) we must do additional 4 assumptions
- For VFE integral operator it is assumed:

$$f'(\eta_0) = f'(\eta_{L+1}) = 0 \qquad f(\eta_0) = f(\eta_1) \qquad f(\eta_{L+1}) = f(\eta_L)$$

- For VFE derivative operator it is assumed:

$$f'(\eta_1) = \frac{f(\eta_1) - f(\eta_2)}{\quad} \qquad f'(\eta_L) = \frac{f(\eta_L) - f(\eta_{L-1})}{\quad}$$

This assumption were determined as an optimal choice from accuracy point of view. The influence of these assumption on stability must be studied. Also the connection between assumptions and the model boundary conditions is not apparent and must be studied.



Basis functions for derivatives for model with 12 levels

VFE scheme – methodology of R&D

Development in the framework of linear isothermal resting atmosphere with small perturbations with respect to

- Stability (2TL ICI NESC scheme with 0,1,2,3 iterations)
  - **With respect to SHB temperature instability** $T - T^{*}$
- Accuracy of operators (consistency)
- Compatibility of existing solution (feasibility of elimination)

Generalisation of operators in NL framework

Implementation and debugging

Testing (2D -> 3D)

VFE scheme – linear isothermal NH model

$$\frac{\partial D}{\partial t} = -RG\Delta T + RT(G - I)\Delta\hat{q} - RT\Delta\hat{q}_s - \Delta\Phi_s$$

$$\frac{\partial T}{\partial t} = -\frac{RT}{C_v}(D + d)$$

$$\frac{\partial q_s}{\partial t} = -ND$$

$$\frac{\partial d}{\partial t} = -\frac{g^2}{RT}L\hat{q}$$

$$\frac{\partial \hat{q}}{\partial t} = -\frac{C_p}{C_v}(D + d) + SD$$

$$(GX)_\eta = \int_\eta^1 \frac{1}{\pi}\frac{d\pi}{d\eta'}X d\eta'$$

$$(SX)_\eta = \frac{1}{\pi}\int_0^\eta \frac{d\pi}{d\eta'}X d\eta'$$

$$(NX)_\eta = \frac{1}{\pi_s}\int_0^1 \frac{d\pi}{d\eta'}X d\eta'$$

$$(LX)_\eta = \frac{\pi}{m}\frac{\partial}{\partial\eta}\left(\frac{1}{m}\frac{\partial \pi X}{\partial\eta}\right)$$

NH specific vertical operators

Laplacian term FE treatment

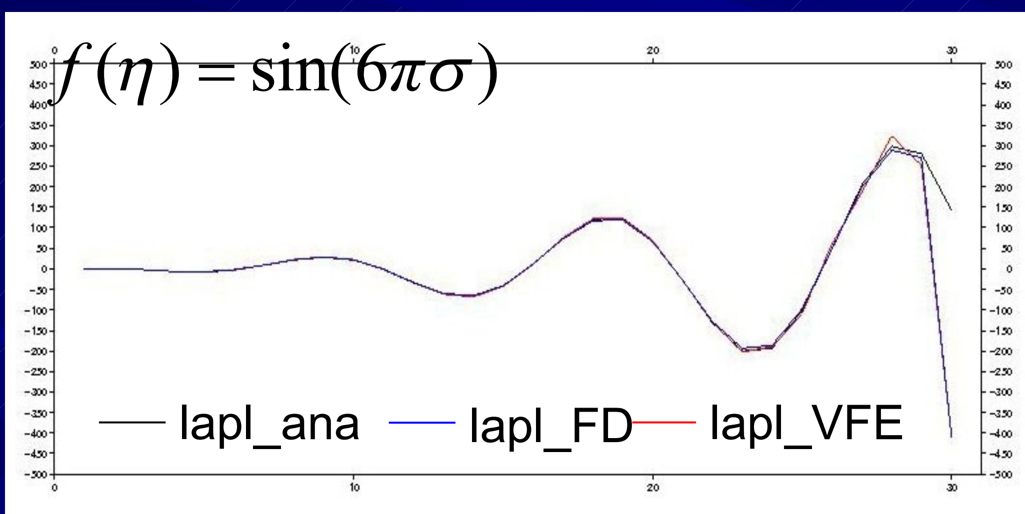
$$LP = \frac{\pi}{m}\frac{\partial}{\partial\eta}\left(\frac{1}{m}\frac{\partial(p-\pi)}{\partial\eta}\right)$$

1. **We compute the quantity g:** $g = \frac{1}{m}\frac{\partial(p-\pi)}{\partial\eta}$
2. **We compute the laplacian using correct BBC**

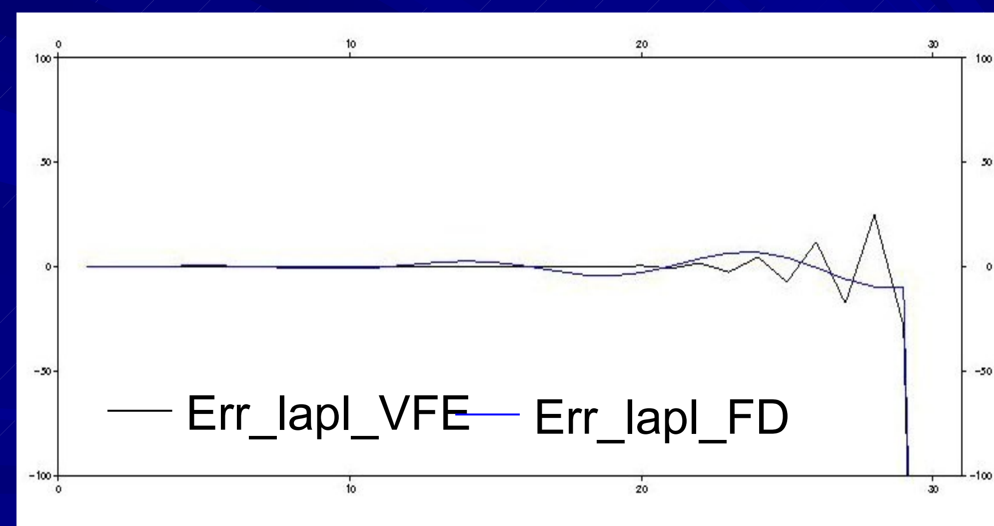
$$\int_0^1 \frac{\partial g}{\partial\eta}\psi_j d\eta = \left[\psi_j g\right]_0^1 + \int_0^1 g\frac{\partial\psi_j}{\partial\eta} d\eta$$

$$\left[\psi_j g\right]_0^1 = \underbrace{\left(\psi_s \frac{1}{m}\frac{\partial(p-\pi)}{\partial\eta}\right)_s}_{\text{BBC (0 in linear model)}} - \underbrace{\left(\psi_0 \frac{1}{m}\frac{\partial(p-\pi)}{\partial\eta}\right)_0}_{\text{Dirichlet TBC (set to 0)}}$$

BBC (0 in linear model) **Dirichlet TBC (set to 0)**



Linear laplacian for 30 regular levels with sigma coordinate

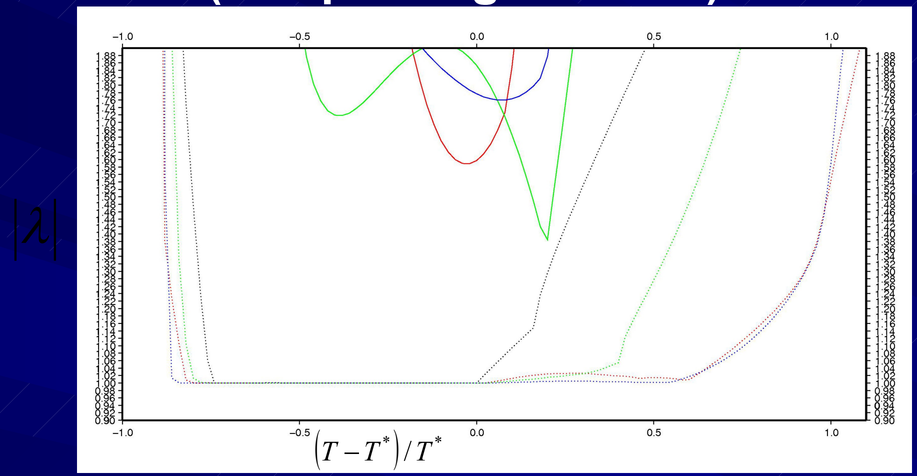


Linear laplacian error. FE linear laplacian is oscillatory near BBC

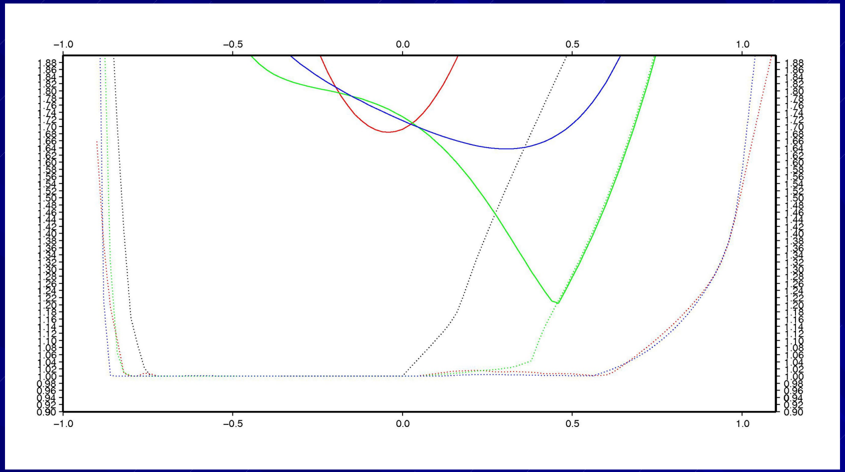
VFE scheme – Laplacian boundary conditions

2TL ICI scheme, dt=60s, stability with respect to (T-T*), monochromatic 5km wave

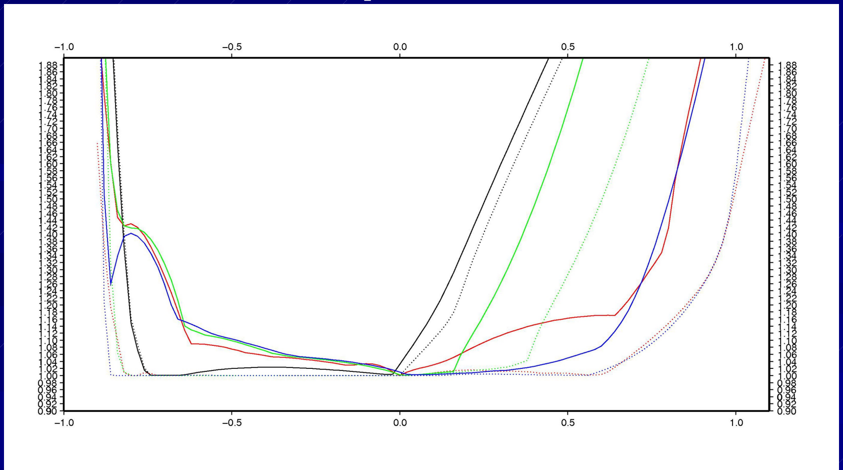
pure FE vertical laplacian (complex eigenvalues)



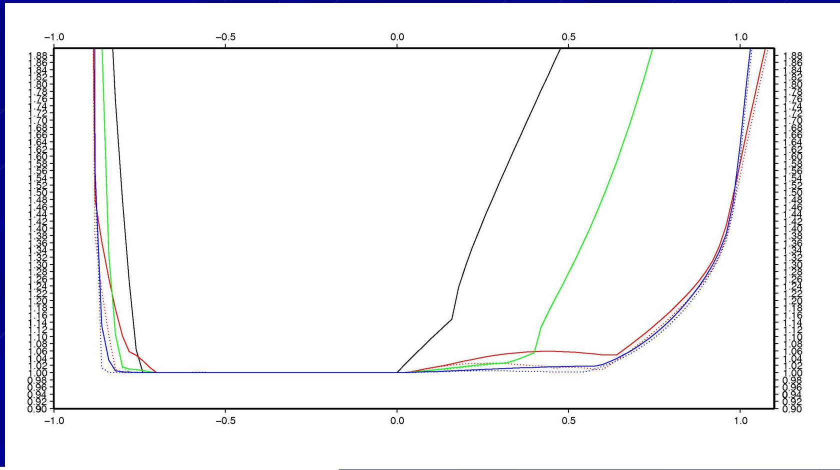
FE vertical laplacian with FD BBC



FE vertical laplacian with FD TBC



FE vertical laplacian with FD TBC and BBC (Real and negative eigenvalues)



Iter=0 (SI scheme) Iter=1 Iter=2 Iter=3

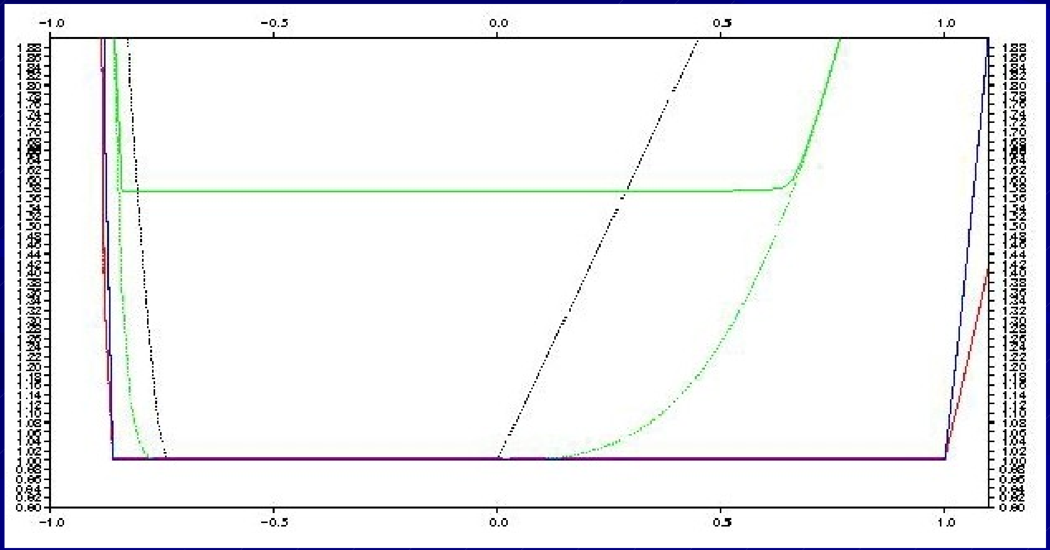
C1 constrain – modification of G*

- To keep compatibility with existing NH ALADIN the single Helmholtz equation must be solved. This is feasible only if discretized system can be fully eliminated. This is feasible only if constrain C1 is satisfied:

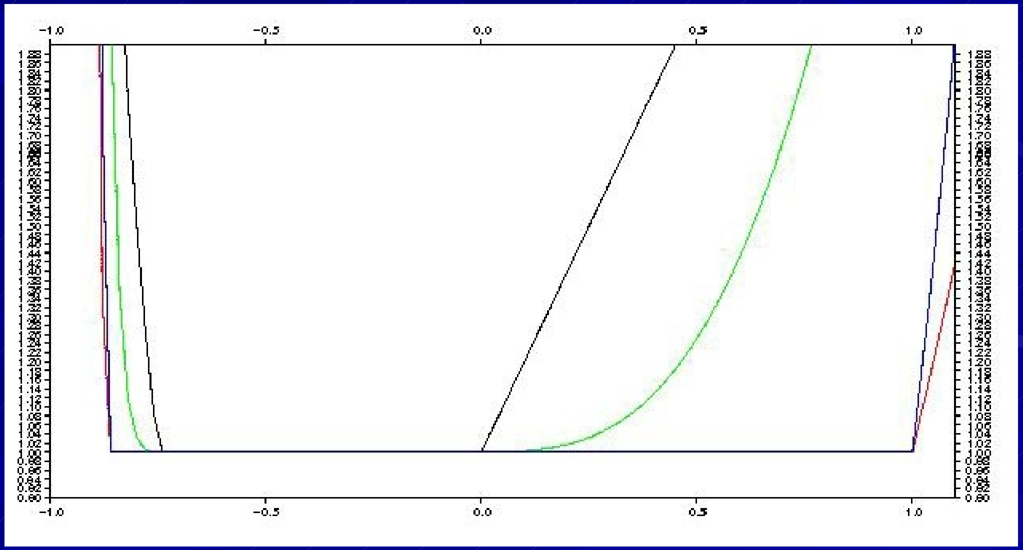
$$G^* S^* - S^* - G^* + N^* = 0$$

- from C1 constrain we can define operator G*. It must be computed via iterative procedure.

Stability – C1 satisfied in linear model only



Stability – C1 satisfied for NL model as well

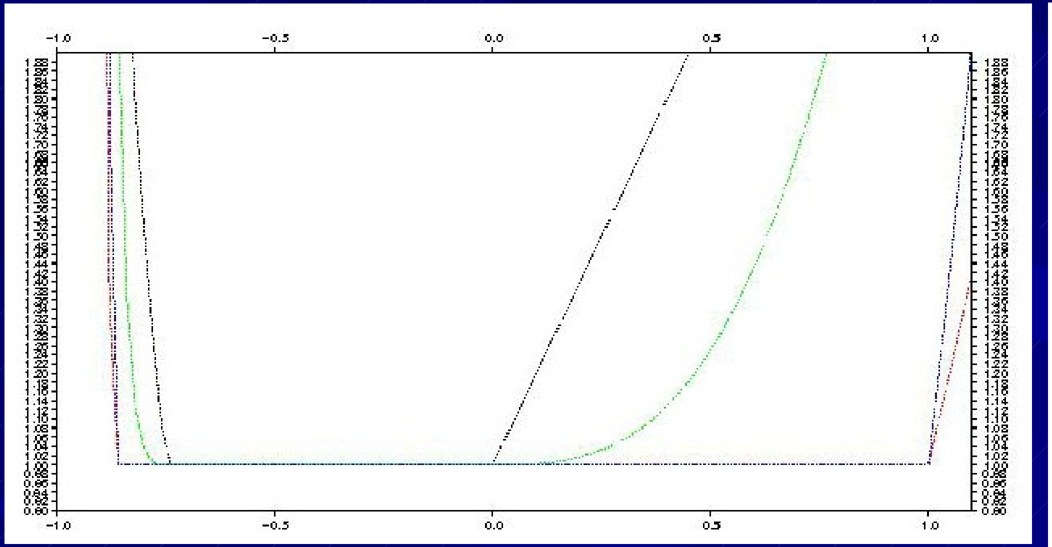


C1 constrain – modification of S*

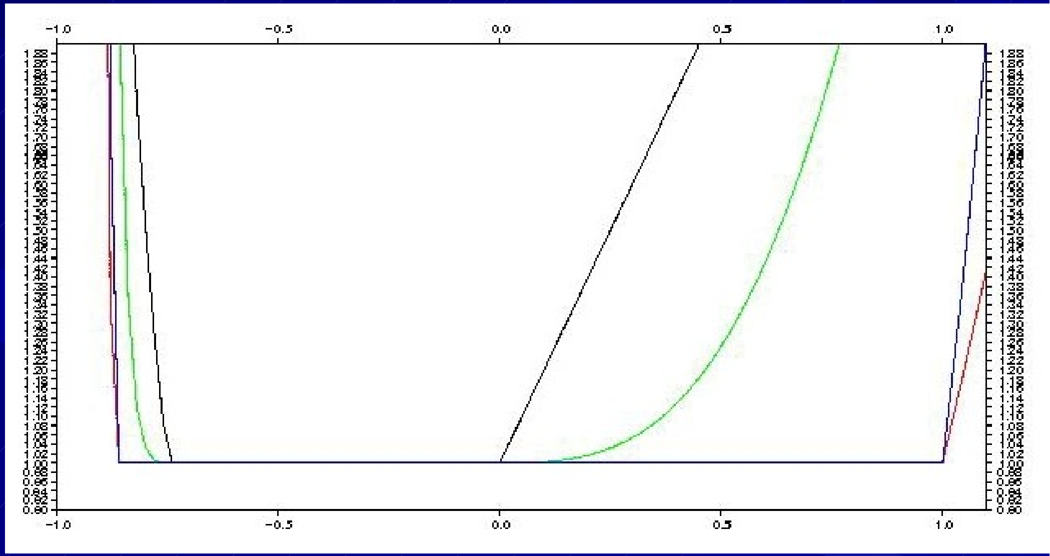
- Directly from C1 constrain we can define operator S*

$$S^{*} = (G^{*} - I)^{-1}(N^{*} - G^{*})$$

Stability – C1 satisfied in linear model only



Stability – C1 satisfied for NL model as well



The time stepping is stable only in the case when the same procedure is applied in NL model. It means the matrix inversion in every model column, every time step.

VFE scheme – conclusions

- Analysis of stability in linear framework suggests that it is possible to extend HY model VFE scheme to NH model
- From stability point of view the crucial is the definition of vertical laplacian operator (all eigenvalues must be real and negative)
- The VFE scheme is stable in linear context when FD boundary conditions are used in VFE (we can adopt BBC and TBC from FD model), but oscillatory behaviour near model bottom is observed
- So far all acceptably stable solutions that satisfy C1 are more expensive in terms of CPU than 2Lx2L solver (C1 unsatisfied)

VFE scheme – near future work

- Non-oscillatory discretization of vertical laplacian
- Extension of just described VFE discretization concept into full NL model
- Coding of “draft” of VFE scheme in NH ALADIN with 2Lx2L solver (29.5.-23.6. in Vienna)
- Visit of DMI (funding already agreed), meeting with HIRLAM colleagues (Karina and Bjarne) that will hopefully enforces active cooperation on further work
- Any suggestions are welcome

Thank you for your attention !

Non-isothermal SI solver

- Current state:
  - bi-isothermal solver (SITR,SITRA)
  - Stability requires SITRA << SITR (SITRA=50-100K, SITR=300-350K) => explicit terms have large magnitude
- Main idea:
  - to replace the occurence of constants SITR and SITRA by vertically dependent profiles

Non-isothermal SI solver

- Vertical discretization:
  - Pseudo-solver is designed with aim to keep C1 in the same form (NDLNPR=1 is still valid)

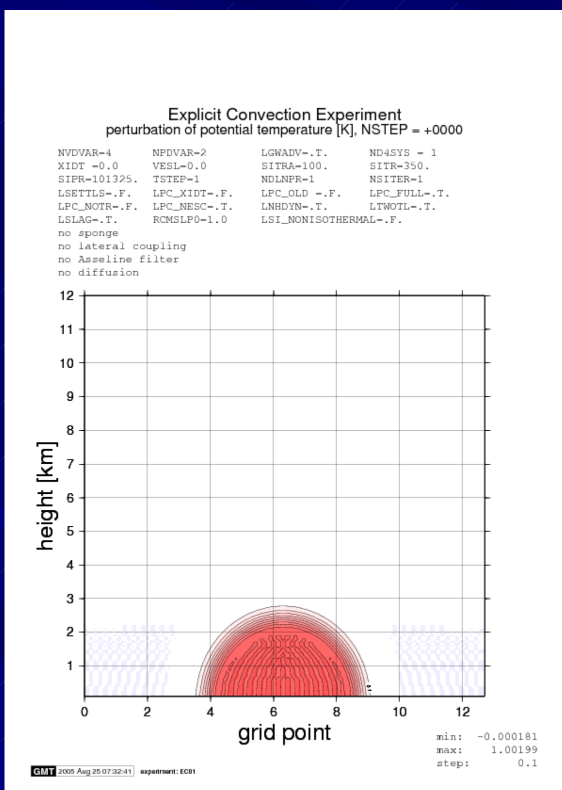
$$C1:(G^{*}S^{*}-S^{*}-G^{*}+N^{*})\psi=0$$

- Spectral space solver
  - Pseudo-solver – vertical operators are not commutative, because T* is vertically dependent => 2Lx2L problem must be solved for each wave number (we solve the system of two partial diff. equations)
- Reference temperature profiles must be statically stable in order to control gravity waves

Test – accuracy test

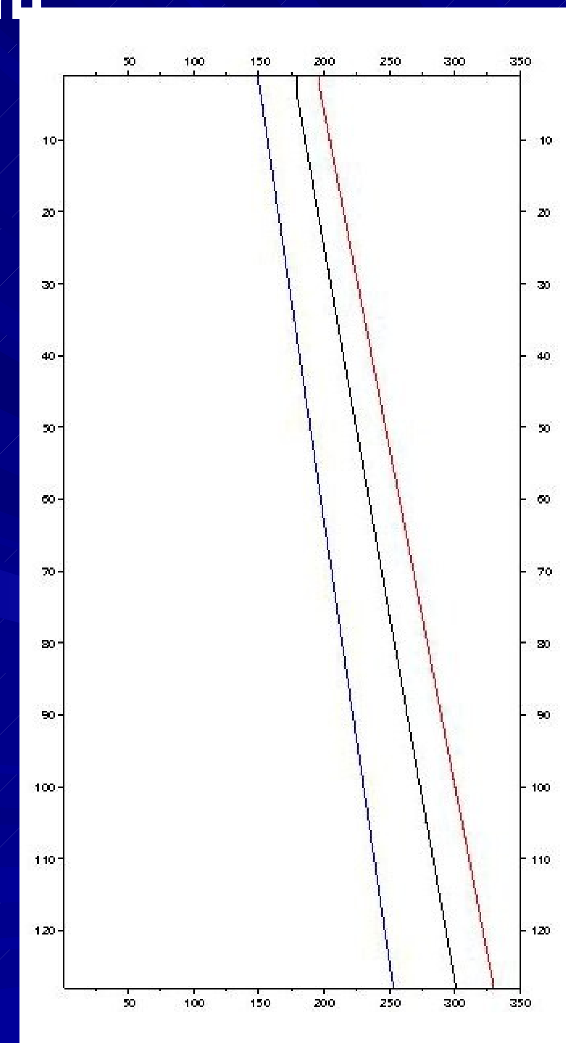
Model setting:

- **the warm half-bubble 5km x 2km at the surface in initial state with neutral stratification (PT=300K)**
- **2D domain 12km x 12km, dx=100m , dz=100m**
- **2TL ICI scheme, iter=1LGWADV=.T.**

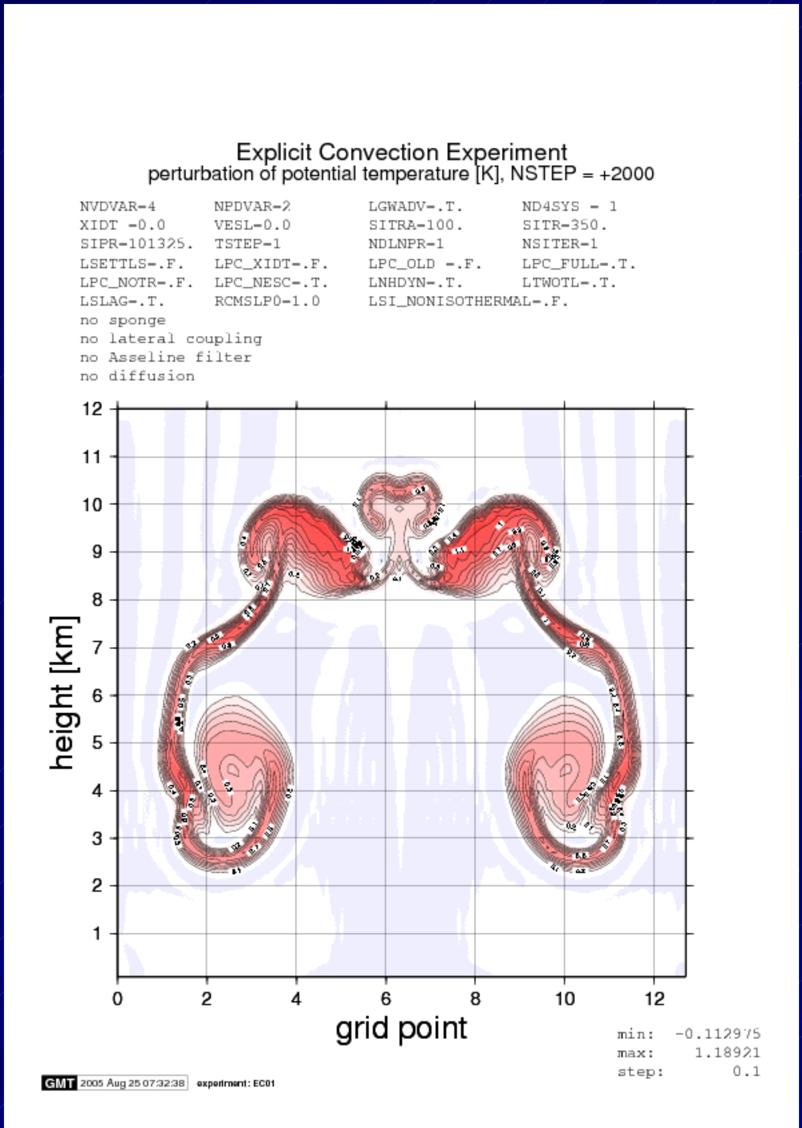


Reference temperature:

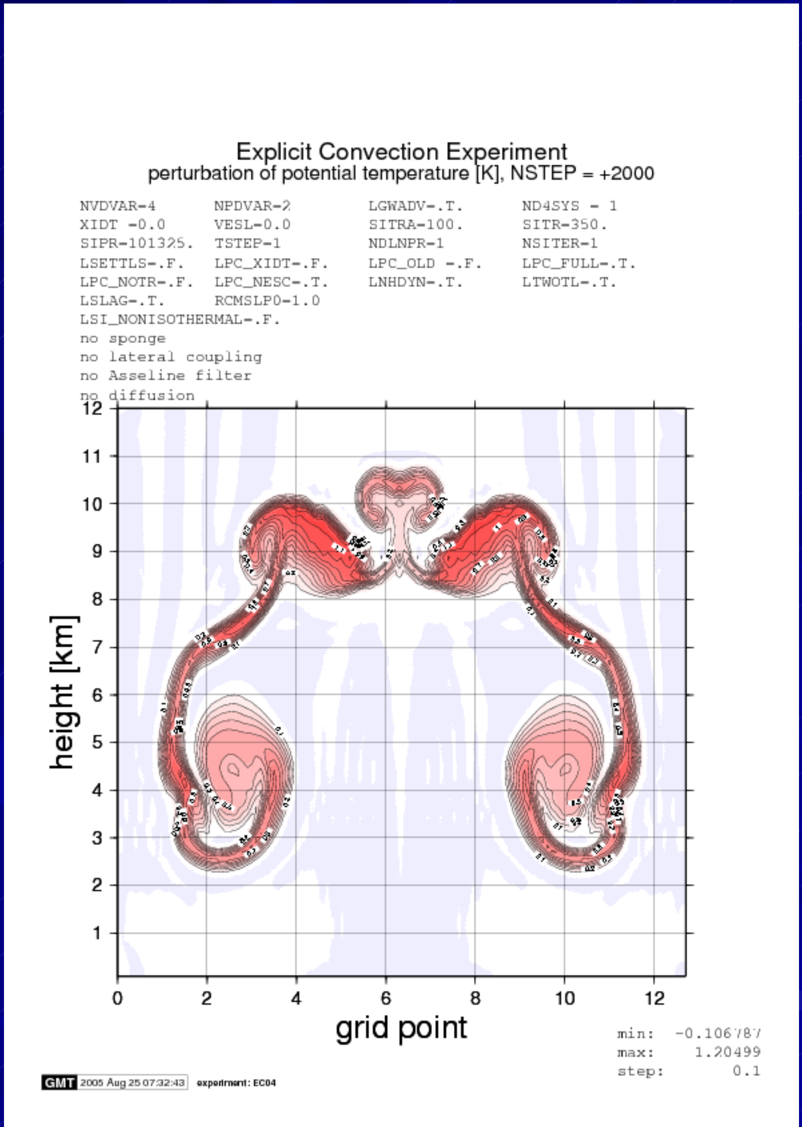
- **Iso:**
  - **SITR=330K**
  - **SITRA=150K**
- **Non-iso:**
  - **SITRA: top=120K, N=0.0019(1/s)**
  - **SITR: surf=320K, N=0.0016(1/s)**



Explicit convection – short dt=0.5s

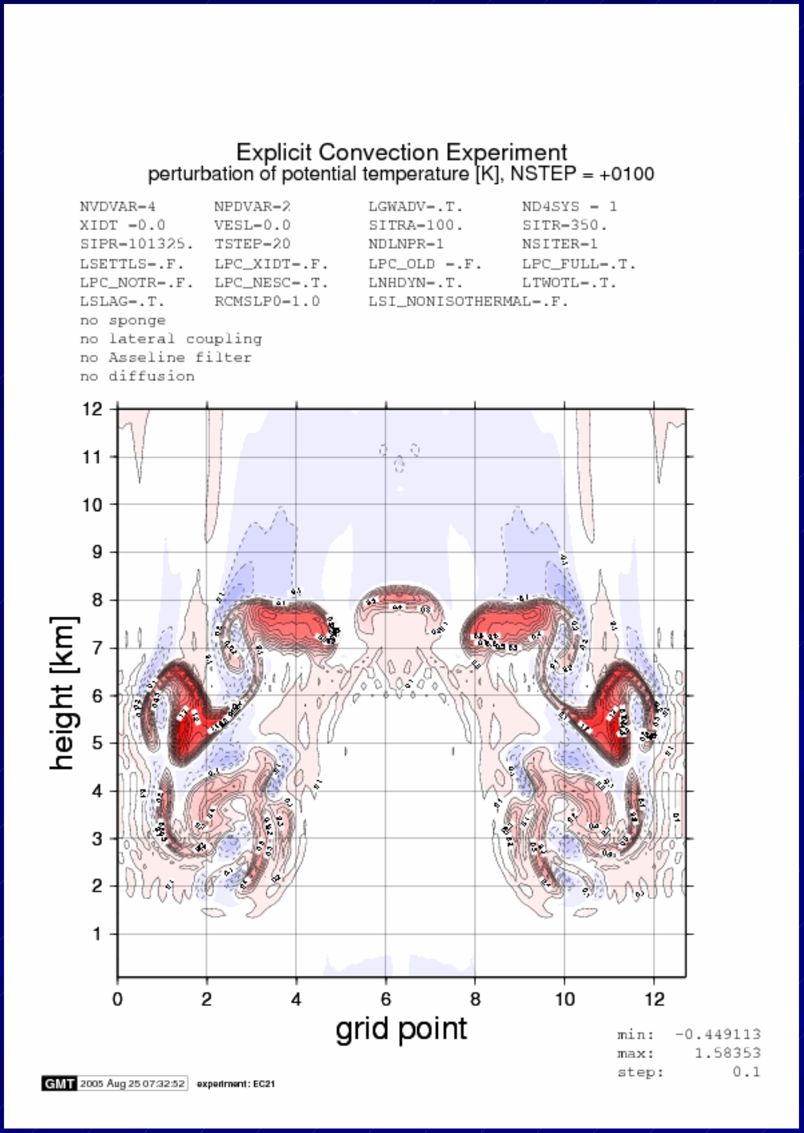


isothermal solver

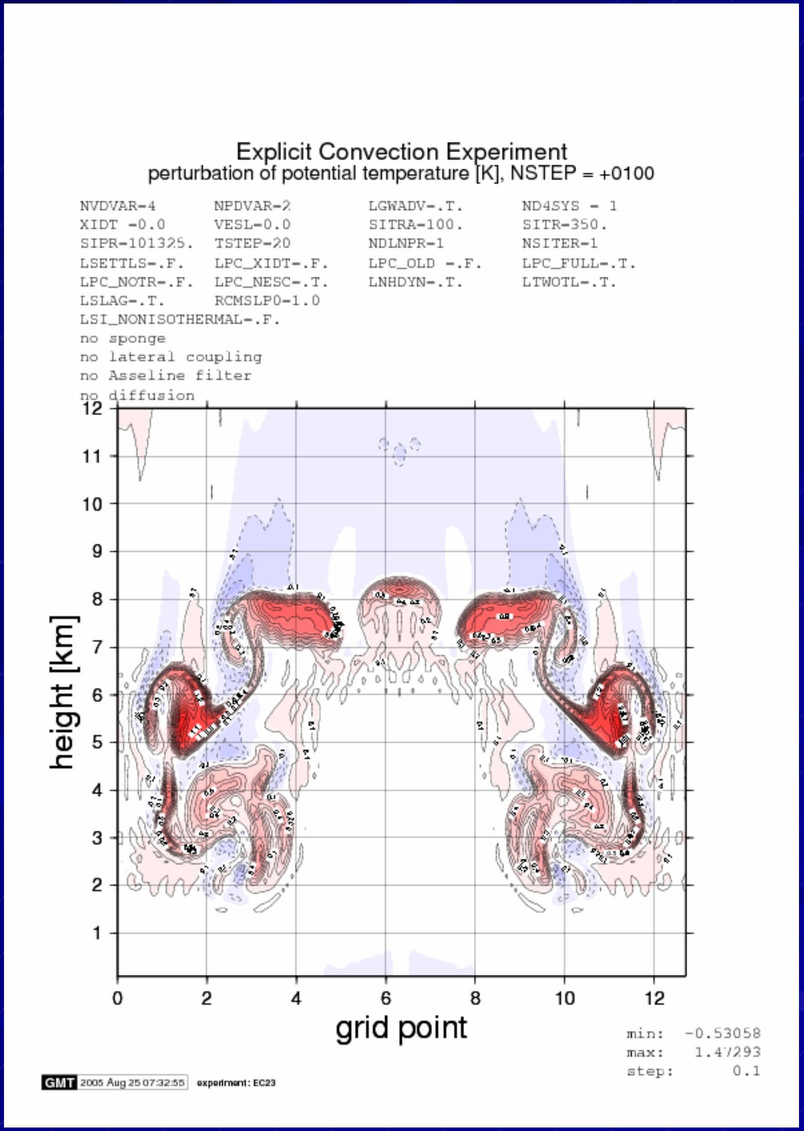


non-isothermal solver

Explicit convection – large dt=20s



isothermal solver

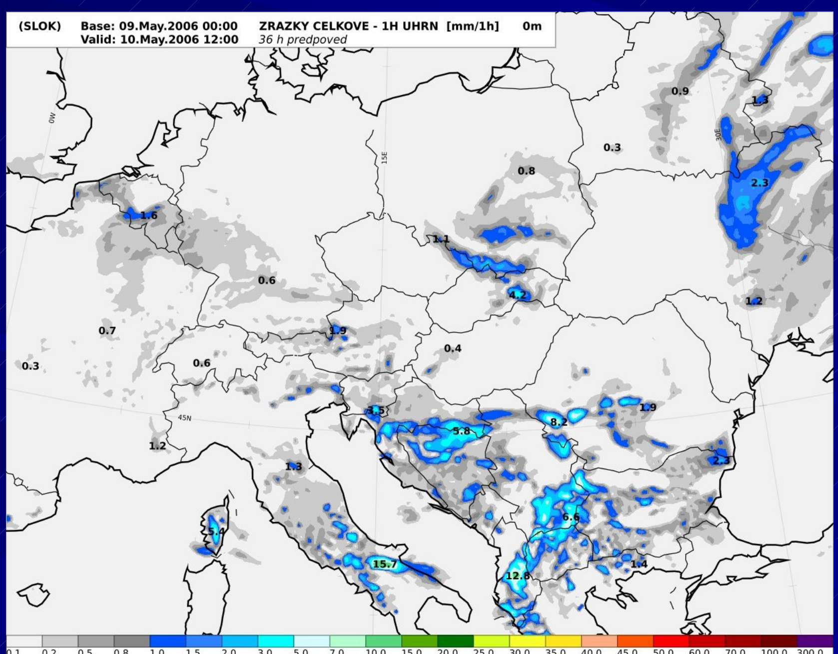


non-isothermal solver

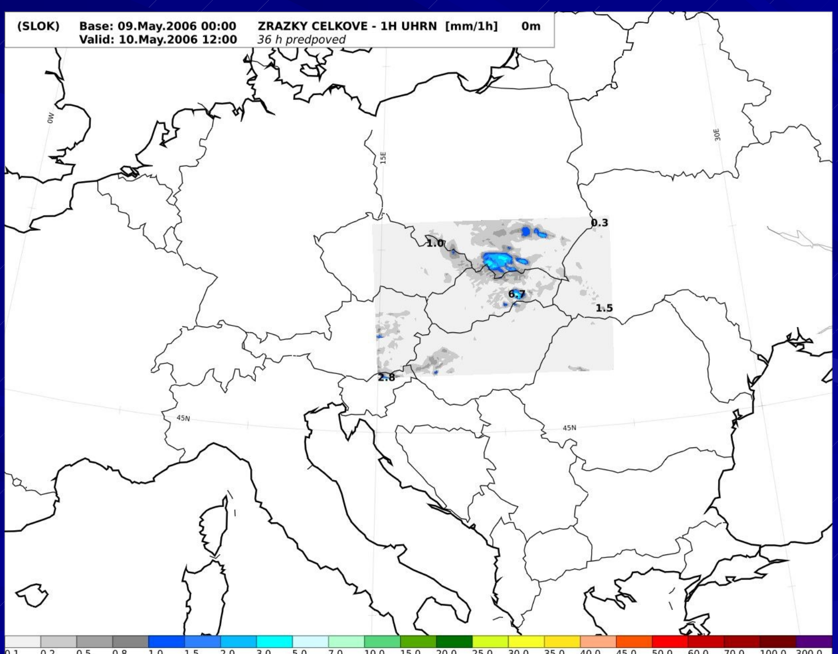
Non-isothermal solver

- 3D diabatic test case from 9.5.2006 00UTC:
  - No significant weather
  - NH run with dx=2.5km and dt=300s
  - Non-isothermal test
    - **with standard atmosphere +-50K used as a reference temperature profiles -> unstable**
    - **With constant static stability profiles -> unstable**

Oper (cy28t3_czphys)



Test with isothermal solver (cy30T1)



Non-isothermal solver - conclusions

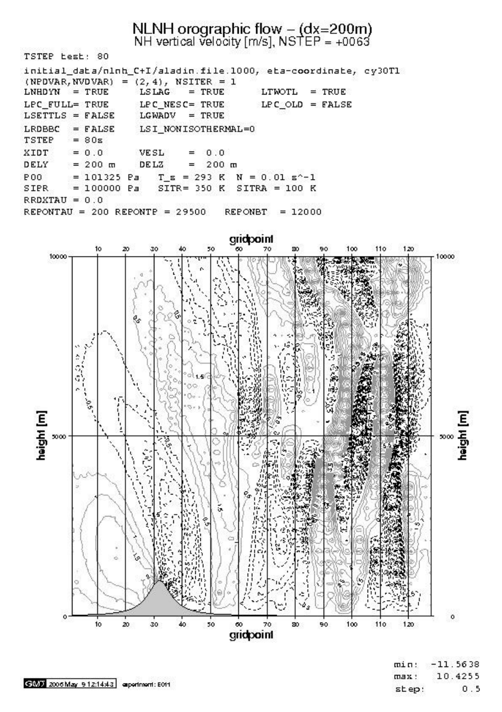
- scheme less effective than the one with isothermal solver (approx . 5% overheads)
- 2Lx2L spectral solver implemented
- Accuracy: neutral
- Stability:
  - impossible to draw conclusion from 2D cases (all cases too sensitive to LBC or sponge layer)
  - 3D real case unstable for standard atmosphere profiles and statically stable profiles
- Theory needed how to set up reference temperature profile (more experiments or theoretical work required)

Stability tests - results

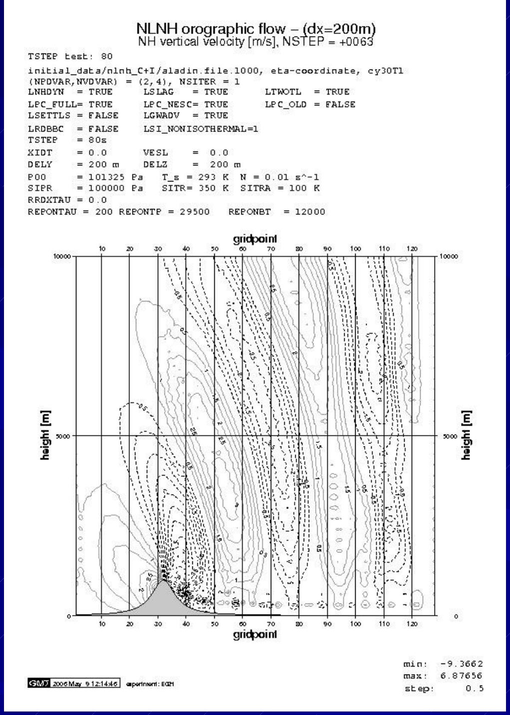
- Max. time step for LRDBBC approx. 20s
- Max. time step for LGWADV approx. Iso: 80s noniso:120s
- no HD used

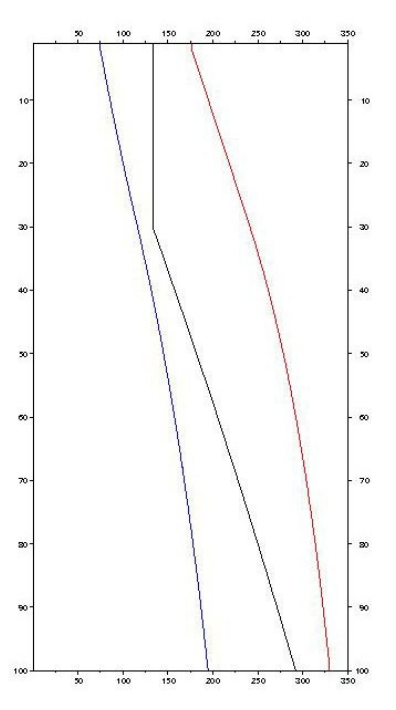
- Iso: SITR=250K, SITRA=50K
- Non-iso:
  - SITR, surf=330K, N=0.016(1/s)
  - SITRA, top=100K, N=0.019(1/s)

Isothermal solver dt=80s



Non-isothermal solver dt=80s





2D framework – NLNH test case with N=0.01(1/s) good candidate but very sensitive to sponge settings (inconsistent behaviour even for isothermal tests)