Bulk convergence of kilometer-scale simulations of moist convection over complex terrain

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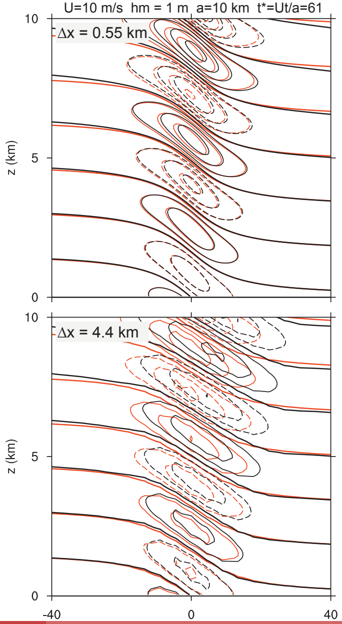
Convergence

Numerical convergence

- Limiting ($\Delta x \rightarrow 0$) behavior of discretization scheme
- Equivalently provided by consistency and stability (Lax and Richtmyer 1956)
- Consistency: In this limit numerical scheme provides solution to the continuous problem



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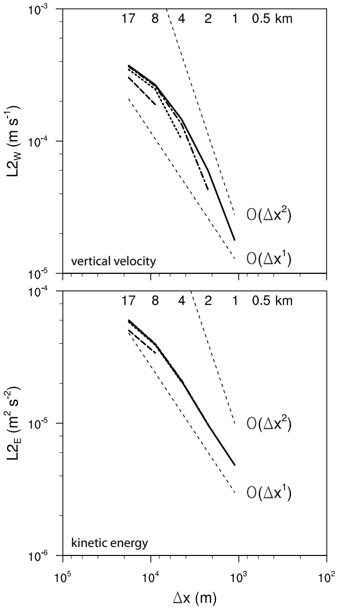


Convergence

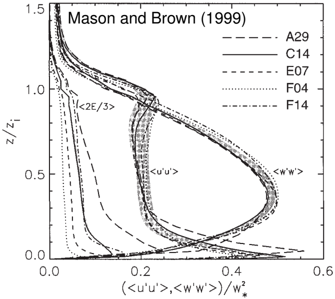
Physical convergence

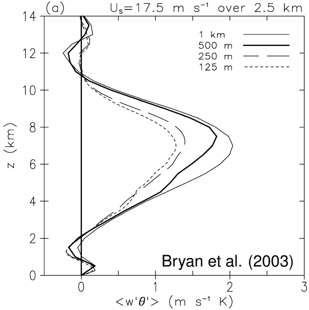
- Insensitivity to grid-spacing *and* modified physics
- Convergence as a result of Reynolds-number similarity

Cloud-resolving modeling

- Horizontal grid-spacing of 1/4 SCL suggested (Petch et al. 2002)
- Lack of convergence found for idealized LES of organized convection (Bryan et al. 2003)
- Subgrid-mixing closures not primarily designed for *O*(1 km)

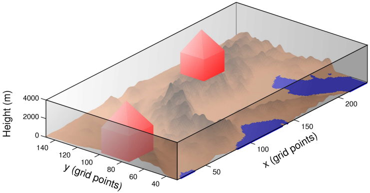
(Wyngaard 2004)



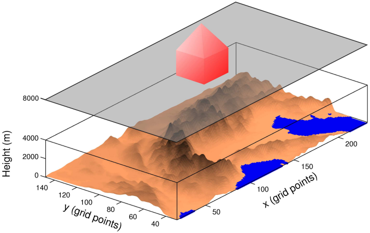


Objectives

- Interest: Numerical and physical convergence of real kilometer-scale simulations
- Process: Locally triggered deep orographic convection
- Parameter: Regional-scale/bulk properties
- Issue: Turbulence closure at kilometer-scales



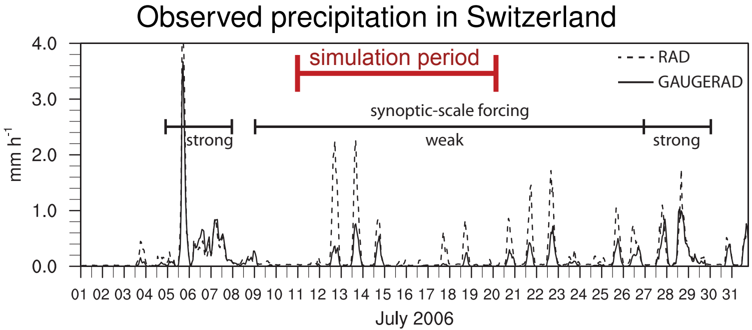
Indicator 1: Heat budget of volume



Indicator 2: Deep-convective fluxes

Methods

Simulation period



- 9-day simulation period
- Weak synoptic-scale forcing
- ECMWF 6-hourly LBC and IC for 0000 UTC 11 July

Nonhydrostatic COSMO model

Dynamics:

- split-explicit RK-3 scheme (Wicker and Skamarock 2002)
- 5th-order advection,
  2nd-order Bott q_x advection

Grid:

Δx (km)	4.4	2.2	1.1	0.55
Δt (s)	30	15	8	4
N (10^6)	3	10	41	166

- Topography: Constant cut-off at $\lambda_c \simeq 20$ km

Physics:

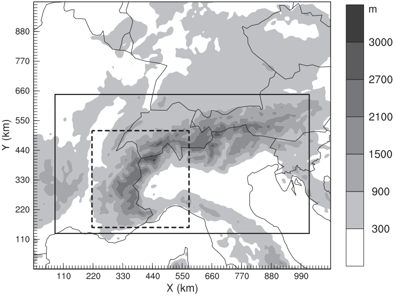
- No convection scheme
- One-moment microphysics incl. graupel
- **Mixing (1):** 1D TKE-based (mesoscale)

  $K_v = S\, l\, (2\bar{e})^{1/2}$
  $K_h = (c_s \Delta x)^2 (0.25(D_{11} - D_{22})^2 + D_{12}^2)^{1/2}$

- **Mixing (2):** Smagorinsky-Lilly (LES)

  $K_{h,v} = l^2 (|D|^2 (1 - \frac{\mathrm{Ri}}{\mathrm{Ri}_{cr}}))^{1/2}$
  $l = c_s (\Delta x \Delta y \Delta z)^{1/3}$

  (COSMO-LES tested for CBL/NBL)



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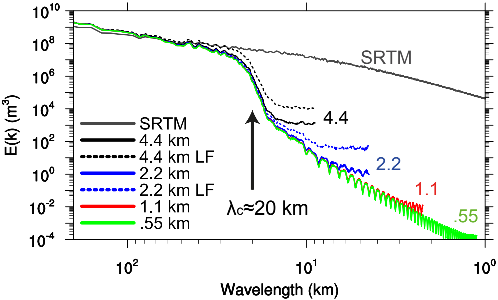
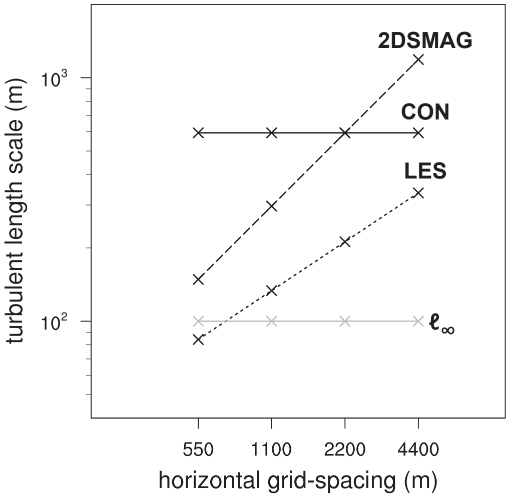


Simulation overview

Turbulent length scales



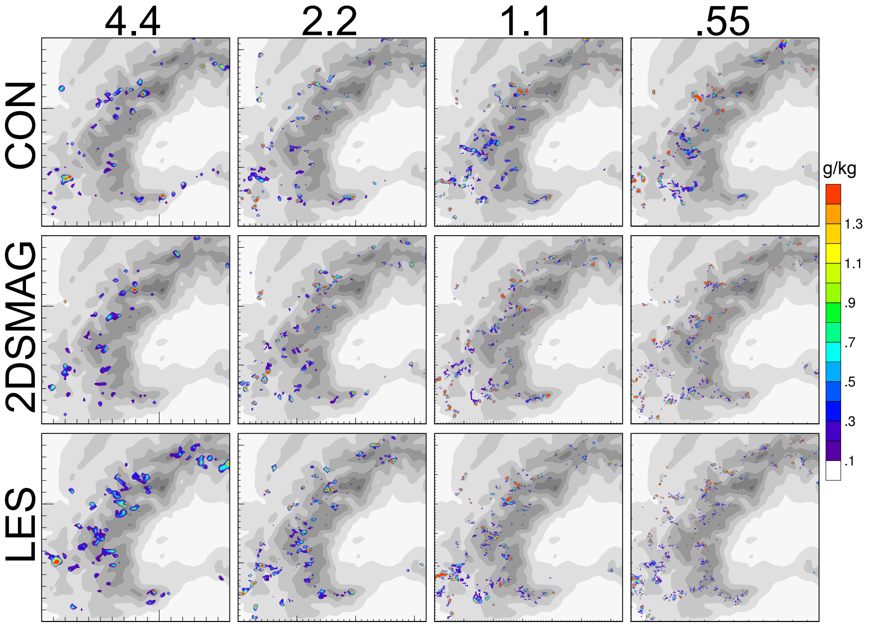
Mixing(1) $l_h \sim \Delta x$

Mixing(1) $l_h = const$

Mixing(2) $l_{h,v} \sim \Delta x^{2/3}$

used with Mixing(1)

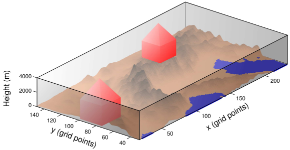
Realization of deep convection



Alpine Heat Budget

Volume-averaged density-weighted budget (Schmidli and Rotunno 2010)

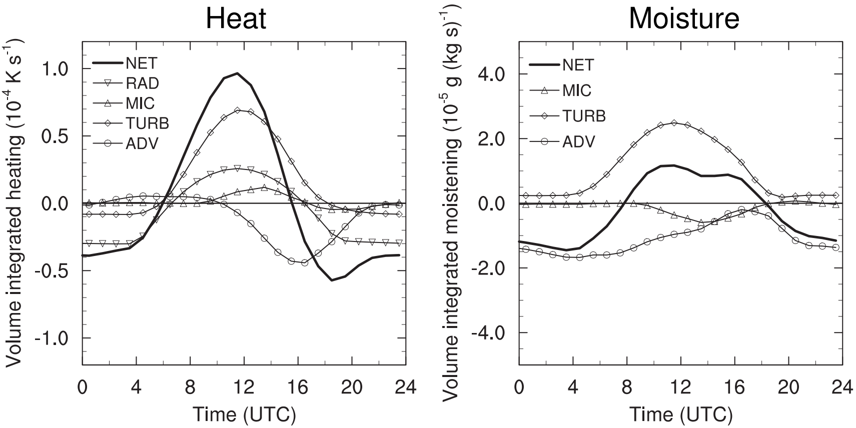
$$\underbrace{\frac{1}{M}\int_V \rho\frac{\partial\theta}{\partial t}dV}_{A} = \underbrace{-\frac{1}{M}\int_V \rho\mathbf{v}\cdot\nabla\theta dV}_{B} + \underbrace{\frac{1}{M}\int_V -\frac{1}{c_p}(\nabla\cdot\mathbf{R})dV}_{C} + \underbrace{\frac{1}{M}\int_V -\frac{1}{c_p}(\nabla\cdot\mathbf{H})dV}_{D} + \underbrace{\frac{1}{M}\int_V \rho L_{v,f}dV}_{E}$$



Convergence of a consistent set

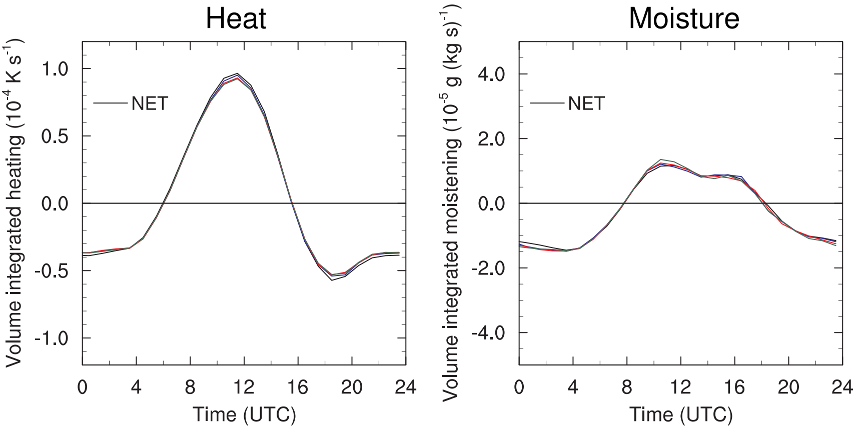
Volume-integrated tendencies

All tendencies
CON 4.4



Volume-integrated tendencies

Net tendencies
CON 4.4 2.2 1.1 0.55



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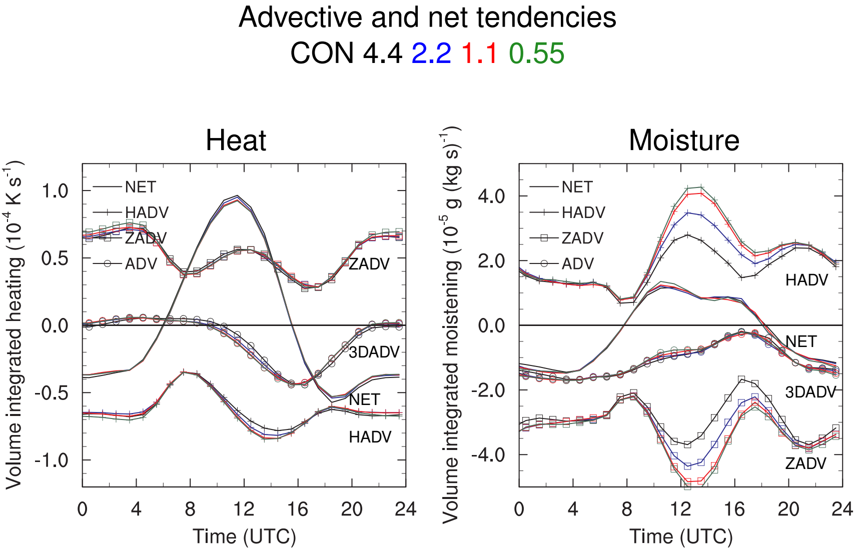
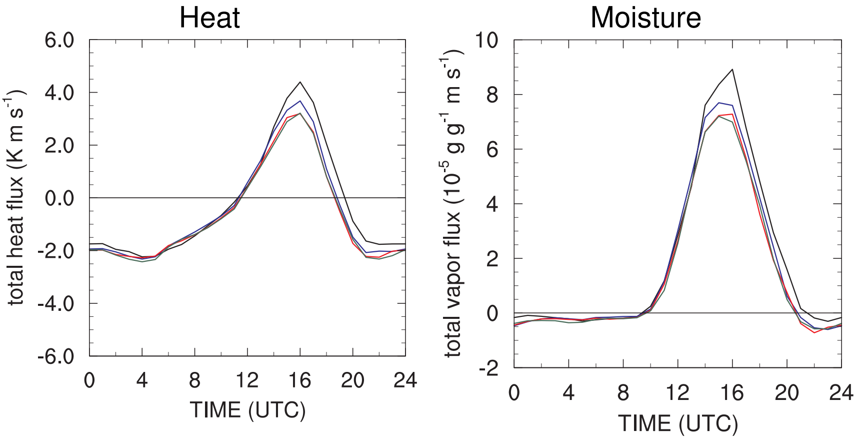


Total deep convective flux (z=6 km)

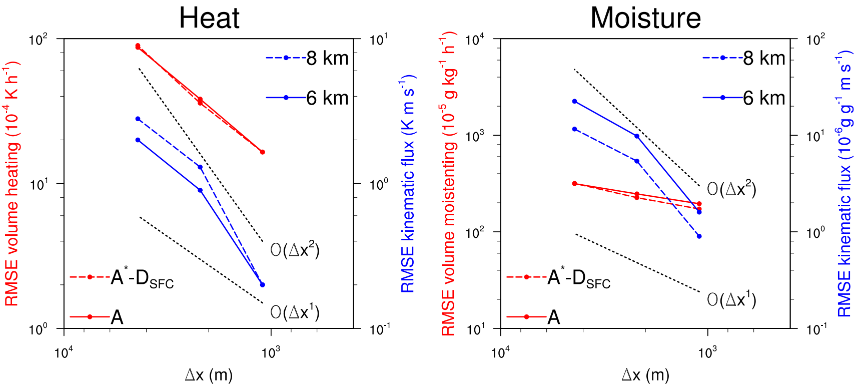
CON

4.4 2.2 1.1 0.55



Numerical convergence (CON)

RMSE of mean diurnal cycle



Effects of viscosity

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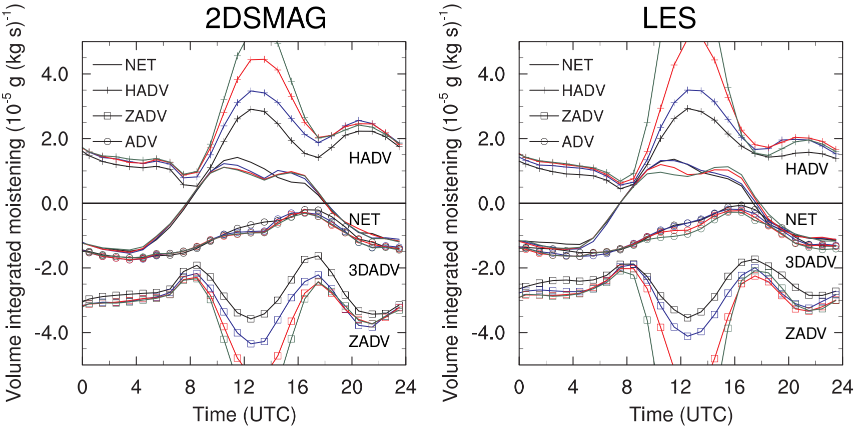
Advective and net moisture tendencies

4.4 2.2 1.1 0.55



Effects of viscosity

Diabatic tendencies

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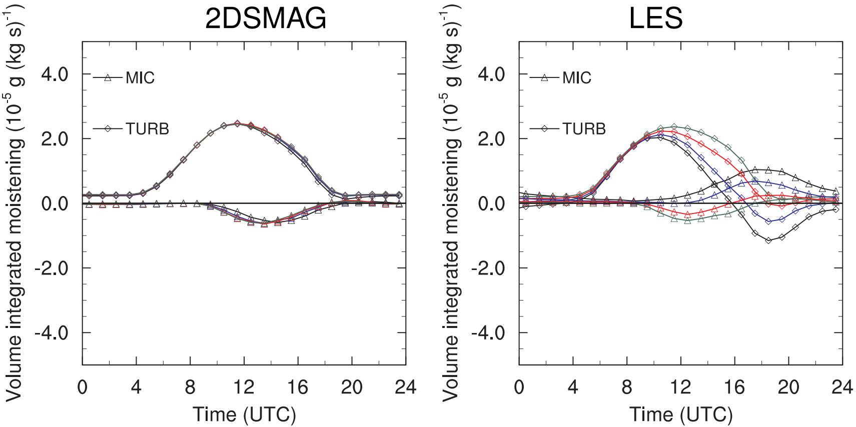
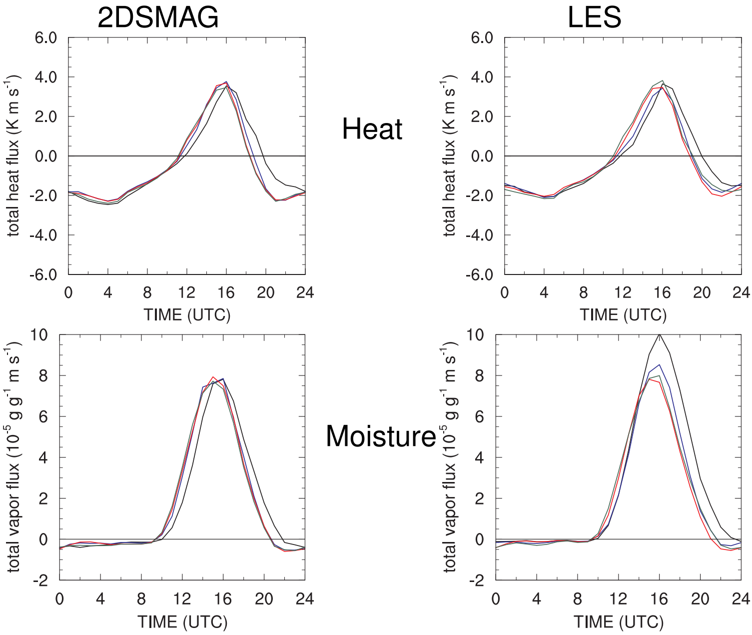
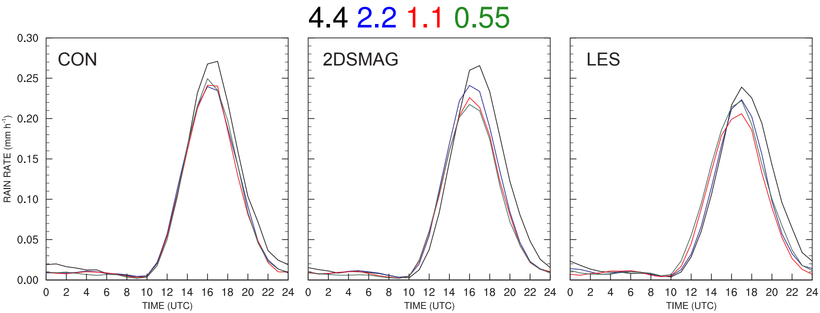


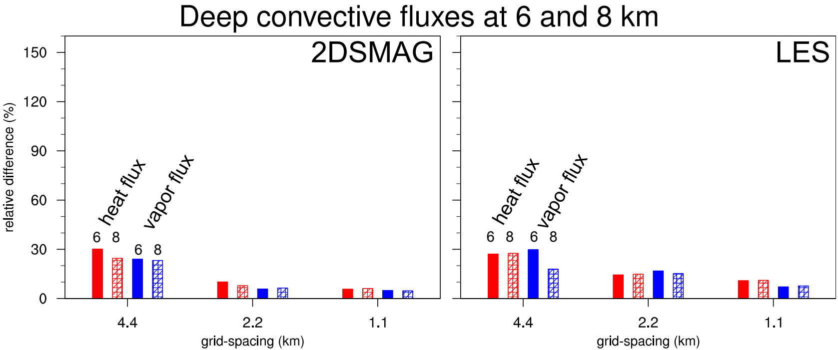
Total deep convective flux



Surface precipitation



Relative difference



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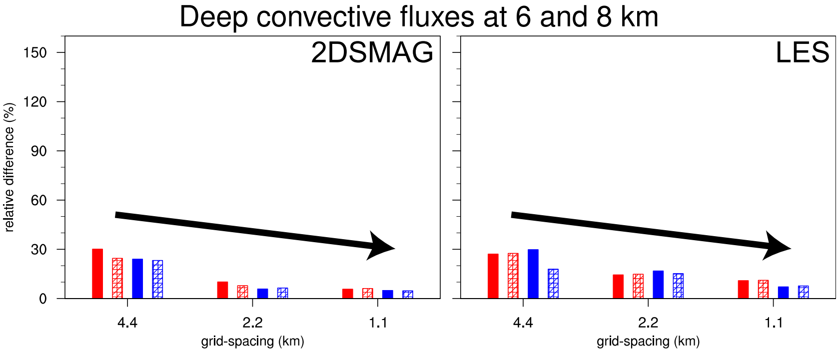

Summary

- Convergence of bulk properties in real-case simulations (4.4, 2.2, 1.1, 0.55 km) has been analyzed
- **Numerical convergence** of bulk deep convective heat/moisture fluxes is of $\sim 2^{\mathrm{nd}}$ order
- Volume (PBL) integrated heating/moistening converges at a slower rate
- **Physical convergence** of deep convection is found independently of the applied turbulence closures ($\sim$ 10 %)
- LES closure results in larger grid-sensitivity of the PBL to FA exchange
- Still, the link between net bulk PBL heating/moistening and grid-spacing appears weak (balance)

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Thanks for your attention!

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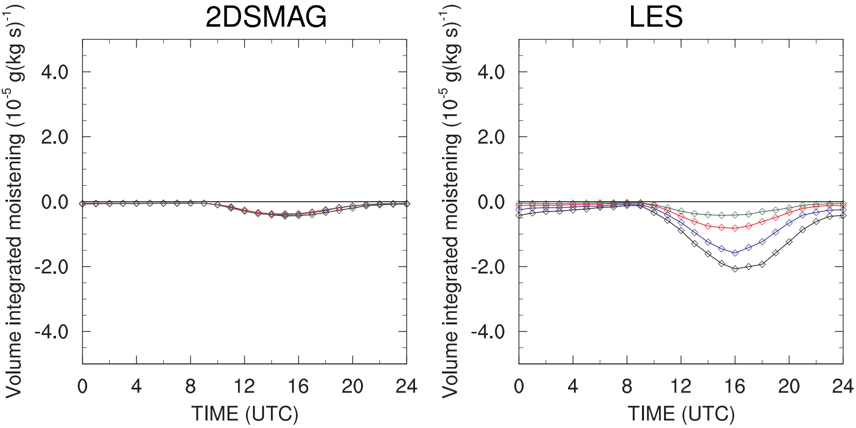
SGS vapor transport through volume top

4.4 2.2 1.1 0.55



Total vapor transport through volume top

4.4 2.2 1.1 0.55