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, Baldauf et al. 2011)

- 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)
Convection-resolving simulations

Two key issues:

(1) The ‘gray zone’ of convection

• Do we still need a (shallow) convection scheme?
• What is the best approach to parameterize turbulence?

(2) Diurnal cycle of convection over complex terrain

• Turbulence parameterizations not designed for mountainous terrain
• Important sensitivities to changes in turbulence parameterization over complex terrain (e.g. Panosetti et al. 2016)
Convergence

- **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

Langhans et al. (2012)
Convergence

“For deep organized convection, (physical) convergence of large-eddy simulations (LES) due to Reynolds-number similarity is not yet obtained at grid spacings $O(100 \text{ m})$”


“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)
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?

• Which spatial extent limits bulk convergence in simulations of deep convection over land?
Idealized simulations

Basic setup

- Diurnal cycle of convection over land (Schlemmer et al. 2012)
- **COSMO v5.0** @ $\Delta x = 4$, $2$, $1$ km and $500$ m
- Domain $200 \times 200$ 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. 2011)

**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)
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Surface precipitation

\[ NRI = \frac{RMSE_{\Delta x}}{\sigma_{500}} = \sqrt{\frac{1}{N} \sum_{\phi=1}^{N} \left[ \psi_{\Delta x}(\phi) - \psi_{\Delta x/2}(\phi) \right]^2} \]

\[ \frac{1}{N} \sum_{\phi=1}^{N} |\psi_{500}(\phi)| \]

- All simulations show physical convergence
- MOUNTAIN shows higher degree of convergence
- WIND and NORAD: worse behavior after \( \Delta x = 2 \) km
Surface radiation balance

> 100 W m$^{-2}$

Currently under investigation...
• **MOUNTAIN** physically convergent setup (except for SSHF)
• Not a significant improvement in **WIND** and **PRESCHR** compared to **CTRL**
Bulk heat tendencies

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

Langhans et al. (2012)
Bulk heat tendencies

- ADV and UNRES scale-dependent by definition
- No physical convergence for RAD
- MOUNTAIN only physically convergent setup for TOT and MIC
Bulk water vapor tendencies

\[ \frac{\partial q_v}{\partial t} = -\mathbf{v} \cdot \nabla q_v - \frac{1}{\rho l_v} (\nabla \cdot \mathbf{L}) + S_v \]

\[ \mathbf{L} = \rho l_v \nabla'' q_v'' \]

\[ \frac{1}{M} \int_V \rho \chi \, dV, \chi = TOT, ADV, UNRES, MIC \]

Langhans et al. (2012)
Bulk water vapor tendencies

- Overall better performance compared to other statistics
- MOUNTAIN shows slightly better convergence behavior
- NORAD worse behavior than CTRL
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 km² (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 (Leutwyler et al. 2016)
• Initialized with and driven by 12.2-km run (Leutwyler et al. 2016)
• 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)