Regional Cooperation for
Limited Area Modeling in Central Europe

LACE
nwp central europe

ACCORD
A Consortium for COnvection-scale modelling
Research and Development

Dynamics for ACCORD model higher numerical stability

Petra Smolíková (CHMI), Fabrice Voitus (MF), Nika Kastelec (ARSO),
Jozef Vivoda (ECMWF)

GeoSphere Austria · DHMZ · Czech Hydrometeorological Institute · HungaroMet · IMGW · METEO ROMANIA · SHMU · ARSO METEO Slovenia

Outline

- ❑ Dynamical core in ACCORD
- ❑ SI time scheme
- ❑ Orographic terms in linear model (based on ideas of Fabrice Voitus and Jozef Vivoda)
- ❑ Idealised test cases
- ❑ Real simulations @200m

Dynamical core in ACCORD

Basic equations

- hydrostatic primitive equation system (HPE) or Euler equations (EE); recently implemented quasi elastic equation system (QE)
- prognostic variables $\vec{v}, T, q_s = \ln(\pi_s)$, in EE with $w, \hat{q} = \ln(\frac{p}{\pi})$

Discretization

- spectral method for horizontal direction
- hybrid vertical coordinate η based on hydrostatic pressure $\pi(\eta) = A(\eta) + B(\eta)\pi_s$; $A(top) = B(top) = 0, A(bottom) = 0, B(bottom) = 1$
- finite differences or finite elements for vertical direction discretization
- semi-implicit or iterative centred implicit scheme for time discretization
- semi-Lagrangian advection

Semi-Implicit time scheme

System evolution

$$\frac{dX}{dt} = \mathcal{M}X$$

Linearization

$$X = \mathbf{X}^* + \mathbf{X}', \quad \mathcal{M} \longrightarrow \mathcal{L}^*$$

Using linear model $\mathcal{L}^*$ we divide

$$\frac{dX}{dt} = \mathcal{L}^*\overline{[X]}^t + (\mathcal{M} - \mathcal{L}^*)X$$

and discretize in time to obtain

Semi-implicit scheme

$$\frac{\mathbf{X}^+ - \mathbf{X}^0}{\Delta t} = \mathcal{L}^*\left(\frac{\mathbf{X}^+ + \mathbf{X}^0}{2}\right) + (\mathcal{M} - \mathcal{L}^*)\mathbf{X}^{+\frac{1}{2}}$$

or

Iterative centered implicit scheme

$$\frac{\mathbf{X}^{+(n)} - \mathbf{X}^0}{\Delta t} = \frac{\mathcal{L}^*\mathbf{X}^{+(n)} + \mathcal{L}^*\mathbf{X}^0}{2} + \frac{(\mathcal{M} - \mathcal{L}^*)\mathbf{X}^{+(n-1)} + (\mathcal{M} - \mathcal{L}^*)\mathbf{X}^0}{2}$$

We know that both can be second order accurate in time when some care is taken (averaging along semi-Lagrangian trajectory).

Full model

LACE
nwp central europe

Temperature

$$\frac{dT}{dt} = \frac{\kappa T}{\kappa - 1}(D + d)$$

Horizontal momentum

$$\frac{d\vec{v}}{dt} = -RT\frac{\nabla\pi}{\pi} - \nabla\phi - RT\nabla\hat{q} - \frac{1}{m}\frac{\partial(p-\pi)}{\partial\eta}\nabla\phi$$

Vertical momentum

$$\frac{dw}{dt} = \frac{g}{m}\frac{\partial(p-\pi)}{\partial\eta}$$

Pressure departure

$$\frac{d\hat{q}}{dt} = \frac{1}{\kappa - 1}(D + d) - \frac{1}{\pi}\frac{d\pi}{dt}$$

Surface pressure

$$\frac{dq_s}{dt} = -\frac{1}{\pi_s}\int_0^1 \nabla\cdot(m\vec{v})d\eta$$

Diagnostic relations

$$\frac{d\pi}{dt} = \vec{v}\cdot\nabla\pi - \int_0^\eta \nabla\cdot(m\vec{v})d\eta'$$

$$\phi = \phi_s - \int_\eta^1 \frac{mRT}{p}d\eta'$$

$$d = \frac{p}{mRT}\left(\nabla\phi\frac{\partial\vec{v}}{\partial\eta} - g\frac{\partial w}{\partial\eta}\right)$$

Definitions

$$D = \nabla\cdot\vec{v}$$

$$\kappa = \frac{c_p}{R}$$

$$m = \frac{\partial\pi}{\partial\eta}$$

Full model

LACE nwp central europe

Temperature

$$\frac{dT}{dt} = \frac{\kappa T}{\kappa - 1}(D + d)$$

Horizontal momentum

$$\frac{d\vec{v}}{dt} = -RT\frac{\nabla\pi}{\pi} - \nabla\phi - RT\nabla\hat{q} - \frac{1}{m}\frac{\partial(p-\pi)}{\partial\eta}\nabla\phi$$

Vertical momentum

$$\frac{dw}{dt} = \frac{g}{m}\frac{\partial(p-\pi)}{\partial\eta}$$

Pressure departure

$$\frac{d\hat{q}}{dt} = \frac{1}{\kappa - 1}(D + d) - \frac{1}{\pi}\frac{d\pi}{dt}$$

Surface pressure

$$\frac{dq_s}{dt} = -\frac{1}{\pi_s}\int_0^1 \nabla\cdot(m\vec{v})d\eta$$

Diagnostic relations

$$\begin{aligned}
\frac{d\pi}{dt} &= \vec{v}\cdot\nabla\pi - \int_0^\eta \nabla\cdot(m\vec{v})d\eta' \\
\phi &= \phi_s - \int_\eta^1 \frac{mRT}{p}d\eta' \\
d &= \frac{p}{mRT}\left(\nabla\phi\frac{\partial\vec{v}}{\partial\eta} - g\frac{\partial w}{\partial\eta}\right)
\end{aligned}$$

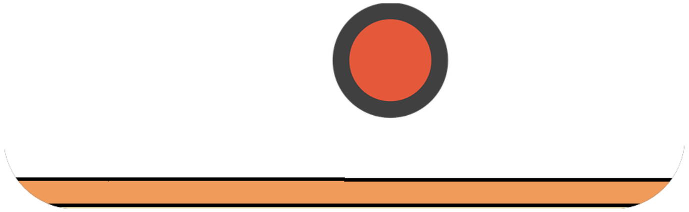
Definitions

$$\begin{aligned}
D &= \nabla\cdot\vec{v} \\
\kappa &= \frac{c_p}{R} \\
m &= \frac{\partial\pi}{\partial\eta}
\end{aligned}$$

Basic state

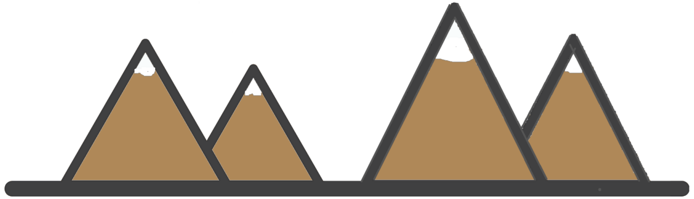
Current:

- stationary
- resting
- hydrostatically balanced (π_s^*)
- dry
- isothermal (T^*)
- with constant orography ($\nabla \phi^* = 0$)



New:

- stationary
- resting
- hydrostatically balanced (π_s^*)
- dry
- isothermal (T^*)
- with constant orographic slope (in absolute value, $|\nabla\phi^*| \neq 0$)



Linear model

LACE nwp central europe

Temperature

$$\frac{\partial T}{\partial t} = \frac{\kappa T^*}{\kappa - 1}(D + d)$$

Horizontal momentum

$$\frac{\partial \vec{v}}{\partial t} = -RT^* \frac{\nabla \pi}{\pi^*} - \nabla \phi - RT^* \nabla \hat{q} - \frac{1}{m^*}\frac{\partial \pi^* \hat{q}}{\partial \eta} \nabla \phi^*$$

Vertical momentum

$$\frac{\partial w}{\partial t} = \frac{g}{m^*}\frac{\partial \pi^* \hat{q}}{\partial \eta}$$

Pressure departure

$$\frac{\partial \hat{q}}{\partial t} = \frac{1}{\kappa - 1}(D + d) + \frac{1}{\pi^*}\int_0^\eta m^* D d\eta'$$

Surface pressure

$$\frac{\partial q_s}{\partial t} = -\frac{1}{\pi_s^*}\int_0^1 m^* D d\eta$$

Diagnostic relations

$$\nabla \phi^* = \nabla \phi_s^* - \int_\eta^1 \nabla \left(\frac{m^* R T^*}{\pi^*}\right) d\eta'$$

$$\nabla \phi_s^* = g \Lambda^*$$

$$d = \frac{\pi^*}{m^* R T^*}\left(\nabla \phi^* \frac{\partial \vec{v}}{\partial \eta} - g \frac{\partial w}{\partial \eta}\right)$$

Definitions

New SI parameter

$$\Lambda^* = \frac{1}{g}\, max\,(||\nabla \phi_s||, \textbf{ over domain})$$

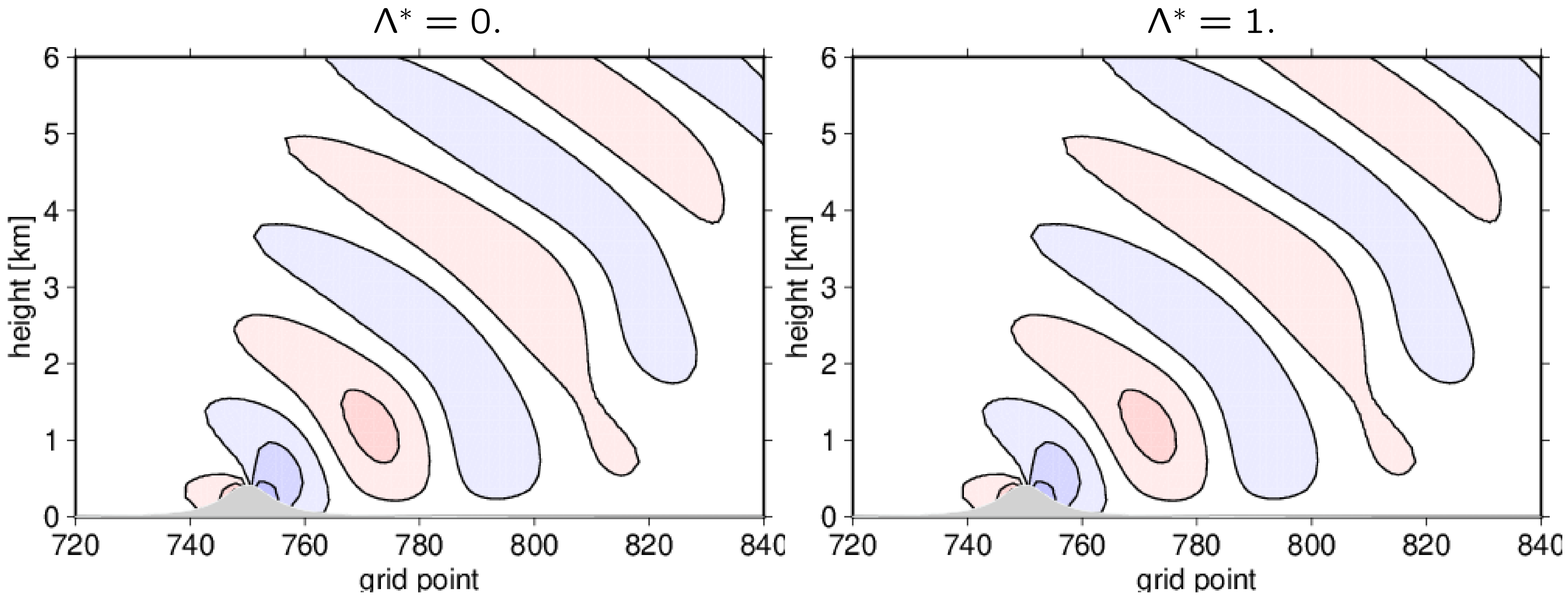
$$m^* = \frac{\partial \pi^*}{\partial \eta}$$

Helmholtz elimination

- formulate time evolution for the modified vertical divergence
- omit the first order terms in $\nabla\phi^*$, then $\frac{\partial\vec{v}}{\partial t}$ is unchanged and all operators of the RHS of $\frac{\partial d}{\partial t}$ apply on $\widehat{q}$
- formulate RHS of $\frac{\partial d}{\partial t}$ as new vertical Laplacian operator applied on $\widehat{q}$
- with no slopes present the new vertical Laplacian collapses to the old one
- new vertical Laplacian has only real and negative eigenvalues in "reasonable cases"
- discretize (we omit the details here)
- eliminate all variables up to horizontal divergence D
- solve the Helmholtz equation for D as usually

LACE nwp central europe

Vertical velocity for the uniform wind over an Agnesi shaped mountain with increasing slope, $max\,(||\nabla\phi_s||) = 0.6$

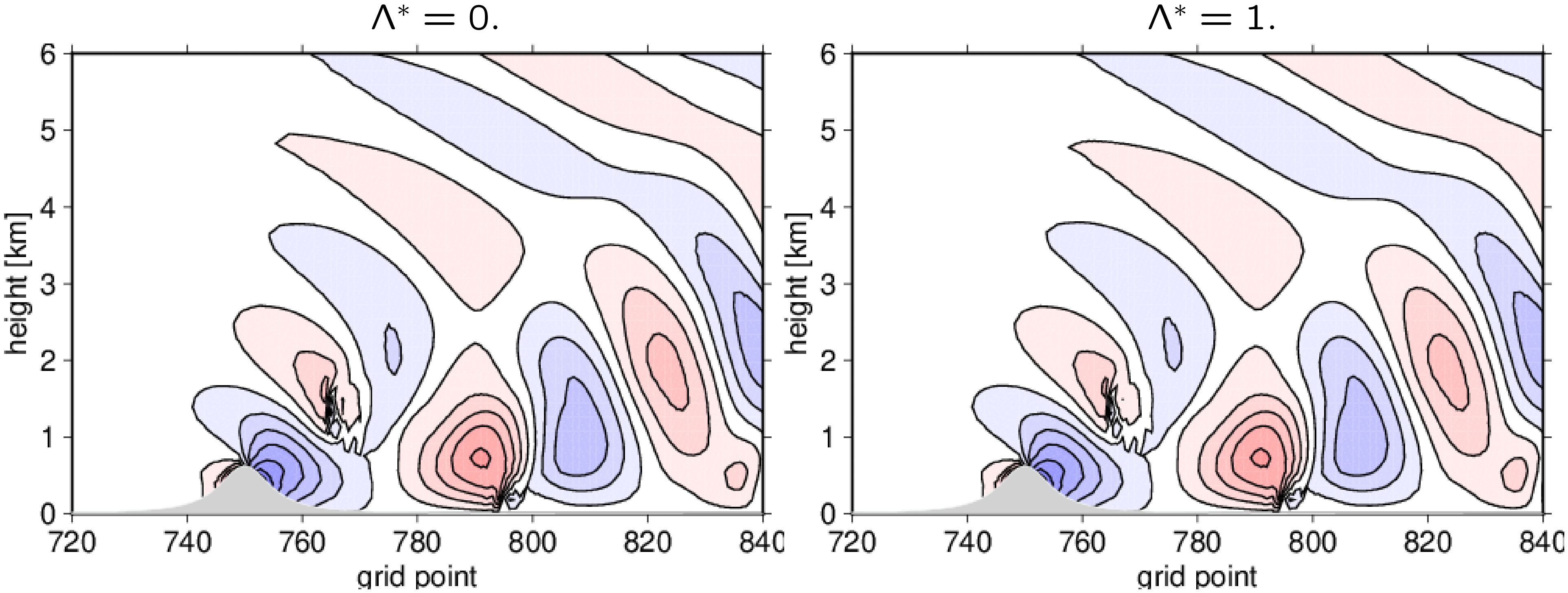


GeoSphere Austria DHMZ Czech Hydrometeorological Institute HungaroMet IMGW METEO ROMANIA SHMU ARSO METEO Slovenia

Idealized tests

LACE
nwp central europe

Vertical velocity for the uniform wind over an Agnesi shaped mountain with increasing slope, $max\,(||\nabla\phi_s||) = 0.9$

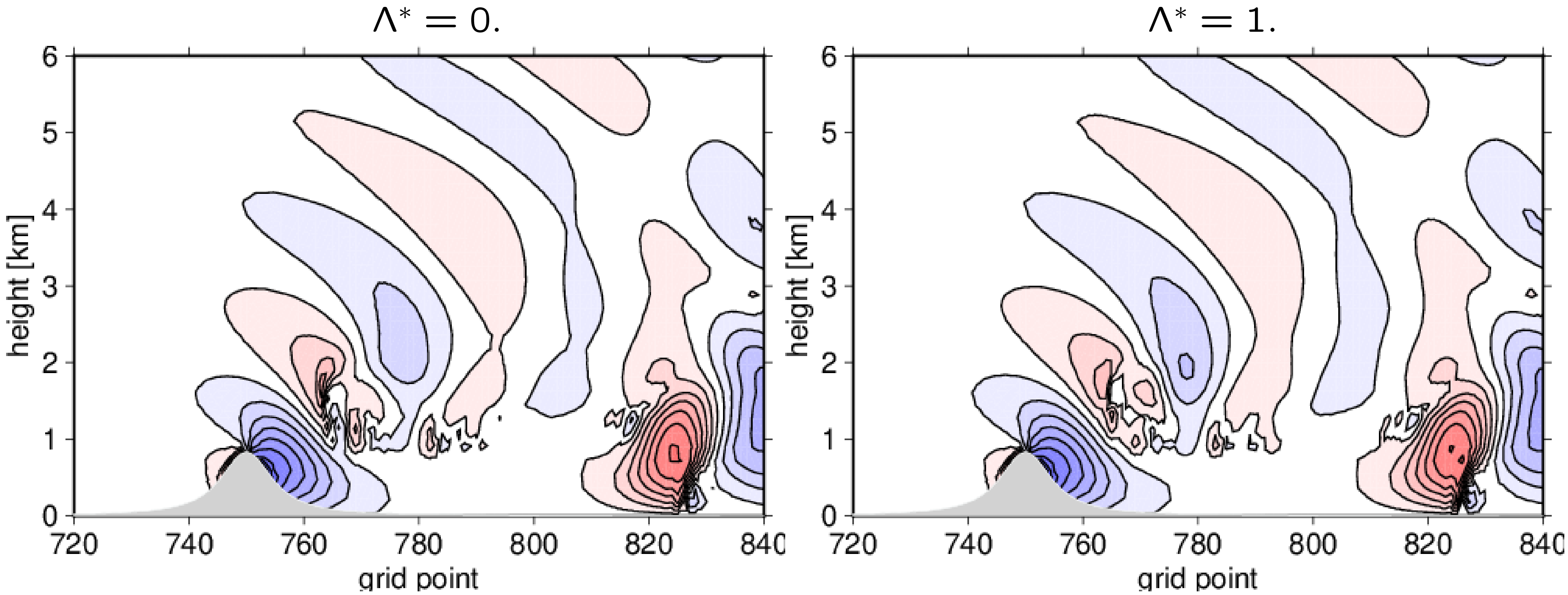


42°

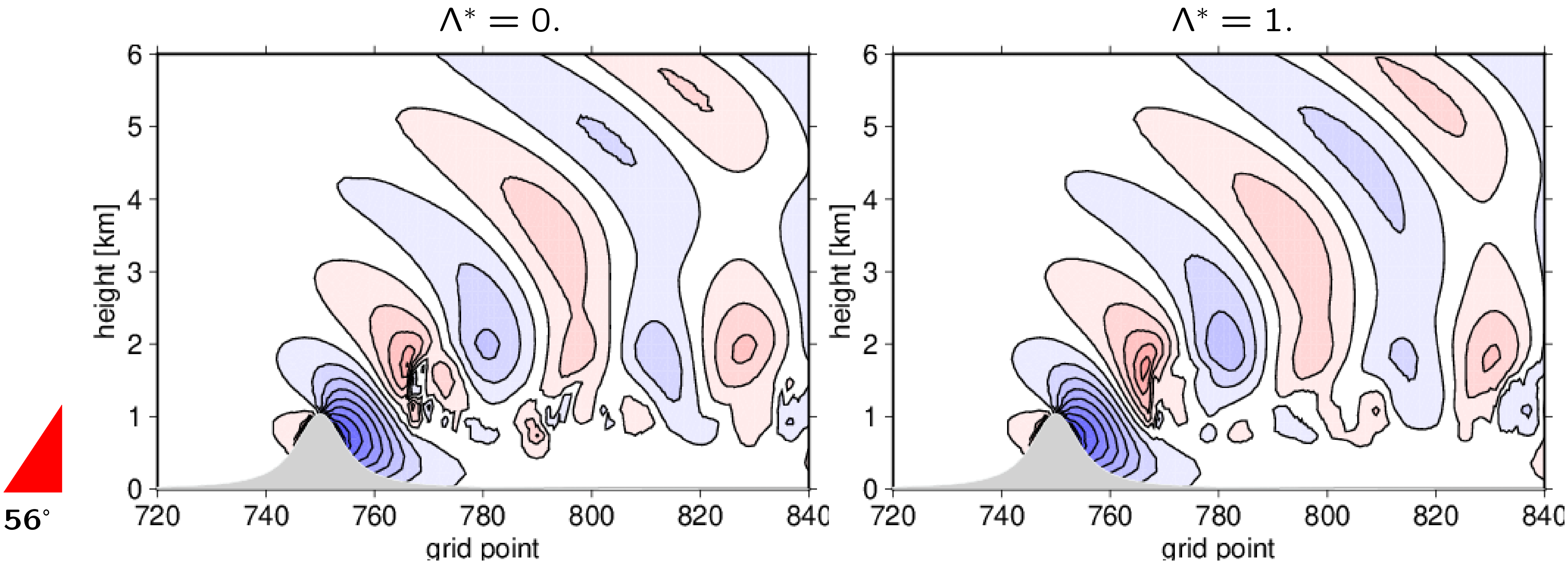
Idealized tests

Vertical velocity for the uniform wind over an Agnesi shaped mountain with increasing slope, $max\,(||\nabla\phi_s||) = 1.2$

50°

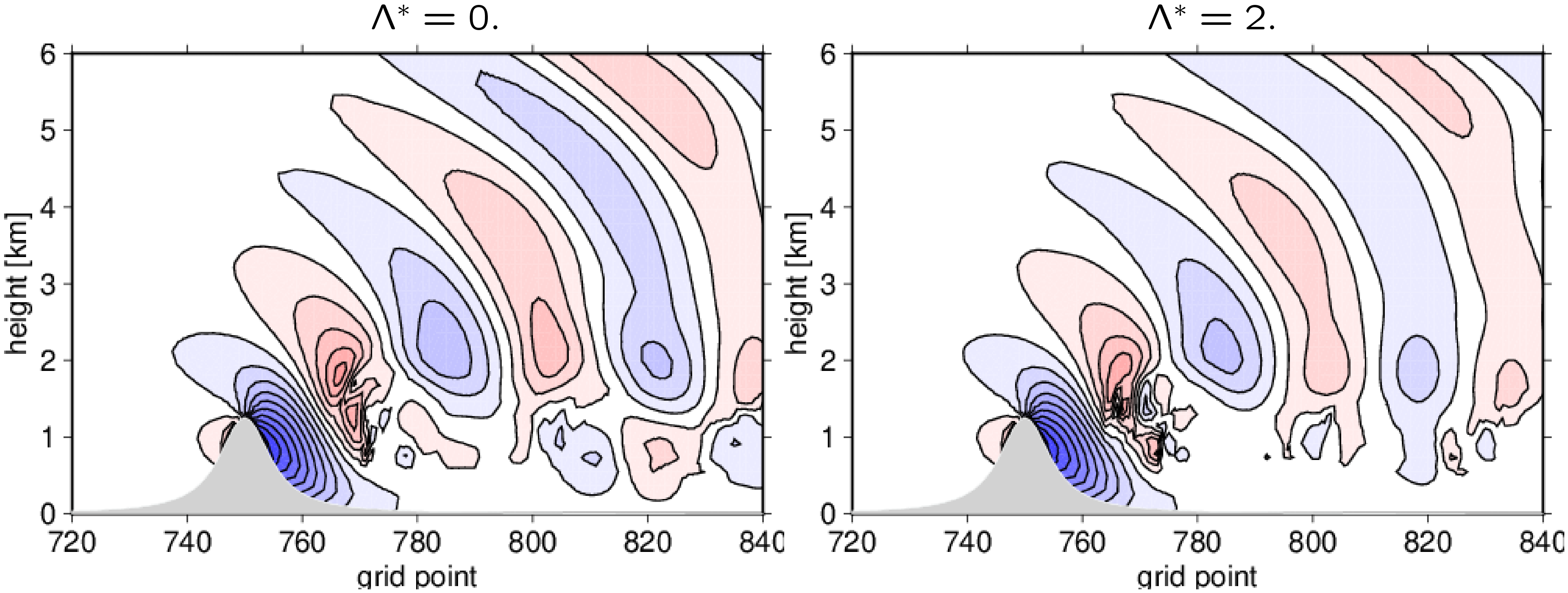


Vertical velocity for the uniform wind over an Agnesi shaped mountain with increasing slope, $max\,(||\nabla\phi_s||) = 1.5$



Vertical velocity for the uniform wind over an Agnesi shaped mountain with increasing slope, $max\,(||\nabla\phi_s||) = 1.8$

61°

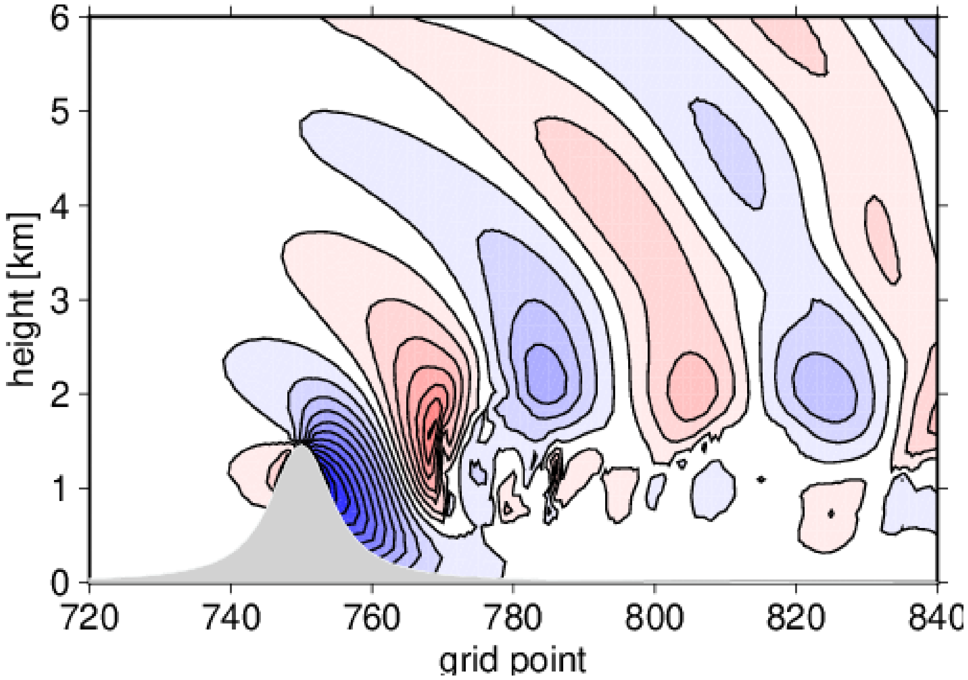


Idealized tests

Vertical velocity for the uniform wind over an Agnesi shaped mountain with increasing slope, $max\,(||\nabla\phi_s||) = 2$

$\Lambda^* = 0.$ $\Lambda^* = 2.$

63°

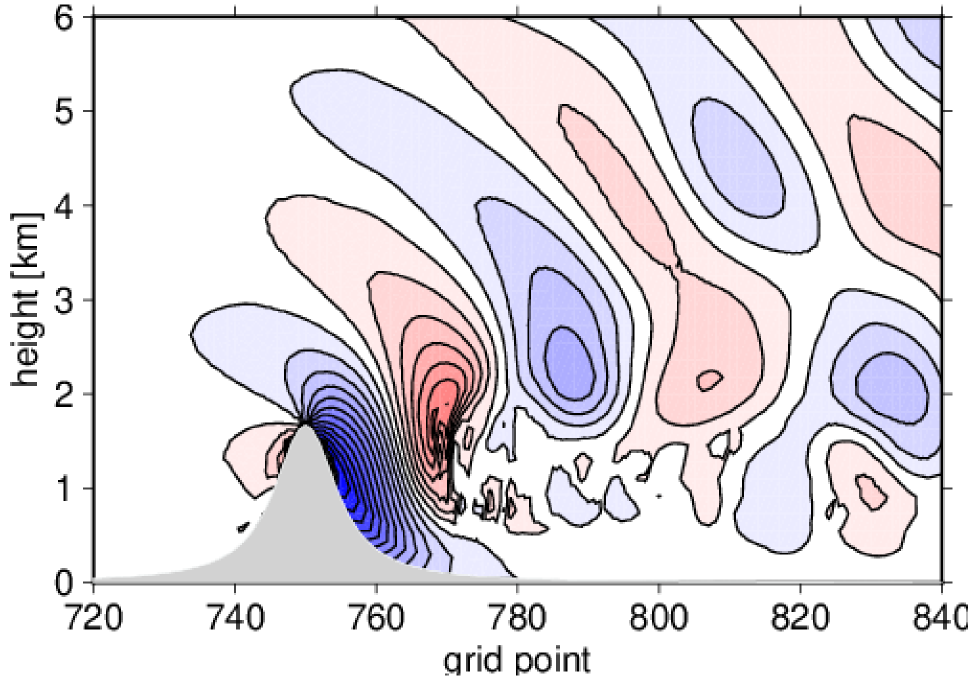


Idealized tests

Vertical velocity for the uniform wind over an Agnesi shaped mountain with increasing slope, $max\,(||\nabla\phi_s||) = 2.4$

$\Lambda^* = 0.$

$\Lambda^* = 2.$



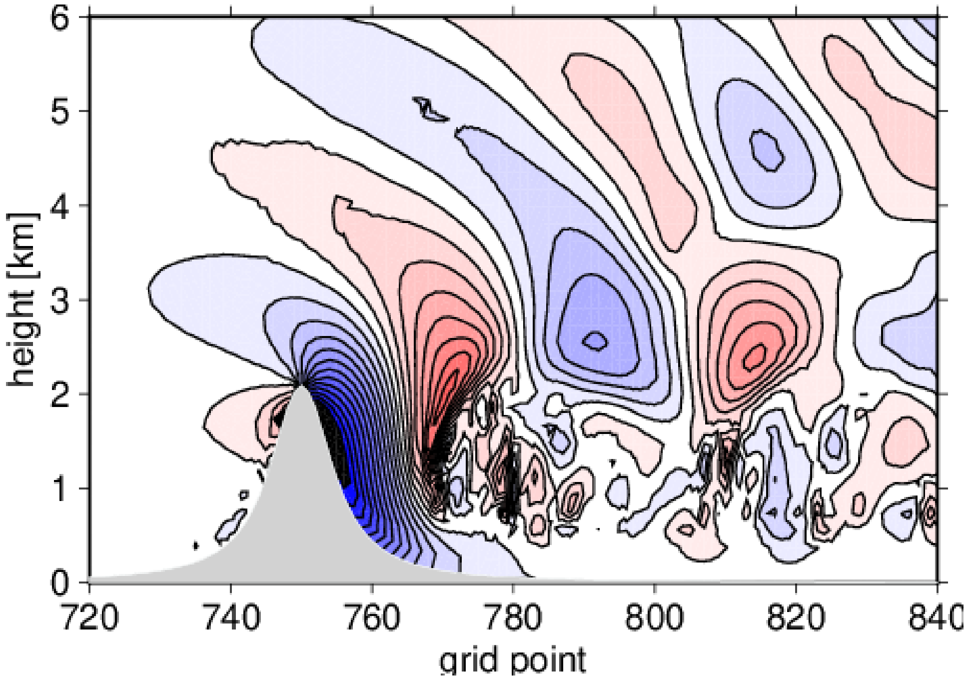
67°

Vertical velocity for the uniform wind over an Agnesi shaped mountain with increasing slope, $max\left(||\nabla\phi_s||\right) = 3$

$\Lambda^* = 0.$

$\Lambda^* = 3.$


72°

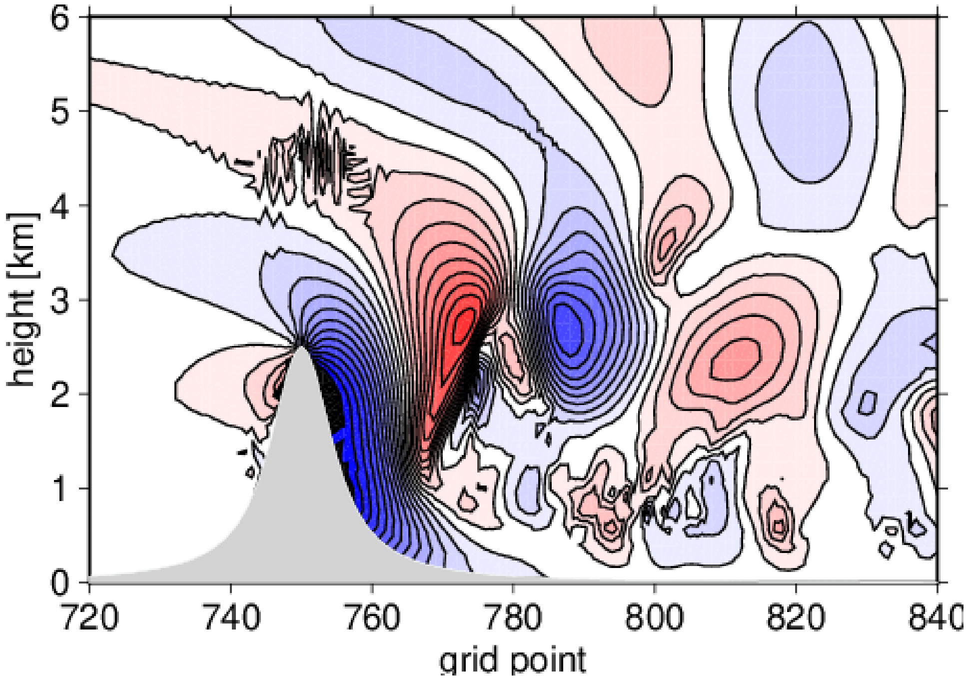


Idealized tests

Vertical velocity for the uniform wind over an Agnesi shaped mountain with increasing slope, $max\,(||\nabla\phi_s||) = 3.5$

$\Lambda^* = 0.$

$\Lambda^* = 4.$

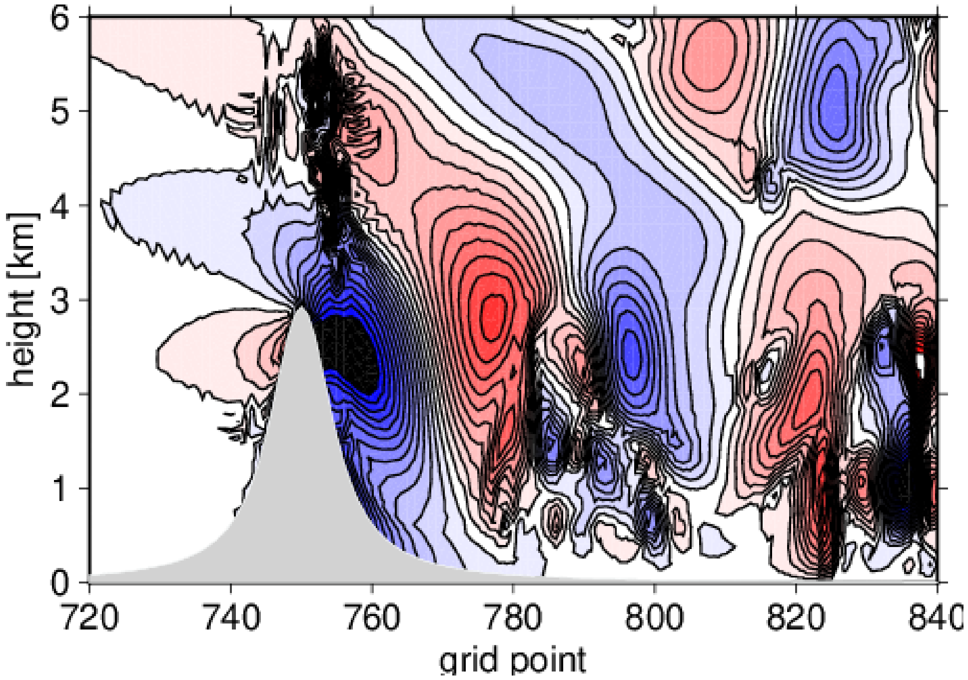


74°

Vertical velocity for the uniform wind over an Agnesi shaped mountain with increasing slope, $max\left(||\nabla\phi_s||\right) = 4$

$\Lambda^* = 0.$ $\Lambda^* = 4.$

76°



Linear model

LACE
nwp central europe

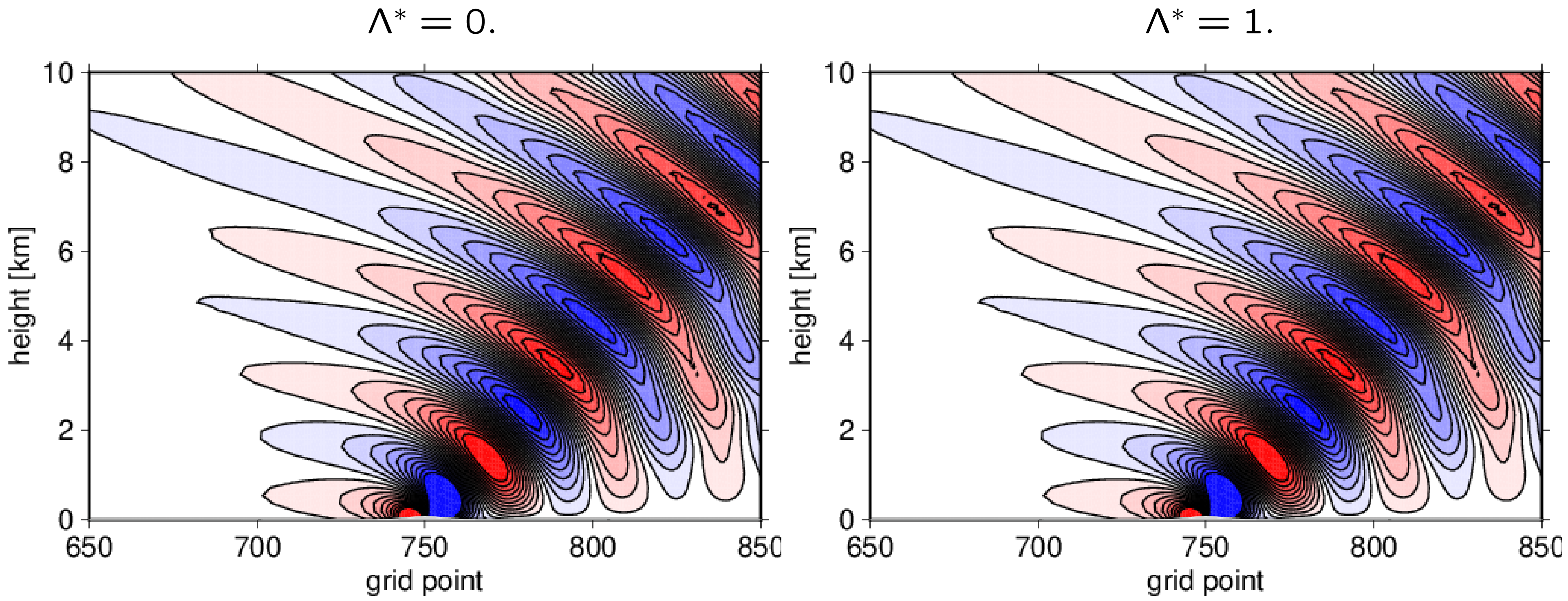
- The ICI scheme in ACCORD uses horizontally constant coefficients.
- In $$\frac{dX}{dt} = \mathcal{L}^*\overline{[X]}^t + (\mathcal{M} - \mathcal{L}^*)X$$

  the linear model $\mathcal{L}^*$ is just a matrix with numbers, constant during the whole integration.
- The Helmholtz matrix calculated from it is constant in time and applied in spectral space on spectral coefficients.
- It means that we chose just one value for each of the reference parameters in the linear model, being the same in the whole domain.
- With the added reference slope it is the same - one value is chosen for the whole domain.
- It follows that we must chose a value which will work well in flat terain too.

GeoSphere Austria DHMZ Czech Hydrometeorological Institute HungaroMet IMGW METEO ROMANIA SHMU ARSO METEO Slovenia

LACE
nwp central europe

Vertical velocity for the uniform wind over an Agnesi shaped mountain with very small height, $max\,(||\nabla\phi_s||) = 0.1$

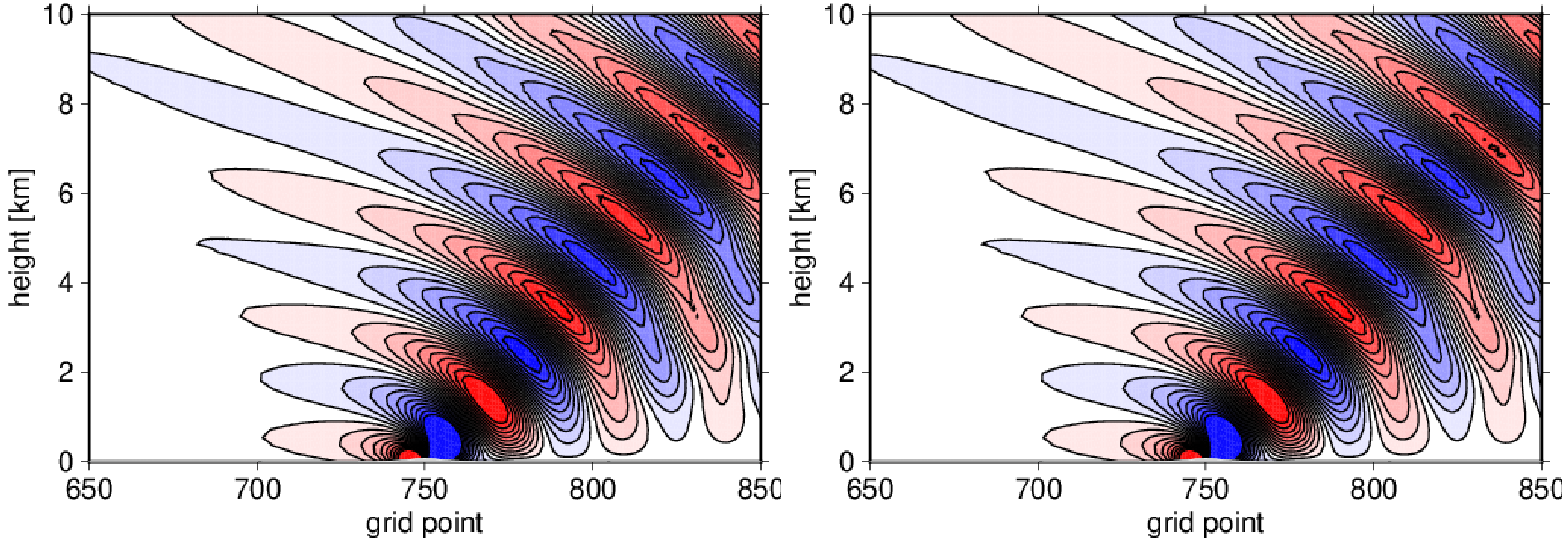


6°

GeoSphere Austria DHMZ Czech Hydrometeorological Institute HungaroMet IMGW METEO ROMANIA SHMU ARSO METEO Slovenia

Vertical velocity for the uniform wind over an Agnesi shaped mountain with very small height, $max\left(||\nabla\phi_s||\right) = 0.1$

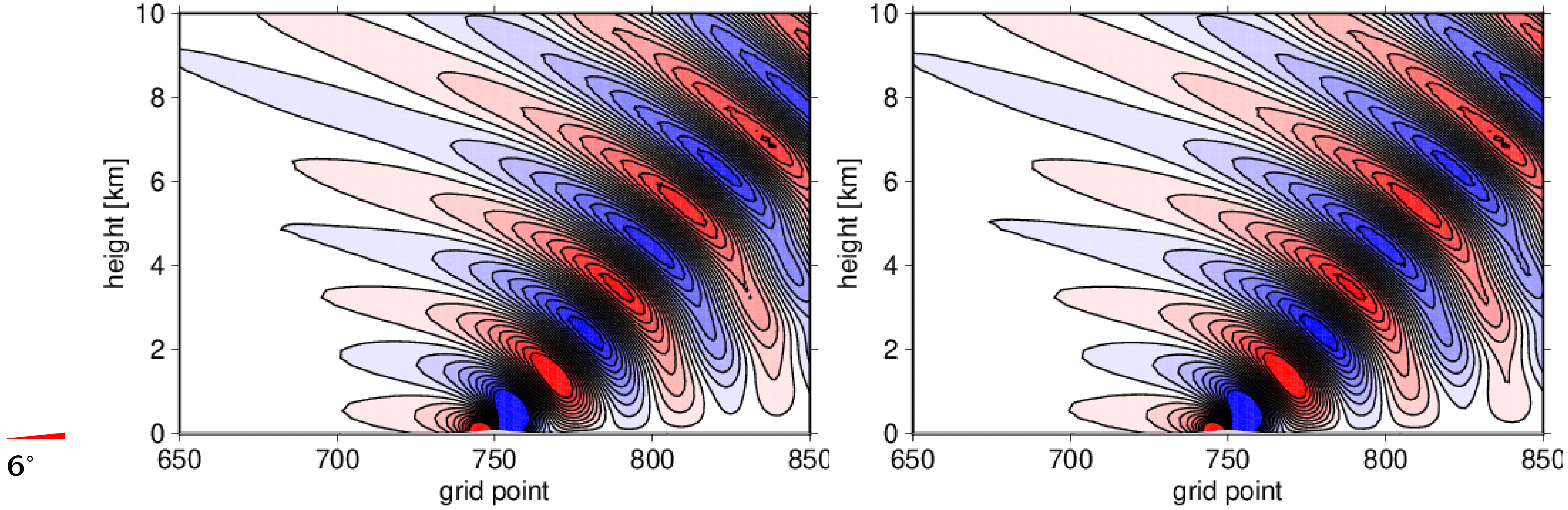
$\Lambda^* = 0.$ $\Lambda^* = 2.$



6°

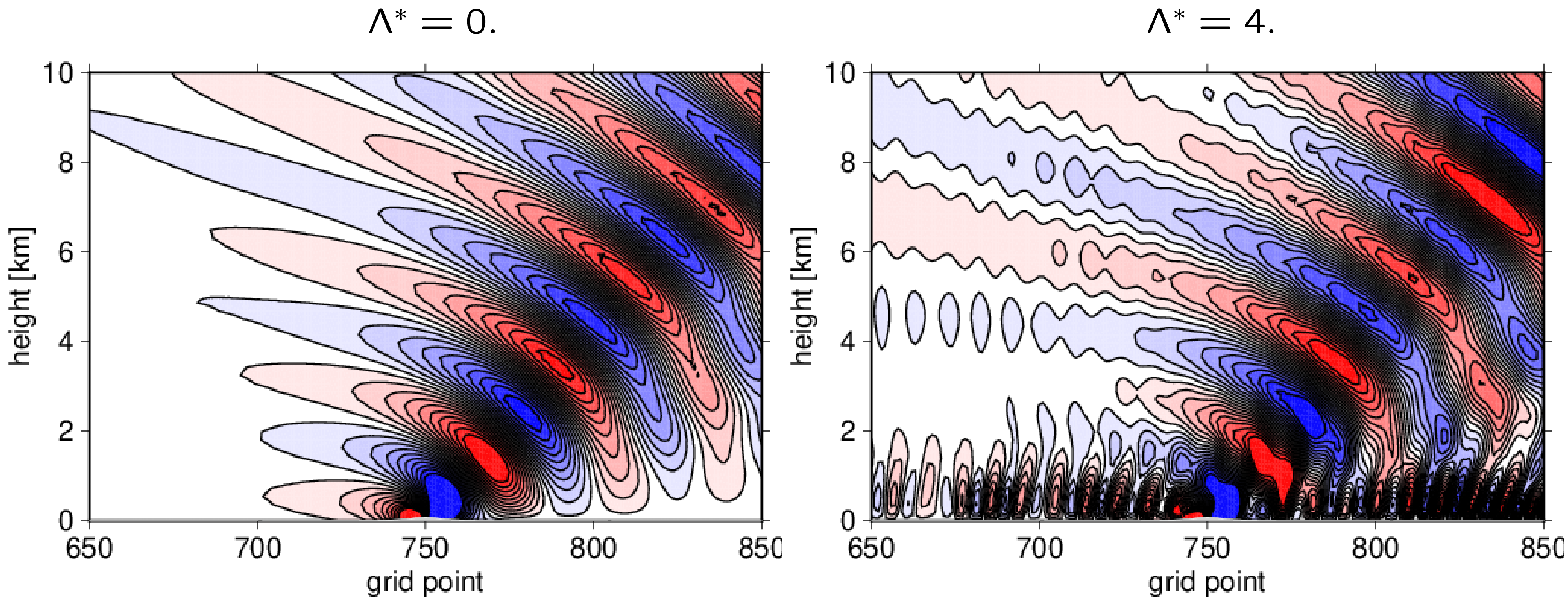
Vertical velocity for the uniform wind over an Agnesi shaped mountain with very small height, $max\left(||\nabla \phi_s||\right) = 0.1$

$\Lambda^* = 0.$ $\Lambda^* = 3.$



Idealized tests

Vertical velocity for the uniform wind over an Agnesi shaped mountain with very small height, $max\,(||\nabla\phi_s||) = 0.1$



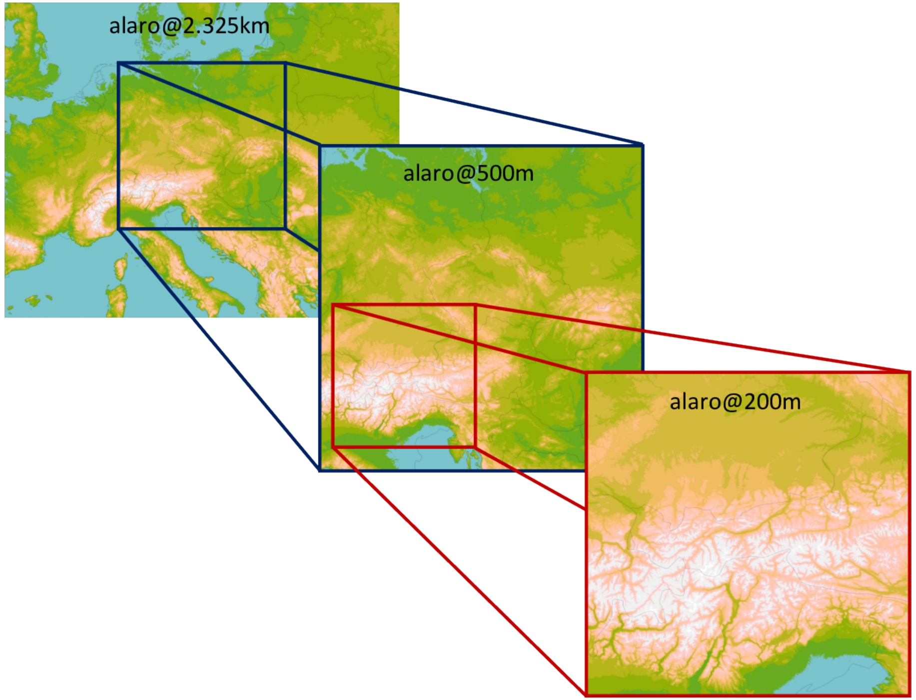
6°

Real simulations @200m

LACE
nwp central europe

The basic algorithmic choices for ALARO configurations are:

- semi-Lagrangian advection with 4 iterations for trajectory calculation
- PC time scheme with one iteration, cheap variant (SL trajectories are not recalculated in corrector)
- modified vertical divergence d4 for vertical motion, transformation to vertical velocity w in the non-linear model
- reference values of the linear model: SITR=300K, SITRA=100K, SIPR=900hPa
- no decentering
- semi-Lagrangian horizontal diffusion applied on all model variables + TKE,TTE, hydrometeors
- linear truncation for all spectral fields except orography; quadratic truncation of orography



GeoSphere Austria DHMZ Czech Hydrometeorological Institute HungaroMet IMGW METEO ROMANIA SHMU ARSO METEO Slovenia

Real simulations @200m

LACE
nwp central europe

ALARO physics

- radiation scheme ACRANEB2
- turbulence and shalow convection scheme TOUCANS, model 2
- scale aware deep convection and microphysics scheme 3MT

Initialization

- initialization with 3DVAR + surface DA (CANARI) for 2.325km run; dynamical adaptation + DFI for 500m and 200m runs

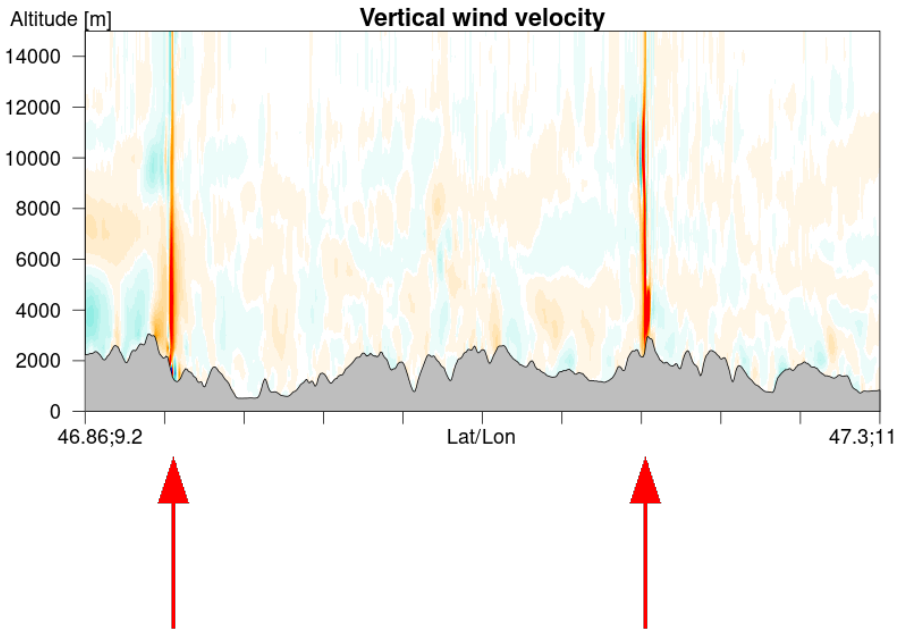
Particular choices for ALARO@200m:

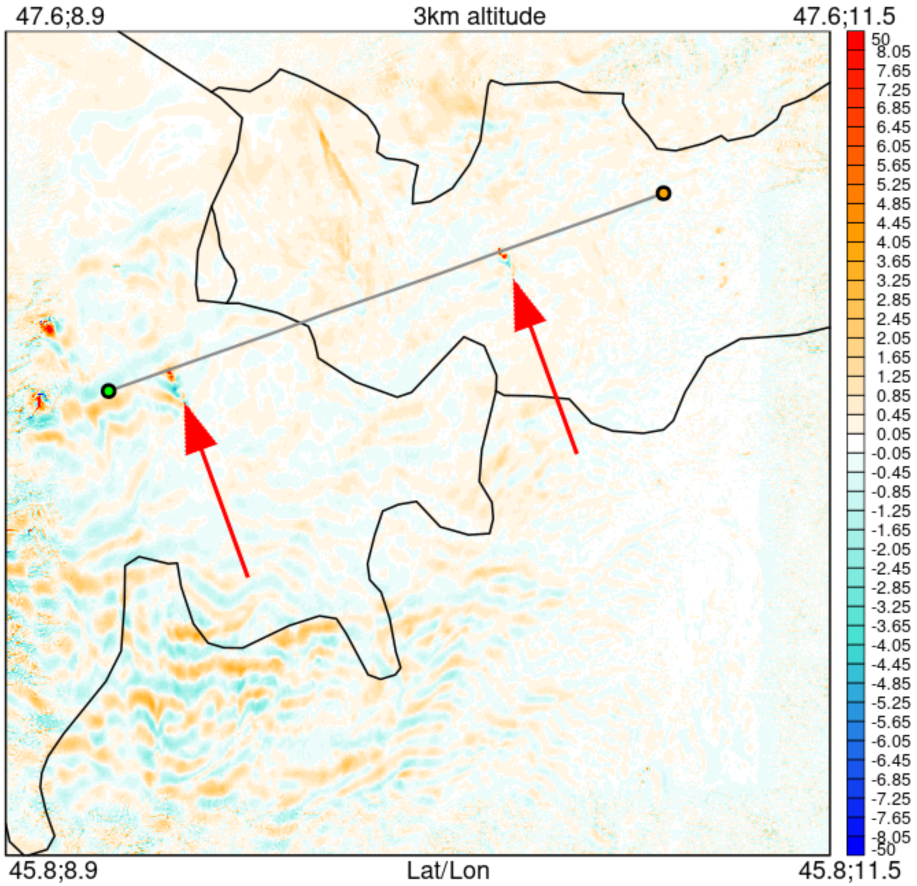
- cubic truncation of orography
- SITRA=50K
- no 3MT (deep convection), only STRAPRO (stratiform precipitation)

Real simulations

LACE nwp central europe

Vertical velocity for the alpine case 19 August 2022 0UTC + 24hours.



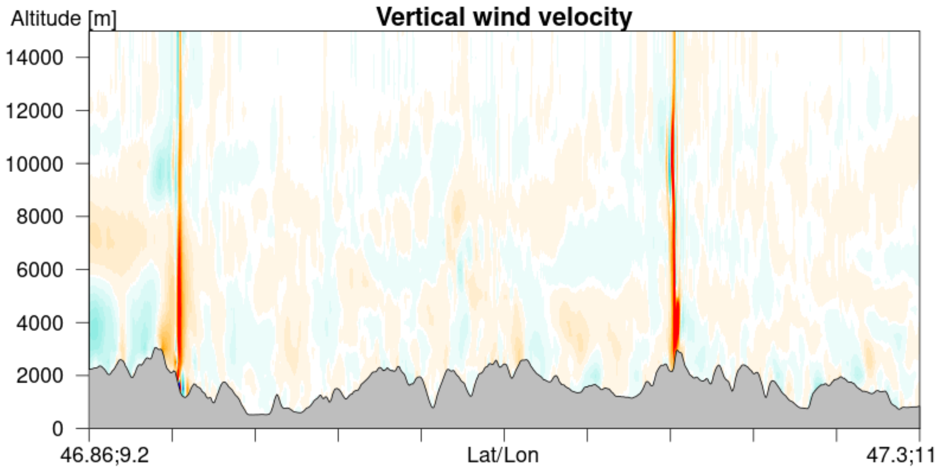


GeoSphere Austria DHMZ Czech Hydrometeorological Institute HungaroMet METEO ROMANIA ARSO METEO Slovenia

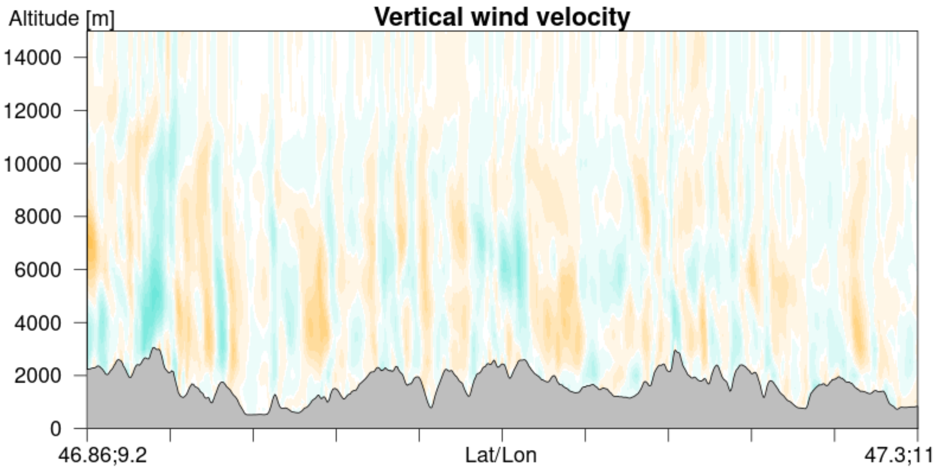
Real simulations

Vertical velocity for the alpine case 19 August 2022 0UTC + 24hours.

$\Lambda^* = 0$



$\Lambda^* = 1$



Conclusions

- Including constant reference slope in the linear model of the ICI time scheme helps to improve stability.
- With moderate values of the reference slope the accuracy of results is not endangered.
- With very high values of the reference slope the results may be spoiled with noise.


Děkuji Vám za pozornost!