Regional Cooperation for
Limited Area Modeling in Central Europe

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ACCORD
A Consortium for COnvection-scale modelling
Research and Development

Dynamics for ACCORD forecast higher numerical consistency, stability and accuracy

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Outline

- Helmholtz elimination up to horizontal divergence
- New vertical divergence formulation
- New bottom boundary condition for vertical velocity
- Consistent inclusion of moisture in vertical motion variables
- Diagnostic definition of the orographic X-term in vertical divergence
- Blended approach for fields initialization

Helmholtz elimination up to horizontal divergence

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Previous solution: **LSI_NHEE=F (default)**

- elimination up to vertical divergence $\hat{d}$ in NHEE
- the vertical operators have to satisfy the necessary constraint
- space discretized solution does not corespond exactly the space continuous one ($\mathbb{T} \neq \mathbb{I}$)

$$\left[\mathbb{I} - \delta t^2 \nabla^2 \mathbb{B}_d^*\right] \hat{d} = d^{\bullet\bullet}$$

$$\mathbb{B}_d^* = \frac{1}{1-\kappa} \mathbf{H}_v^{*-1} \left(RT^* + \kappa g^2 \delta t^2 \mathbb{T}\right)$$

Proposed solution: **LSI_NHEE=T**

- elimination up to horizontal divergence D in NHEE
- no constraint
- similar to HPE elimination
- B-matrix has hydrostatic and non-hydrostatic part (allows for blended NH-HY approach)
- more suitable for VFE discretization

$$\left[\mathbb{I} - \delta t^2 \nabla^2 \mathbb{B}_D^*\right] D = D^{\bullet\bullet}$$

$$\mathbb{B}_D^* = \underbrace{RT^* \left[\kappa \mathbf{G}^* \mathbf{S}^* + \mathbf{N}^*\right]}_{\text{hydrostatic}} + \underbrace{RT^* \frac{1}{1-\kappa} \mathbf{G}_\kappa{}^* \mathbf{H}_v^{*-1} \mathbf{S}_\kappa^*}_{\text{nh increment}}$$

(developed by Fabrice Voitus)

Vertical motion variables

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LGWADV=T (default from CY50T1) allows for the usage of vertical divergence "d" in the linear model and vertical velocity w in the non-linear model with the transformations between them

$$\hat{d} = -\frac{p}{mRT}\frac{\partial gw}{\partial \eta}$$

$$w = \frac{1}{g}\int_{\eta}^{1}\left(\frac{mRT}{p}\ \hat{d}\right) d\eta'$$

The advantages: d helps with stability of the implicit linear solver, while w with the accuracy of the non-linear residual.

Moreover, the "d" variable can be modified three times

$$d = \hat{d} + \mathbf{X}$$

$$\mathbf{X} = \delta_S \mathbf{X}^S + \delta_d \mathbf{X}^d + \delta_w \mathbf{X}^w$$

where

δ_S is mastered with NVDVAR=4

δ_d is mastered with NVDVAR=5

δ_w is mastered with LBIGW=T

(developed by Fabrice Voitus)

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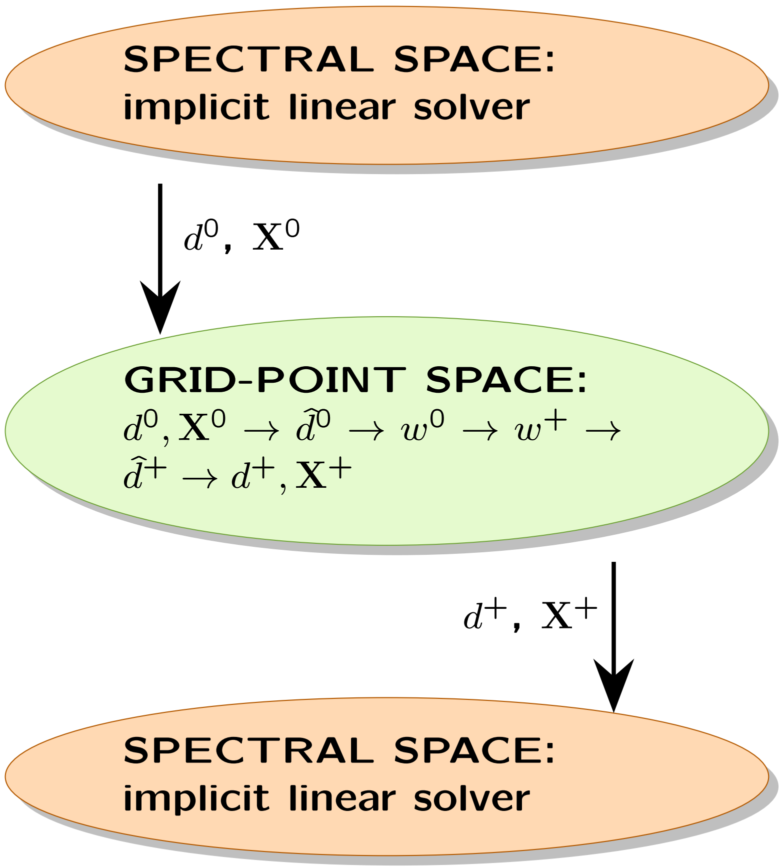
Vertical motion variables

At each time step or at each iteration of the ICI time scheme the following process is realized:

- the implicit part is realized in the SP space
- the vertical divergence d is transformed into the GP space, possibly together with the X-term (option LSPNHX=TRUE)
- the true vertical divergence $\hat{d}$ is being calculated as $\hat{d} = d - \mathrm{X}$ and w is calculated from $\hat{d}$
- this value is available as w^0 in predictor and as $w^{(k)}$ in the $(k+1)$-th iteration (corrector)
- the new value $w^{(k+1)}$ comes from

$$\frac{w_F^{(k+1)} - w^0_{O(k+1)}}{\Delta t} = \frac{RHS[w]^0_{O(k+1)} + RHS[w]^{(k)}_F}{2}$$

- $w^{(k+1)}$ is transformed to $\hat{d}^+$ and d^+
- d^+ is transformed back into the SP space for implicit calculations for the next iteration or the next time step, possibly together with the newly calculated X-term (option LSPNHX=TRUE)



Vertical motion variables

- The horizontal derivatives of the X-term are not needed in this case anywhere in the time marching scheme. (Not true for L3DTURB etc.)

Vertical divergence

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NVDVAR=3

$$\frac{dT}{dt} = -\kappa T \frac{1}{1-\kappa}(D + \hat{d} + \mathbf{X}^S)$$
$$\frac{d\hat{q}}{dt} = -\frac{1}{1-\kappa}(D + \hat{d} + \mathbf{X}^S + \mathbf{X}^d) + \mathrm{S}D$$

$$\mathbf{X}^S = \frac{p}{mRT}\nabla\phi\frac{\partial\vec{v}}{\partial\eta}$$
$$\mathbf{X}^d = (1-\kappa)\left(\vec{v}\cdot\frac{\nabla\pi}{\pi} - \frac{1}{\pi}\int_0^\eta \vec{v}\cdot\nabla m \ d\eta'\right)$$

NVDVAR=4

$$d_4 = \hat{d} + \mathbf{X}^S$$
$$\frac{dT}{dt} = -\kappa T \frac{1}{1-\kappa}(D + d_4)$$
$$\frac{d\hat{q}}{dt} = -\frac{1}{1-\kappa}(D + d_4 + \mathbf{X}^d) + \mathrm{S}D$$

NVDVAR=5

$$d_5 = d_4 + \mathbf{X}^d$$
$$\frac{dT}{dt} = -\kappa T \frac{1}{1-\kappa}(D + d_5 - \mathbf{X}^d)$$
$$\frac{d\hat{q}}{dt} = -\frac{1}{1-\kappa}(D + d_5) + \mathrm{S}D$$

In linear model

$$\frac{dT}{dt} = -\kappa T \frac{1}{1-\kappa}(D + d_i)$$
$$\frac{d\hat{q}}{dt} = -\frac{1}{1-\kappa}(D + d_i) + \mathrm{S}D$$

The non-linear term $\mathbf{X}^d$ is hidden inside the vertical divergence variable in $\hat{q}$-equation and temperature equation stays closer to the HPE solution

$$\frac{dT}{dt} = \kappa T\left(\frac{1}{1-\kappa}\mathbf{X}^d - \mathrm{S}D\right)$$

(developed by Fabrice Voitus)

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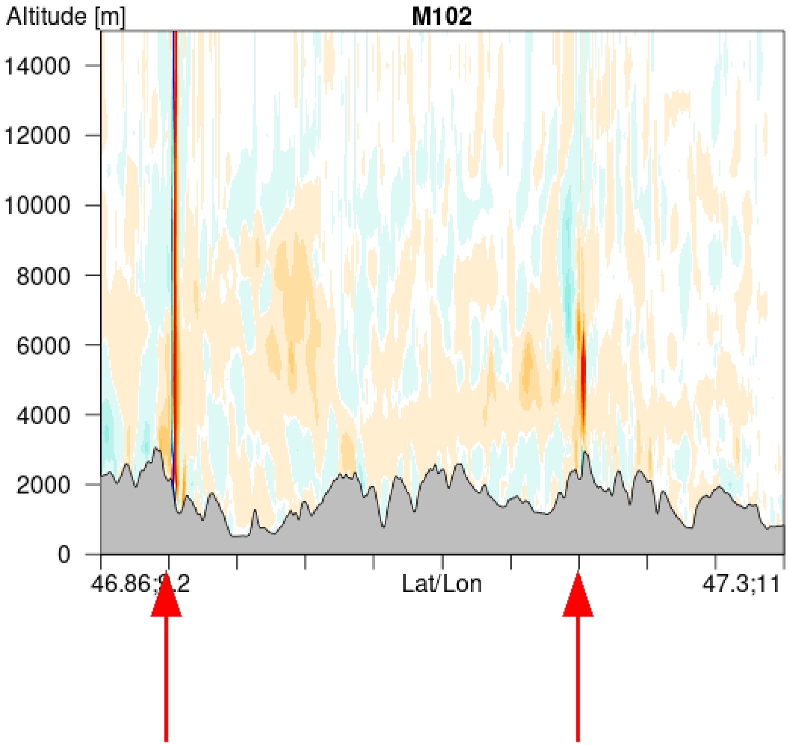
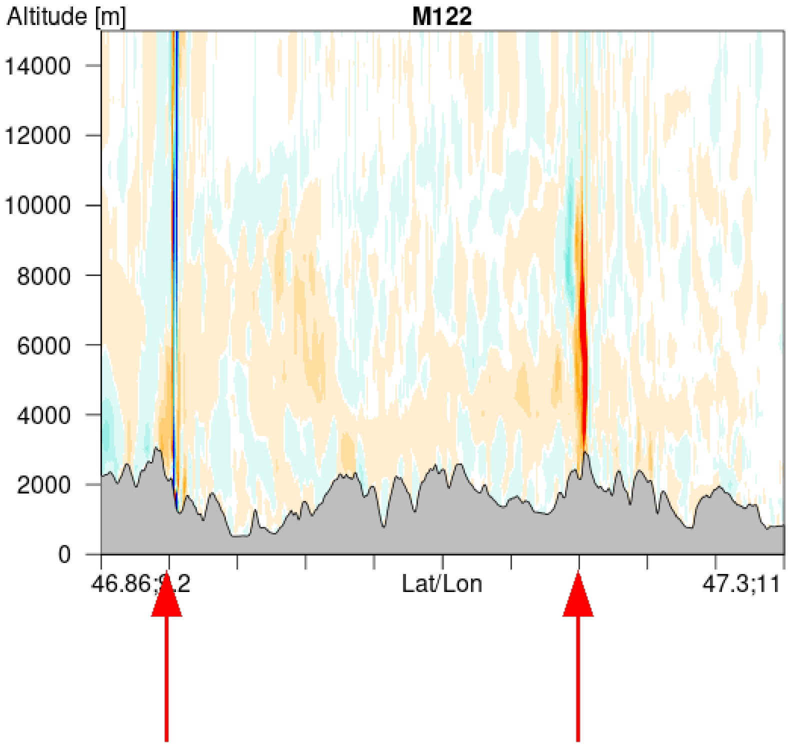
Vertical divergence

NVDVAR=4



NVDVAR=5



- more consistent
- the chimney like patterns still persistent

Vertical velocity

LBIGW=.TRUE.

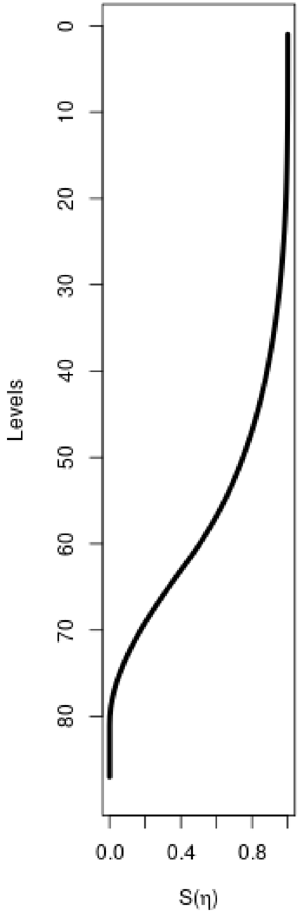
New vertical velocity $g\mathbf{W} = g\mathbf{w} - S(\eta)\vec{V} \cdot \nabla\Phi_S$

where $S(\eta) = \dfrac{B(\eta)\pi_{ref}}{A(\eta) + B(\eta)\pi_{ref}}$

- $S = S(\eta)$ is a prescribed monotonic vertical function satisfying $S(0) = 0$ at the top, and $S(1) = 1$ at the bottom
- $S(\eta)\nabla\Phi_S$ fits $\nabla\Phi$ for a stationary isothermal hydrostatic atmosphere
- W behaves as w at the top and as $\dot{\eta}$ at the bottom.
- Rigid BBC reads $\mathbf{W}_S = 0$.
- It can be seen as a third $\mathbf{X}$–term part added to vertical divergence definition

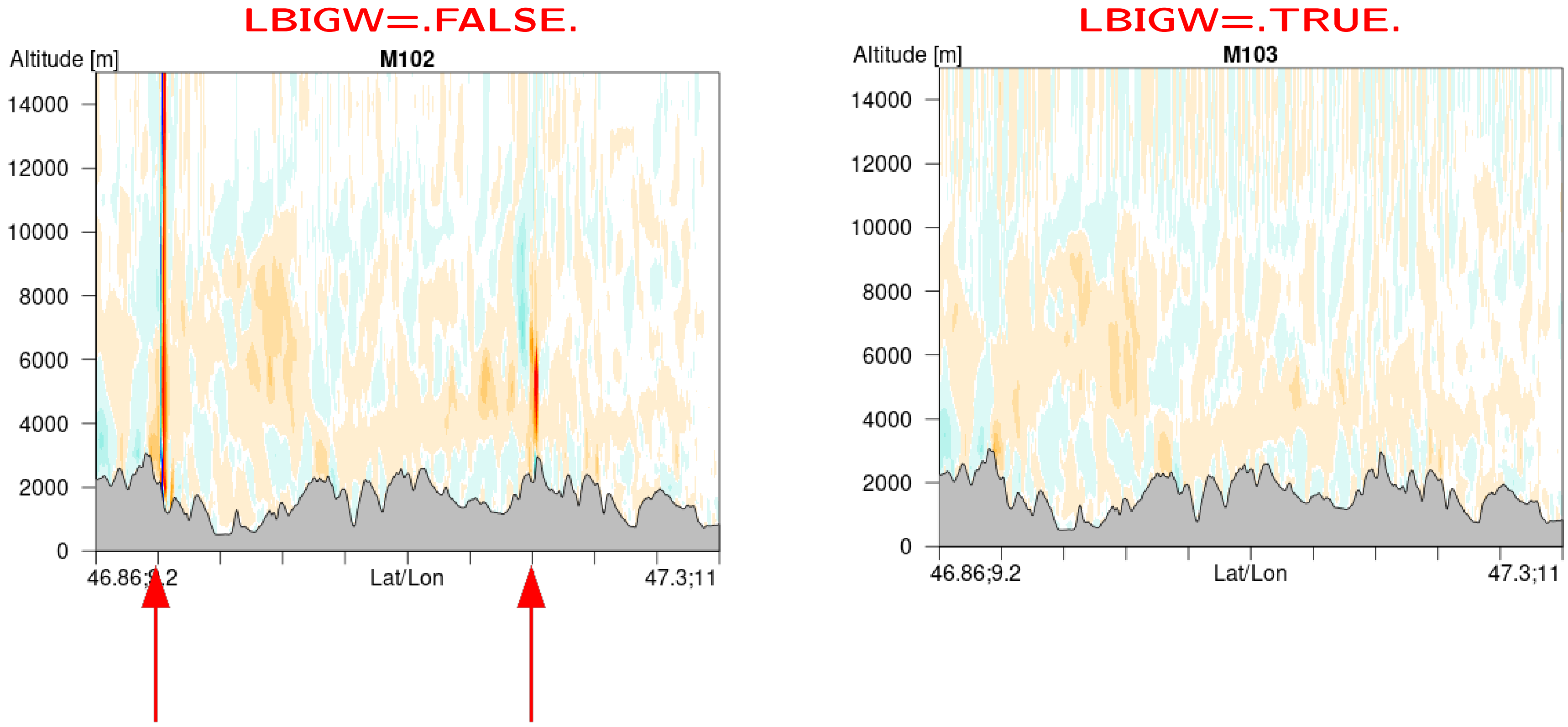
$$d_i{}^w = d_i + \mathbf{X}^w$$

$$\mathbf{X}^w = -\frac{p}{mRT}\frac{\partial}{\partial\eta}(g\mathbf{W} - g\mathbf{w})$$



(developed by Fabrice Voitus)

Vertical velocity



- simple BBC
- the chimney like patterns disappear

Consistent inclusion of moisture in $\hat{d}$ and X

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L_RDRY_VD=T (default)

The definition of the vertical divergence variable is made consistently everywhere in the code with the dry variant of the gaz constant R_d.

$$\hat{d} = -\frac{p}{m(\delta_v R_d + (1-\delta_v)R)T}\frac{\partial g w}{\partial \eta}$$

The definition of X-term is treated independently depending on the key L_RDRY_NHX.

L_RDRY_NHX=T

The definition of the X-term is made consistently everywhere in the code with the dry variant of the gaz constant R_d.

$$\mathrm{X} = \frac{p}{m(\delta_X R_d + (1-\delta_X)R)T}\nabla\phi\frac{\partial \vec{v}}{\partial \eta}$$

The true 3D-divergence is always calculated with the moist $\hat{d}$.

(developed by Fabrice Voitus)

Diagnostic treatment of the X-term

ND4SYS=1 and ND4SYS=2

The time evolution of $\hat{d}$ is being solved by

$$\frac{d\,\hat{d}}{dt} = RHS[\hat{d}] + \frac{d\mathbf{X}}{dt}$$

Then $\frac{d\mathbf{X}}{dt}$ is discretized in the following way:

$$\frac{d\mathbf{X}}{dt} = \frac{\mathbf{X}_F^0 - \mathbf{X}_{O(k+1)}^0}{\Delta t}$$

for ND4SYS=1 oscillating in time

$$\frac{d\mathbf{X}}{dt} = \underbrace{\frac{\mathbf{X}_F^{(last)} - \mathbf{X}_F^0}{\Delta t}}_{\text{last iteration only}} + \frac{\mathbf{X}_F^0 - \mathbf{X}_{O(k+1)}^0}{\Delta t}$$

for ND4SYS=2 less oscillating

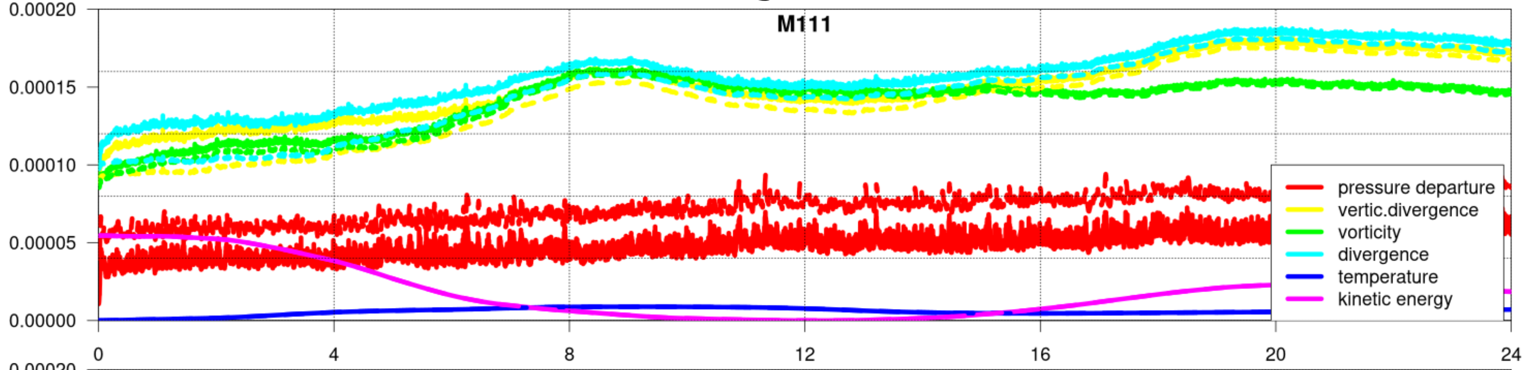
ND4SYS=0

$$\hat{d} = \Delta t RHS[\hat{d}] + \mathrm{X}$$

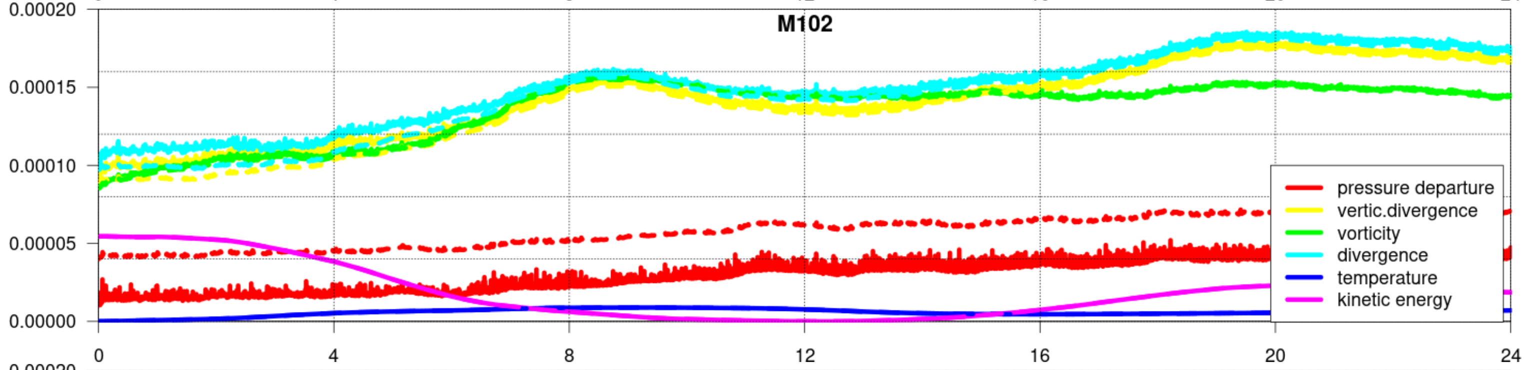
The X-term may be calculated at the beginning and at the end of the grid-point calculations. The transformation of the X-term to and from spectral space may be avoided resulting in the reduced usage of the CPU time ($\approx 6-8\%$ with LSPNHX=.TRUE.).

Diagnostic treatment of the X-term

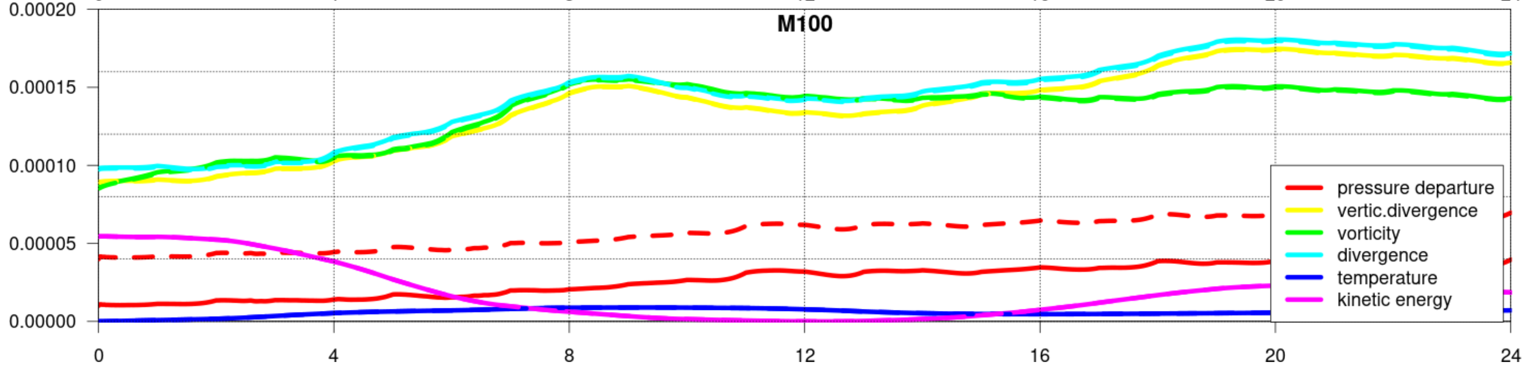
Time evolution of the domain averaged spectral norms of model variables



ND4SYS=1



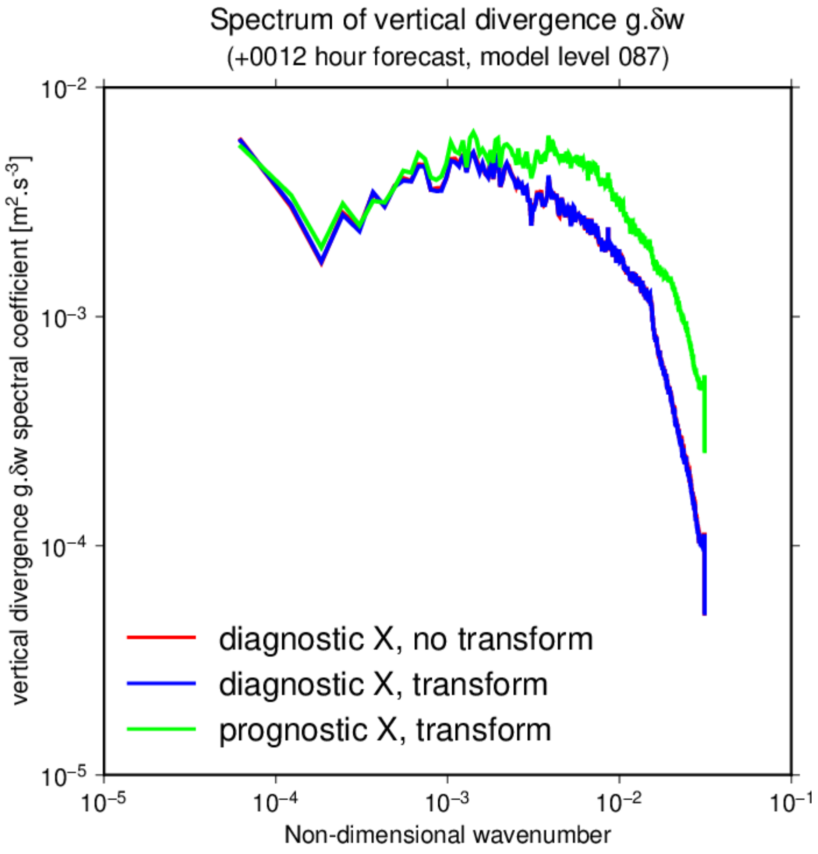
ND4SYS=2
prognostic X

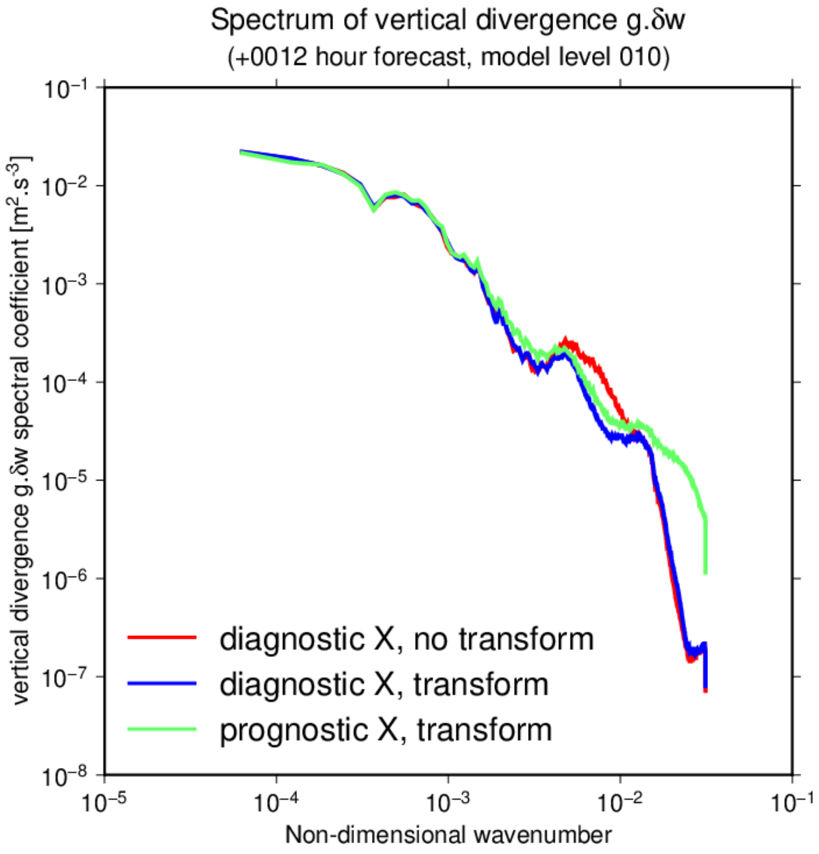


ND4SYS=0
diagnostic X

Diagnostic treatment of the X-term

Vertical divergence spectra for the model levels 87 and 10





Diagnostic treatment of the X-term

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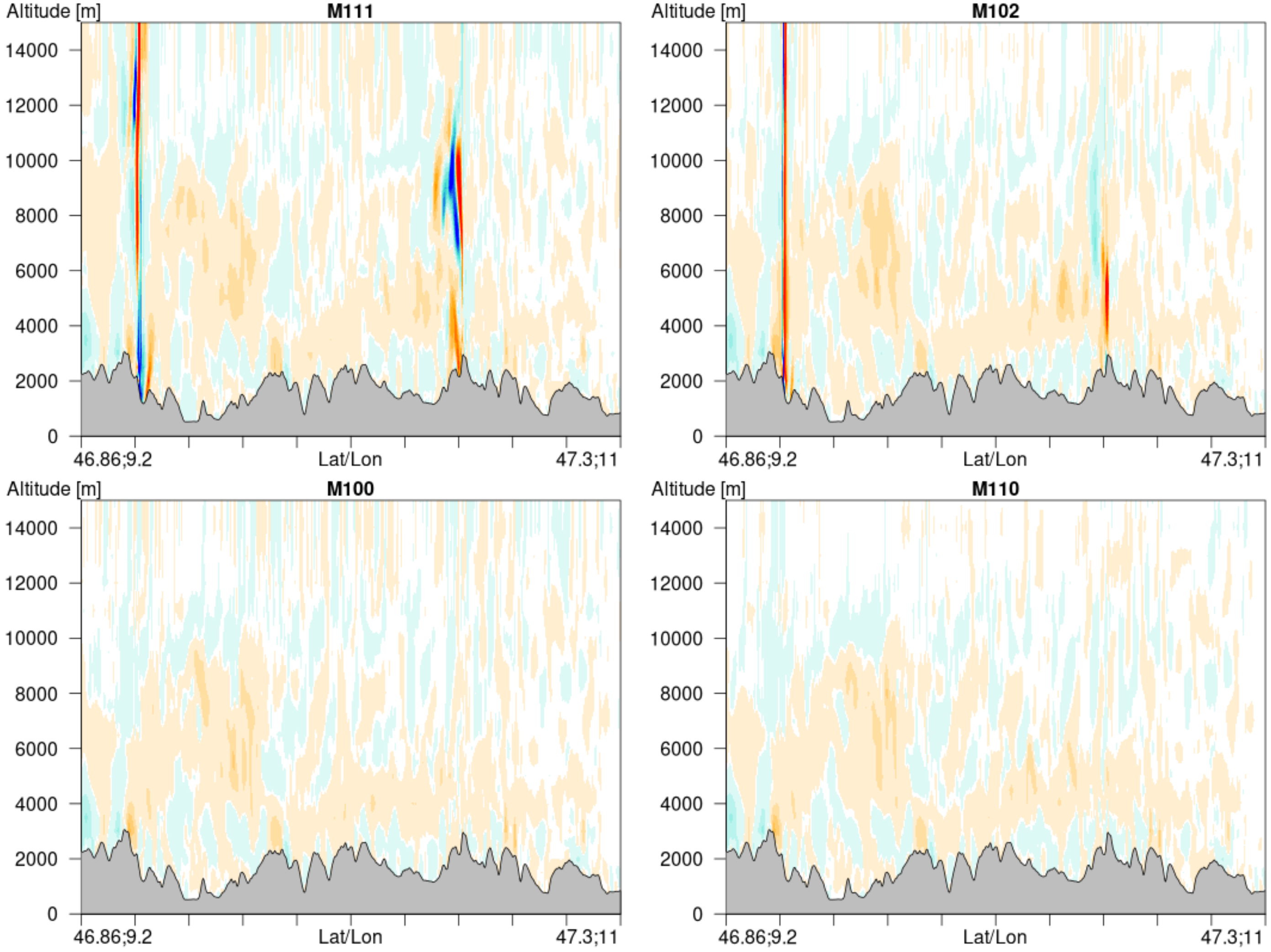
Vertical velocity vertical cross section above orography

ND4SYS=1

ND4SYS=2

ND4SYS=0
X transformed

ND4SYS=0
X not transformed



Blended approach for fields initialization

We use one control parameter δ, $0 \leq \delta \leq 1$.

$$\frac{dT}{dt} = \kappa T \frac{\dot{\pi}}{\pi} - \delta \frac{\kappa T}{(1-\kappa)} (d_5 + \mathbf{S}_\kappa D)$$

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

$$\frac{dgw}{dt} = g^2 \frac{\delta}{m} \frac{\partial(p-\pi)}{\partial\eta}$$

$$\frac{d\hat{q}}{dt} = -\frac{\delta}{(1-\kappa)} (d_5 + \mathbf{S}_\kappa D)$$

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

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

where

$$\frac{\dot{\pi}}{\pi} = \frac{1}{1-\kappa}\mathbf{X}^d - \mathbf{S}D$$

$$\phi = \phi_s + \int_\eta^1 \frac{mRT}{\pi} \; d\eta' - \delta \int_\eta^1 \frac{mRT}{p}\left(\frac{p-\pi}{\pi}\right) \; d\eta'.$$

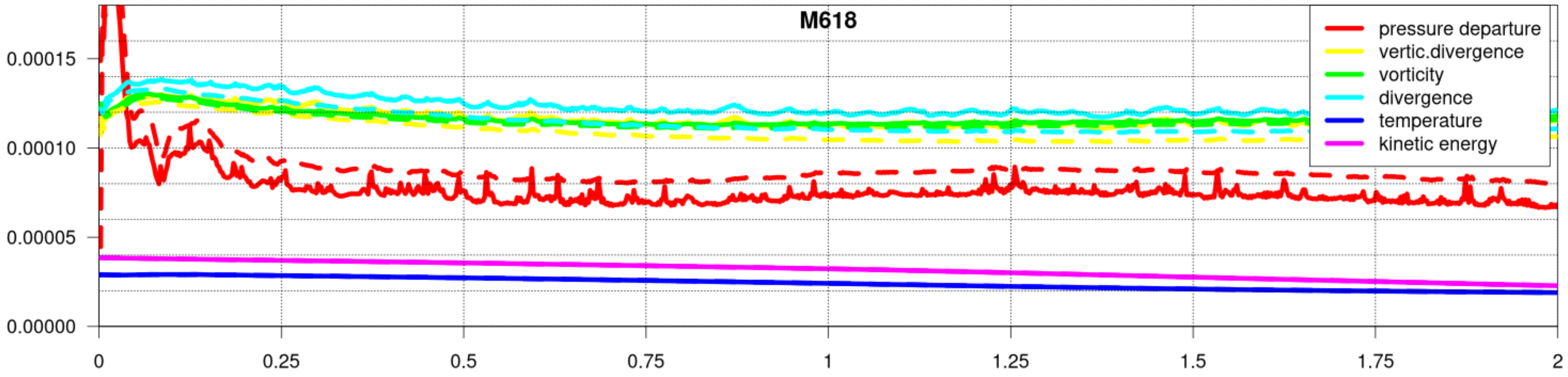
HPE system $\sim \delta = 0$

EE system $\sim \delta = 1$

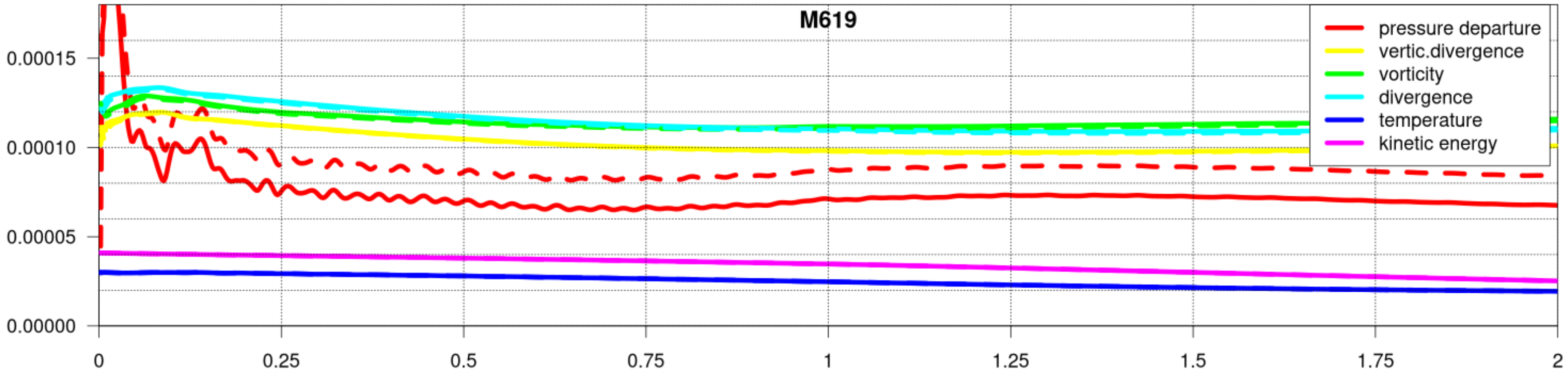
a blended system is available with $0 < \delta < 1$
- filtering fast moving waves without meteorological relevance
- may garantee higher numerical stability

Blended approach for fields initialization

Coupling from global model, initial conditions from global model



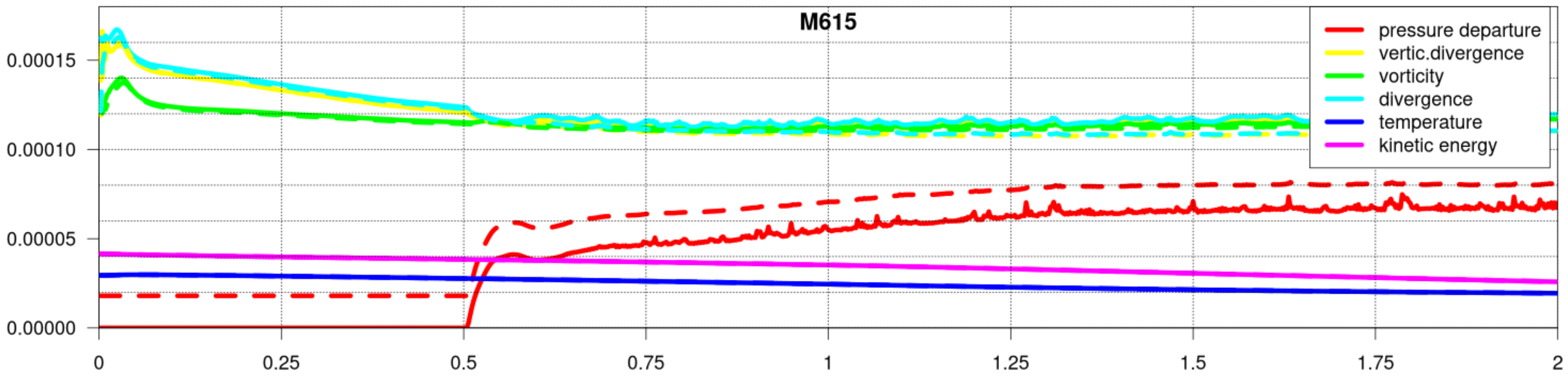
ND4SYS=2
NVDVAR=4
LBIGW=F



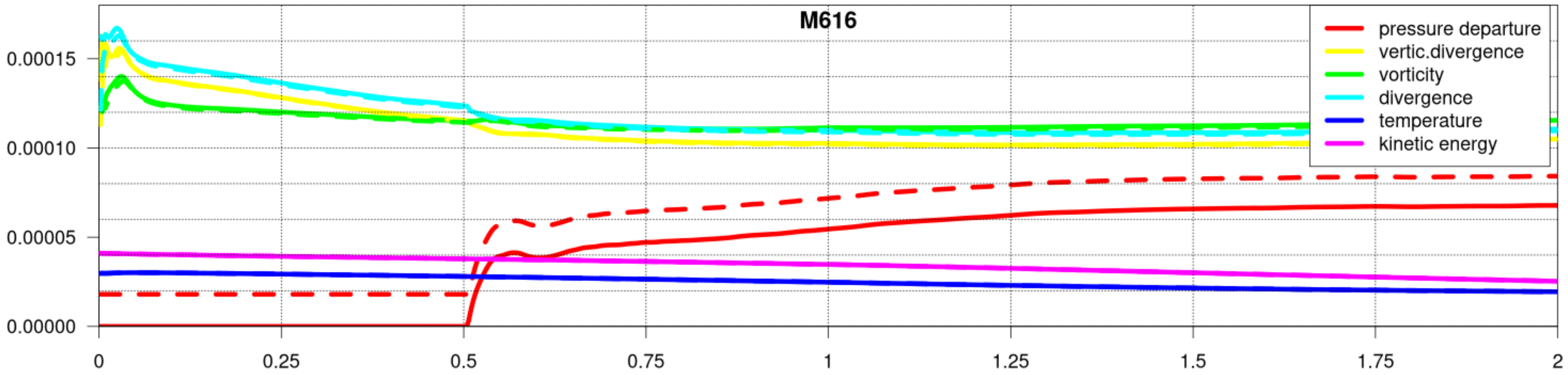
ND4SYS=0
NVDVAR=5
LBIGW=T

Blended approach for fields initialization

HPE, blended approach 30min - 2hours, NH

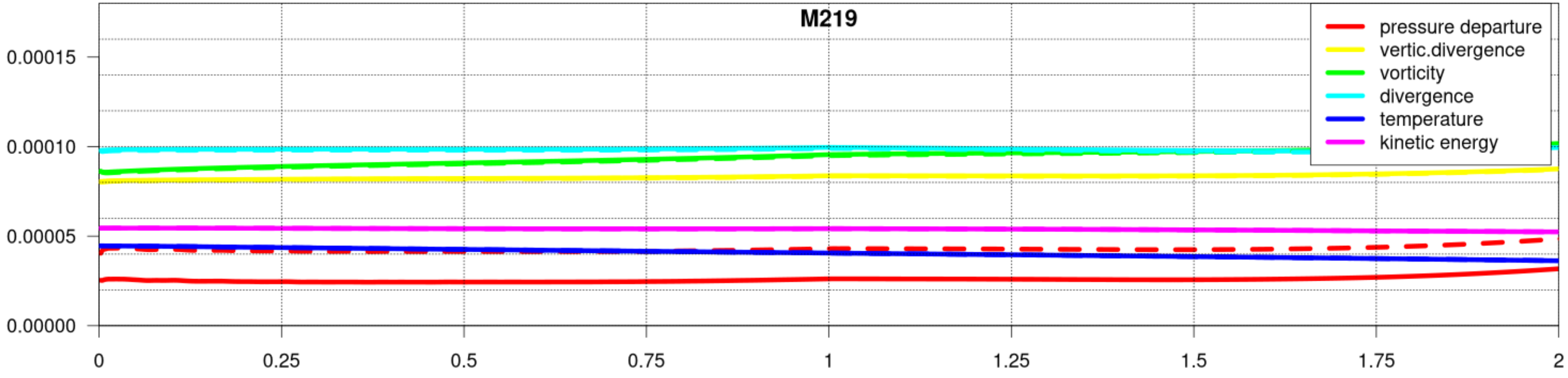


ND4SYS=2
NVDVAR=4
LBIGW=F

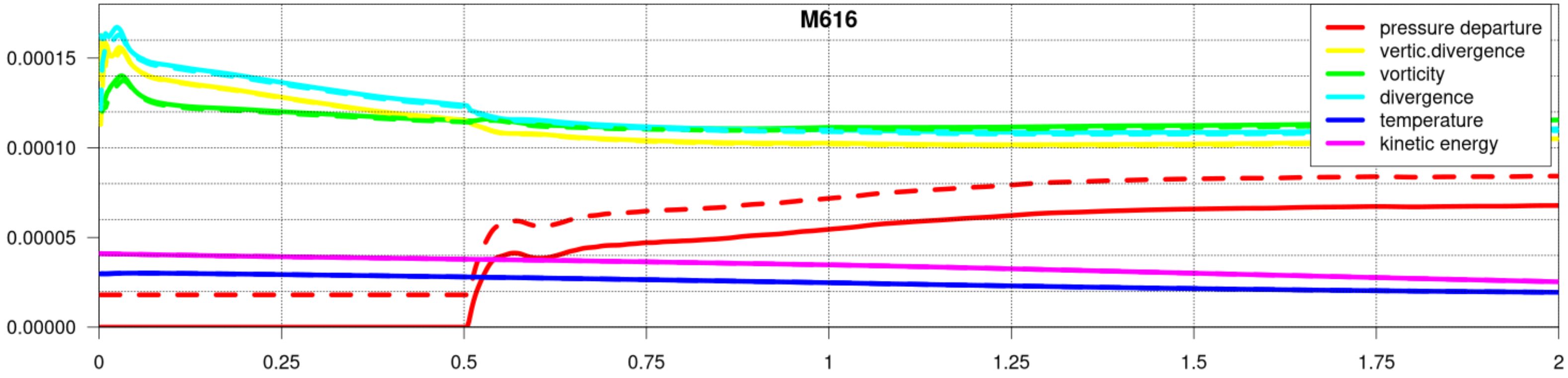


ND4SYS=0
NVDVAR=5
LBIGW=T

Blended approach for fields initialization



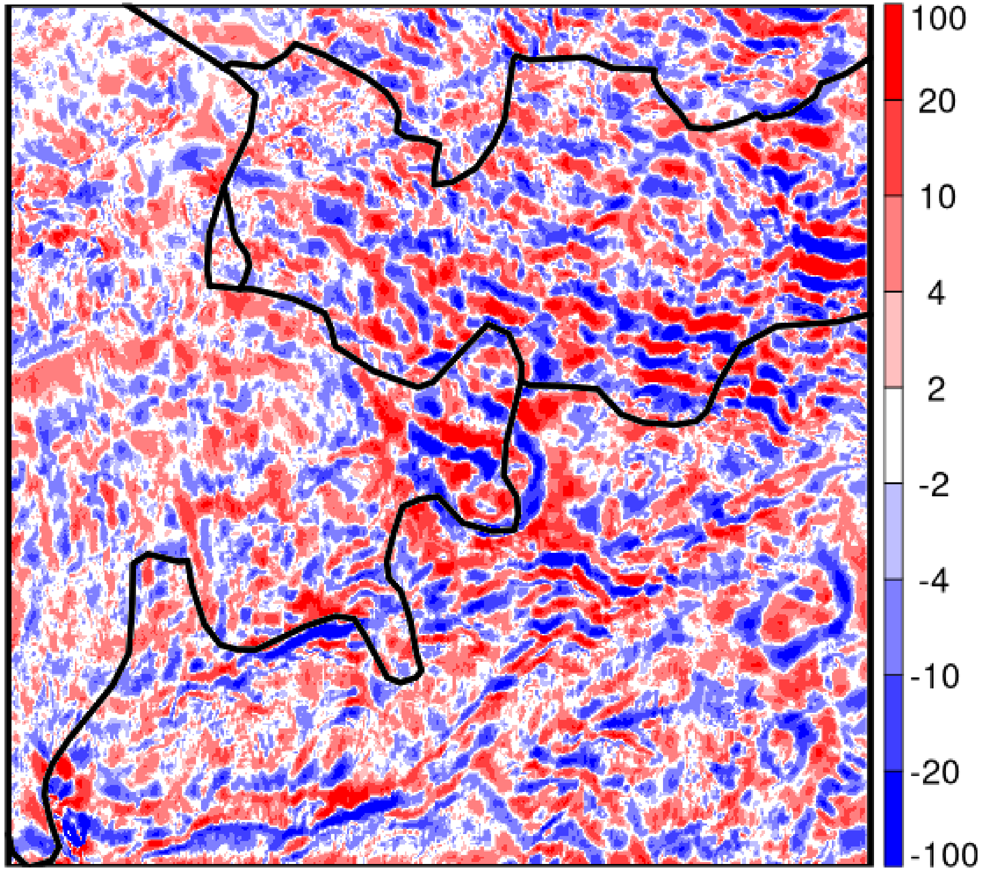
coupling from HRES LAM and DFI



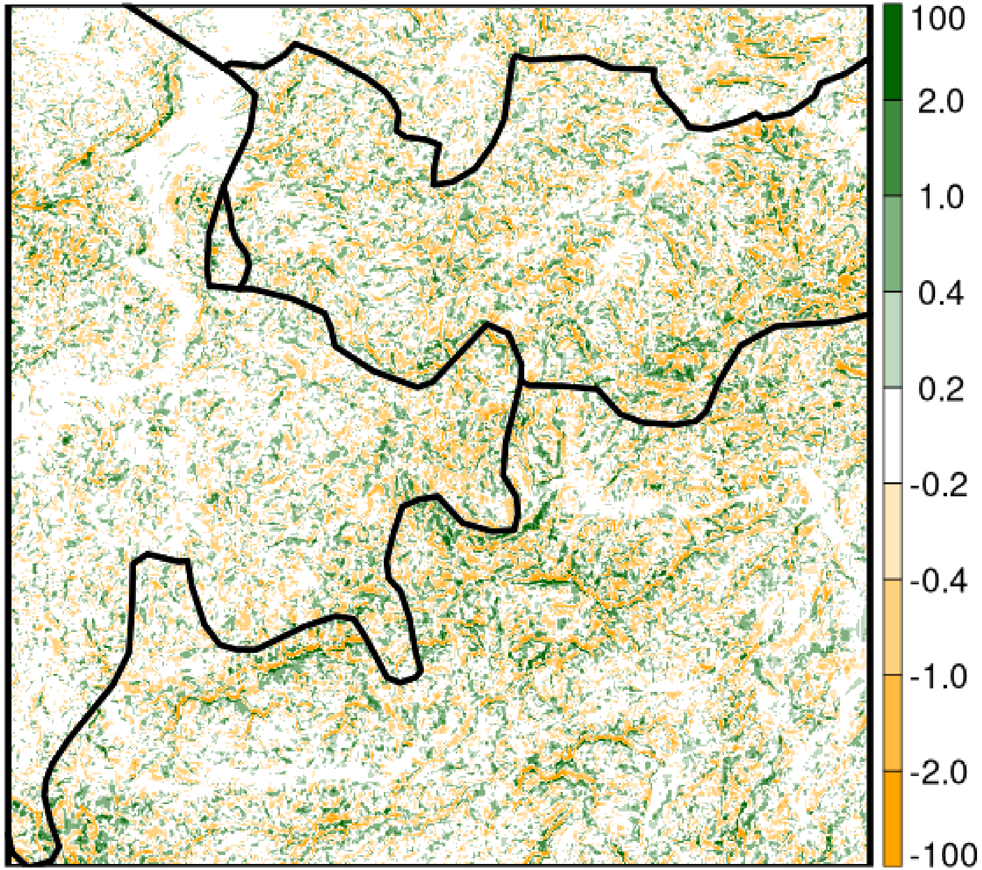
ND4SYS=0
NVDVAR=5
LBIGW=T

Blended approach for fields initialization

Difference between NH and blended approach



+ 30 minuts: pressure departure



vertical divergence

Blended approach for fields initialization

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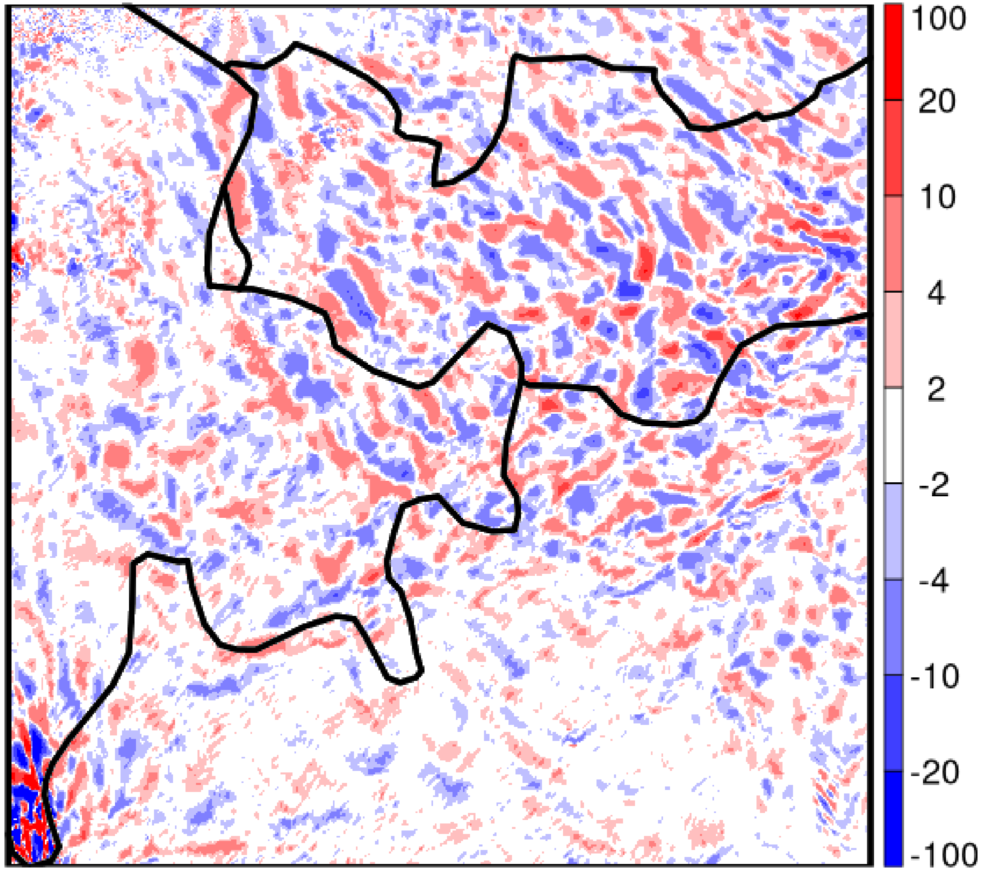
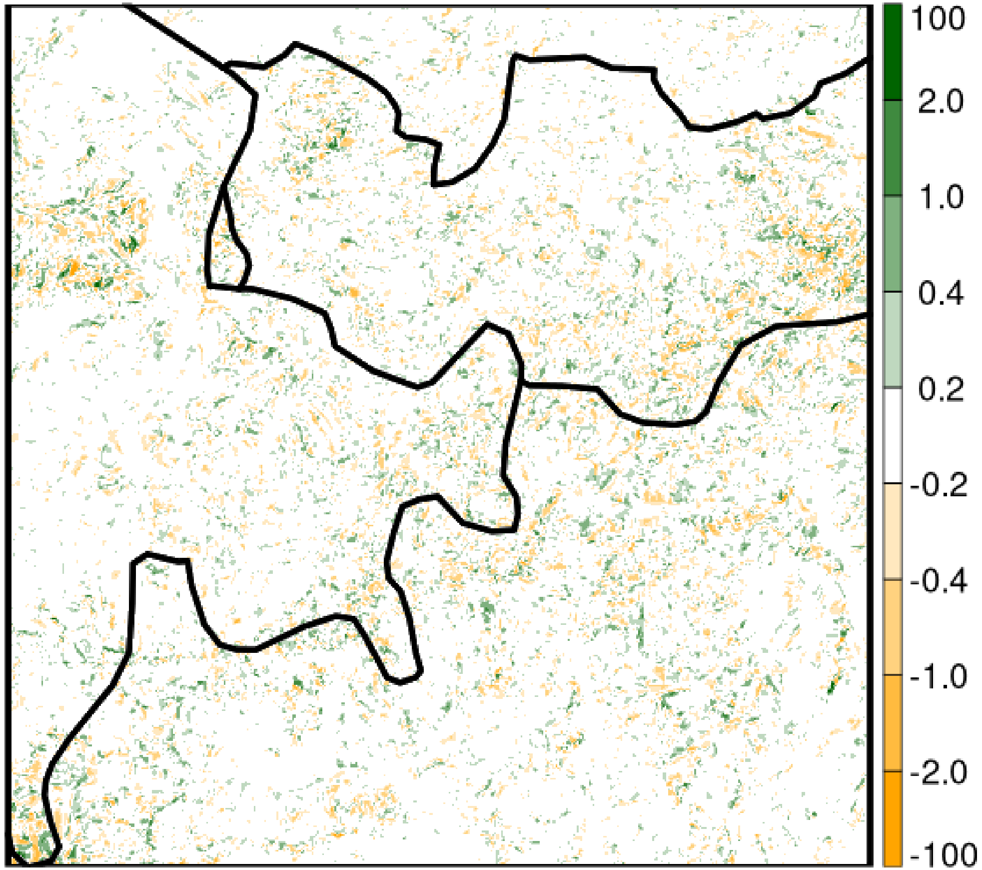
Difference between NH and blended approach



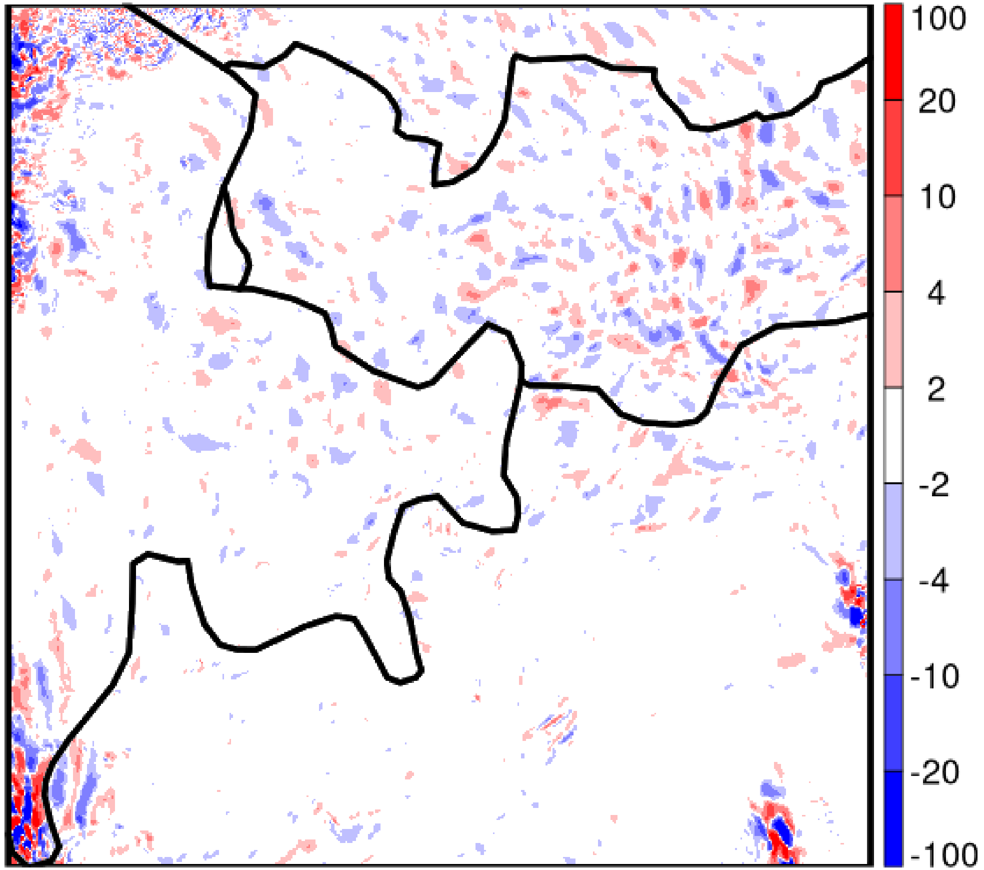
+ 1 hours: pressure departure

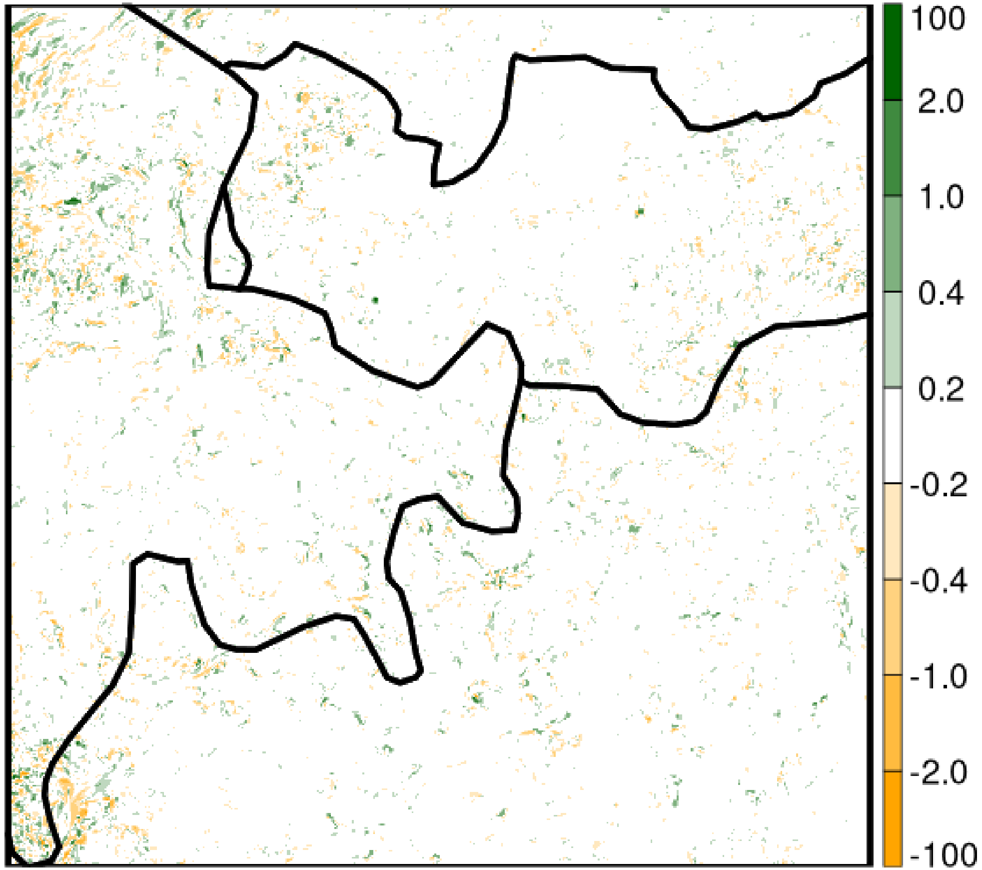


vertical divergence

Blended approach for fields initialization

Difference between NH and blended approach



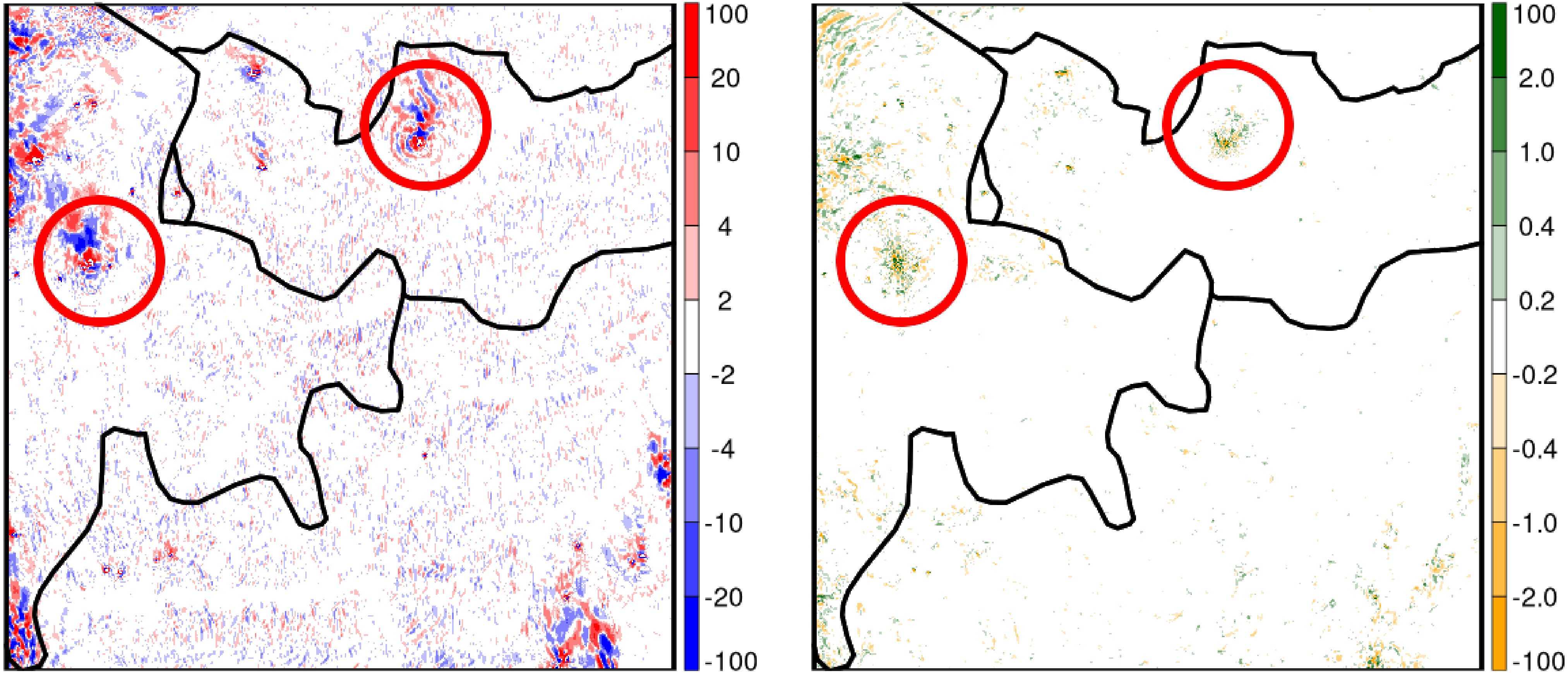


+ 2 hours: pressure departure

vertical divergence

Blended approach for fields initialization

Difference between NH with "old dynamics" and NH with "new dynamics"



+ 2 hours: pressure departure

vertical divergence

Namelist modification

New dynamic options available in CY48T3_deode:

```
&NAMDYNA
    L_RDRY_NHX=.T.,
    LBIGW=.T.,
    LSI_NHEE=.T.,
    LSPNHX=.F.,
    ND4SYS=0,
    NVDVAR=5,
    ...
/
```

Will be available in CY49T2_deode and CY50T1 soon ☺.

Köszönöm a figyelmüket!

Thank you for your attention!