Regional Cooperation for
Limited Area Modeling in Central Europe

LACE
nwp central europe

ACCORD
A Consortium for COnvection-scale modelling
Research and Development

Dynamics in LACE - towards hectometric scales

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Outline

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- 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
- Consecutive domain approach

Dynamical core in ACCORD

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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
- semi-implicit or iterative centred implicit scheme for time
- semi-Lagrangian advection

Semi-Implicit time scheme

System evolution

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

Linearization

$$X = \mathbf{X}^* + \mathbf{X}', \quad \frac{\partial}{\partial t} \quad \mathcal{M} \longrightarrow \mathcal{L}^*$$

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

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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

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Definitions

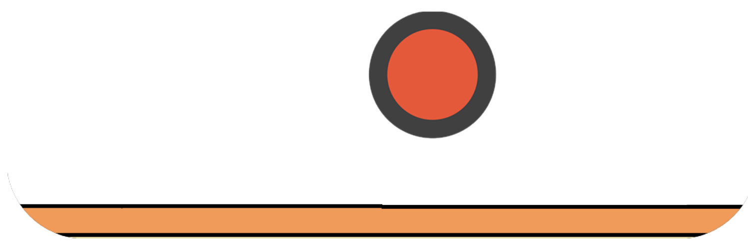
$$D = \nabla\cdot\vec{v}$$

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

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

Current:

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



Basic state

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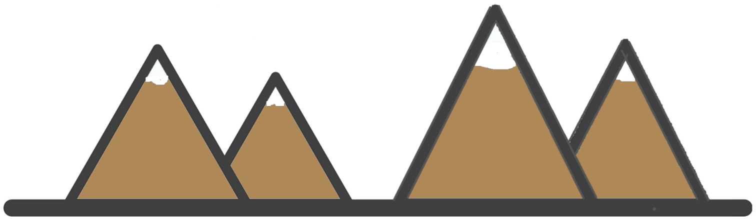
New:

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



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Linear model

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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

$$\nabla \phi = \nabla \phi_s - \int_\eta^1 \nabla \left(\frac{mRT}{p} \right) d\eta'$$

$$(\nabla \phi)^* = g \Lambda^* S^*(\eta)$$

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

Definitions

$$\Lambda^* = \frac{1}{g} ||\nabla \phi_s||^*$$

$$S^*(\eta) = \frac{B \pi_s^*}{\pi^*}$$

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

Linearized slope in SI

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Modified vertical divergence

$$d = \frac{1}{RT^*}\left((\nabla\phi)^* \partial^* \vec{v} - g\partial^* w\right)$$

where

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

Time evolution in linear model

$$\frac{\partial \vec{v}}{\partial t} = A - \Lambda^* S^*(\eta) B$$

$$\frac{\partial w}{\partial t} = B$$

$$\frac{\partial d}{\partial t} = \frac{1}{RT^*}\left[g\Lambda^* S^*(\eta)\partial^*\left(\frac{\partial \vec{v}}{\partial t}\right) - g\partial^*\left(\frac{\partial w}{\partial t}\right)\right]$$

$$= \frac{1}{RT^*}\left[g\Lambda^* S^*(\eta)\partial^* A - g\Lambda^{*2} S^*(\eta)\left(S^*\partial^* B + B\partial^* S^*\right) - g\partial^* B\right]$$

Linearized slope in SI

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We omitt the first order terms in Λ^* and then $\frac{\partial \vec{v}}{\partial t}$ is unchanged and all operators of the RHS of $\frac{\partial d}{\partial t}$ apply on $\hat{q}$.

Time evolution in linear model

$$\frac{\partial \vec{v}}{\partial t} = A - \Lambda^* S^* (\eta) B$$

$$\frac{\partial d}{\partial t} = \frac{1}{RT^*}\left[g\Lambda^* S^* (\eta)\partial^* A - g\Lambda^{*2} S^* (\eta) \left(S^* \partial^* B + B\partial^* S^*\right) - g\partial^* B\right]$$

Finally, since $B = g\left(\partial^* + 1\right)\hat{q}$

Time evolution in linear model

$$\frac{\partial \vec{v}}{\partial t} = A \rightsquigarrow \frac{\partial D}{\partial t} = \frac{\partial(\nabla \cdot \vec{v})}{\partial t} = \nabla \cdot A$$

$$\frac{\partial d}{\partial t} = \mathcal{L}^*_{new}\hat{q}$$

Linearized slope in SI

We can define

New vertical Laplacian operator

$$\mathcal{L}^*_{new} = \alpha\partial^*\left(\partial^*+1\right)+\beta\left(\partial^*+1\right)$$

$$\alpha = \left(1+\Lambda^{*2}S^2\right)$$

$$\beta = \Lambda^{*2}\left(S\partial^*S\right)$$

$$\Lambda^*=0:\mathcal{L}^*_{new}\rightarrow\mathcal{L}^*_v = \partial^*\left(\partial^*+1\right)$$

How to discretize the proposed solution?

New discretized vertical Laplacian operator

$$[\partial^*(\partial^*+1)X]_l = \ldots$$

$$[(\partial^*+1)X]_l = \ldots$$

$$S(\eta_l) = \ldots$$

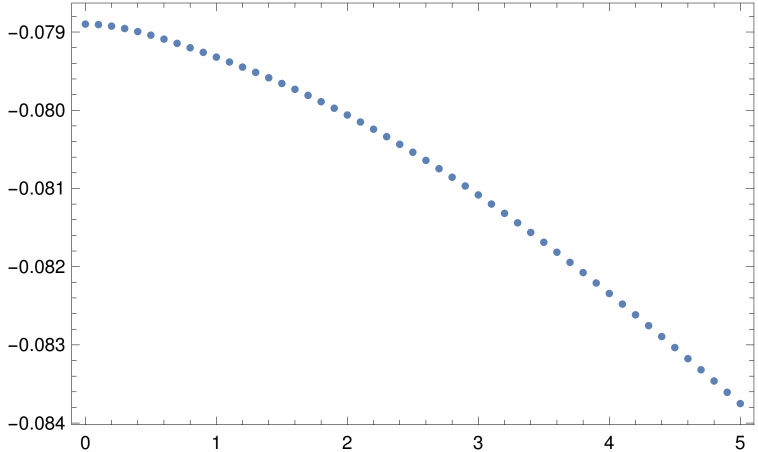
$$\partial^*S(\eta_l) = \ldots$$

How to set boundary conditions?

Linearized slope in SI

Does $\mathcal{L}^*_{new}$ have only real and negative eigenvalues?

For an example of 87 vertical levels used in Czech operations we are safe.



(courtesy of N.Kastelec)

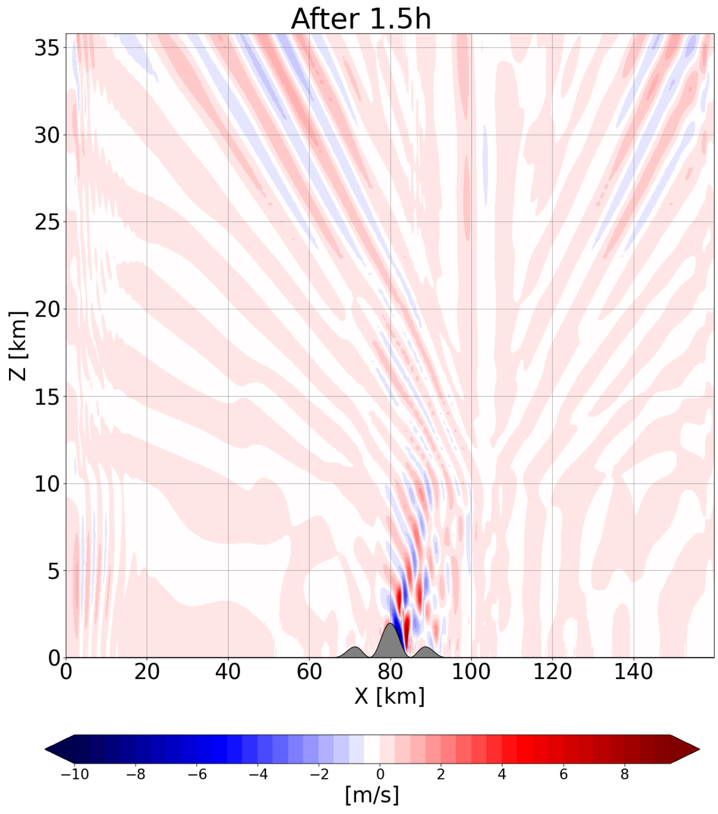
Max value of eigen values depending on Λ

Then we can eliminate the discretized equations up to horizontal divergence D and solve the Helmholtz equation for D.

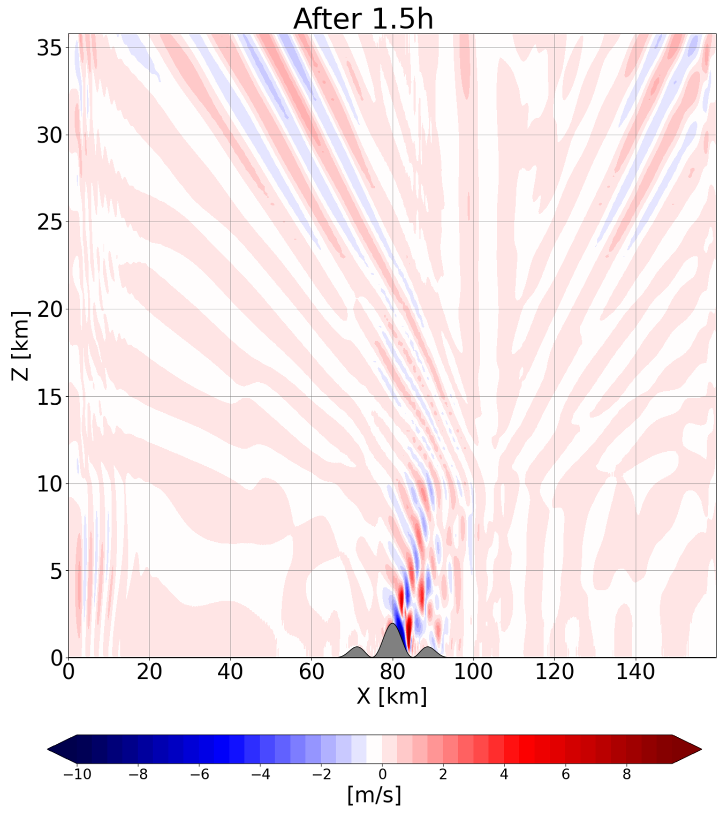
Idealized tests

Vertical velocity for the Schär mountain case depending on the slope Λ^*.

$\Lambda^* = 0$



$\Lambda^* = 0.23$



(courtesy of N.Kastelec)

Idealized tests

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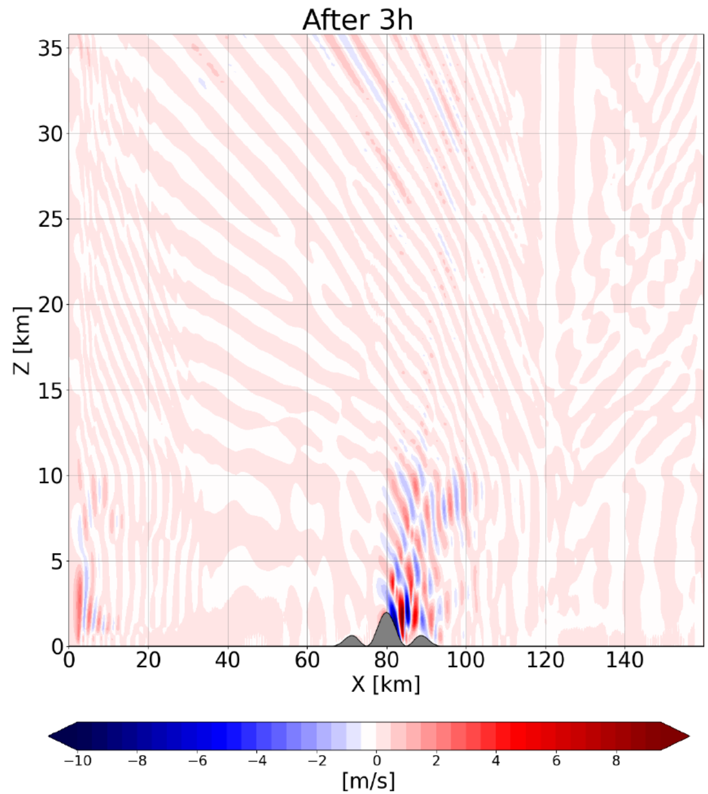


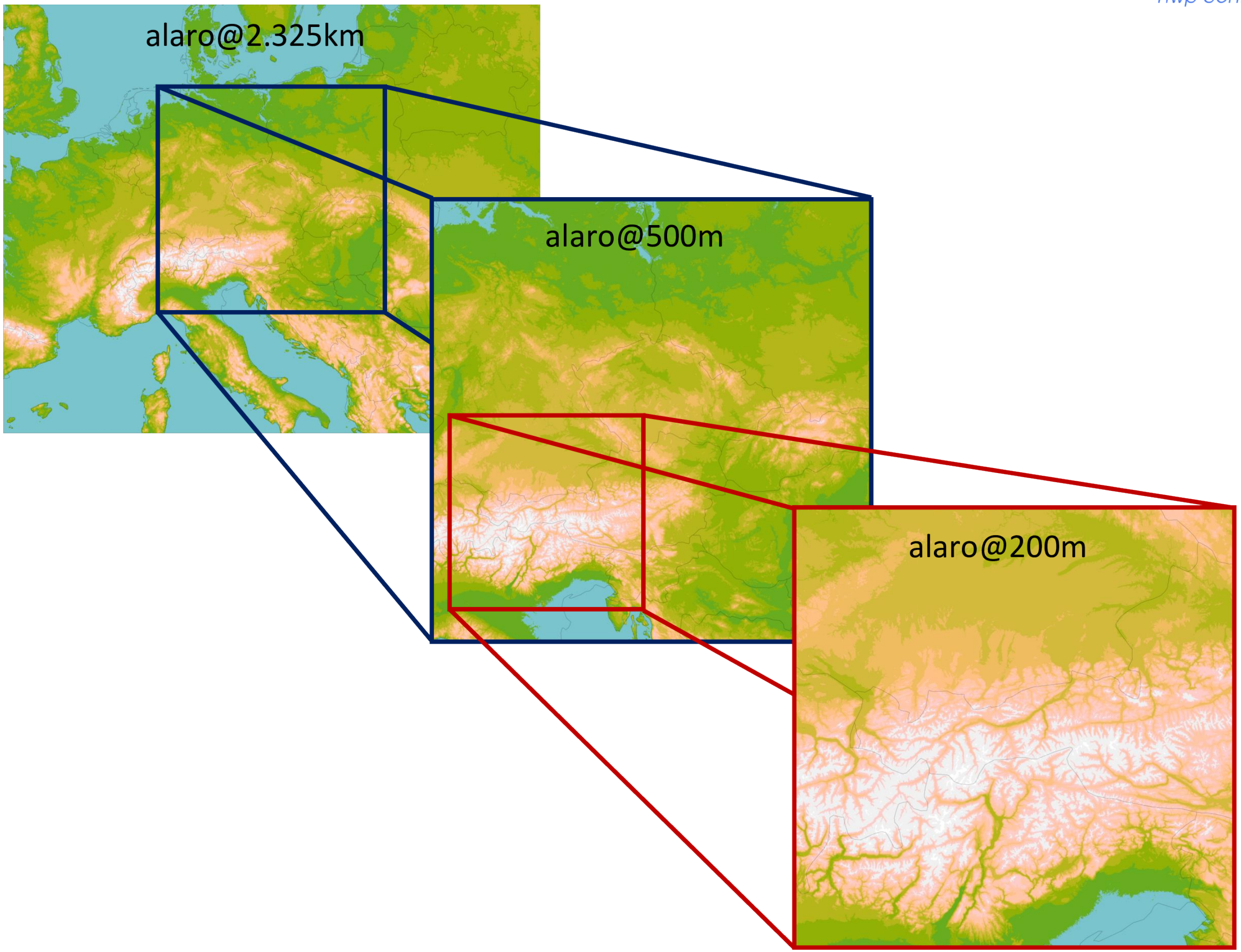
(courtesy of N.Kastelec)

Conclusions

- We must continue our efforts.
- We plan to test various possible discretizations.
- We plan to test various possible boundary conditions.
- We plan to make further idealised tests and real simulations.

PROJECT DE_330

Real simulations @200m



Real simulations @200m

The basic algorithmic choices for ALARO configurations are:

Dynamical core

- semi-Lagrangian advection scheme 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

Real simulations @200m

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ALARO physics

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

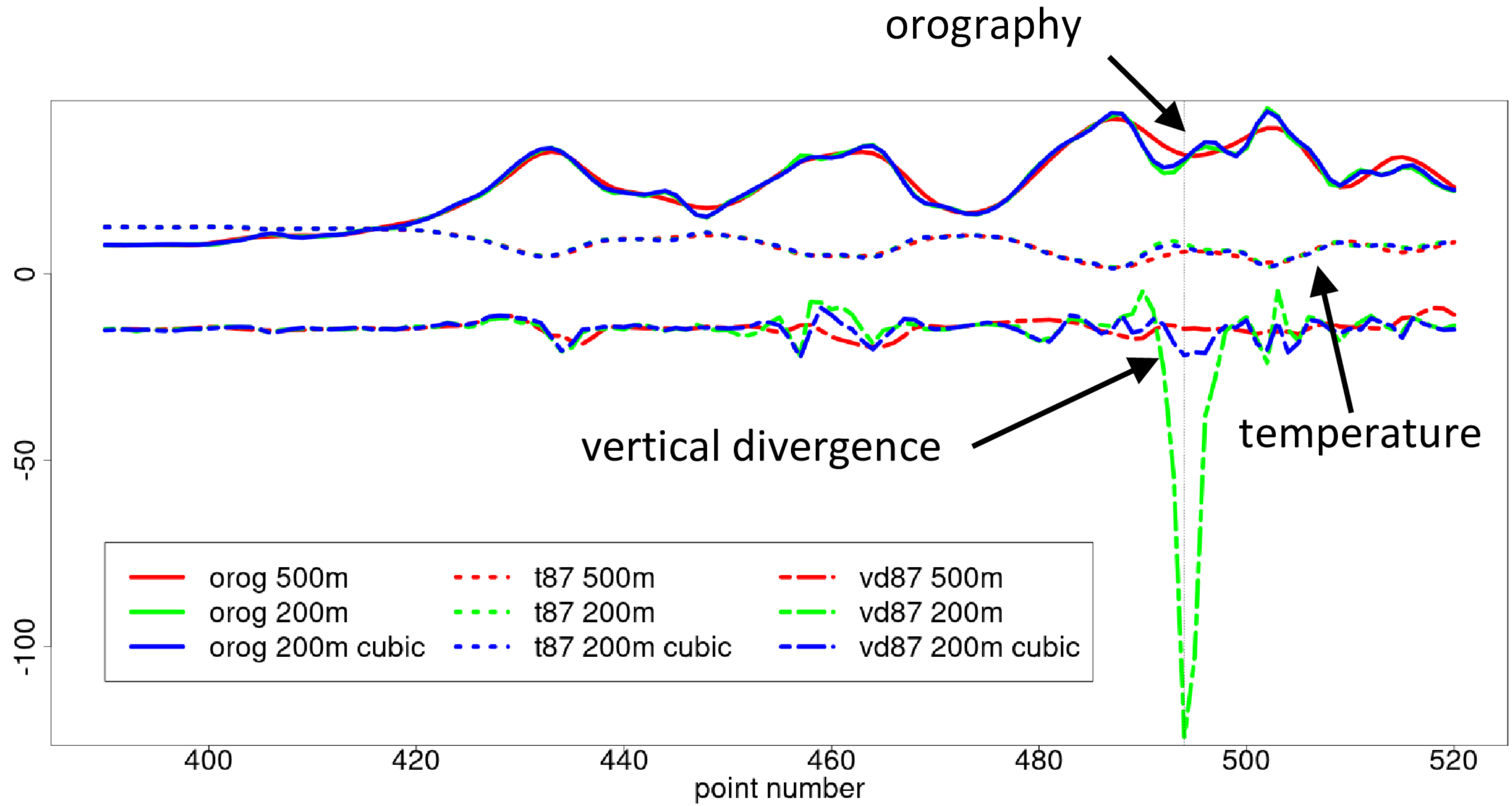
Initialization

- 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 @200m

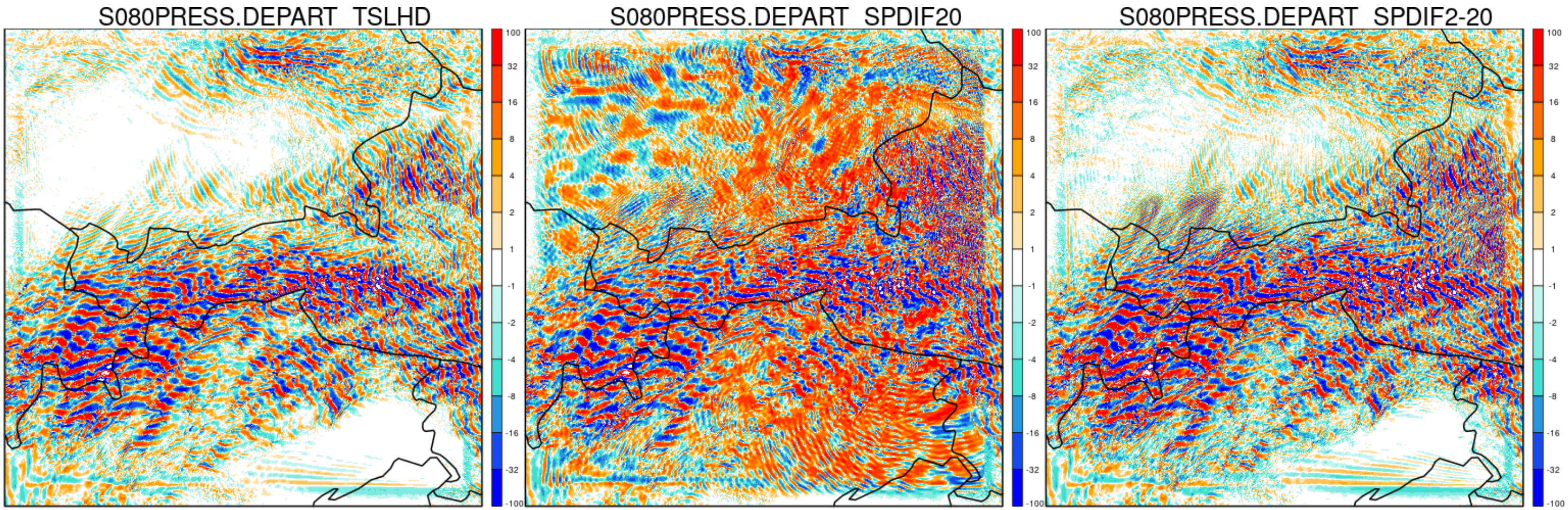


Initialization with DFI using cubic or quadratic orography truncation: small difference in orography, but big difference in vertical divergence.

Real simulations @200m

Sensitivity to horizontal diffusion setting

- **SLHD (flow dependent semi-Lagrangian horizontal diffusion, Váňa) + additional spectral diffusion of 6^{th} order + spectral diffusion of 2^{nd} order close to the model top**
- **4^{th} order spectral diffusion similar as used in lower resolutions**
- **4^{th} order spectral diffusion stronger for motion variables ($\vec{v}$, d)**



SLHD | **spectral dif. normal** | **spectral dif. stronger on $\vec{v}, d$**

Consecutive domain approach

Several AROME runs (2.5km, 1.25km, 500m) were prepared at Geosphere Austria for the case of 18/08/2022 0UTC + 24h in the so called "consecutive domain" approach, i.e. run a big domain on 1.25km coupled to IFS HRES and then run AROME on several 500m domains nested inside (partly overlapping) coupled to the AROME 1.25km. The position of these domains follows the high impact phenomena we are interested in.

Stability issues were observed for the 500m runs which could not be solved by simple namelist parameters changes.

Consecutive domain approach

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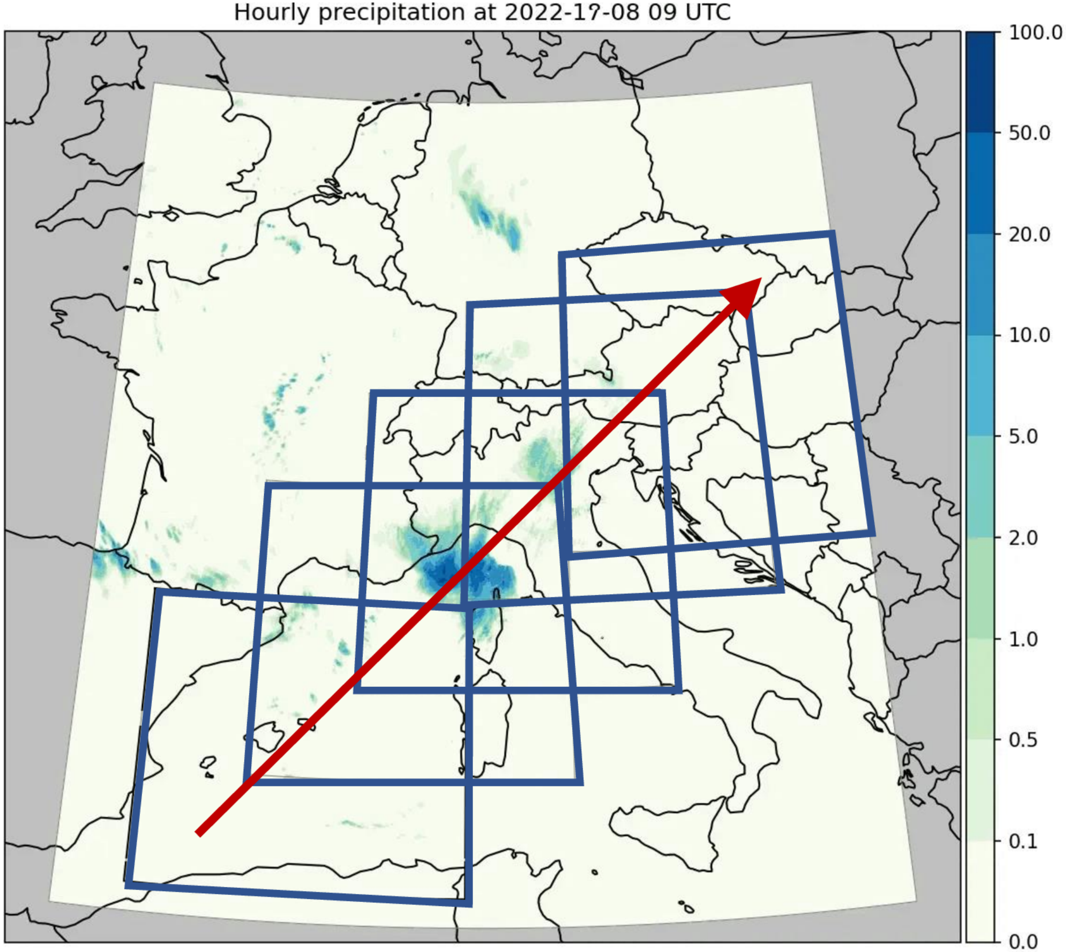

(courtesy of Ch.Wittman)

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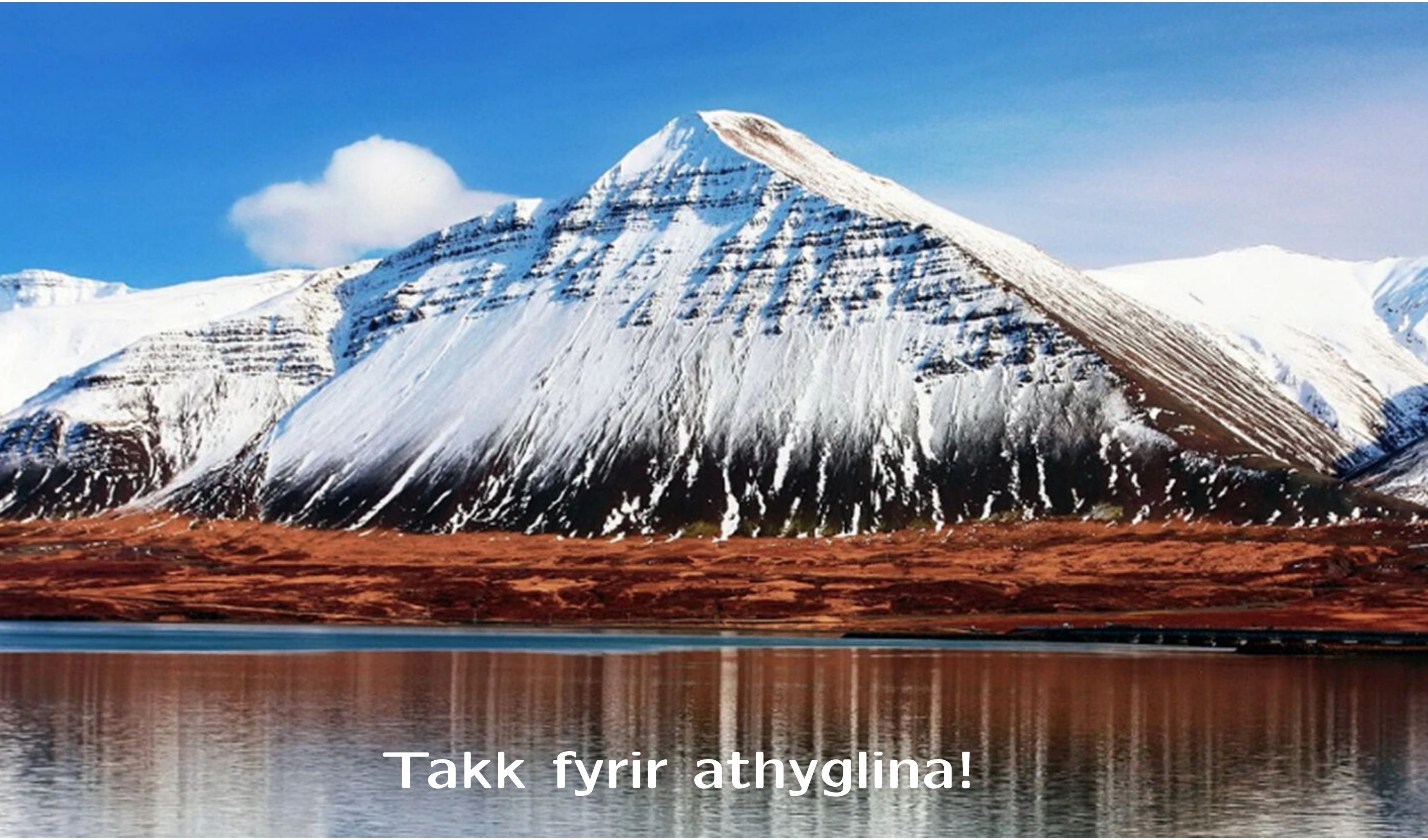
Takk fyrir athyglina!