AROME Training Course:

Mountain Waves - experiments

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Content of presentation

1. experiments setup
2. absorbing layer at the top
3. different flow regimes modeled by NH model
4. NH flow regimes modeled by HY and NH model version
5. conclusion

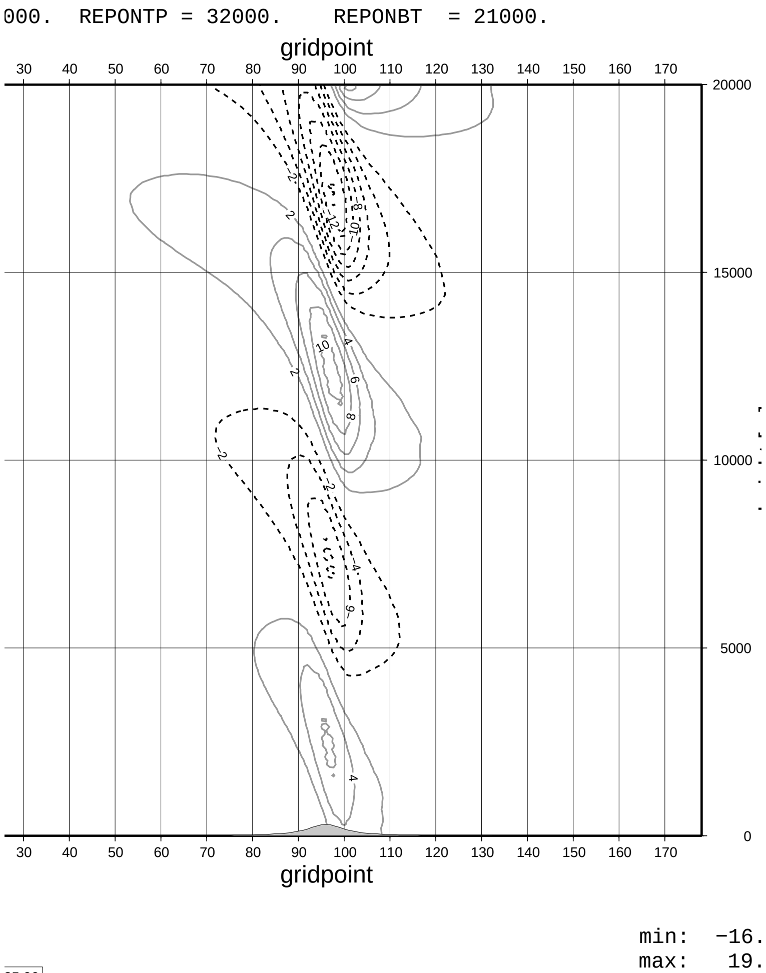
Experiments setup

- run with 2D irrotational plane model version of NH ALADIN
- absorbing layer at the top of the model
- lateral coupling 14 points
- initial conditions - fields constant along η levels (not balanced) with constant Brunt-Vaisala frequency N and uniform wind field U
- run with two time level semi-Lagrangian ICI scheme with 1 iteration
- the obstacle is Agnesi shape $h(x) = \frac{h}{(1+(\frac{x-x_0}{L})^2)}$, with h being mountain height and L mountain half width.
- hydrostaticity of flow is characterized by dimensionless numbers $C_h = \frac{U}{LN}$ and linearity by inverse Freude number $C_l = \frac{hN}{U}$

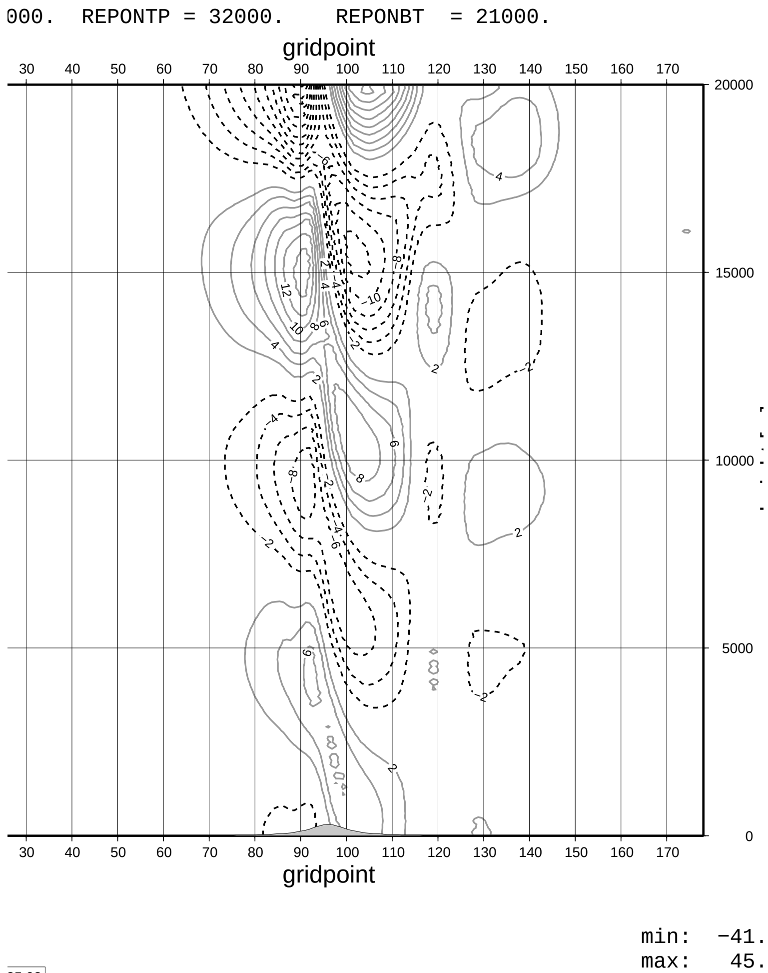
Absorbing layer - motivation

The simulation with absorbing layer and without absorbing layer.

sponge



no sponge



Absorbing layer I.

- lid condition $\dot{\eta} = 0$ is reflective to the upward propagating waves
- to avoid wave reflections the absorbing layer - sponge is applied near the top of model domain
- We apply newtonian relaxation on each model layer towards the background values

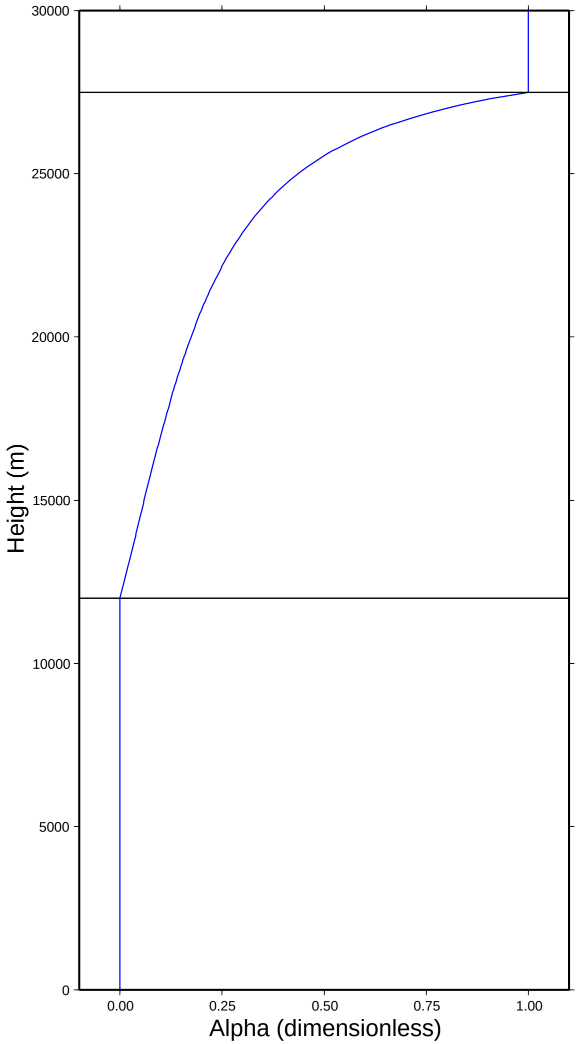
$$\frac{dX}{dt} = -\frac{X - X_b(z)}{\tau(z)} \qquad \Rightarrow \qquad \frac{\tilde{X} - X}{\Delta t} = -\frac{\tilde{X} - X_b(z)}{\tau(z)}$$

It gives

$$\tilde{X} = \frac{\tau(z)}{\tau(z) + \Delta t} X + \frac{\Delta t}{\tau(z) + \Delta t} X_b(z) \qquad \Rightarrow \qquad \tilde{X} = \alpha(z) X + (1 - \alpha(z))\, X_b(z)$$

In model: REPONGF and REPONGH are vertical profiles of α computed for full resp. half levels.

Absorbing layer II.



$z > z_t$		0	$\alpha = 0$
$z_t > z > z_b$	$\tau =$	$\tau_r tan\left(\frac{\pi}{2}\frac{z_t - z}{z_t - z_b}\right)$	$\alpha \in (0, 1)$
$z_b > z$		∞	$\alpha = 1$

REPONTP	top of model layer z_t
REPONBP	bottom of model layer z_b
REPONTAU	reference time of absorption τ_r in the middle of sponge layer

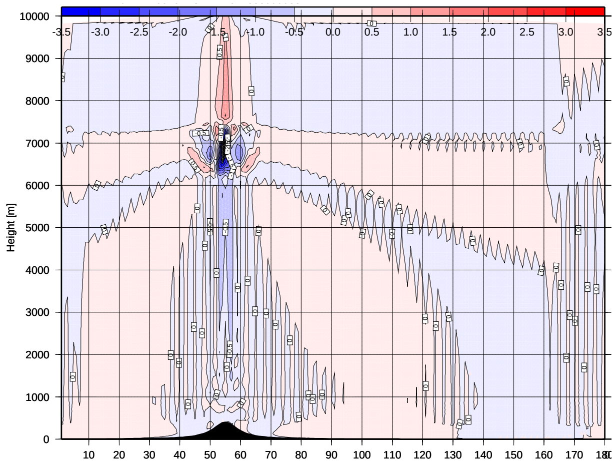
- in ALADIN - sponge works for 2D (yz) version of model only
- background field $X_b(z)$ is considered to be horizontally constant (hor. derivatives are relaxed towards 0) on z-levels
- depth of absorbing layer $z_t - z_b > 2\pi \frac{U}{N}$
- reference time scale of absorption τ_r has to be set experimentally

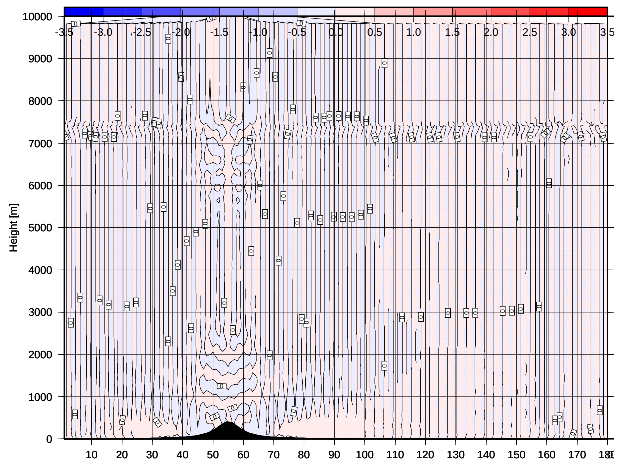
How to setup absorbing layer I.

The relaxation is assumed to be on z levels but in practice it is applied on η levels.

z-levels can not be used in ALADIN, therefore the hybrid levels in sponge layer shall be close to the true pressure levels (set B coefficient in $\pi = A(\eta) + B(\eta)\pi_s$ close to 0).

levels in sponge ($\pi = \sigma\pi_s$) levels in sponge ($\pi = A(\eta)$)



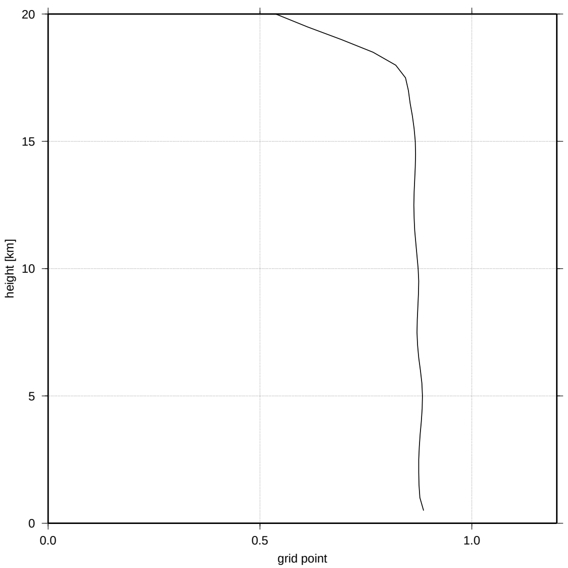


How to setup absorbing layer II.

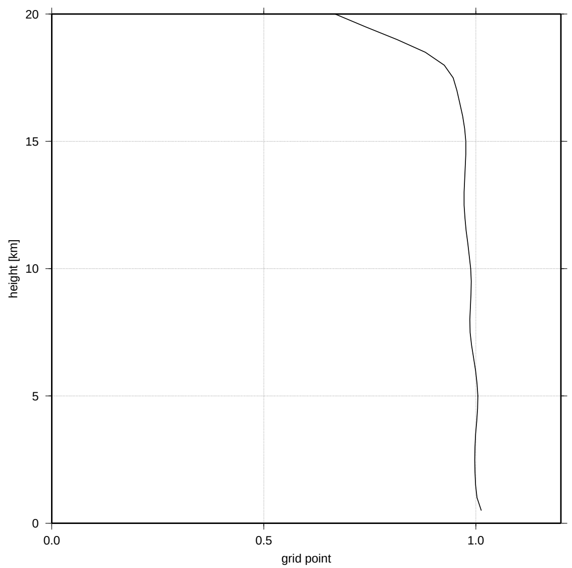
By tuning the τ_r parameter we could reach the normalized vertical momentum flux to be as close as possible to the theoretical analytical value.

Example is from linear hydrostatic flow regime. The relation between the normalized vertical momentum flux and the τ_r is approx. linear in this case.

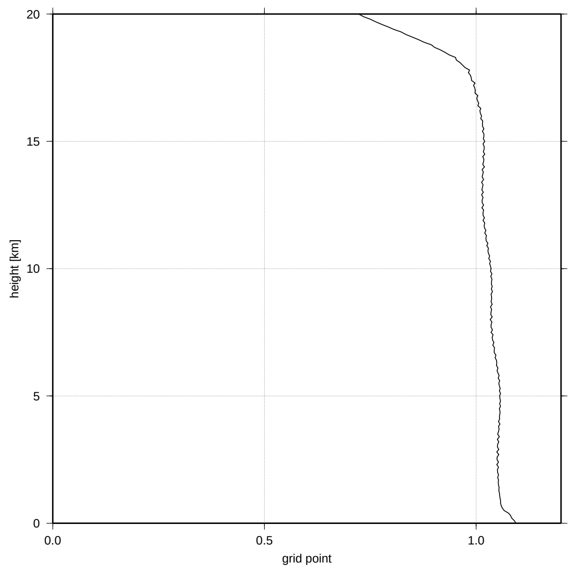
$\tau_r = 2000s$



$\tau_r = 2650s$



$\tau_r = 3000s$



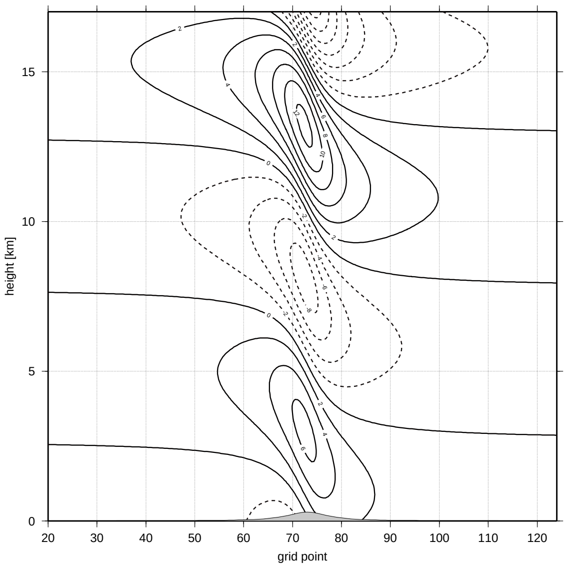
Linear Hydrostatic flow regime

- isothermal atmosphere $T_0 = 273.16K$ with uniform wind $30ms^{-1}$
- Agnesi mountain with height 300m and half width 30km
- model resolution $dx = 6km$ and aproximately $dz = 250m$ in vertical
- 150 vertical levels
- horizontal resolution 192 grid points and quadratic truncation (63 horizontal wave components)
- time step $60s$
- sponge setting $z_t = 29000m$, $z_b = 17500m$ and $\tau_r = 2500s$

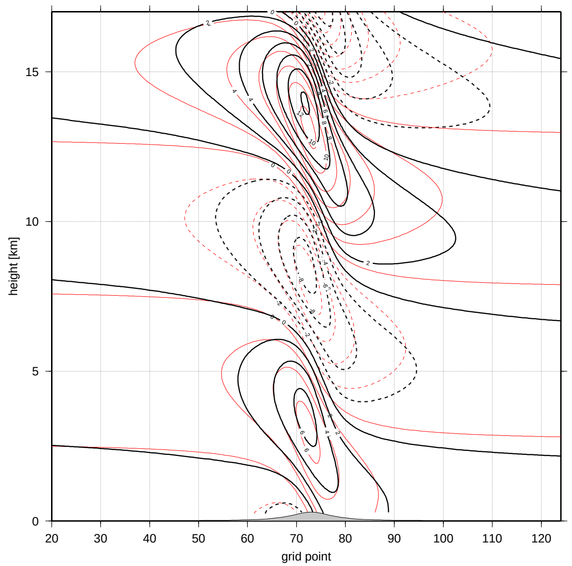
Linear Hydrostatic flow regime

linearity: $C_l = \frac{hN}{U} = 0.1$ hydrostaticity: $C_h = \frac{U}{LN} = 0.05$ after: $\frac{Ut_s}{L} = 80$

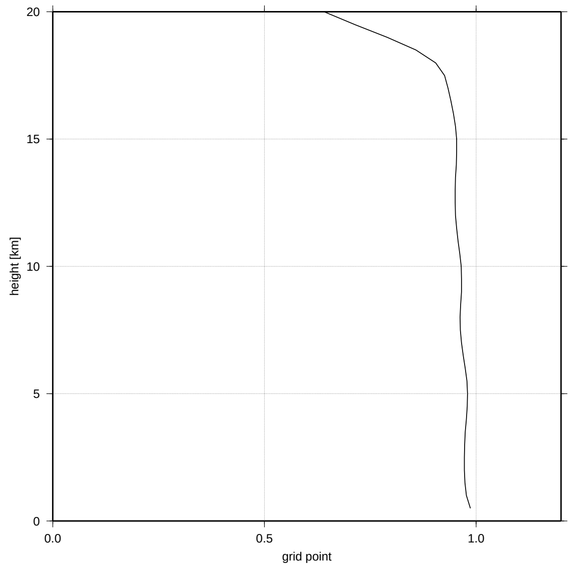
Analytical solution $u - U$



ALADIN



norm. flux



$U = 30ms^{-1}$ $h = 300m$ $L = 30km$ $N = 0.018s^{-1}$ $dx = 6000m$ $dz = 250m$

Normalized surface drag:1.02 Analytical value:1.00

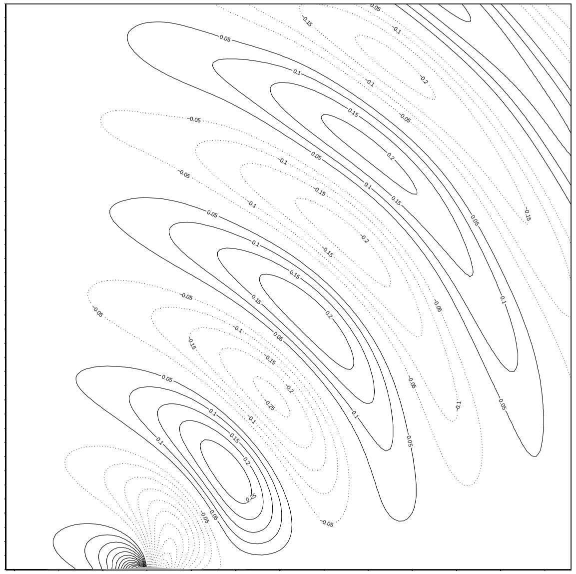
Linear Non-hydrostatic flow regime

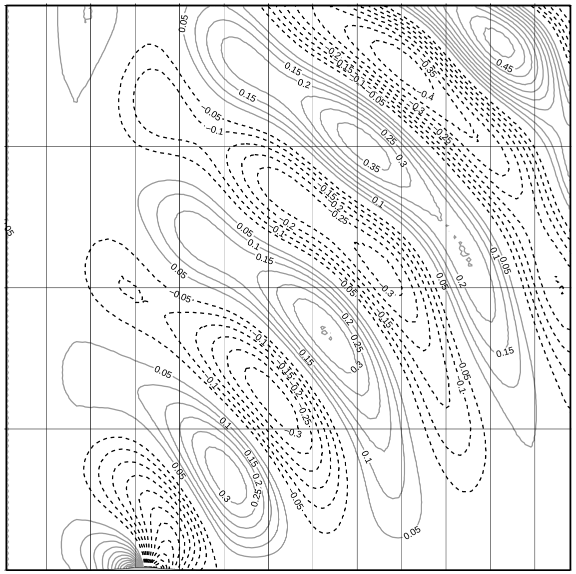
- non-isothermal atmosphere with surface temperature $T_0 = 293K$ and constant $N = 0.01s^{-1}$ and uniform wind $10ms^{-1}$
- Agnesi mountain with height 100m and half width 1000m (narrow mountain)
- model resolution $dx = 200m$ and aproximately $dz = 200m$ in vertical
- 150 vertical levels
- horizontal resolution 192 grid points and quadratic truncation (63 horizontal wave components)
- time step $5s$
- sponge setting $z_t = 29700m$, $z_b = 21000m$ and $\tau_r = 750s$

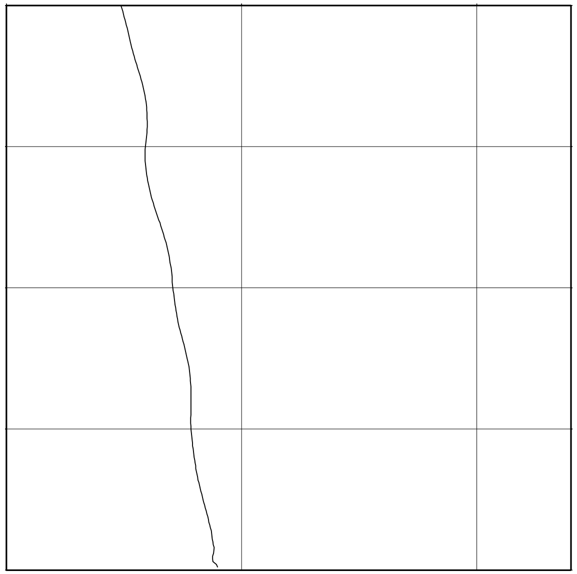
Linear Non-hydrostatic flow regime

linearity: $C_l = \frac{hN}{U} = 0.1$ hydrostaticity: $C_h = \frac{U}{LN} = 1$ after: $\frac{Ut_s}{L} = 80$

Analytical solution w ALADIN norm. flux







$U = 10ms^{-1}$ $h = 100m$ $L = 1km$ $N = 0.01s^{-1}$ $dx = 200m$ $dz = 200m$

Normalized surface drag:0.45 Analytical value:0.47

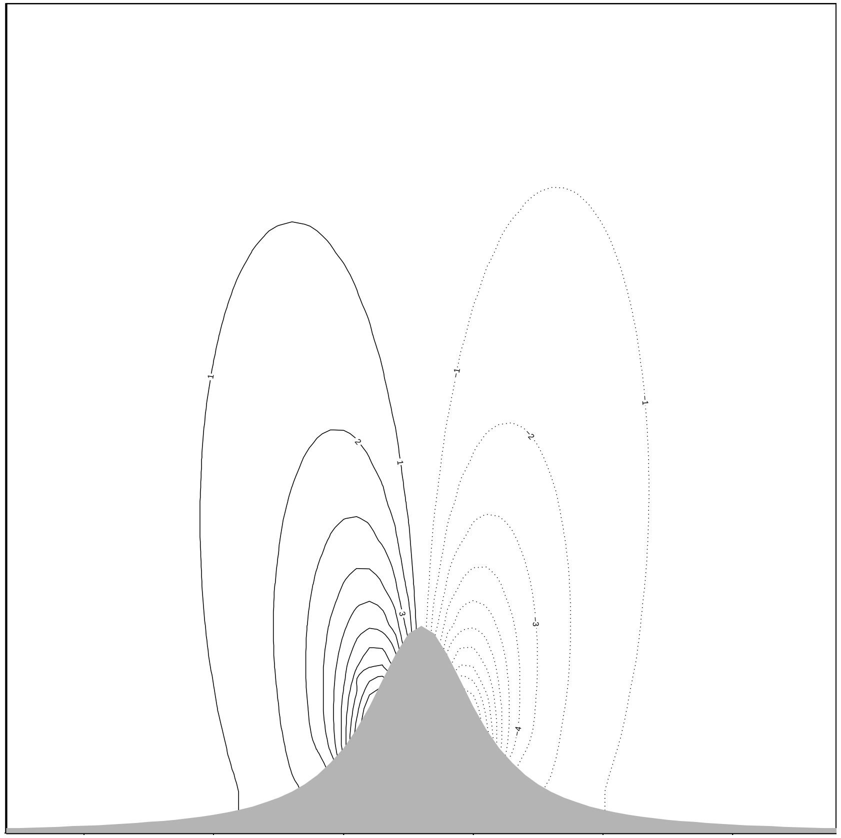
Potential flow regime

- isothermal atmosphere with temperature $T_0 = 239.5K$ ($N = 0.02s^{-1}$) and uniform wind $15ms^{-1}$
- Agnesi mountain with height 100m and half width 100m (narrow mountain)
- model resolution $dx = 20m$ and aproximately $dz = 20m$ in vertical
- 100 vertical levels
- horizontal resolution 128 grid points and quadratic truncation (42 horizontal wave components)
- time step $0.2s$
- sponge setting $z_t = 750m$, $z_b = 450m$ and $\tau_r = 1s$

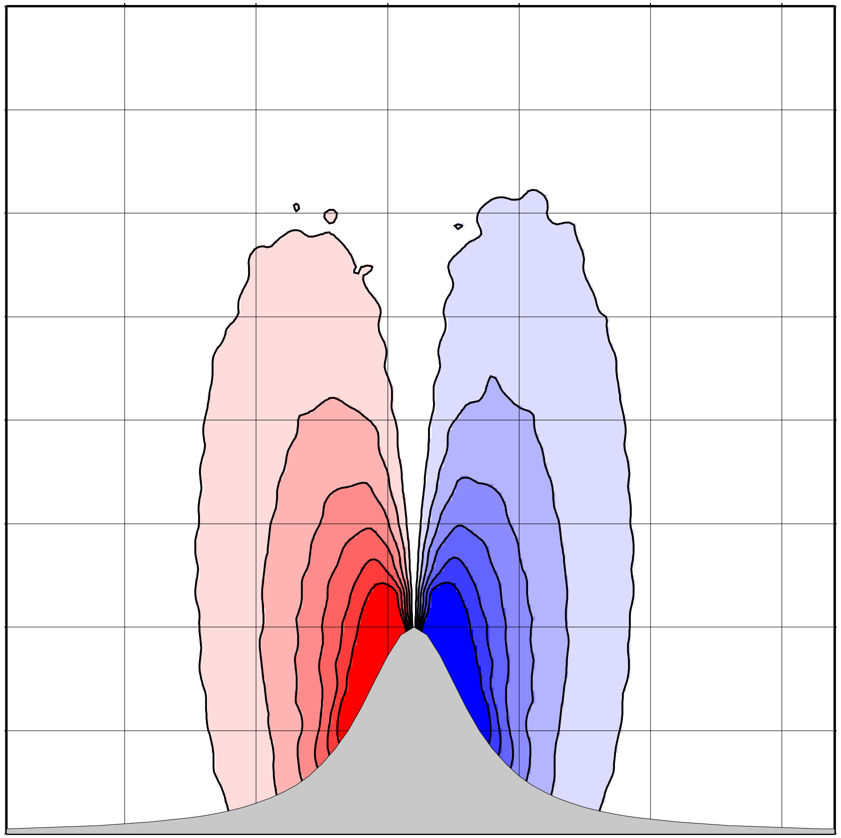
Potential flow regime

linearity: $C_l = \frac{hN}{U} = \frac{2}{15}$ hydrostaticity: $C_h = \frac{U}{LN} = 7.5$ after:$\frac{Ut_s}{L} = 50$

Analytical solution



ALADIN



$U = 15ms^{-1}$ $h = 100m$ $L = 100m$ $N = 0.02s^{-1}$ $dx = 20m$ $dz = 20m$

Normalized surface drag:0.04 Analytical value:0.00

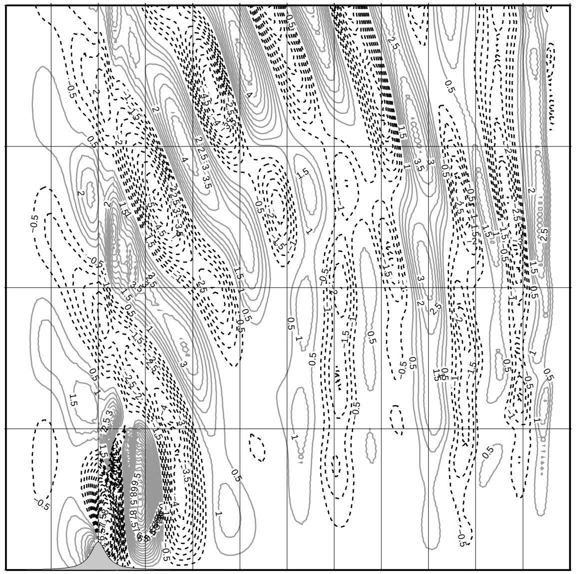
Nonlinear Non-hydrostatic flow regime

- non-isothermal atmosphere with surface temperature $T_0 = 293K$ and constant $N = 0.01s^{-1}$ and uniform wind $10ms^{-1}$
- Agnesi mountain with height 1000m and half width 1000m (narrow mountain)
- model resolution $dx = 200m$ and aproximately $dz = 200m$ in vertical
- 150 vertical levels
- horizontal resolution 128 grid points and quadratic truncation (42 horizontal wave components).
- time step $10s$ ($CFL \approx 1$)
- sponge setting $z_t = 29700m$, $z_b = 21500m$ and $\tau_r = 200s$

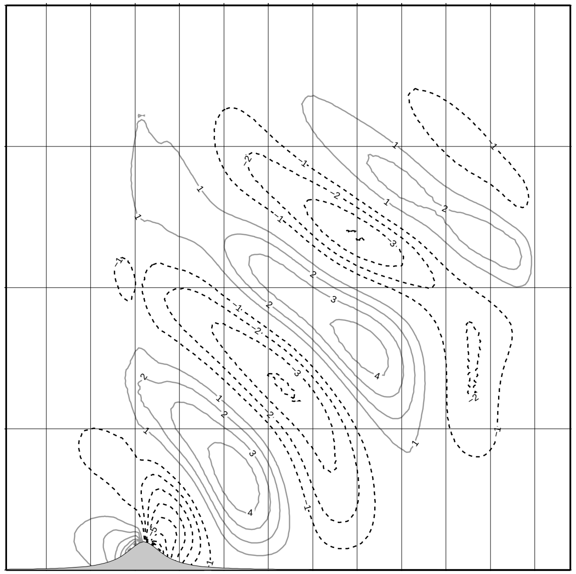
Nonlinear Non-hydrostatic flow regime

- case is very sensitive to the reflections (top and lateral as well). Therefore it demands the tuning of domain size as well
- horizontal diffusion must be used

Large domain ($nx = 300$)



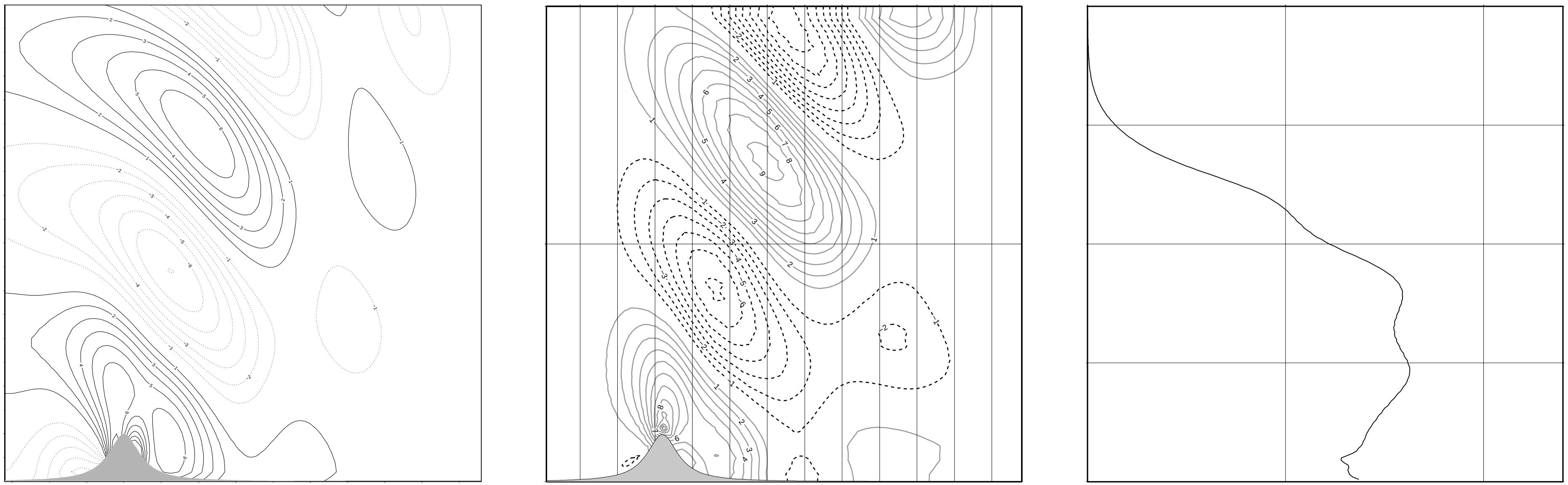
Small domain ($nx = 128$)



Nonlinear Non-hydrostatic flow regime

linearity: $C_l = \frac{hN}{U} = 1$ hydrostaticity: $C_h = \frac{U}{LN} = 1$ after:$\frac{Ut_s}{L} = 50$

Analytical solution $u - U$ ALADIN norm. flux



$U = 10ms^{-1}$ $h = 1000m$ $L = 100m$ $N = 0.01s^{-1}$ $dx = 200m$ $dz = 200m$

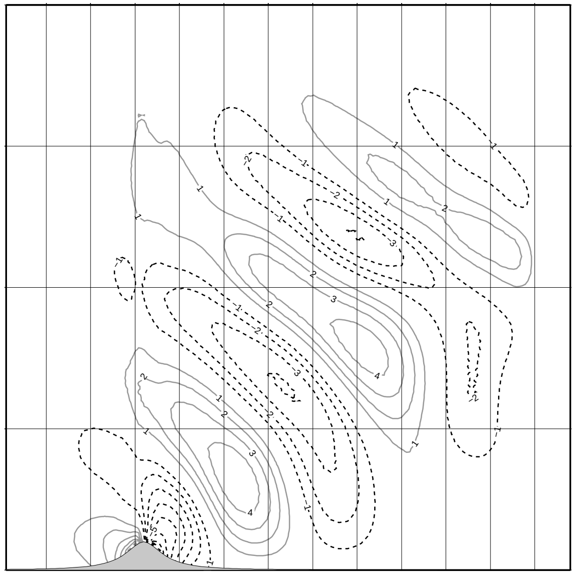
Normalized surface drag:0.69 Analytical value:0.77

(with better tuning of sponge and horizontal diffusion better result could be obtained)

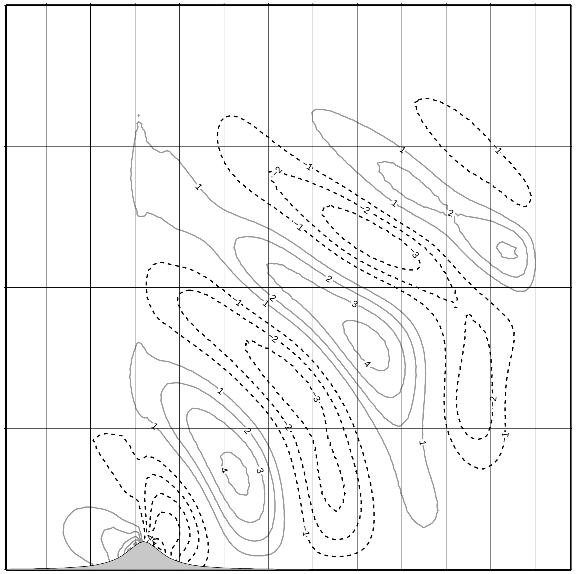
Nonlinear Non-hydrostatic flow regime

linearity: $C_l = \frac{hN}{U} = 1$ hydrostaticity: $C_h = \frac{U}{LN} = 1$ after: $\frac{Ut_s}{L} = 50$

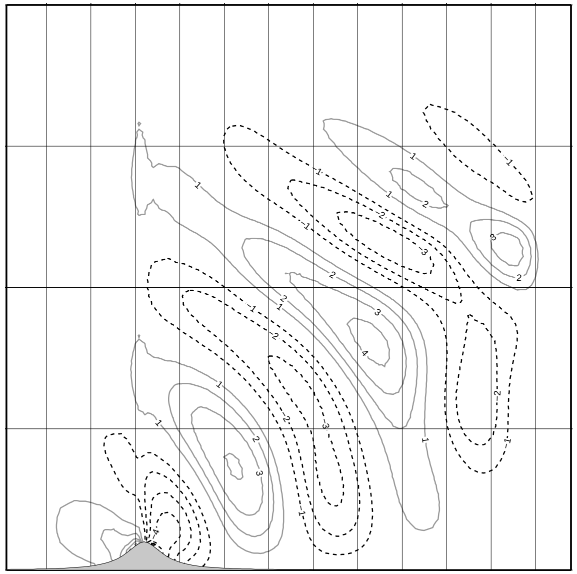
$CFL = 2$



$CFL = 3$



$CFL = 4$



Normalized surface drag	$CFL = 2$	0.61
	$CFL = 3$	0.23
	$CFL = 4$	0.17

Results obtained with $LGWADV$ switch (see presentation about BBC).
Traditional scheme is unstable for $CFL > 3$ in this particular case.

NH regimes with HY and NH model

- tests are performed with constant static stability profile $N = 0.01s^{-1}$

- the wind speed U and the mountain height h are adjusted in order to keep constant C_l, constant C_h and constant $CFL = k_{max}Udt$ for different resolutions (200m, 1000m and 2000m)

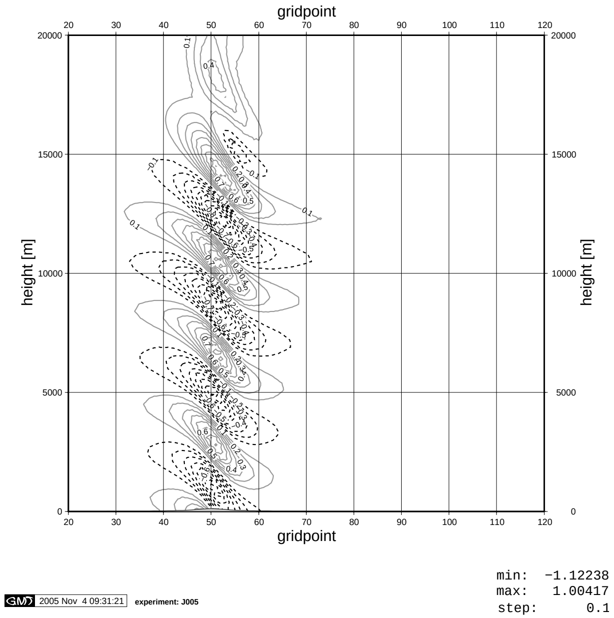
- the cases are integrated to allow particle to fly over mountain the same amount of times ($\frac{UdtN_{steps}}{L} = const. = 50$)

$$C_l = 0.2 \quad C_h = 0.6$$

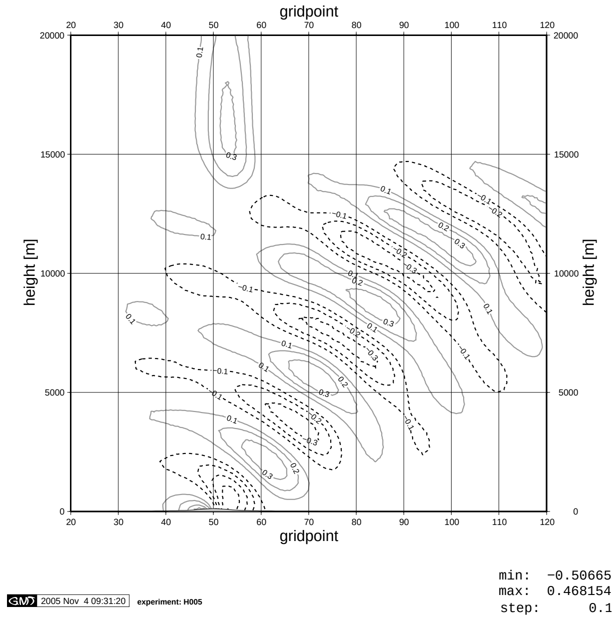
NH quasi-linear flow regime dx=200m

linearity: $C_l = \frac{hN}{U} = 0.2$ hydrostaticity: $C_h = \frac{U}{LN} = 0.6$ after:$\frac{Ut_s}{L} = 50$

HY dynamics



NH dynamics



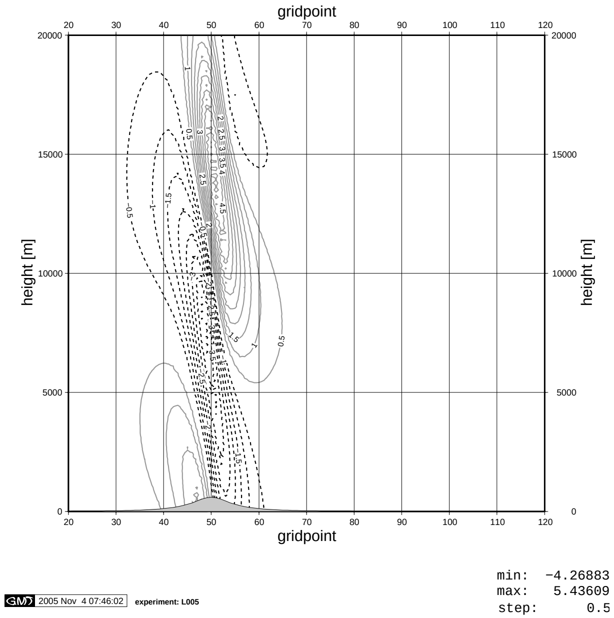
$U = 6ms^{-1}$ $h = 120m$ $L = 1km$ $N = 0.01s^{-1}$

HY model overestimates vertical velocity approx. 2x

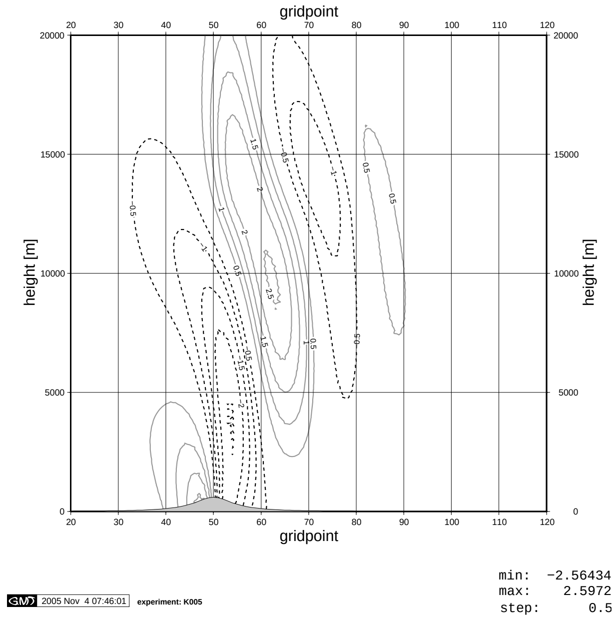
NH quasi-linear flow regime dx=1000m

linearity: $C_l = \frac{hN}{U} = 0.2$ hydrostaticity: $C_h = \frac{U}{LN} = 0.6$ after:$\frac{Ut_s}{L} = 50$

HY dynamics



NH dynamics



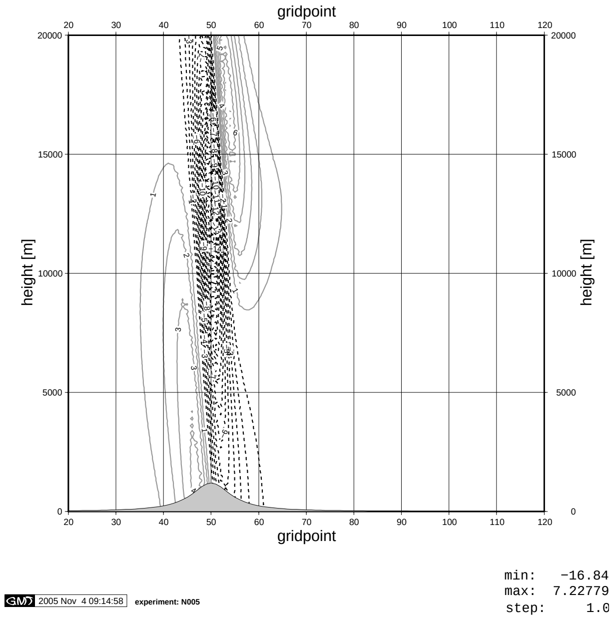
$$U = 30ms^{-1}\ h = 0.6km\ L = 5km\ N = 0.01s^{-1}$$

HY model overestimates vertical velocity approx. 2x

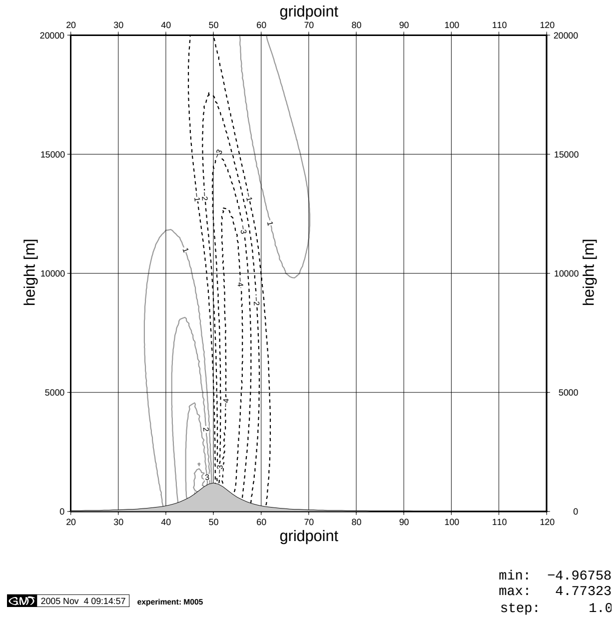
NH quasi-linear flow regime dx=2000m

linearity: $C_l = \frac{hN}{U} = 0.2$ hydrostaticity: $C_h = \frac{U}{LN} = 0.6$ after:$\frac{Ut_s}{L} = 50$

HY dynamics



NH dynamics



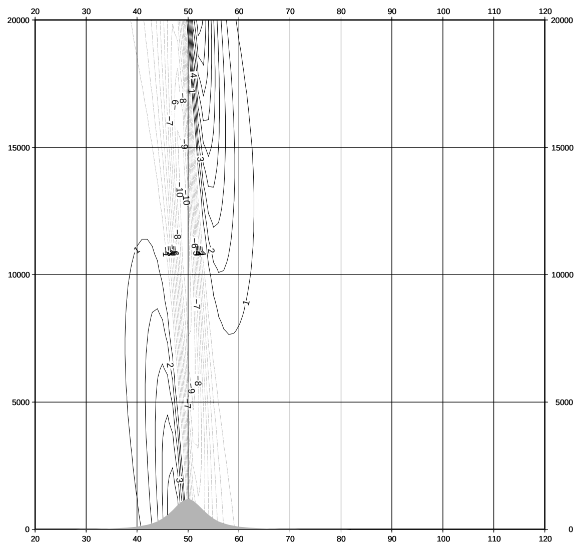
$$U = 60ms^{-1}\ h = 1.2km\ L = 10km\ N = 0.01s^{-1}$$

HY model overestimates vertical velocity

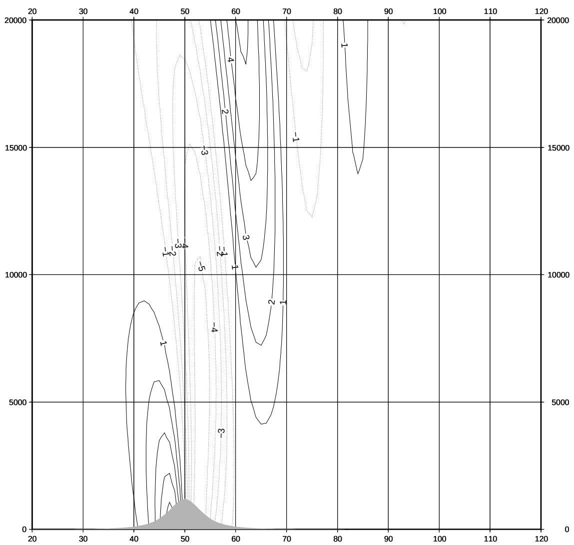
NH quasi-linear flow regime dx=2000m
Analytical solution

linearity: $C_l = \frac{hN}{U} = 0.2$ hydrostaticity: $C_h = \frac{U}{LN} = 0.6$ after: $\frac{Ut_s}{L} = 50$

HY dynamics



NH dynamics



$U = 60ms^{-1}$ $h = 1.2km$ $L = 10km$ $N = 0.01s^{-1}$

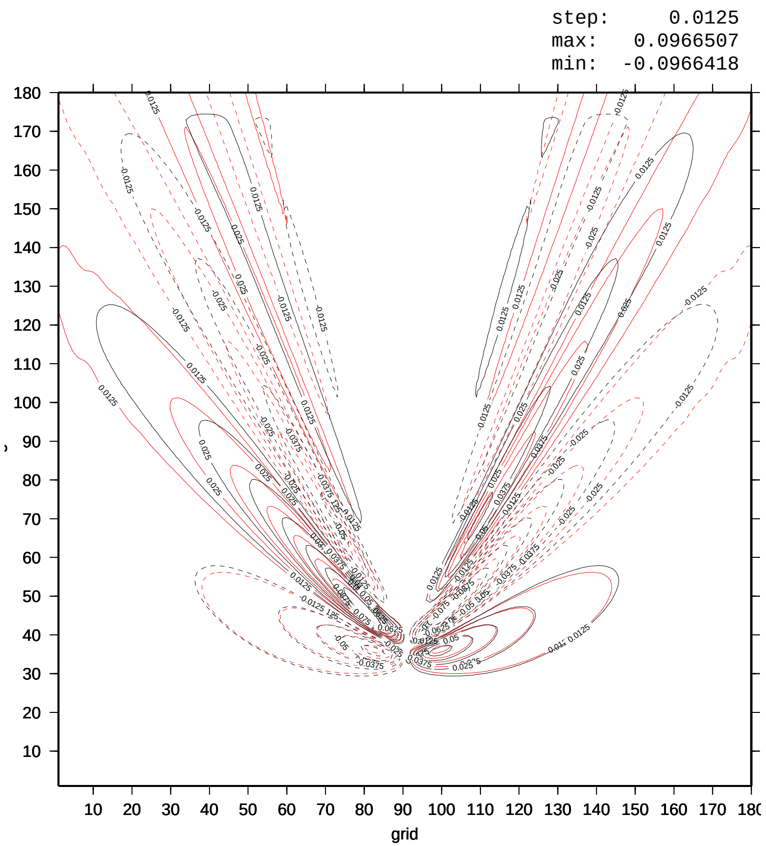
HY model overestimates vertical velocity more than 2x. Waves with $l_x < 37.7km$ remained evanescend in NH dynamics.

3D experiments - linear hydrostatic wave dx=2000m

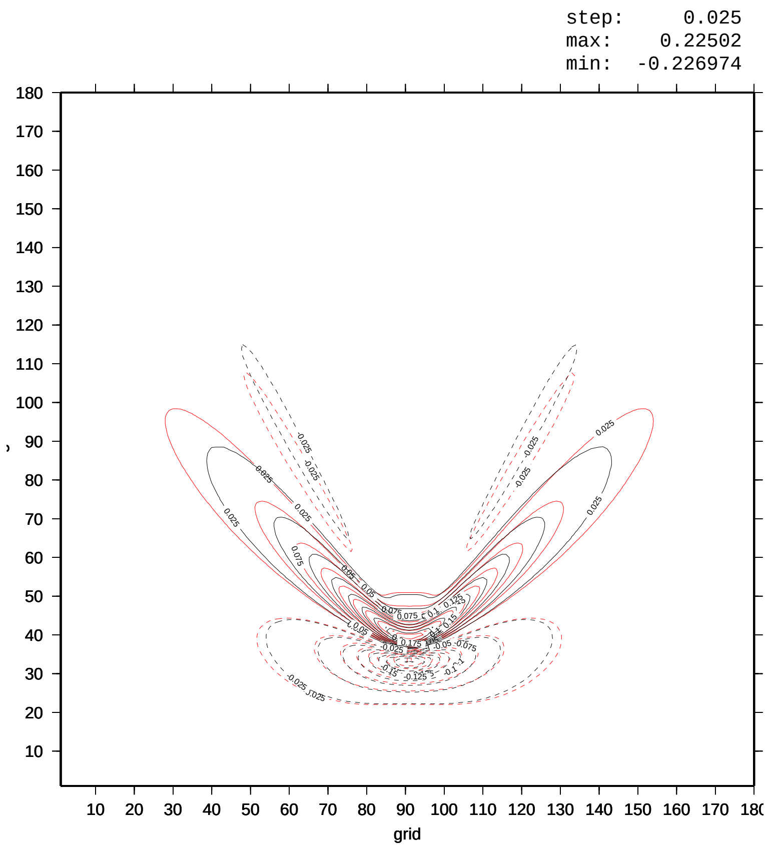
linearity: $C_l = \frac{hN}{U} = 0.1$ hydrostaticity: $C_h = \frac{U}{LN} = 0.06$ after: $\frac{Ut_s}{L} = 40$

anaytical solution ALADIN result

U



V-pert



$U = 0ms^{-1}$ $V = 10ms^{-1}$ $h = 50m$ $L = 10km$ $N = 0.018s^{-1}$

3D results - NH regime dx=2000m

linearity: $C_l = \frac{hN}{U} = 0.2$ hydrostaticity: $C_h = \frac{U}{LN} = 0.6$ analytical results

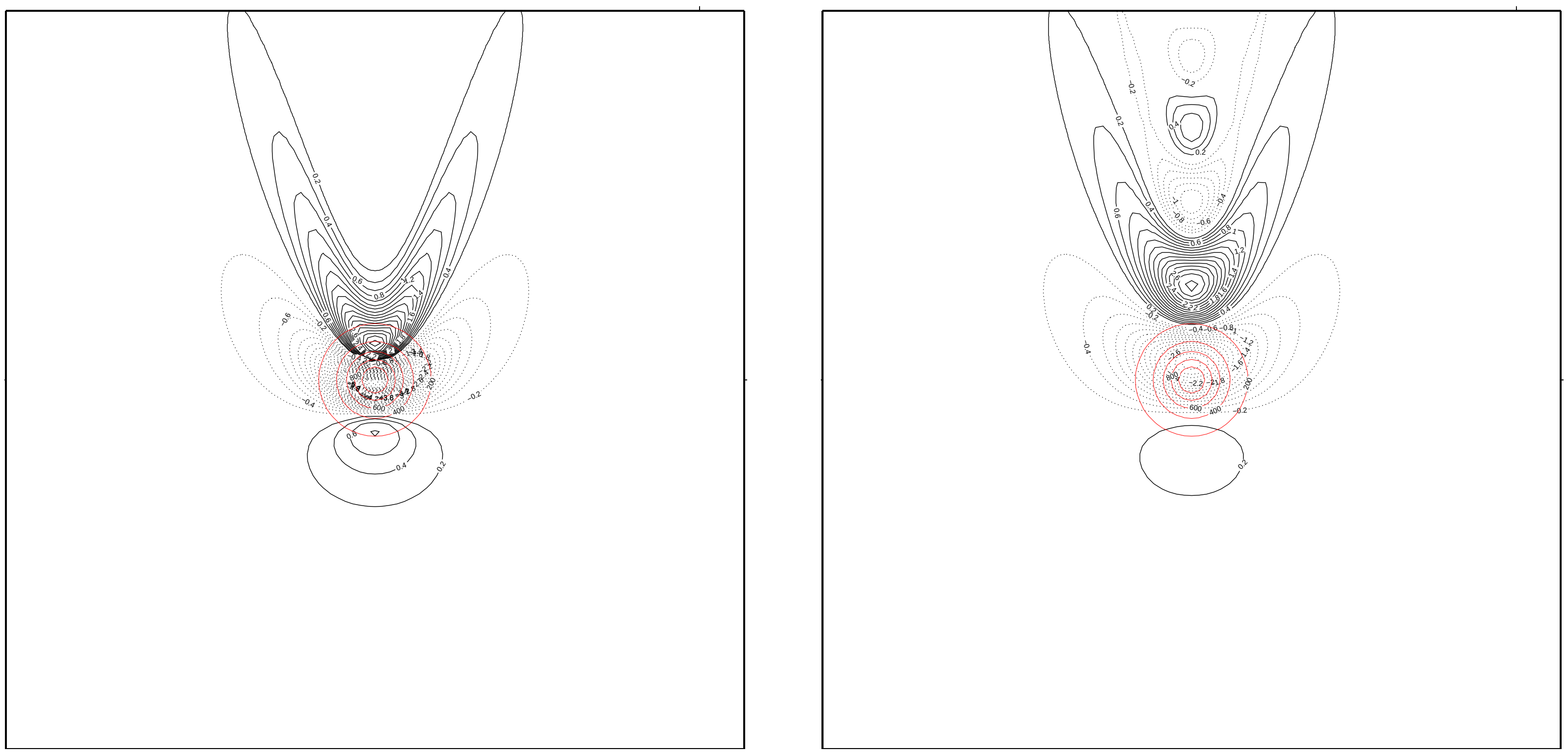
crossection at $z = 9500m$ $(\frac{1}{4}\lambda_G)$

HY model

$w_{min} = -7.7ms^{-1}$ $w_{max} = 3.7ms^{-1}$

NH model

$w_{min} = -3.1ms^{-1}$ $w_{max} = -3.0ms^{-1}$



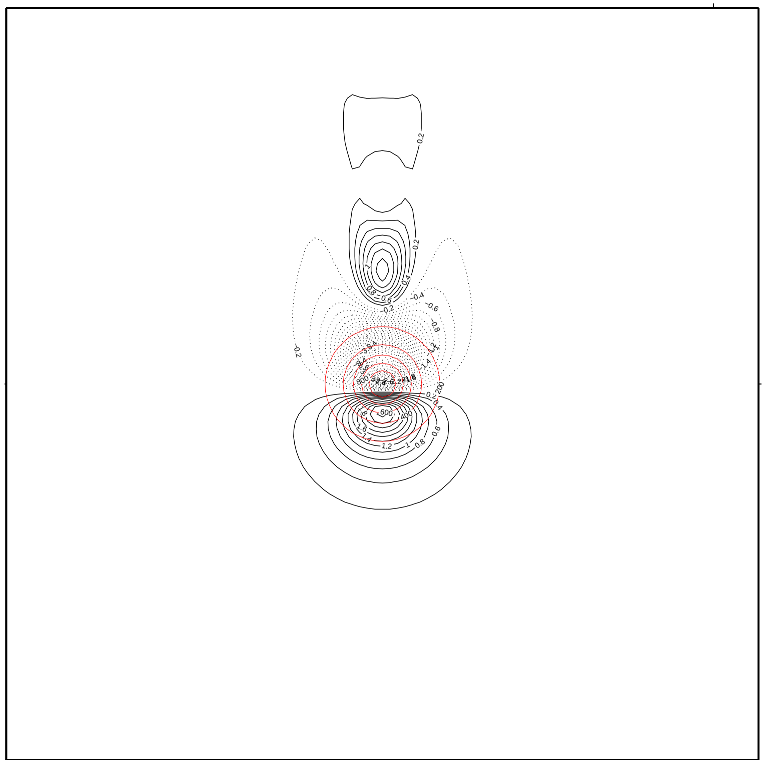
$U = 0ms^{-1}$ $V = 60ms^{-1}$ $h = 1200m$ $L = 10km$ $N = 0.01s^{-1}$

3D results - NH regime dx=2000m

linearity: $C_l = \frac{hN}{U} = 0.2$ hydrostaticity: $C_h = \frac{U}{LN} = 0.6$ analytical results

crossection at $z = 3000m$ $(\frac{1}{12}\lambda_G)$

HY model	NH model
$w_{min} = -7.7ms^{-1}$ $w_{max} = 3.7ms^{-1}$	$w_{min} = -5.4ms^{-1}$ $w_{max} = -2.4ms^{-1}$



$U = 0ms^{-1}$ $V = 60ms^{-1}$ $h = 1200m$ $L = 10km$ $N = 0.01s^{-1}$

Mountain waves - conclusion I.

- the dynamics of NH model ALADIN simulates the internal gravity waves correctly. The wave patterns are close to the analytical results.
- the value of surface drag can be reached close to the analytical value by tuning the absorbing layer properties at the top
- for the non-hydrostatic regimes the tuning of domain size is necessary to minimize the reflection of waves from the lateral boundaries
- the model was run without any additional damping or additional filtering except for non-linear nonhydrostatic flow regime where horizontal diffusion was used
- when running model with higher values of CFL the wave amplitude is decreased. The orographic resonance is handled with Tangay-Ritchie method.

Mountain waves - conclusion

Following conclusion are drawn from idealized simulation with atmopshere with

constant Brunt-Vaisala frequency and constant wind profile.

- the trapped modes in HY simulations are represented as a wave modes (and the waves near this value are distorted). This leads to overestimation of vertical velocities when run in NH flow regimes

- the evanescend modes occur in the ALADIN approximately for resolutions $dx < \pi\frac{U}{N}$ (linear truncation considered) and it seems that the NH dynamics shall be important. For typical atmospheric conditions $dx < \pi\frac{30ms^{-1}}{0.02s^{-1}} = 4700m$.

- for the domain with $dx = 2.5km$, $NDGL = 300$, linear truncation ($NSMAX = 149$) and typical conditions ($U = 30ms^{-1}$ and $N = 0.02s^{-1}$) approx. 46% modes is evanescend