Bulk convergence behavior of convection-resolving simulations of summertime deep convection over land

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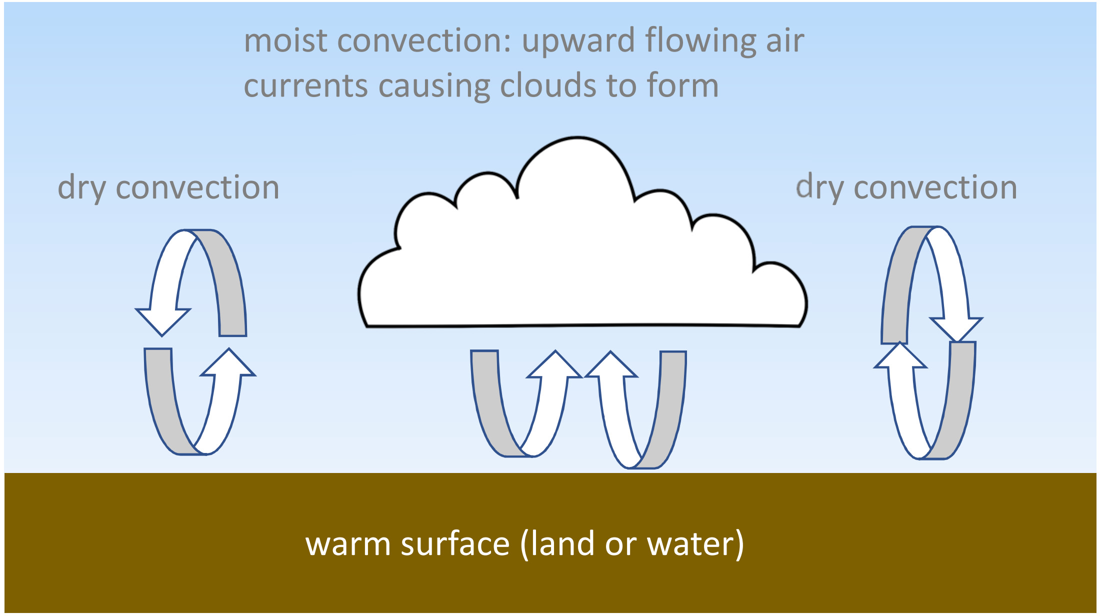
…why do we care about convection?

Direct concern

- forecast convective precipitation
- important feature of the water cycle

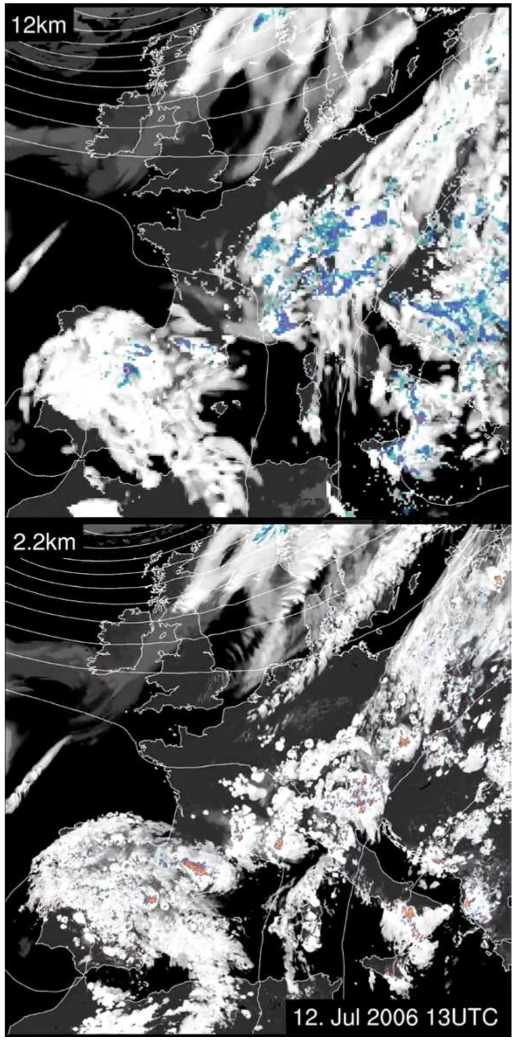


Feedbacks to larger scale

- changes vertical stability
- generates and redistributes heat
- removes and redistributes moisture
- makes clouds, strongly affecting surface heating and atmospheric radiation

Convection-resolving simulations

- Clouds and convective transport partly resolved (e.g. Weisman et al. 1997, Hohenegger et al. 2008, Prein et al. 2015)
- Better representation of topography and surface fields
- Improved diurnal cycle of precipitation compared to convection-parameterizing models (e.g. Richard et al. 2007, Ban et al. 2014)
- Can be applied to decade-long, continental-scale climate simulations (e.g. Ban et al. 2014, Leutwyler et al. 2016)



Leutwyler et al. (2016)

Convection-resolving simulations

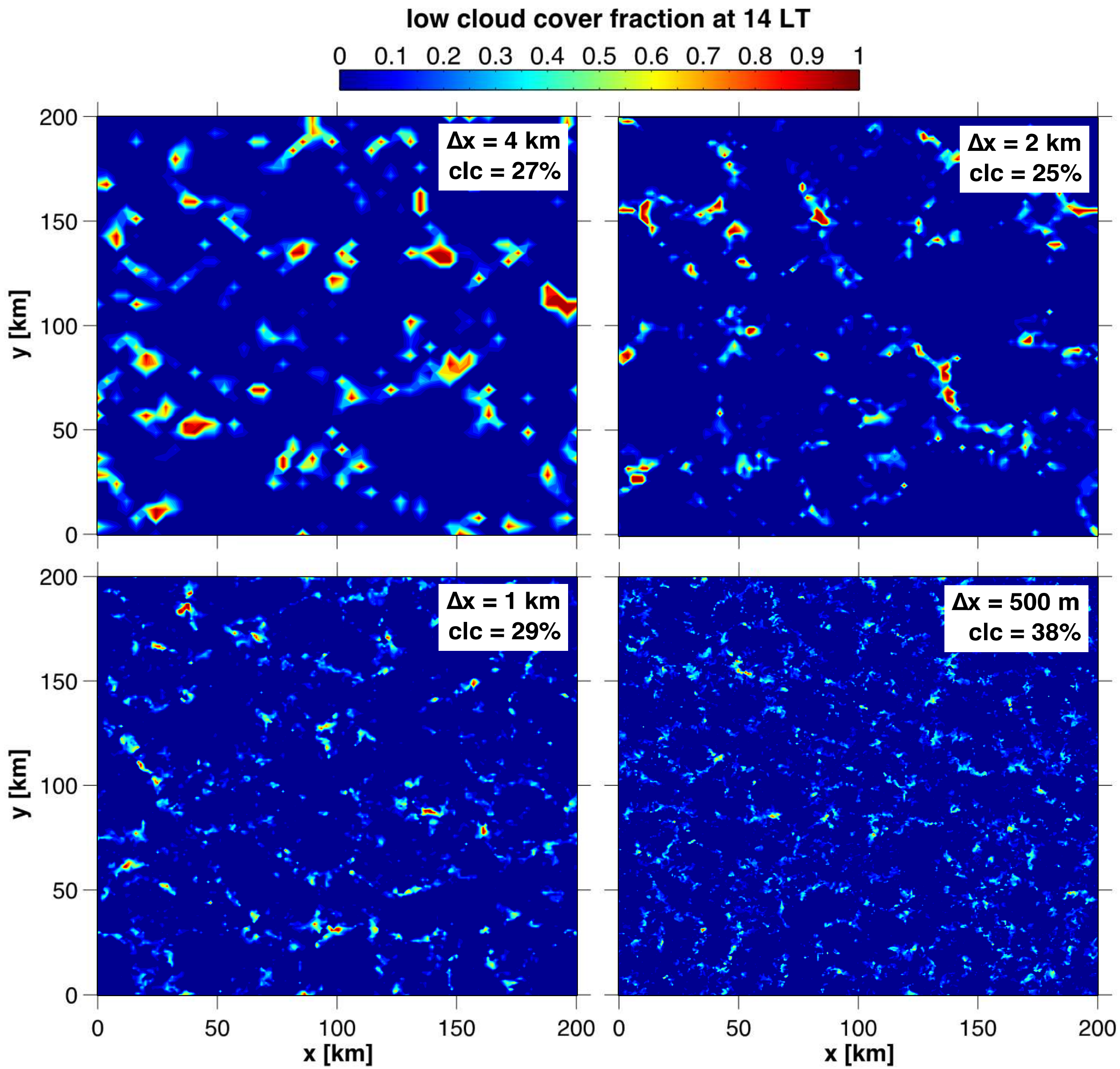
The 'grey zone' of convection

Explicit dynamics?

- Fully resolving deep convection needs LES at $\Delta x < 100$ m
- Smallest features scale with numerical filter: solution sensitive to numerics and details of physical parameterizations

Traditional convection parameterization?

- Grid-box state no longer a good approximation of the "large-scale" state
- Horizontal fluxes may become important


low cloud cover fraction at 14 LT
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Δx = 4 km
clc = 27%
Δx = 2 km
clc = 25%
Δx = 1 km
clc = 29%
Δx = 500 m
clc = 38%
y [km]
x [km]
0
50
100
150
200

Bulk convergence

What should be the goal of convection-resolving simulations?

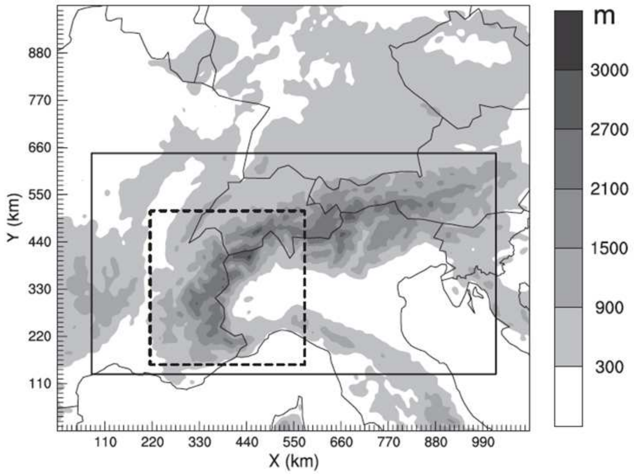
at the right place, at the right time

bulk feedbacks to the larger scale (radiation balance, heat and water vapor budget, precipitation, ...)

Bulk convergence

"Good numerical and physical convergence of bulk (averaged over a large control volume centered over the Alps) properties of an ensemble of moist convective cells in kilometer-scale simulations "

Langhans et. al (2012)



Langhans et al. (2012)

- *Numerical convergence*: considers an increasingly resolved numerical representation of a fixed set of equations
- *Physical convergence*: insensitivity of flow statistics with respect to both grid spacing and flow physics
- *External convergence*: includes the influence of better-resolved external parameters (topography, soil variables, …) at higher resolution

Bulk convergence

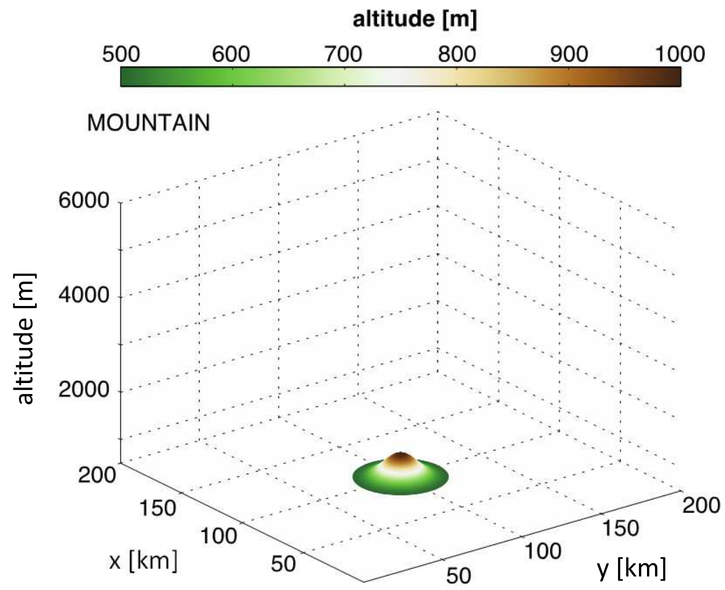
Overarching goal

Understand the bulk convergence behavior of convection-resolving simulations with respect to the feedbacks of summertime deep convection over land

Key questions:

- How does the representation of mass, moisture, temperature and momentum fluxes across various horizontal resolutions influence the distribution of precipitation, cloud cover and the radiative balance?
- Which physical processes and parameterizations yield better convergence properties? Does complex terrain (mountains) improve bulk convergence?

Idealized simulations



Basic setup

- Diurnal cycle of convection over land (Schlemmer et al. 2012)
- **COSMO v5.0** @ Δx = 4, 2, 1 km and 500 m
- Domain 200 x 200 km^2
- Run for 6 days, consider last 5 days for analysis
- Interactive soil model and radiation scheme
- Explicit convection, hybrid 1D TKE-based/2D Smagorinsky turbulence parameterization

Experiments

CTRL: control run, standard case with no background wind (+ensemble)

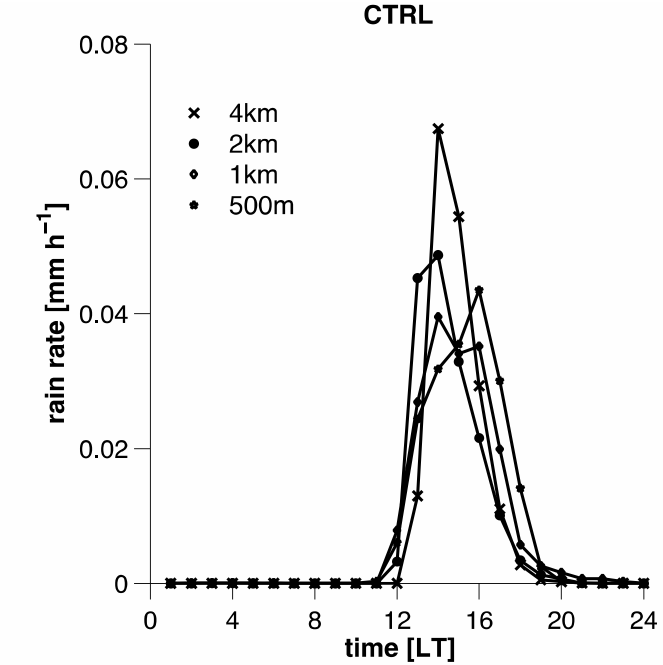
WIND: CTRL + background wind (Schlemmer et al. 2012)

MOUNTAIN: CTRL + 500-m 3D gaussian hill

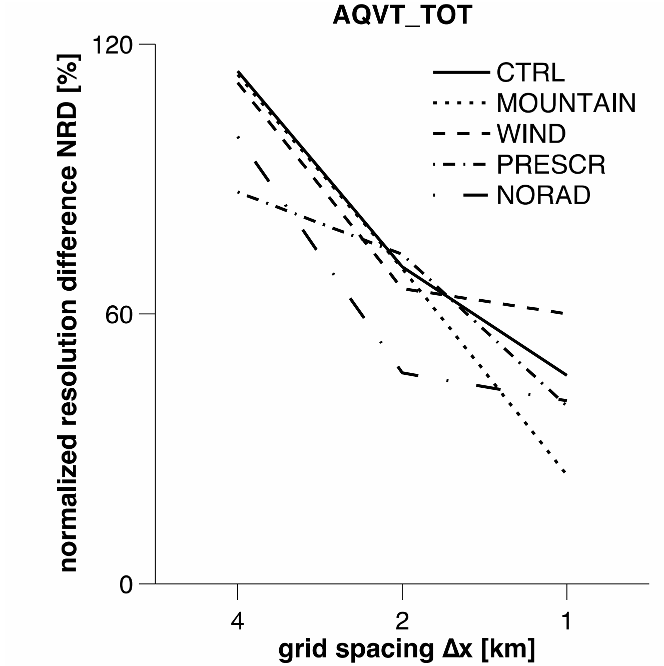
PRESCR: CTRL - land-surface scheme (prescribed surface fluxes)

NORAD: PRESCR - radiation scheme (prescribed cooling of 2.5K/day)

Surface precipitation

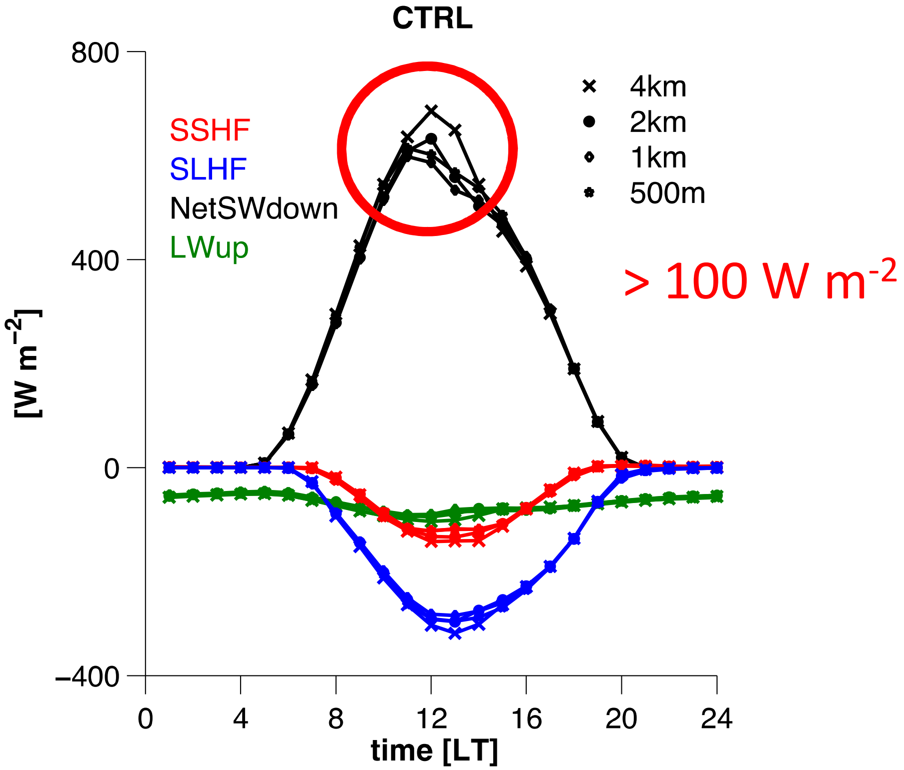


$$NRD = \frac{RMSD_{\Delta x}}{\sigma_{500}} = \frac{\sqrt{\frac{1}{N}\sum_{n=1}^{N}\left[\psi_{\Delta x}(n) - \psi_{\Delta x/2}(n)\right]^2}}{\frac{1}{N}\sum_{n=1}^{N}\left|\psi_{500}(n)\right|}$$



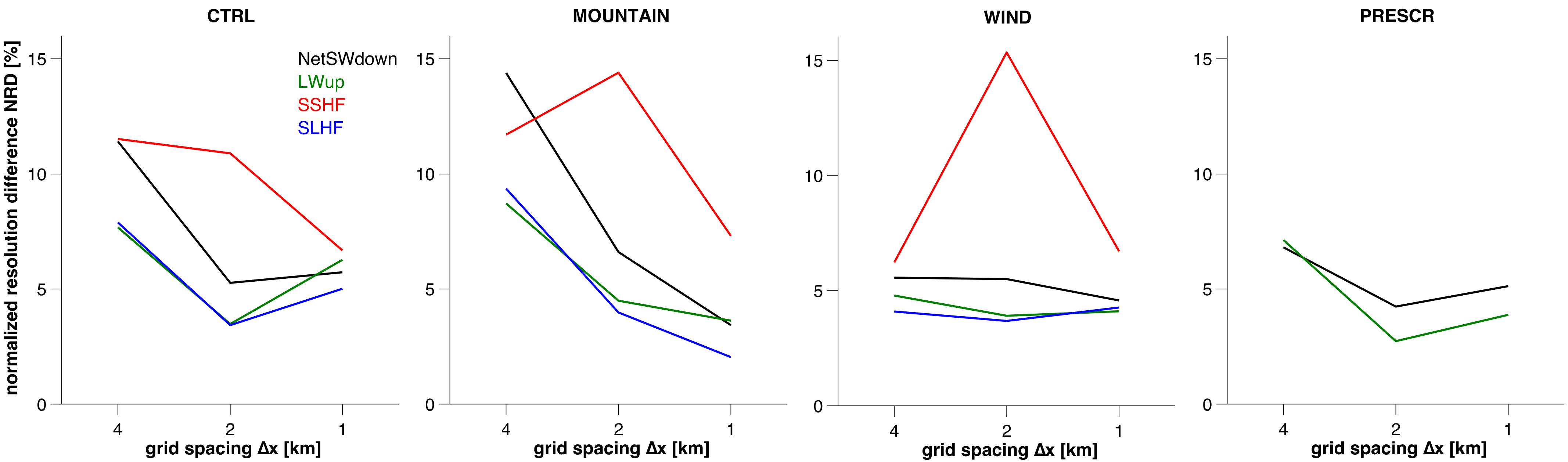
- *All simulations show physical convergence*
- *MOUNTAIN shows higher degree of convergence*
- *WIND and NORAD: worse behavior after Δx = 2 km*

Surface radiation balance



currently under investigation…

Surface radiation balance



- *MOUNTAIN only physically convergent setup (except for SSHF)*
- *No significant improvement in PRESCR compared to CTRL*

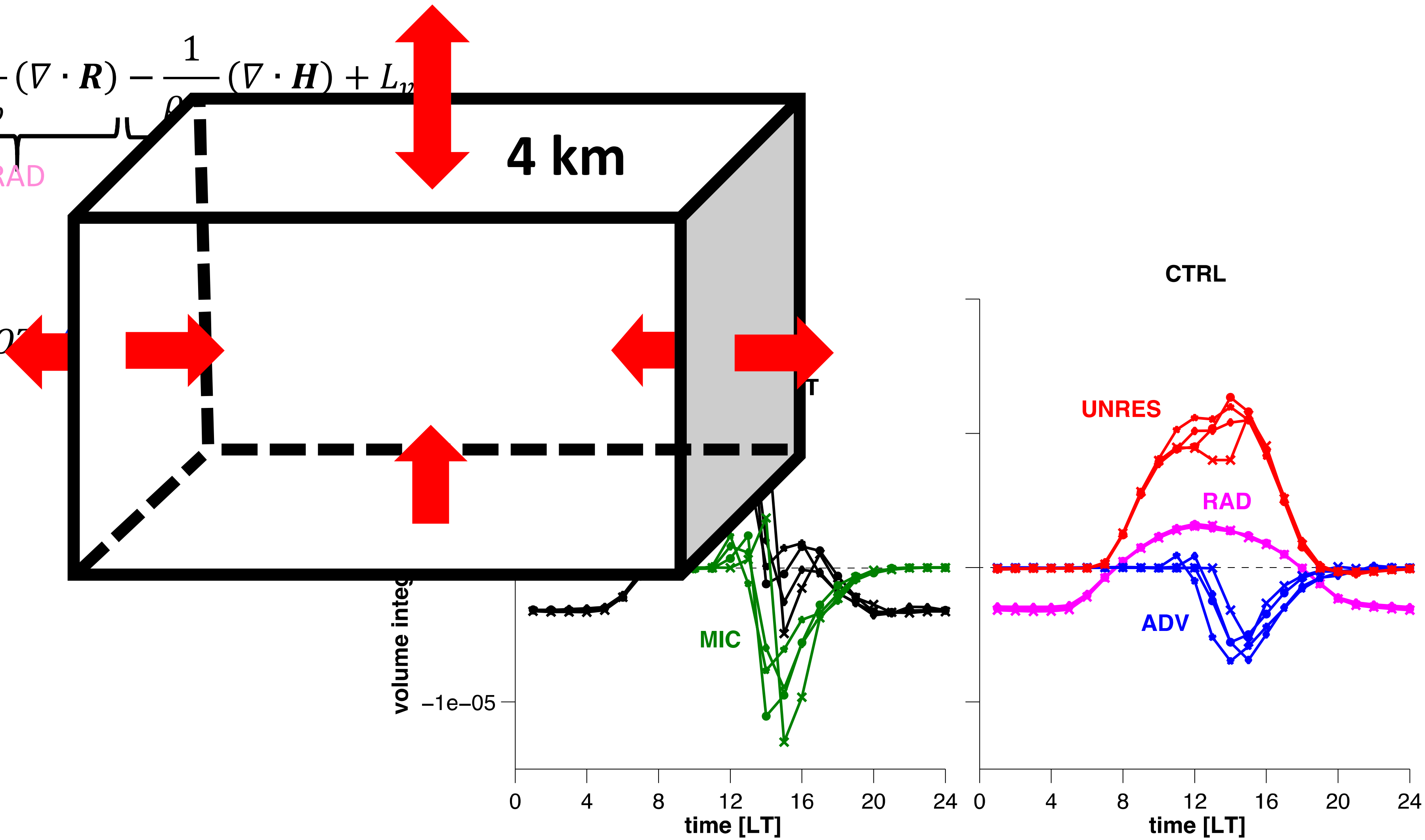
Bulk heat tendencies

$$\frac{\partial\theta}{\partial t} = -\mathbf{v}\cdot\nabla\theta - \frac{1}{\rho c_p}(\nabla\cdot\boldsymbol{R}) - \frac{1}{\rho \ldots}(\nabla\cdot\boldsymbol{H}) + L_v \ldots$$

TOT ADV RAD

$$\boldsymbol{H} = \rho c_p \overline{\boldsymbol{v}''\theta''}$$

$$\frac{1}{M}\int_V \rho\chi\, dV, \chi = TO\ldots$$

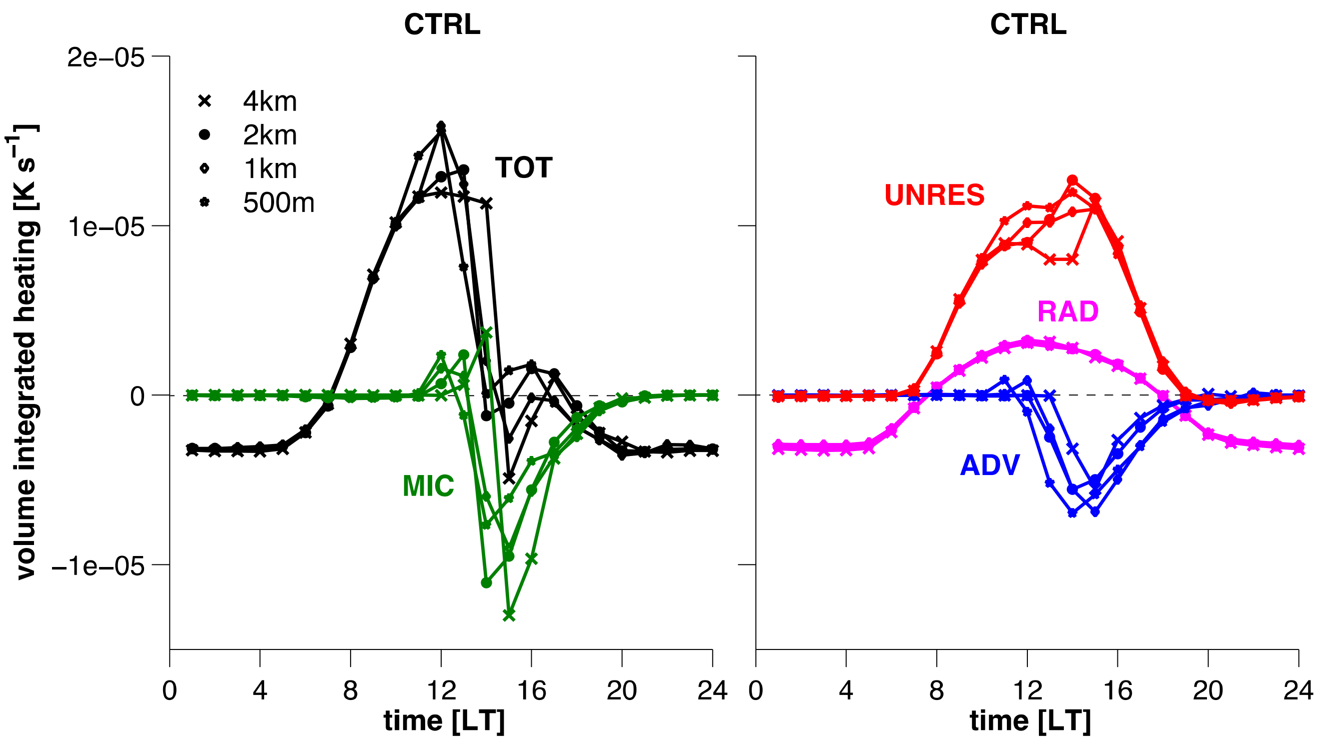


Bulk heat tendencies

$$\underbrace{\frac{\partial\theta}{\partial t}}_{\text{TOT}} = \underbrace{-\mathbf{v}\cdot\nabla\theta}_{\text{ADV}} \underbrace{-\frac{1}{\rho c_p}(\nabla\cdot\boldsymbol{R})}_{\text{RAD}} \underbrace{-\frac{1}{\rho c_p}(\nabla\cdot\boldsymbol{H})}_{\text{UNRES}} + \underbrace{L_v}_{\text{MIC}}$$

$$\boldsymbol{H} = \rho c_p \overline{\boldsymbol{v}''\theta''}$$

$$\frac{1}{M}\int_V \rho\chi\, dV, \chi = TOT, ADV, \ldots$$

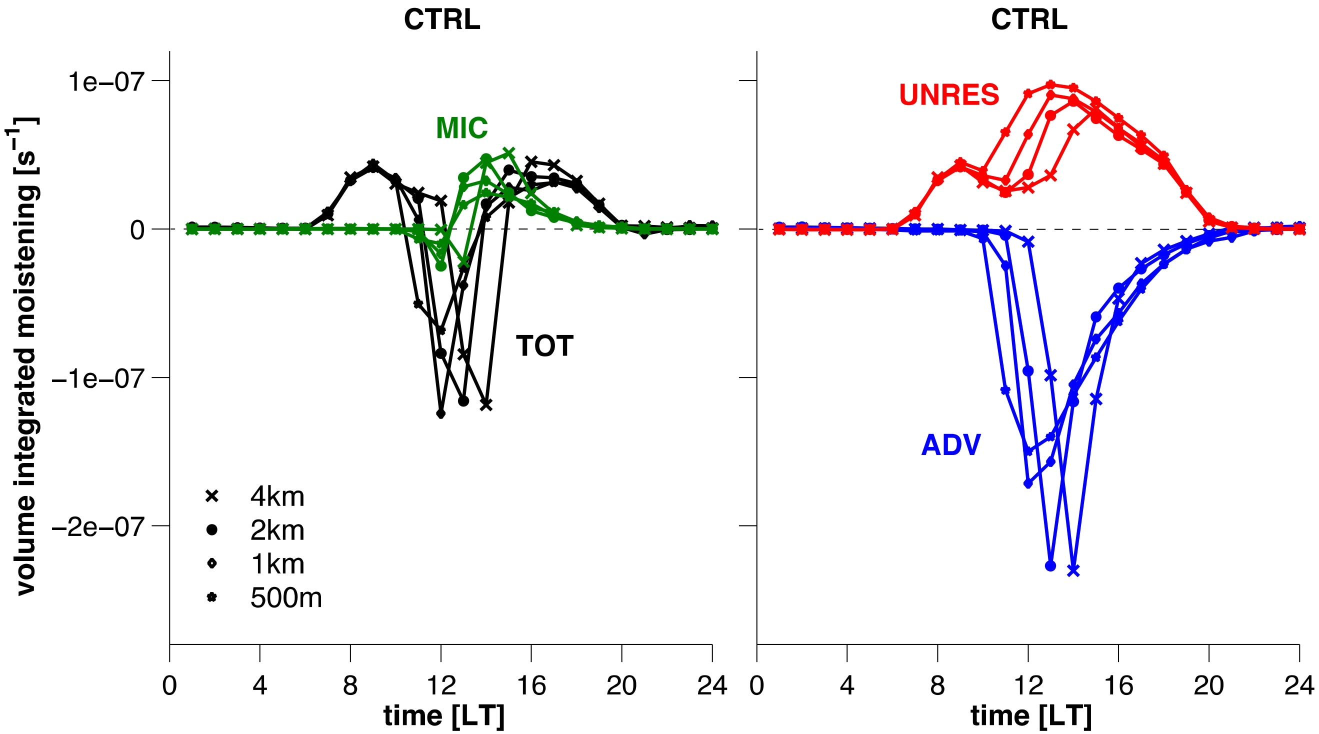


Bulk water vapor tendencies

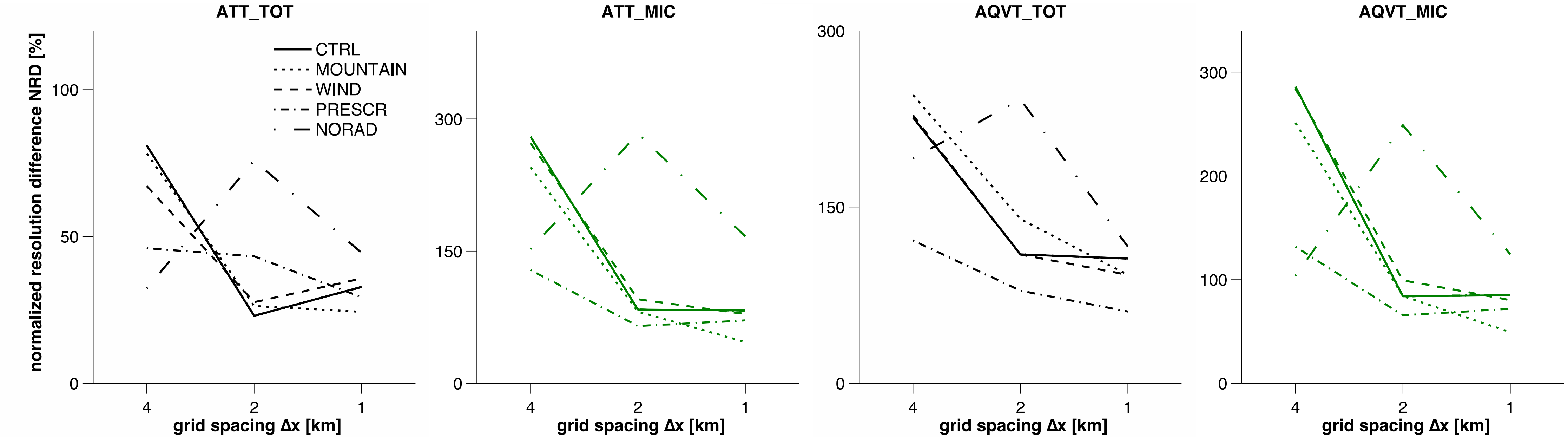
$$\underbrace{\frac{\partial q_v}{\partial t}}_{\text{TOT}} = \underbrace{-\mathbf{v}\cdot\nabla q_v}_{\text{ADV}} \underbrace{- \frac{1}{\rho l_v}(\nabla\cdot\boldsymbol{L})}_{\text{UNRES}} + \underbrace{S_v}_{\text{MIC}}$$

$$\boldsymbol{L} = \rho l_v \overline{\boldsymbol{v}'' q_v''}$$

$$\frac{1}{M}\int_V \rho\chi\, dV,\ \chi = TOT, ADV, \ldots$$



Bulk heat and water vapor tendencies



- *ADV and UNRES grid-dependent by definition*
- *MOUNTAIN only physically convergent setup for ATT_TOT*
- *Overall better performance for AQVT*
- *NORAD bad convergence behavior*

Preliminary conclusions

- Although domain-averaged precipitation shows convergence for all simulations, the same does not hold for surface radiation balance and domain-averaged heat and moisture tendencies.

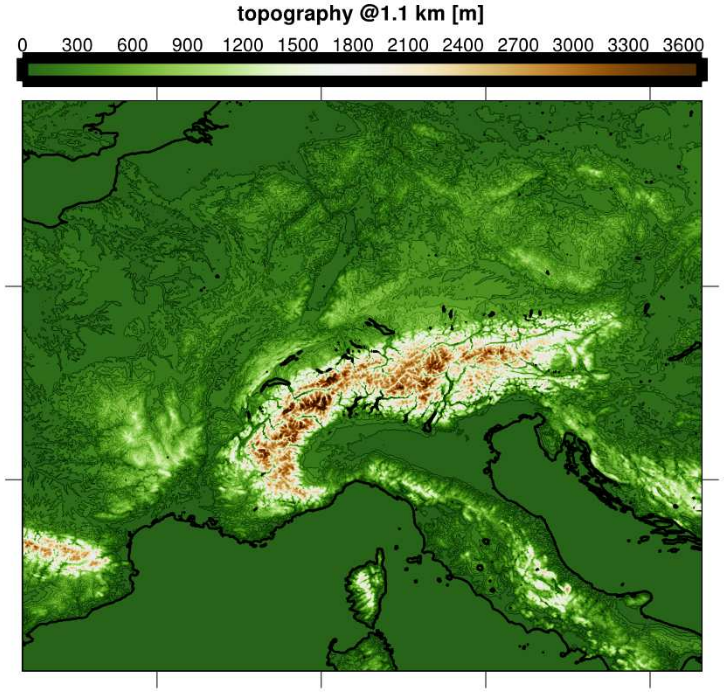
- The presence of orography improves the convergence behavior in CRM simulations compared to runs with flat terrain only.

- Reducing the model complexity by switching off the land-surface and radiation schemes does not reduce or even increases the sensitivity to the model grid spacing in higher-resolution simulations.

Real-case simulations

Basic setup

- Domain 1100 x 900 km^2 (Langhans et al. 2012)
- **COSMO v5.0** @ Δx = 4.4, 2.2, 1.1 km and 550 m
- Soil initialized from 10-yr climate run at 12.2-km horizontal grid spacing (Ban et al. 2014)
- Initialized with and driven by 12.2-km run
- Explicit convection, hybrid 1D TKE-based/2D Smagorinsky turbulence parameterization



Surface data

GLOBE topography (1 km resolution)

GC2009 land cover (300 m resolution)

HWSD soil type (1 km resolution)

Raymond filter for topography (cutoff ~ 5 Δx)