HYMACS in ICON
First idealized tests and adaptions of the dynamical core to subgrid-scale mass fluxes

Michael Langguth, Volker Kuell and Andreas Bott

Sturmjäger NRW

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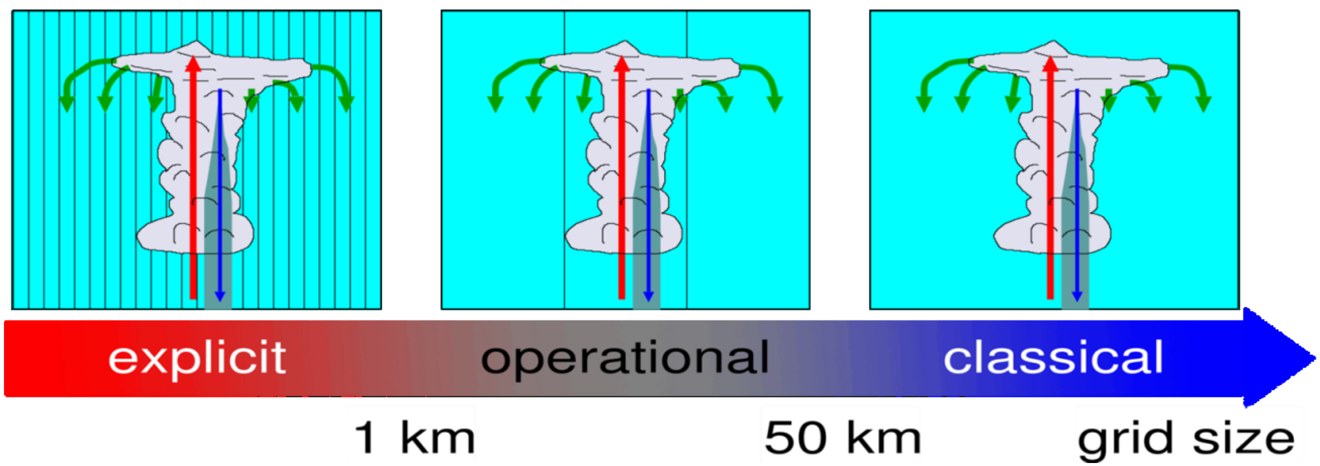
Motivation

- Cumulus convection: major driver for atmospheric dynamics
- NWP models (still) require convection parametrization schemes, but operate in convective grey zone

  → conceptual adaptions required
- **Hy**brid **Ma**ss Flux **C**onvection **S**cheme (**HYMACS**) abandons assumption of local subsidence → local mass sources / sinks
- Merit of HYMACS in COSMO (*Kuell and Bott, 2009, 2011; Uebel and Bott, 2015* etc.), in WRF (*Ong et al., 2017*)



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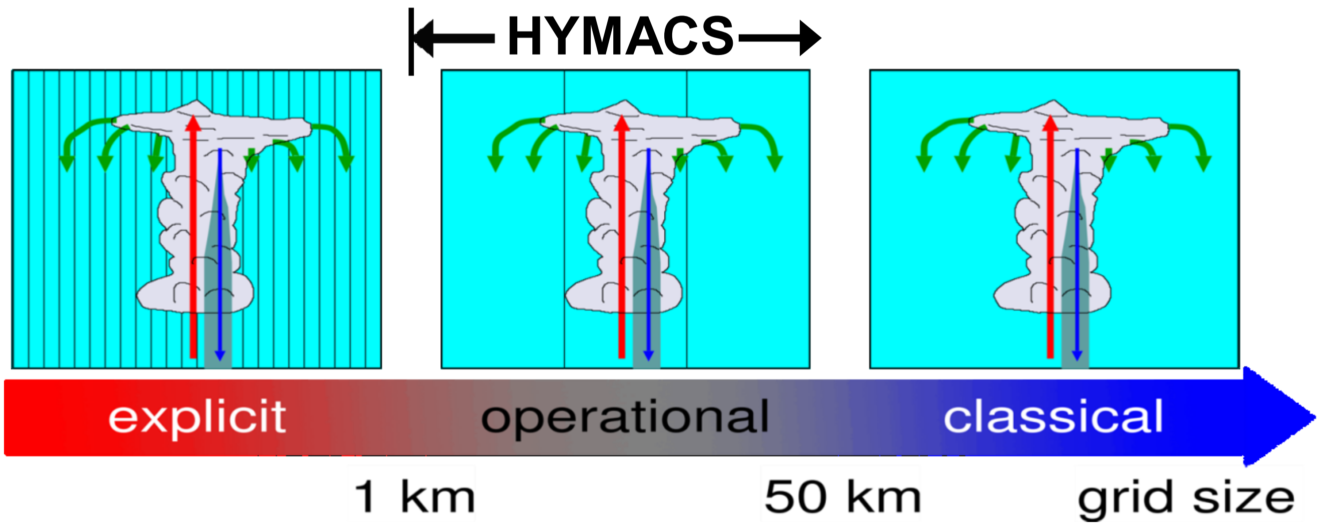

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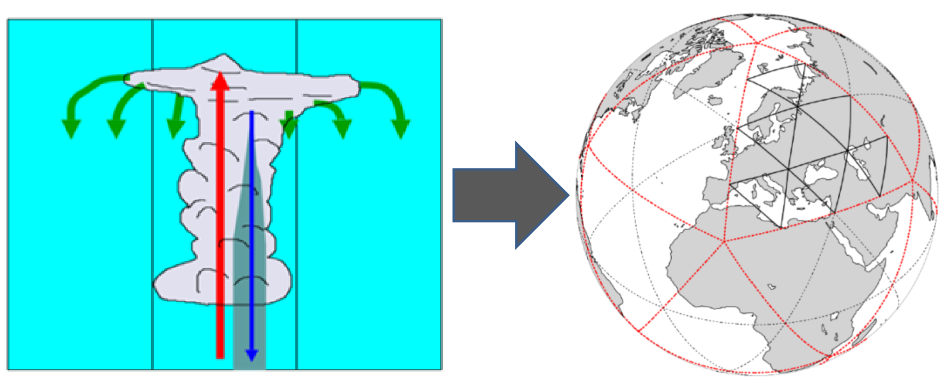

HYMACS **ICON**

HYMACS core

- HYMACS introduces an additional convective mass flux term $\mathbf{J_c}$ in the continuity equation

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v}_e) + \left.\frac{\partial \rho}{\partial t}\right|_{conv} = 0 \quad \text{with} \quad \left.\frac{\partial \rho}{\partial t}\right|_{conv} = -\nabla \cdot \mathbf{J_c} = -\frac{1}{A_c}\left(\frac{\partial M_u}{\partial z} + \frac{\partial M_d}{\partial z}\right)$$

Local change in density through **grid scale** (calculated in the dynamical core) <u>and</u> **convective** (to be parametrized) mass flux divergence

- Physics-dynamics coupling is neither isobaric nor isochoric!
- Cloud model also gives convective tendencies of enthalpy h, of specific moisture species q^x and horizontal momentum $\mathbf{v}_h$
- Convective Exner pressure tendency:

$$\left.\frac{\partial \pi}{\partial t}\right|_{conv} = f\left(\left.\frac{\partial h}{\partial t}\right|_{conv}, \left.\frac{\partial \rho}{\partial t}\right|_{conv}, \left.\frac{\partial q^x}{\partial t}\right|_{conv}\right)$$

Mass Lifting Experiment

Approach
Compare mass lifting experiments in ICON with experiments in COSMO (see *Kuell et al., 2007*)

General Model Setup
Dry, polytrope $\left(\frac{dT}{dz} = -6\ \mathrm{K/km}\right)$ background atmosphere at rest
69 equidistant vertical levels ($\Delta z = 300\ \mathrm{m}$)
Rayleigh sponge layer $@z \geq 14\ \mathrm{km}$
Central grid column with mass sink (bottom layer) and mass source ($@z = 8.85\ \mathrm{km}$) → 1 hour „convective cell“
Mass transfer only → no enthalpy tendency

Specific COSMO Setup	Specific ICON Setup
Rectangular grid with $\Delta x_{cos} = 0.0625° \cong 7\ \mathrm{km}$	Triangular grid with $\Delta l_e = 10.5\ \mathrm{km}\ (A_{ICON} \cong A_{cos})$

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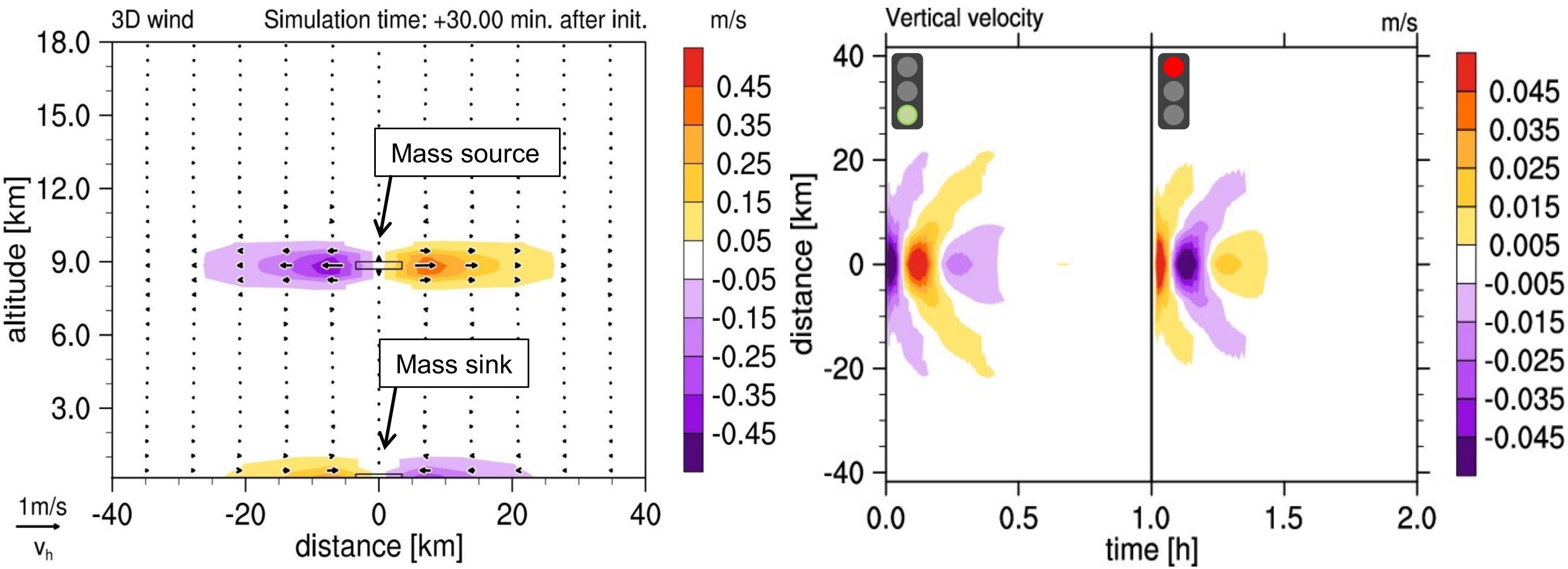
Mass Lifting Experiment

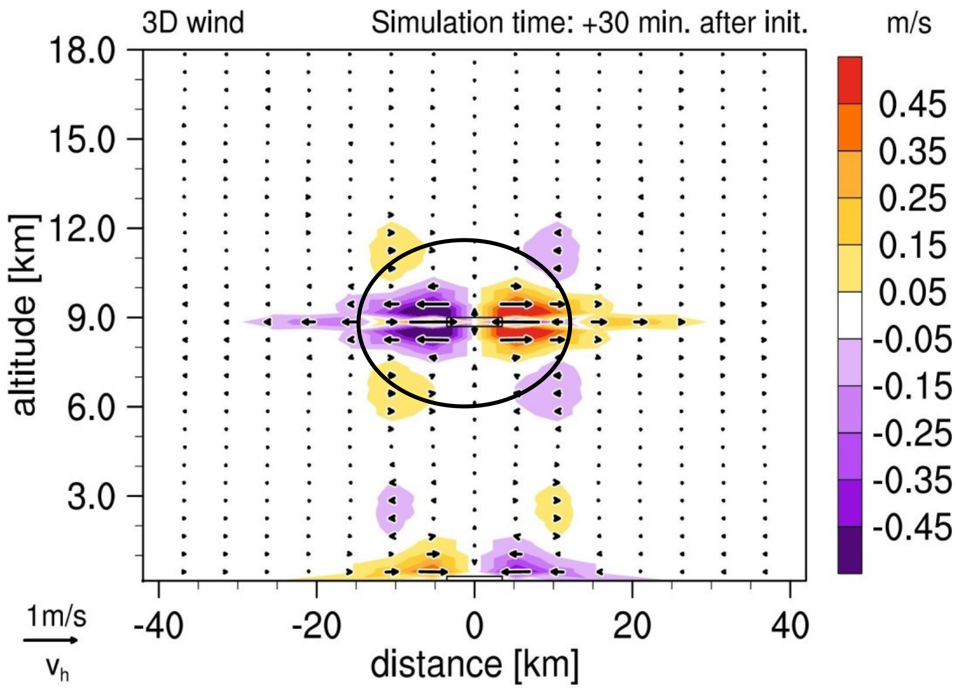
Results of COSMO simulation (v5.1., reference):

Dynamical flow response and gravity wave emission



Mass Lifting Experiment

Results of an ad-hoc implementation in ICON:



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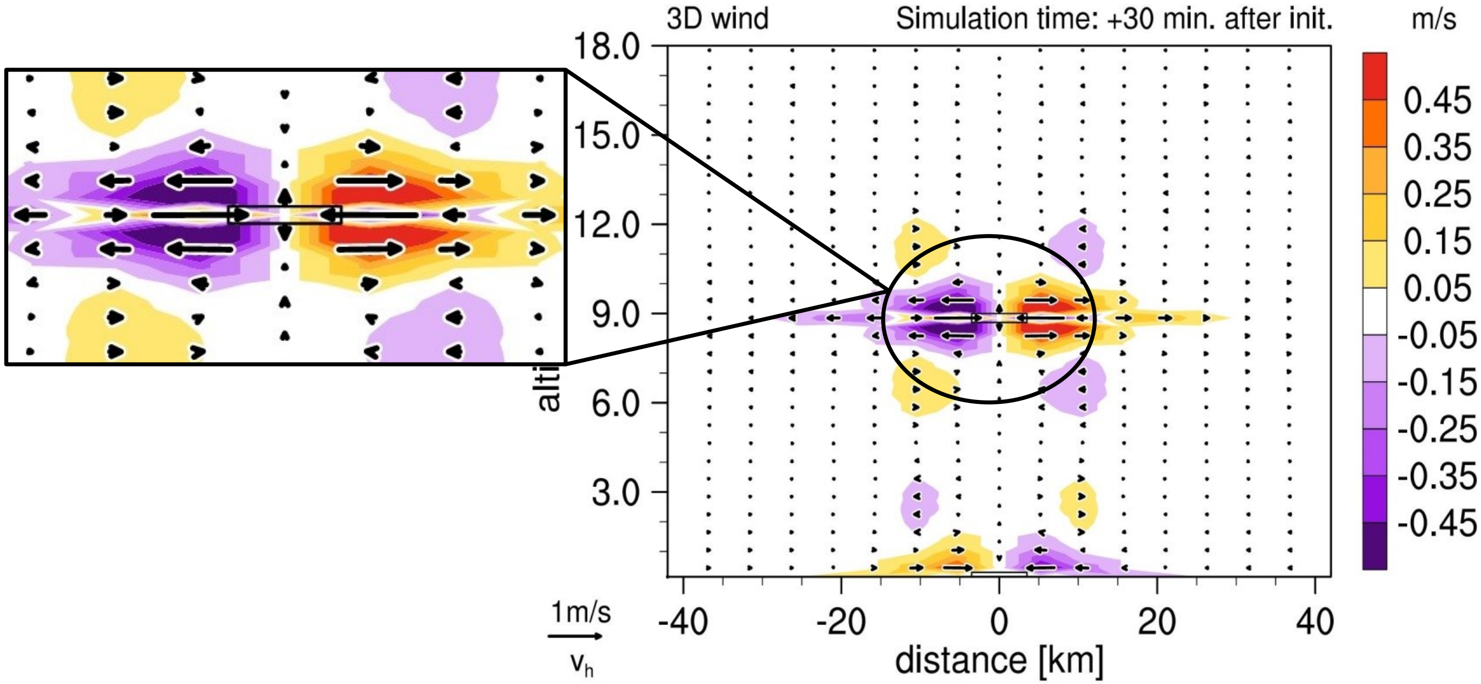

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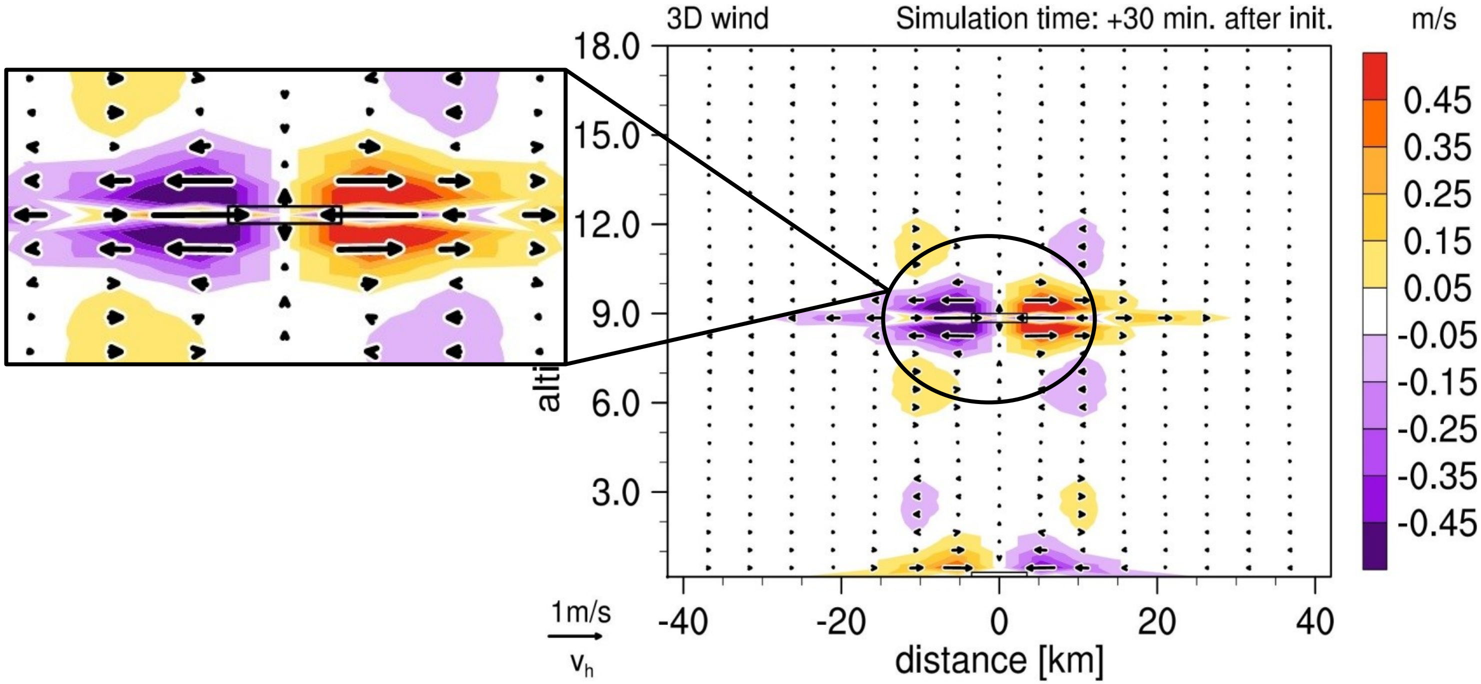

- Distorted dynamical response due to **anisotropic** 4th order divergence damping

$$\frac{\partial v_n}{\partial t} + \mathrm{adv}(v_n) = -c_{pd}\theta_v \frac{\partial \pi}{\partial n} + F_s(v_n) + F_d(\mathbf{v})$$

$$\text{with} \quad F_d(\mathbf{v}) = -f_d \overline{A}_c^2 \nabla_n \left(\widetilde{\nabla} \cdot \left[\nabla_n \left(D_h + \frac{\partial w}{\partial z}\right)\right]\right)$$

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Mass Lifting Experiment

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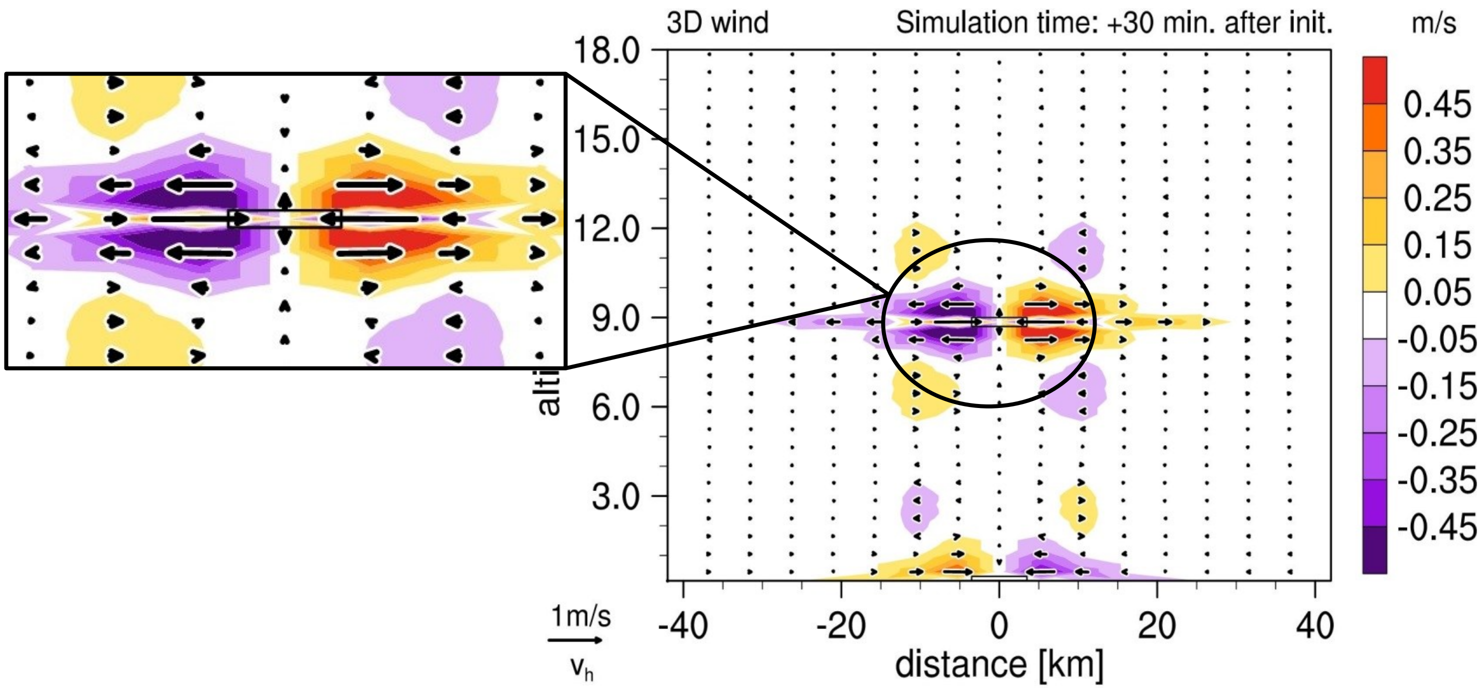

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Vertical divergence affects v_n, but w is unaffected

So, what is the task of the divergence damping in ICON?

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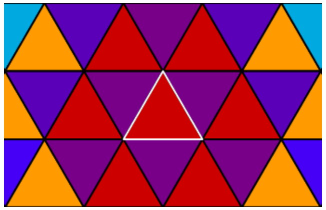
The Checkerboard Problem

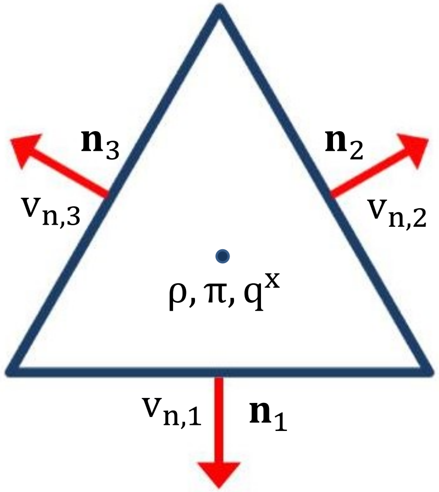
- Major obstacle during development of ICON: Divergence polluted with checkerboard noise



- Inherent property of the triangular grid (*Gassmann, 2011*) :
  - Vector components in trivariate coordinate system are linearly dependent

$$\tilde{v}_{n,1} + \tilde{v}_{n,2} + \tilde{v}_{n,3} = 0$$

  - Any violation of the constraint gives raise to checkerboard noise
- Numerical filter (<u>divergence damping</u>, hyper-diffusion etc.) is indispensable !!!



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Mitigating the Checkerboard Problem

Known approaches:

- **4th order divergence damping acting on 3D divergence** (operational, see *Zaengl et al. (2015)*)
- **Hyper-diffusion** (i.e. as in *Wan et al. (2013)*; different discretizations possible)

→ **Strong grid imprinting** ⚠

New approach:

→ Combination of divergence damping techniques (**CDD**)

- **4th order divergence damping acting on 2D divergence**

✓ Compatible with HYMACS
✓ Very efficient noise filter

✗ Damping of gravity waves

- **Isotropic 2nd order divergence damping**

✓ Compatible with HYMACS
✓ No degeneration of gravity waves

✗ Less efficient noise filter

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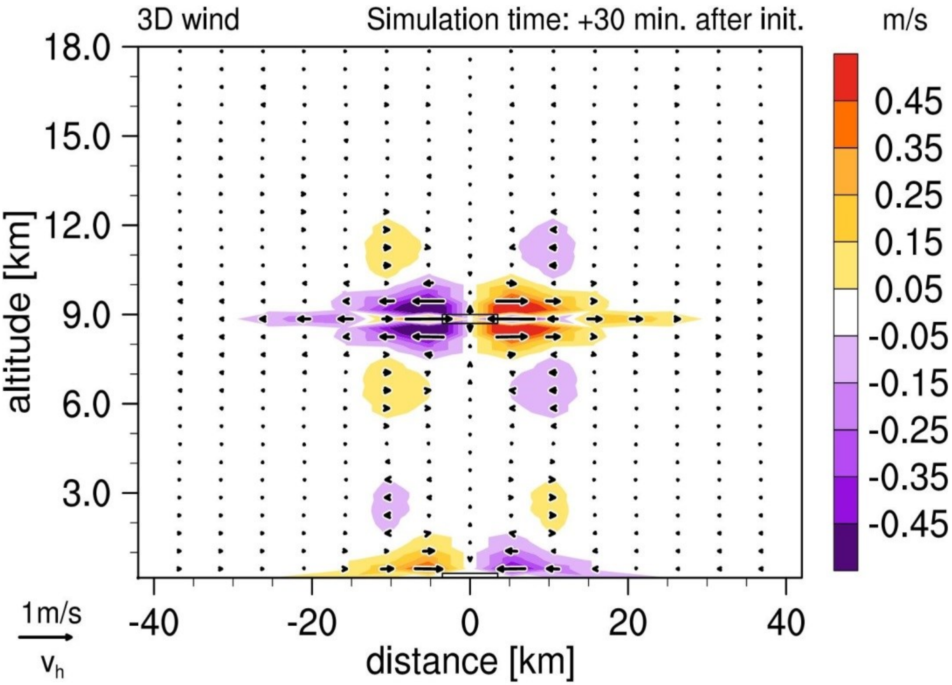
Mass Lifting Experiment

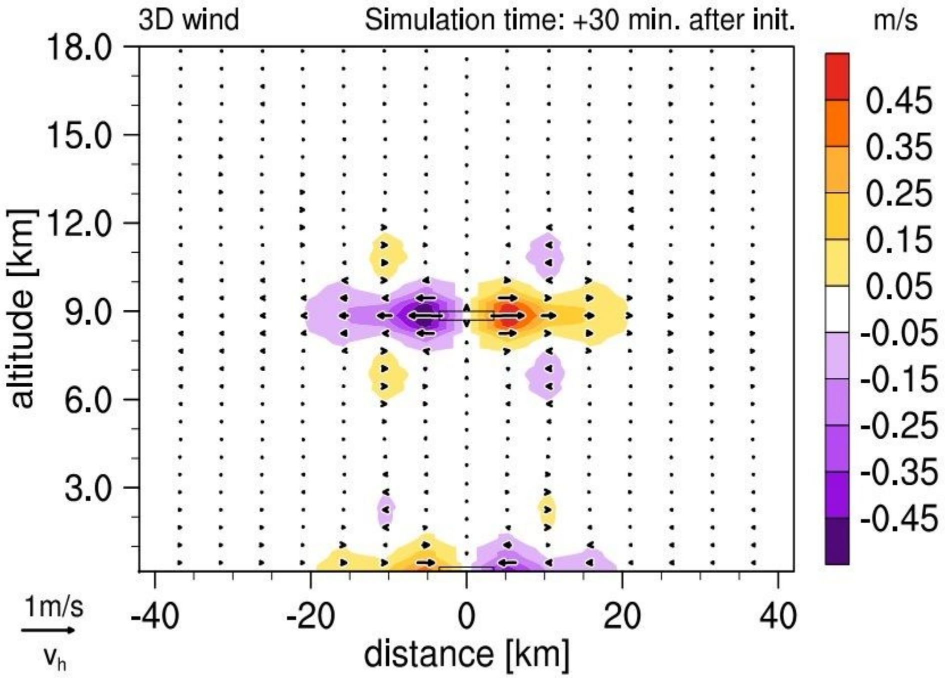
Results with combined divergence damping in dynamical core:

Dynamical flow response

Conventional divergence damping



Combined divergence damping



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Results with combined divergence damping in dynamical core:

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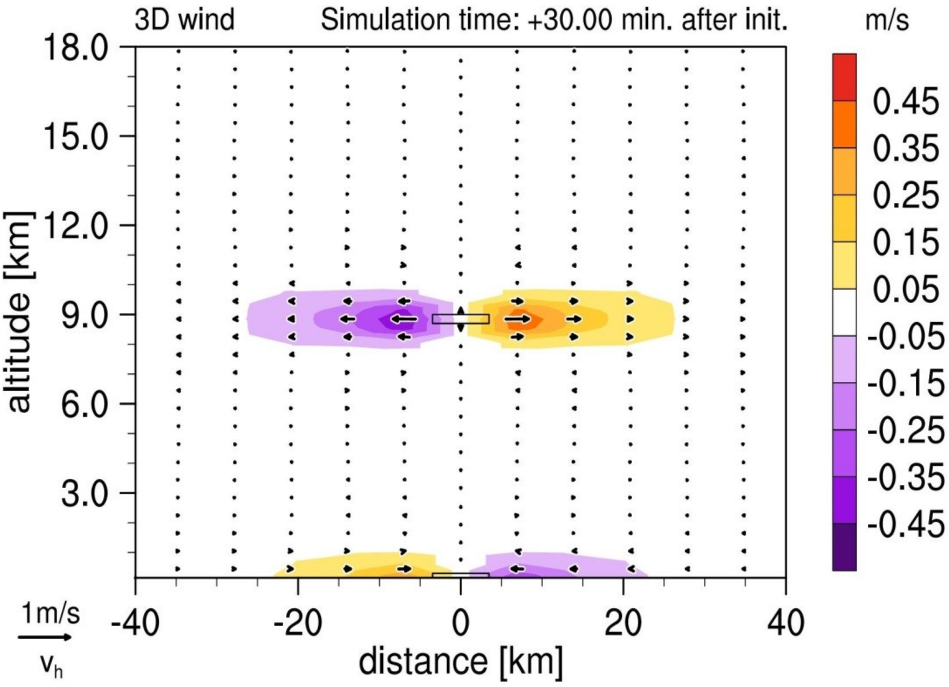
COSMO (reference)



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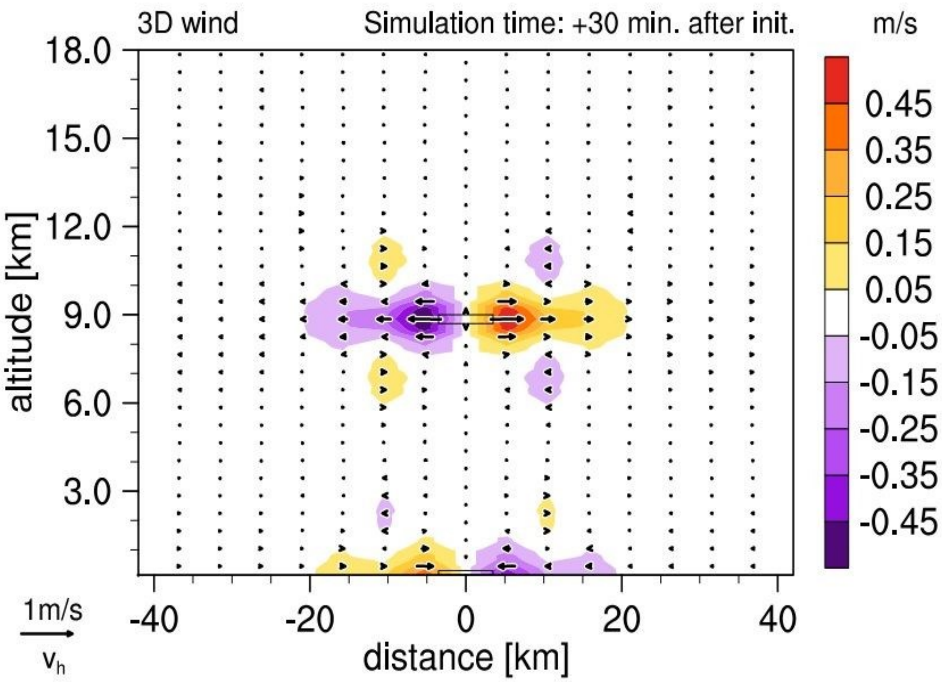

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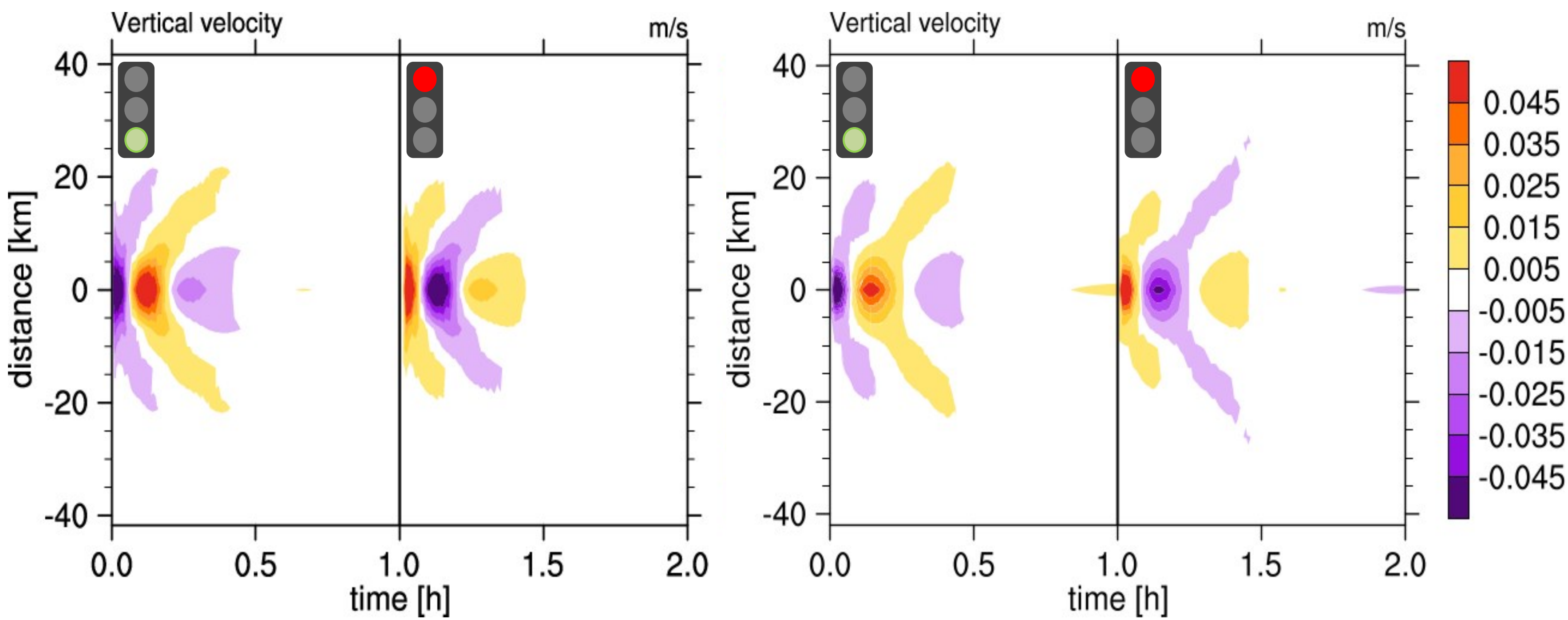
Mass Lifting Experiment

Results with combined divergence damping in dynamical core:

Gravity wave emission

COSMO (reference)

Combined divergence damping



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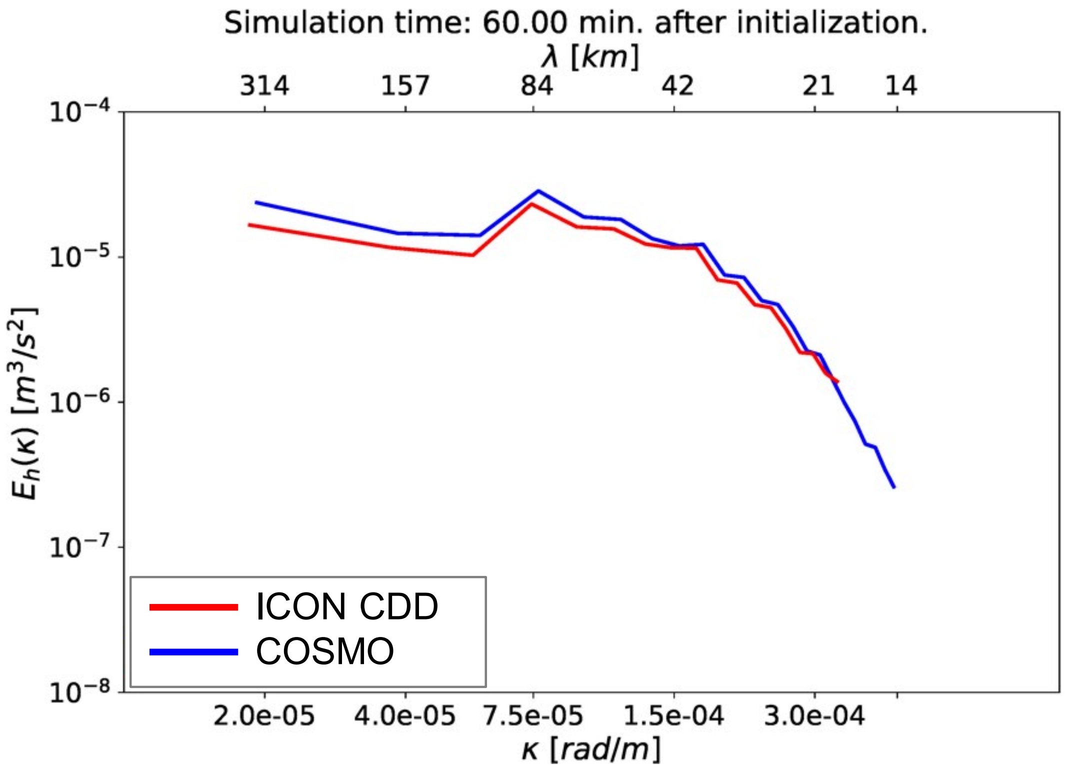
Mass Lifting Experiment

Results with combined divergence damping in dynamical core:

Quantifying Checkerboard-Noise in energy spectra
→ interpolation of horizontal wind onto regular grid ($\Delta x = 0.87\Delta l_e$ following *Dipankar et al. (2015)*) in ICON



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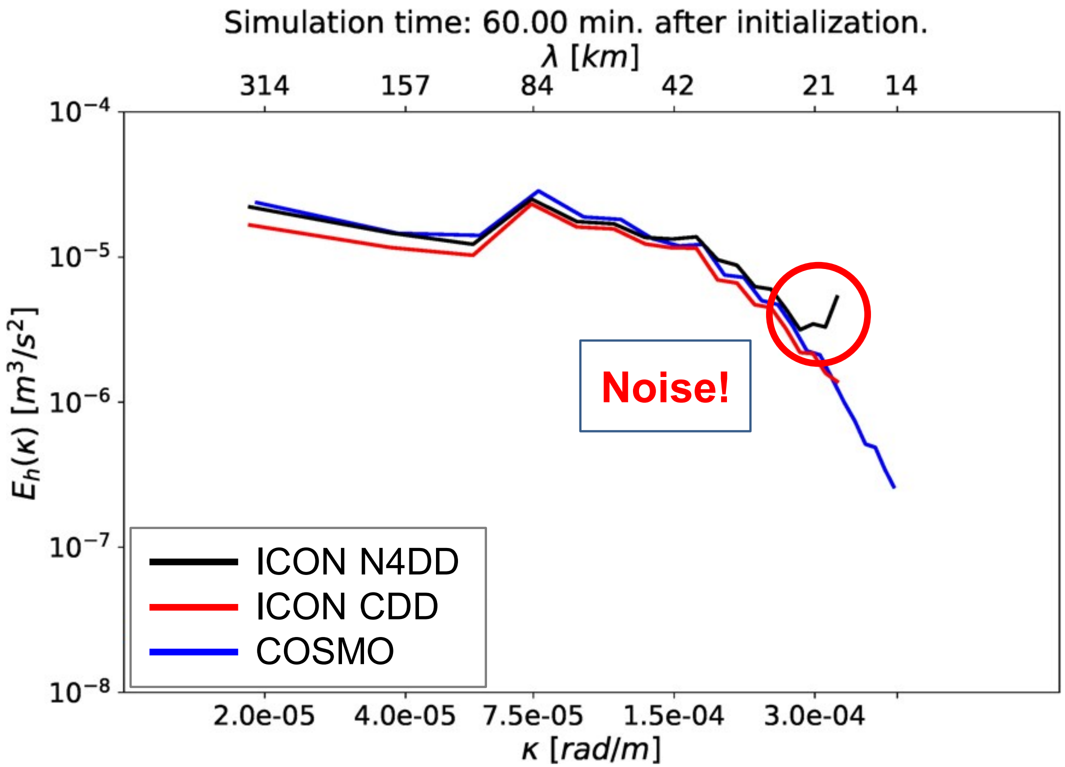

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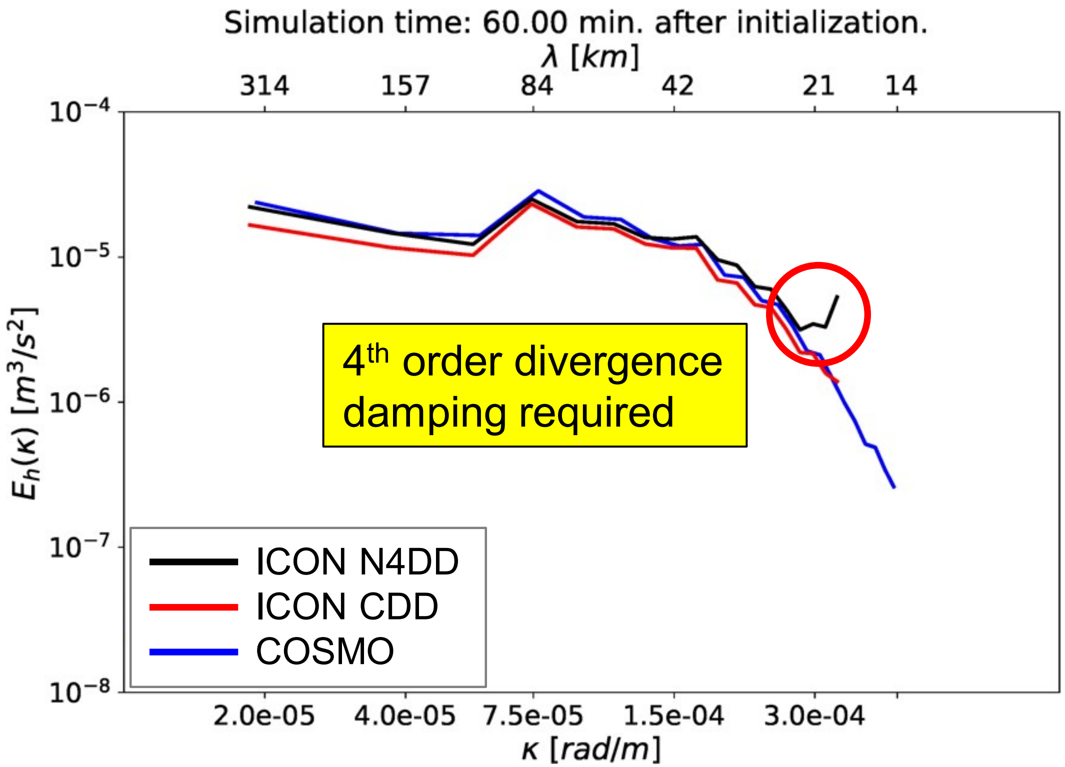

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Conclusion and Outlook

HYMACS in ICON is not trivial…

- no conventional physics-dynamics coupling
- inherent checkerboard problem in divergence of the triangular grid
  - ⚠ HYMACS forces divergent/convergent wind pattern at smallest model scale
  - ⚠ Conventional numerical filter inappropriate

Implementation of a combined divergence damping

- ✓ Compatible with HYMACS
- ✓ Effective reduction of checkerboard noise
- ✓ Comparable performance in Jabolonowski-Williamson test cases

Further steps

- Idealized tests with moisture (activated cloud model)
- Real case tests in ICON-LAM

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Offenbach, 2019/03/18

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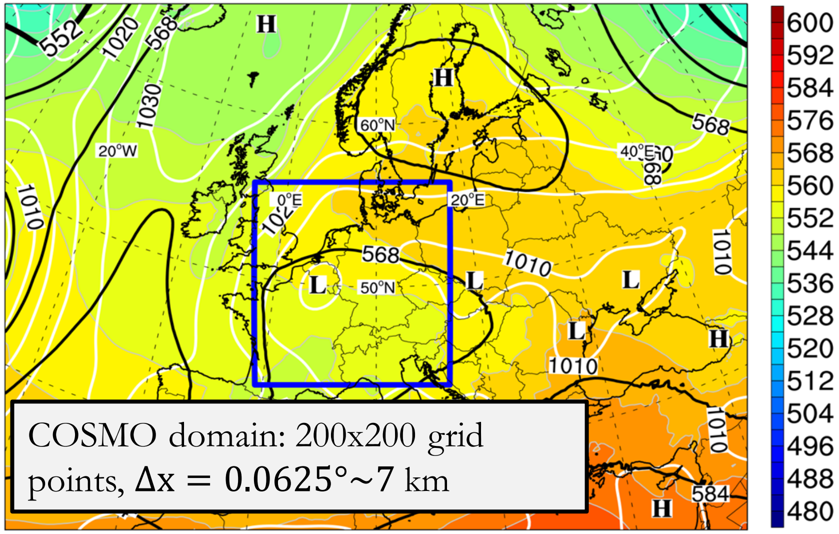
Motivation

- Virtues of introducing net mass transfer in simulating deep convection:
  - Theoretically: idealized experiments of convective systems (*Shutts and Gray, 1994; Gray et al., 1998; Gray, 1999; Chagnon and Bannon, 2006; Kuell et al., 2007* etc.)
  - Practical applications: HYMACS in COSMO
- Case study with COSMO (v5.01) during a persistent high-over-low weather situation over Central Europe in June 2016:
  - Seven 24h-simulations with different CPS: HYMACS (HYM) and Tiedtke (Tie)
  - Verification against RADOLAN observations

Rel. Topography, 500 hPa Geopotential, PMSL



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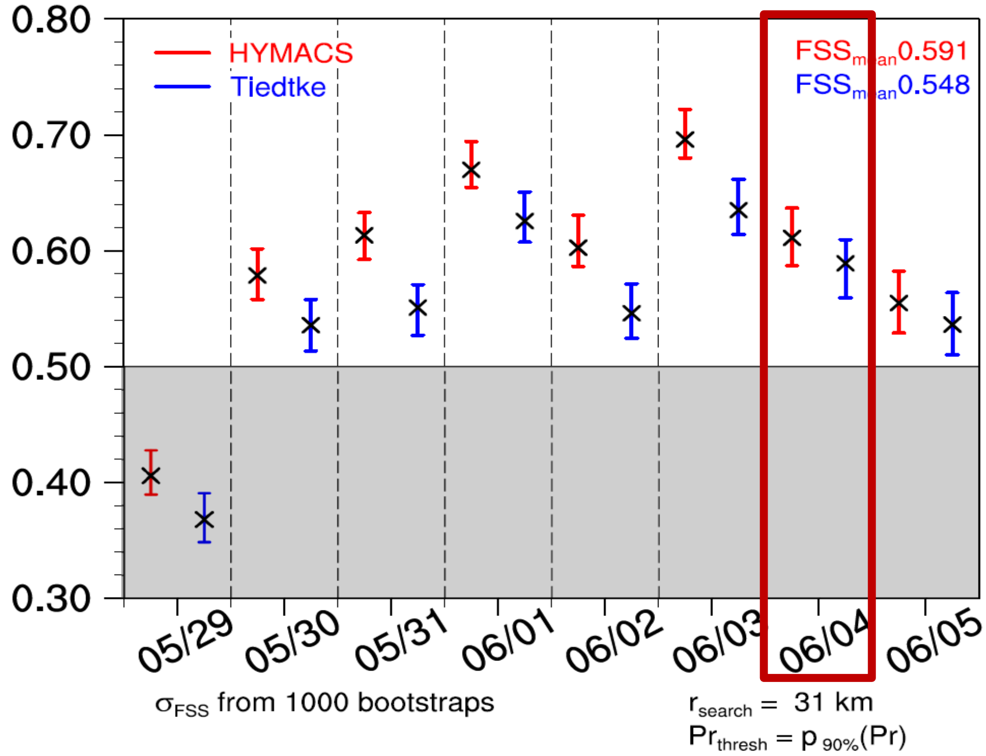
Motivation

Spatial verification:

(Bias-corrected) Fractional Skill Score-analysis:



\+ Better simulation of precipitation patterns with HYMACS

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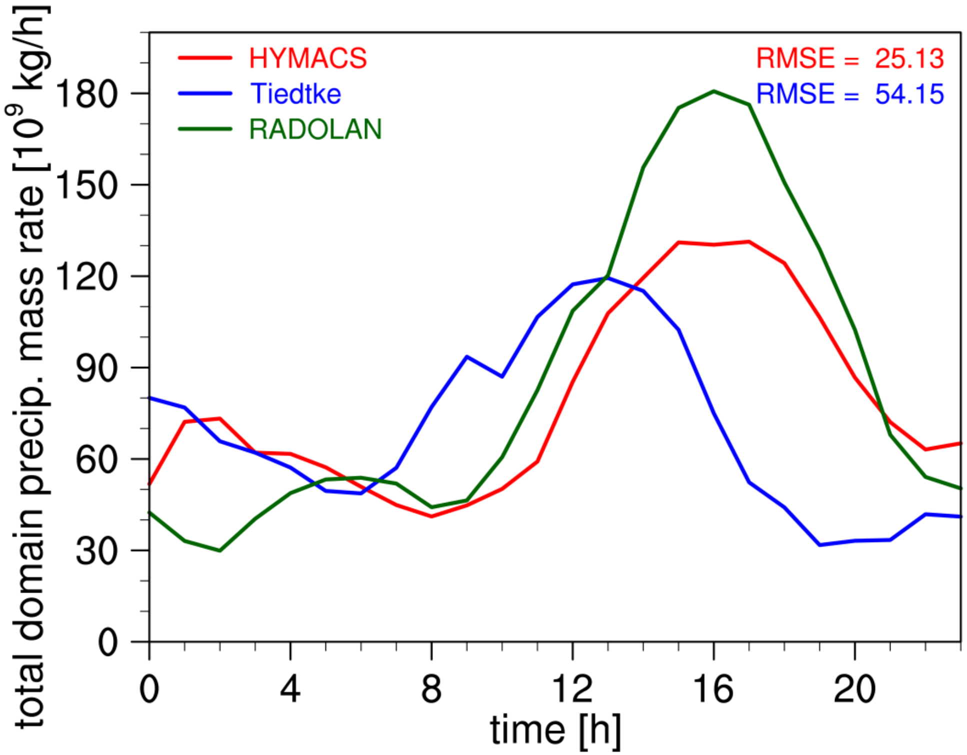
Diurnal cycle:

Area-integrated precipitation rates:

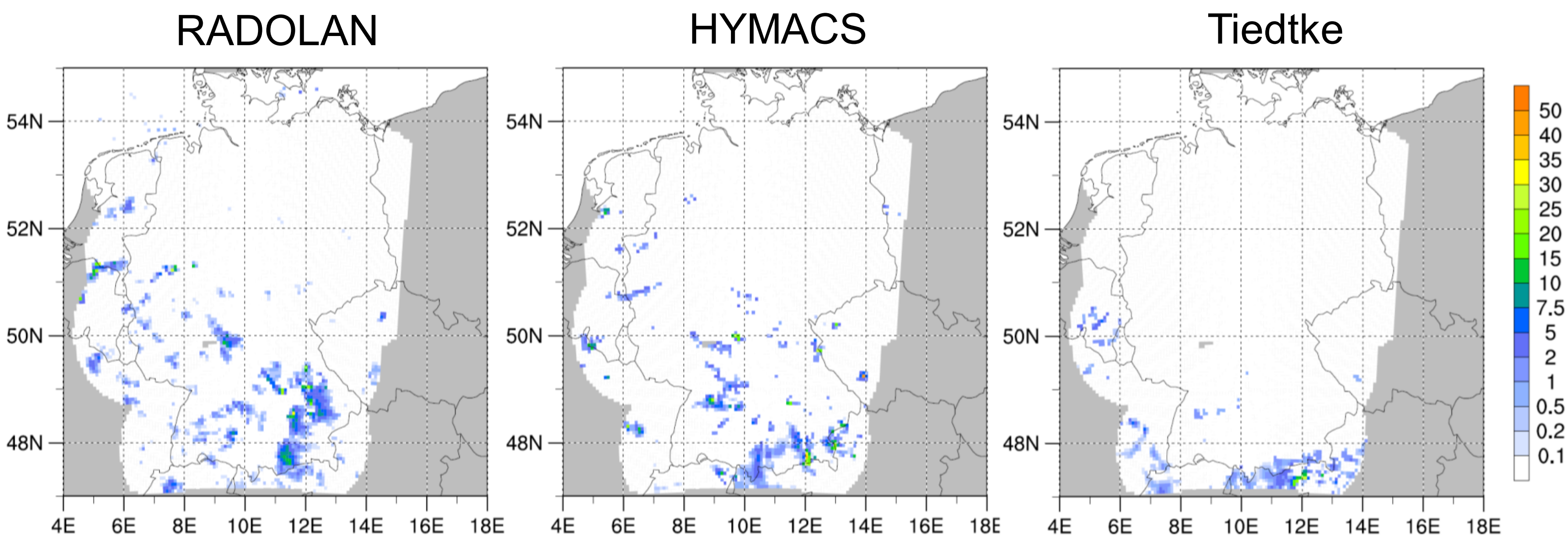


+ Better representation of the diurnal cycle with HYMACS

Motivation

Diurnal cycle:

Precipitation rates on 4th June 2016 20 UTC:



+ Better representation of the diurnal cycle with HYMACS

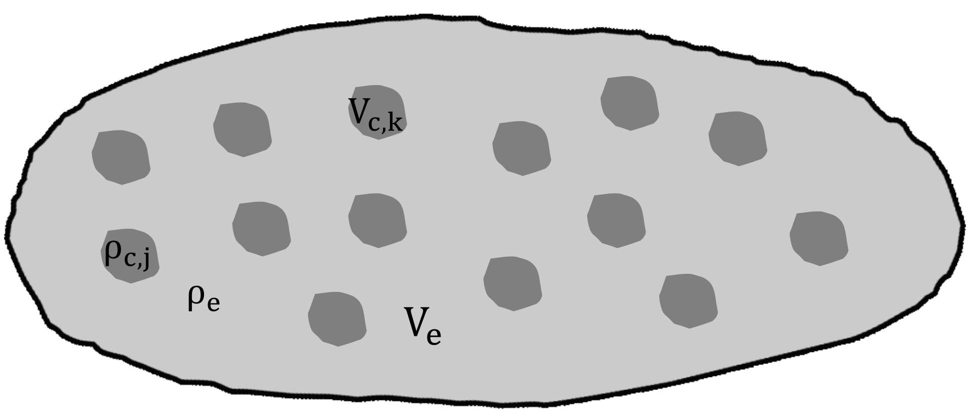
HYMACS - Theoretical Background

- Arbitrary volume consisting of environmental and convective part with partial densities ρ_e and ρ_c
- Momentum of conv. part $\tilde{\mathbf{v}}_c$ as superposition of environmental $\mathbf{v}_e$ and convective $\mathbf{v}_c$
- Balance equation (no internal sources):

$$\frac{D\rho}{Dt} = 0 = \frac{\partial\rho}{\partial t} + \boldsymbol{\nabla}\cdot(\rho\mathbf{v}_e + \rho_c\mathbf{v}_c)$$
$$= \frac{\partial\rho}{\partial t} + \boldsymbol{\nabla}\cdot(\rho\mathbf{v}_e) + \boldsymbol{\nabla}\cdot\mathbf{J}_c$$

- Dominance

$$+ \frac{\partial M_d}{\partial z})$$



$$V = V_e + V_c = V_e + \sum_i^n V_{c,i}$$

Barycentric momentum:

$$\rho\mathbf{v} = \rho_e\mathbf{v_e} + \rho_c\tilde{\mathbf{v}}_\mathbf{c}$$

Physics-dynamics coupling

- Convective tendency of any scalar ψ considering mass transfer

$$\left.\frac{\partial\psi}{\partial t}\right|_{conv} = \left(\frac{\rho(t^n)}{\rho^*} - 1\right)\frac{\psi(t^n)}{\Delta t} - \frac{1}{A\Delta z\rho^*}\left(\varepsilon_{u,d}\psi - \delta_{u,d}\psi_{u,d}\right)$$

$$\text{with } \rho^* = \rho(t^n) + \Delta t \left.\frac{\partial\rho}{\partial t}\right|_{conv}$$

- Update of density ρ and Exner pressure π through convective tendencies in the dynamical core
- π−tendency derived from 1st law of thermodynamics:

$$\left.\frac{\partial\pi}{\partial t}\right|_{conv} = \frac{R_d}{c_{vd}}\frac{\pi}{\rho}\left.\frac{\partial\rho}{\partial t}\right|_{conv} + \frac{1}{\theta_v}\frac{R_d(1+\alpha)}{c_{vd}c_{pd}}\left.\frac{\partial h}{\partial t}\right|_{conv} + \frac{R_d\pi}{c_{vd}(1+\alpha)}\left.\frac{\partial\alpha}{\partial t}\right|_{conv}$$

with $\alpha = \left(\frac{R_d}{R_v} - 1\right)q^v - q^l - q^f$

- Update of moisture species q^x and momentum v_n at physical time step (conventional approach)

Similarity of diffusion and divergence damping

- Former diffusion operator based on identity of vector laplacian (Wan et al., 2013)

$$\nabla^2 \mathbf{v} = \boldsymbol{\nabla}(\boldsymbol{\nabla} \cdot \mathbf{v}) - \boldsymbol{\nabla} \times (\boldsymbol{\nabla} \times \mathbf{v})$$

$$\Rightarrow \qquad \left(\nabla_d^2 \mathbf{v}\right)_e \cdot \mathbf{N}_e = \nabla_n(D_h) - \nabla_t \zeta$$

- Properties of the fourth-order hyper laplacian $\left(\nabla_d^4 \mathbf{v}\right)_{\mathbf{e}} \cdot \mathbf{N}_e = \nabla_d^2\left(\nabla_d^2 \mathbf{v}\right)$

Advantage	Disadvantage
✓ Effective noise removal	× High diffusivity required for effective noise removal
	× Numerical errors near pentagon points (→ distorted triangles)

- First term of hyper laplacian operator **corresponds** to fourth order divergence damping term (involving D_h)

☺ Fourth order divergence damping may be tuned to remove checkerboard pattern **<u>without</u>** excessive diffusivity

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Isotropic 2nd order divergence damping

- implicit numerical solution process for prognostic vertical wind
  → standard algorithm for three-band matrix (Thomas algorithm)
- Damping term applied in corrector step of two-timelevel integration scheme

$$\mathrm{AD} = f_{d,2o} A_c \left(\beta_1 \left(\frac{\partial D_h}{\partial z} + \frac{\partial}{\partial z}\left(\frac{\partial w}{\partial z}\right)\right)^{n+1} + \beta_2 \left(\frac{\partial D_h}{\partial z} + \frac{\partial}{\partial z}\left(\frac{\partial w}{\partial z}\right)\right)^{n+1*} \right)$$

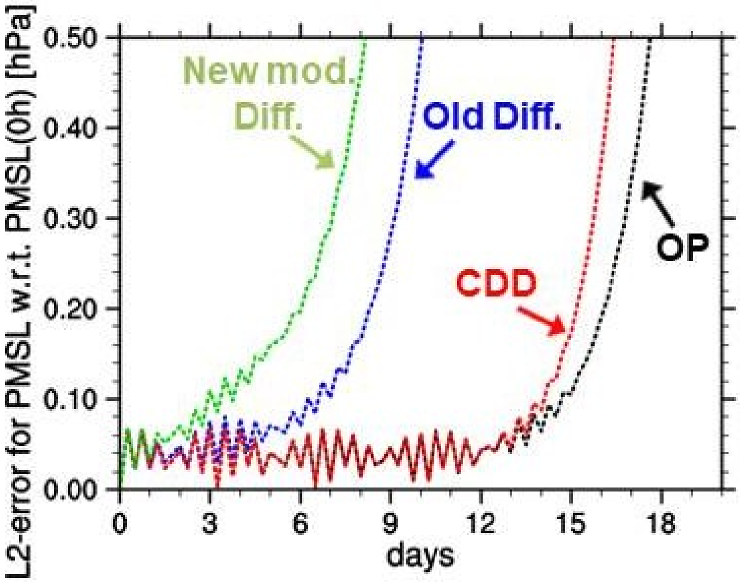
with $\beta_1 = 1 - \beta_2$: Crank−Nicholsen parameter

and $n+1$: new timelevel, $n+1*$: intermediate timelevel

- Less scale-selective than 4th order divergence damping
- Averaging of D_h for *pure* 2nd order divergence damping → reduce noise, but not fully isotropic

Jabolonowski-Williamson test cases

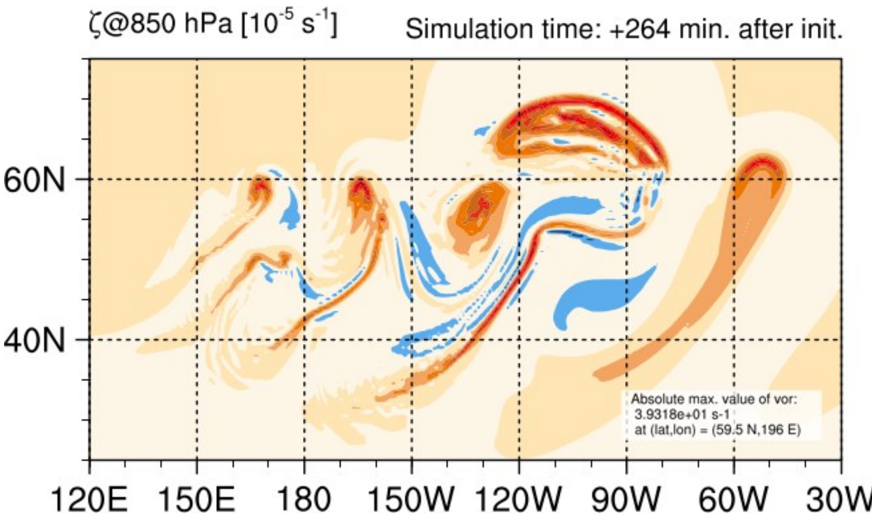
- Standard test for dyn. cores of global models (*Jabolonowski and Williamson, 2006*)
- *Steady state* configuration:
  - Zonally symmetric, strong baroclinic atmosphere
  - No perturbation imposed, i.e. hydrostatic and geostrophic balance
- Grid imprinting due to numerical discretization errors become visible → baroclinic wave development
- L2 error of surface pressure > 0.5 hPa → initial state broken



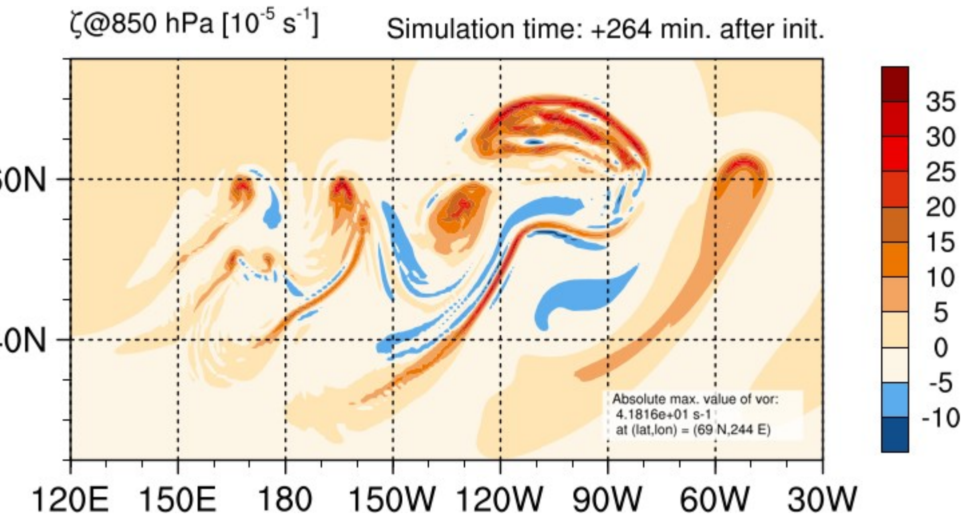
Baroclinic wave test case

- *Baroclinic wave* configuration:
  - Initialization with zonal wind pertubation
    → triggers (explosive) baroclinic wave train after 7 days

ICON OP



ICON CDD



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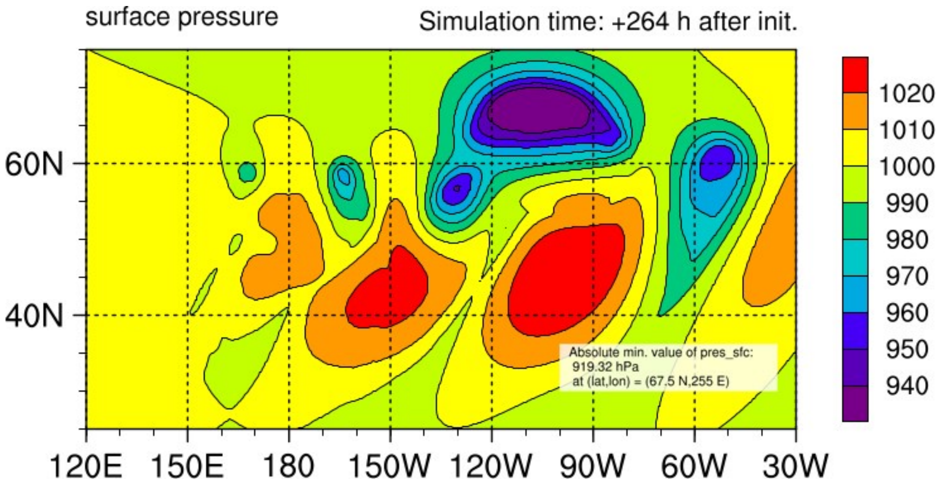
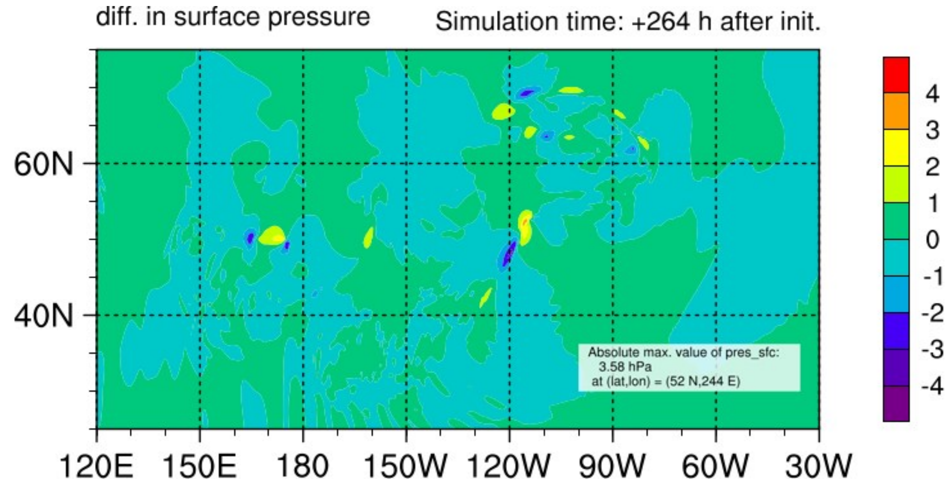


ICON CDD – ICON OP



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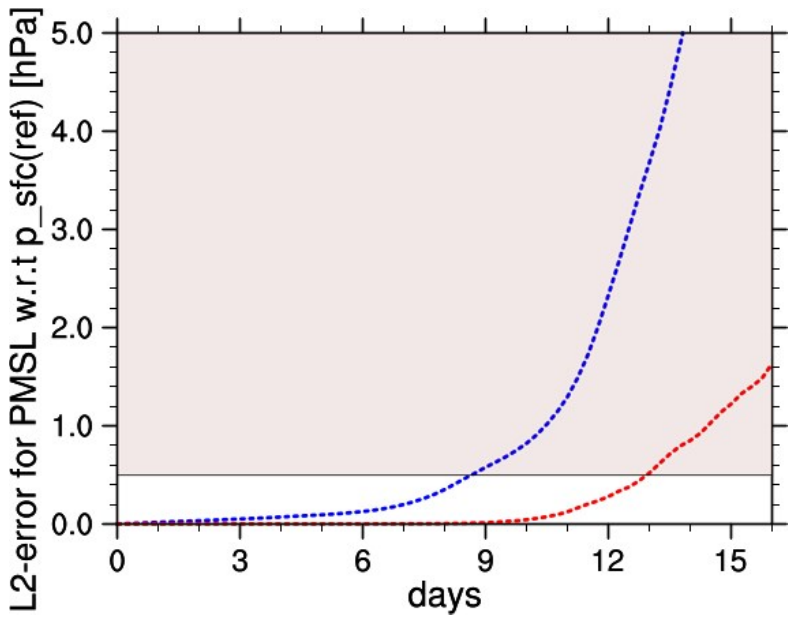

✓ Baroclinic wave train practically indistinguishable until simulation day 13

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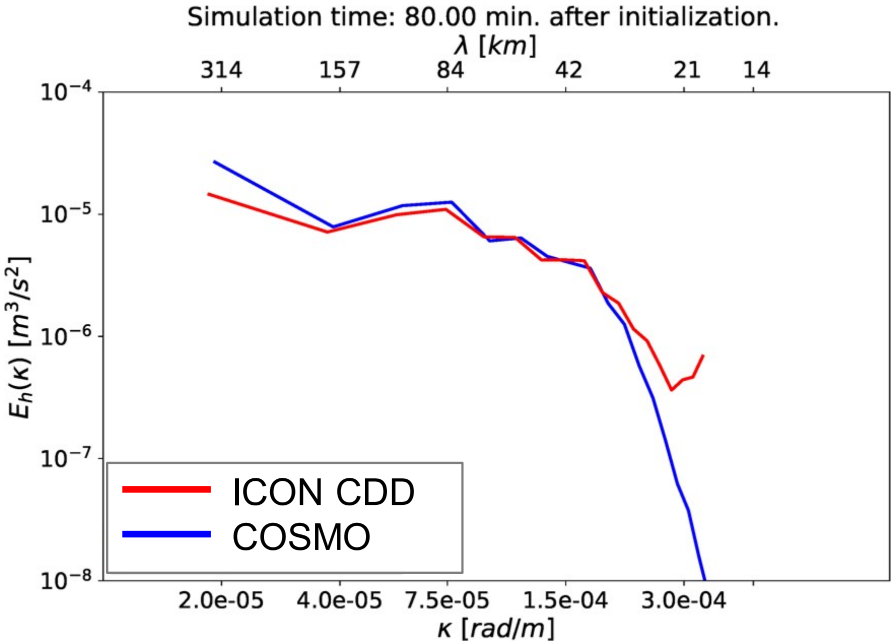
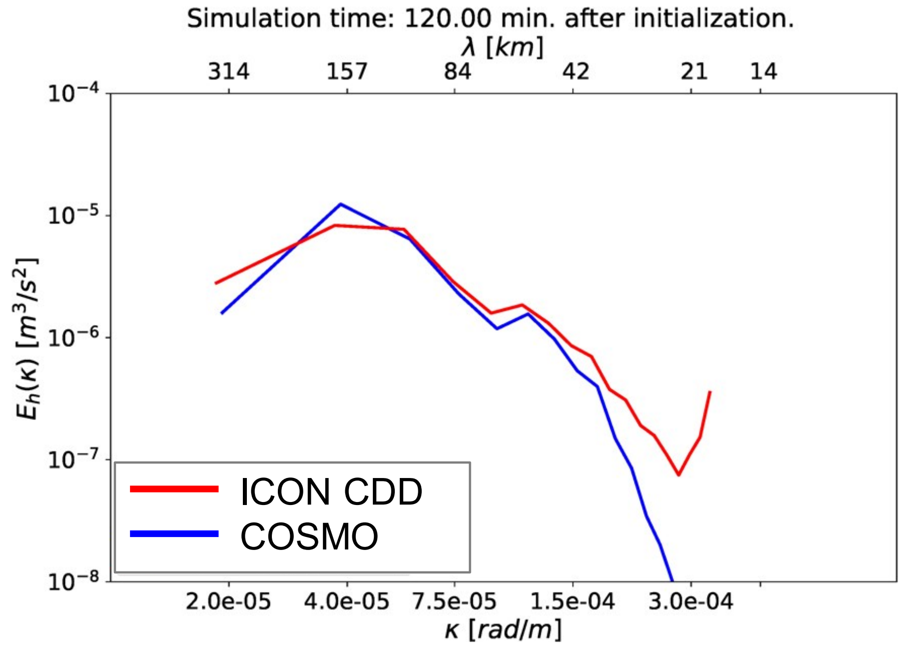
Noise in the dissipation phase

- In principle, dynamical response ok after switching off mass transfer, but…





- Slower dissipation at shortest wave spectrum $\lambda \sim 2\Delta x$
- Quicker dissipation at $\lambda \sim (3-5)\Delta x$ due to 2nd order divergence damping

Further testing required with focus on real case studies

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