Max-Planck-Institut für Meteorologie

Hans-Ertel-Zentrum für Wetterforschung
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Toward a stochastic parameterization of shallow convection for weather and climate models

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joint work with Mirjana Sakradzija and Thijs Heus

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A few reasons for stochastic parameterizations

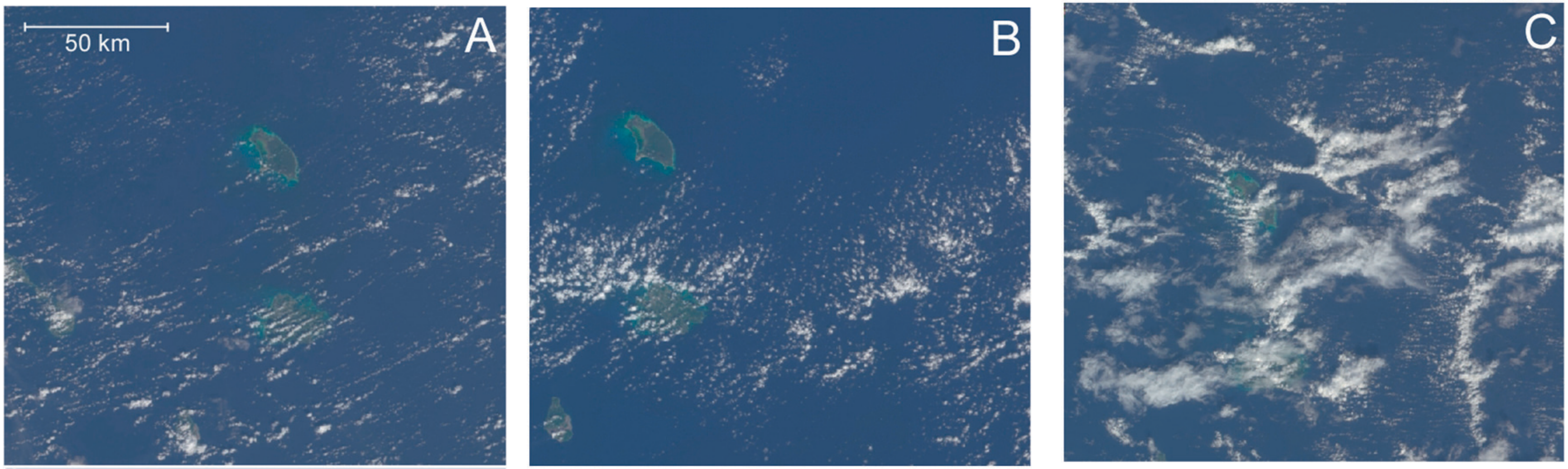
- Ensemble spread in convective-scale NWP, e.g., for DWD‘s COSMO-DE EPS at 2-3 km grid spacing.
- Scale adaptivity for models with varying mesh size, e.g., the new ICON model of DWD and MPI-M.
- Parameterization problems like non-equilibrium behavior of convection, self-organization, lack of scale separation etc.

Shallow convection

- Shallow convection is important due to it contribution to cloud cover, vertical moisture transport and, in some regions, surface precipitation.
- The trades are the natural and ideal environment for shallow convection.
- But they are also important in mid-latitudes, e.g., in post-frontal situations
- Shallow convection (including congestus) can prepare the environment for deeper modes of convection.

(Picture by Bjorn Stevens)

Mesoscale cloud patterns of trade wind cumulus



Typical cloud mesoscale organization: (a) wind-parallel cloud streets, (b) small cumulus clusters, and (c) cumulus clusters along propagating cold pools (from Snodgrass et al. 2009).

Can stochastic methods help to simulate such cloud regimes better?

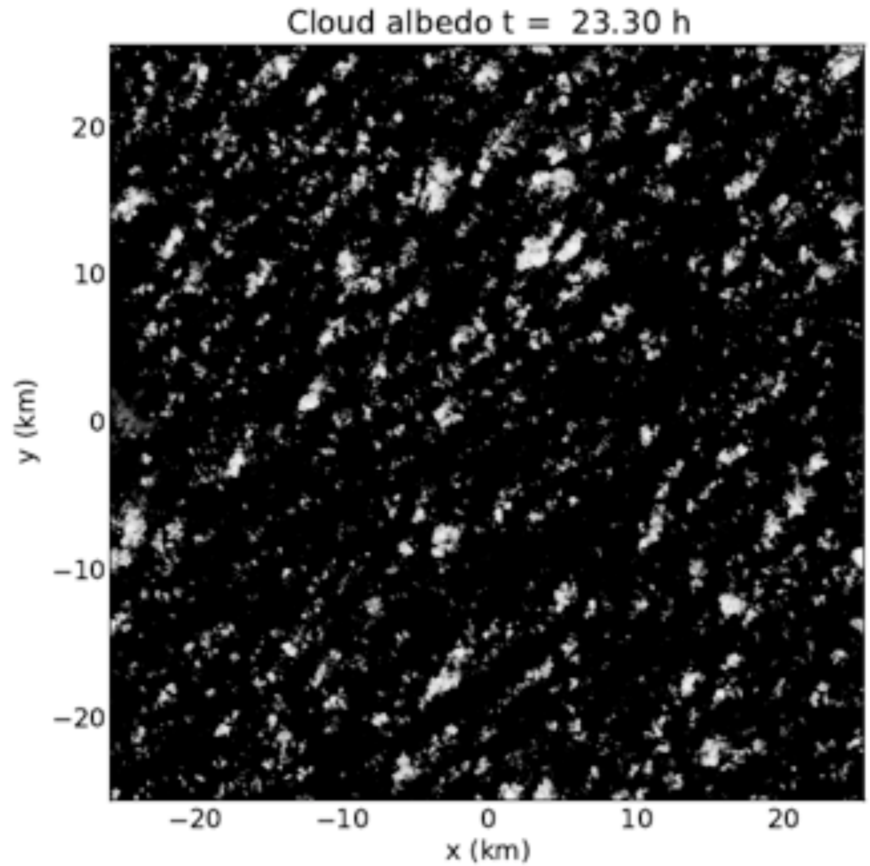
Outline

- Large-eddy simulation of precipitating shallow cumulus
- Tracking of clouds and the cloud size distribution
- Stochastic parameterization similiar to Plant-Craig
- The problem of mesoscale organization
- Parameterization of rain formation
- Outlook

LES of shallow convection

LES simulation can reproduce the observed features:

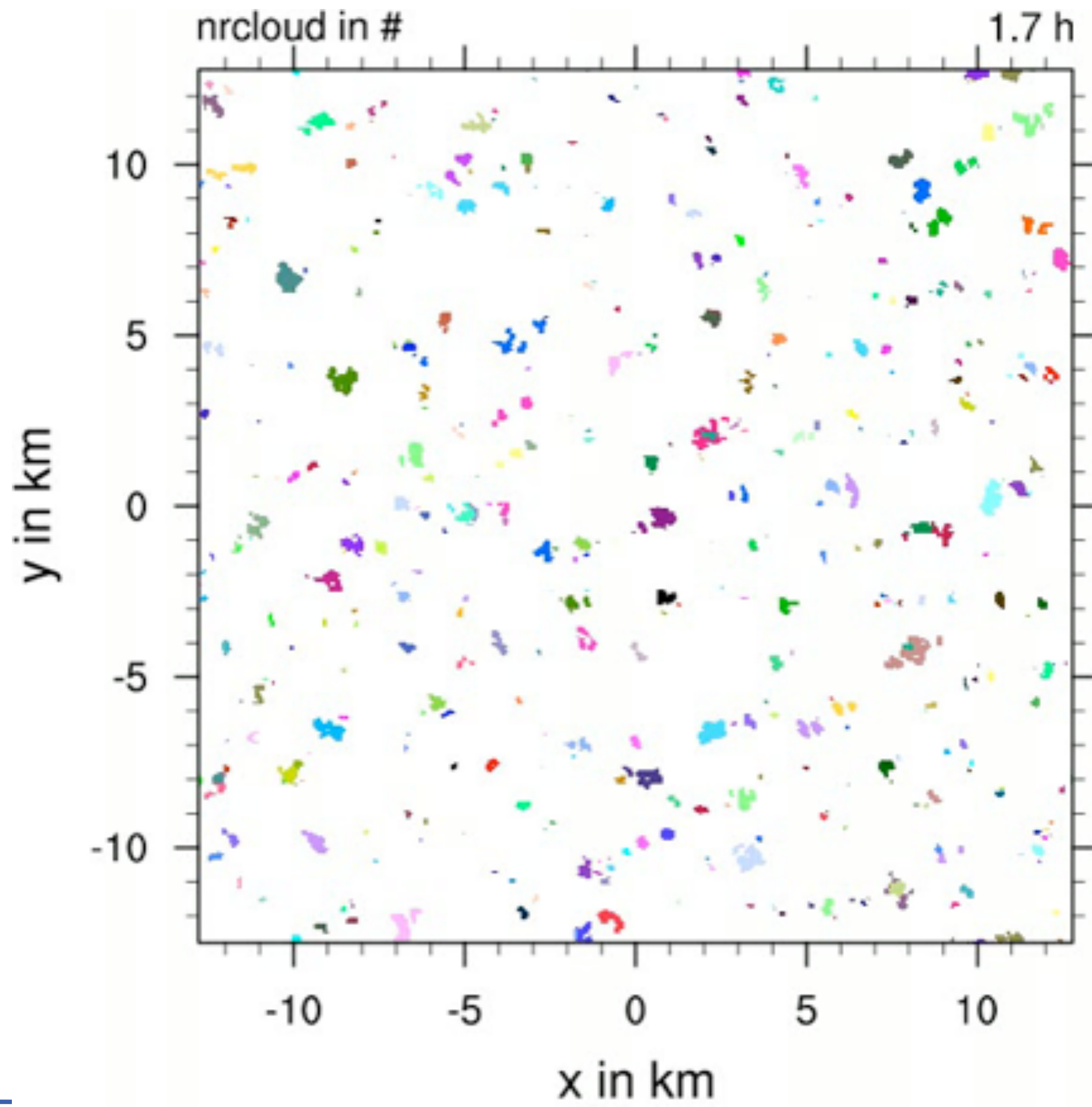
- clouds of various sizes which are randomly distributed in space
- thin ‚high‘ clouds from convective outflow.
- cloud tops are well below 3000 m height.
- precipitation rate stays below 1 mm/day



Standard RICO case of Stevens and Seifert (2008) on a 25 m isotropic grid with 25 km domain size (1024x1024x160 grid points). See also Seifert and Heus (2013, Atmos. Chem. Phys.)

2D Cloud Tracking

- Object identification based on liquid water path.
- Connectivity in space and time.
- Splitting of large clouds based on active clouds cores (buoyant updrafts).



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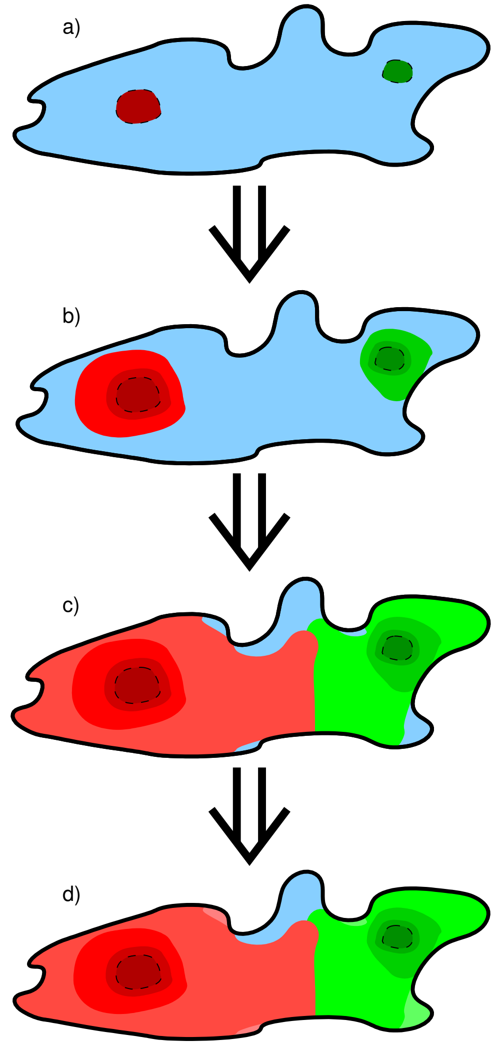

Find cloud cores within the cloud

.. successive region growing

.. successive region growing

... some part might be left over as „remnant“ because the jump in cloud base is too large.

Towards a stochastic cloud scheme

To derive a stochastic cloud parameterization we start from the cloud size distribution. Here $\ell = \sqrt{A}$ is a scalar cloud size defined as the square root of the projected area.

$n(\ell, t)d\ell$ — Number of clouds which exist at time t in the size range $[\ell, \ell + d\ell]$

$g(\ell_m, t)d\ell_m dt$ — Number of clouds generated in the time interval with a maximum dimension during the lifetime in the size range $[\ell, \ell + d\ell]$

From these distributions we can calculate the cloud cover, the total number of clouds or the cloud number rate:

$$C(t) = \int_0^\infty \ell^2 n(\ell, t)d\ell \qquad N(t) = \int_0^\infty n(\ell, t)d\ell$$

$$N_g(t_1, t_2) = \int_{t_1}^{t_2} \int_0^\infty g(\ell, t)d\ell dt \qquad \dot{N}(t) = \int_0^\infty g(\ell, t)d\ell$$

Cloud size distributions

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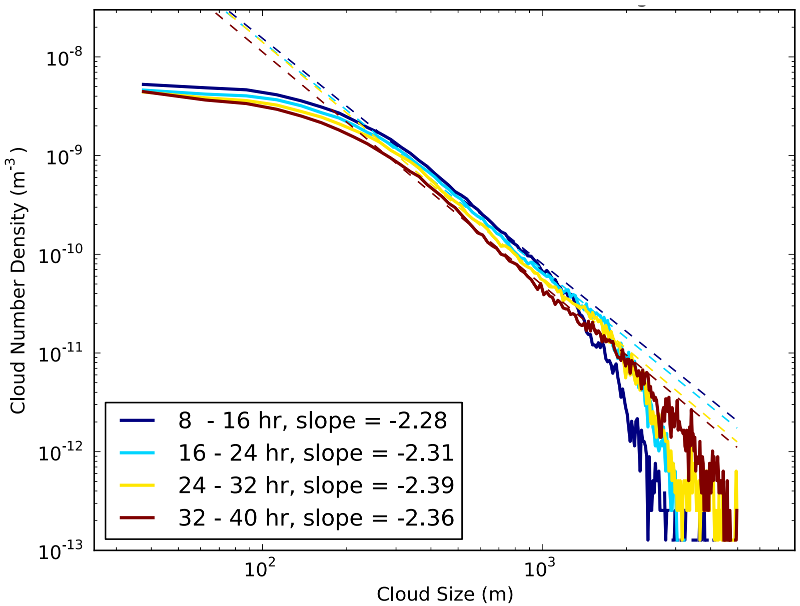
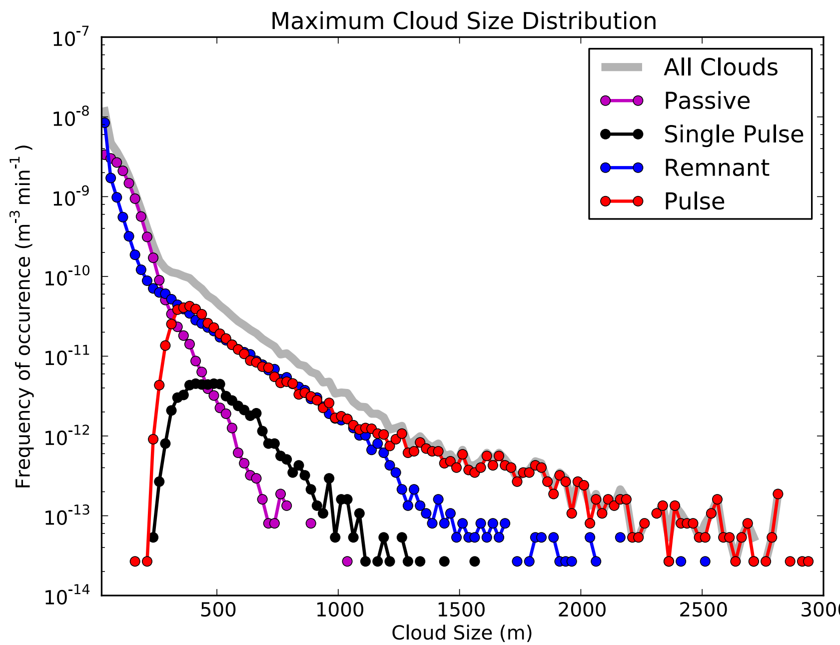


- Instantaneous cloud size distribution shows power law behavior. This agrees well with satellite observations.

- Generating cloud size distribution reveals exponential behavior consistent with results of Craig and Cohen (2006).



LES-based empirical relations

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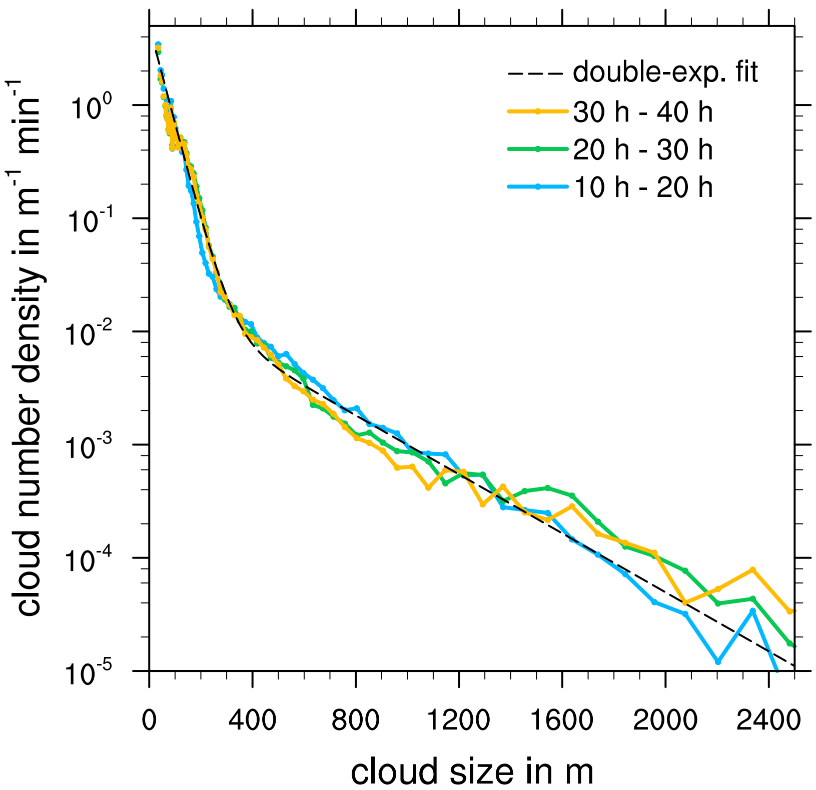
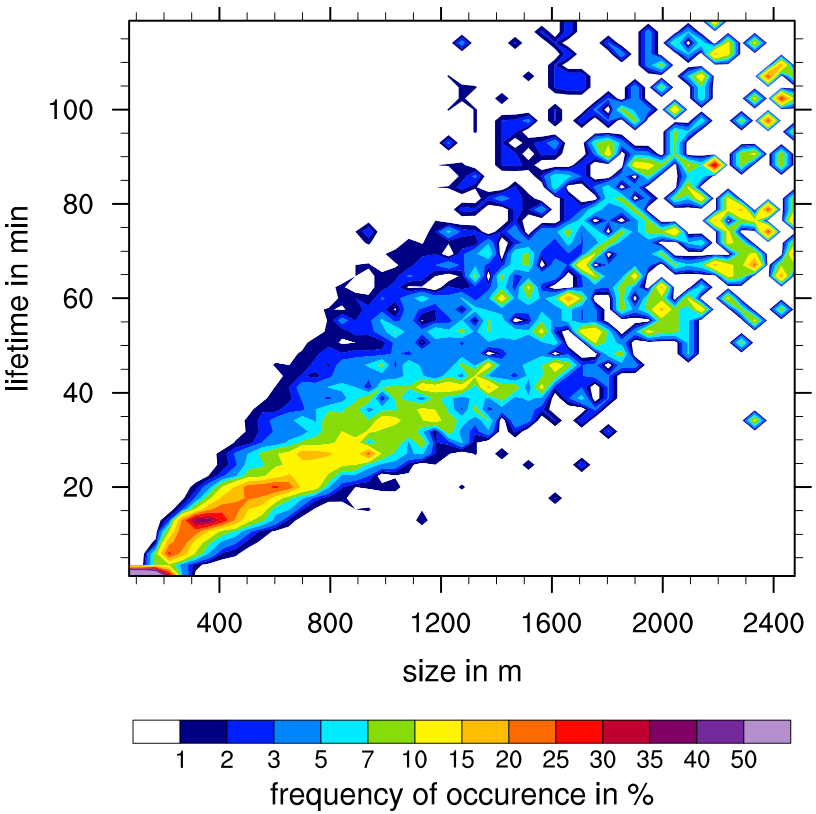
From the cloud tracking we get the necessary information like the cloud size distribution, cloud lifetime etc.:

cloud size distribution or cloud number rate



cloud lifetime as a function of cloud size



Microscopic stochastic parameterization

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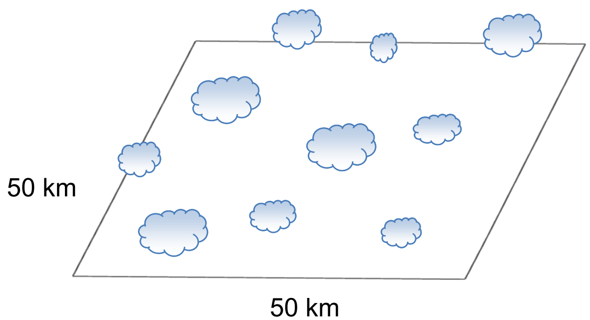
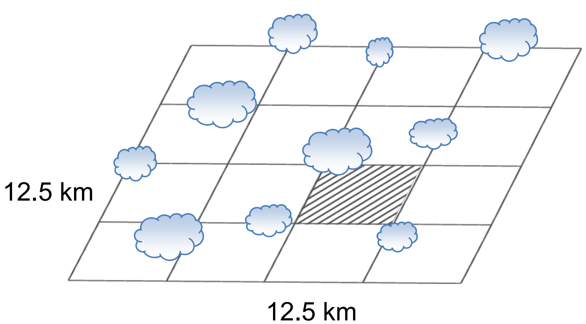
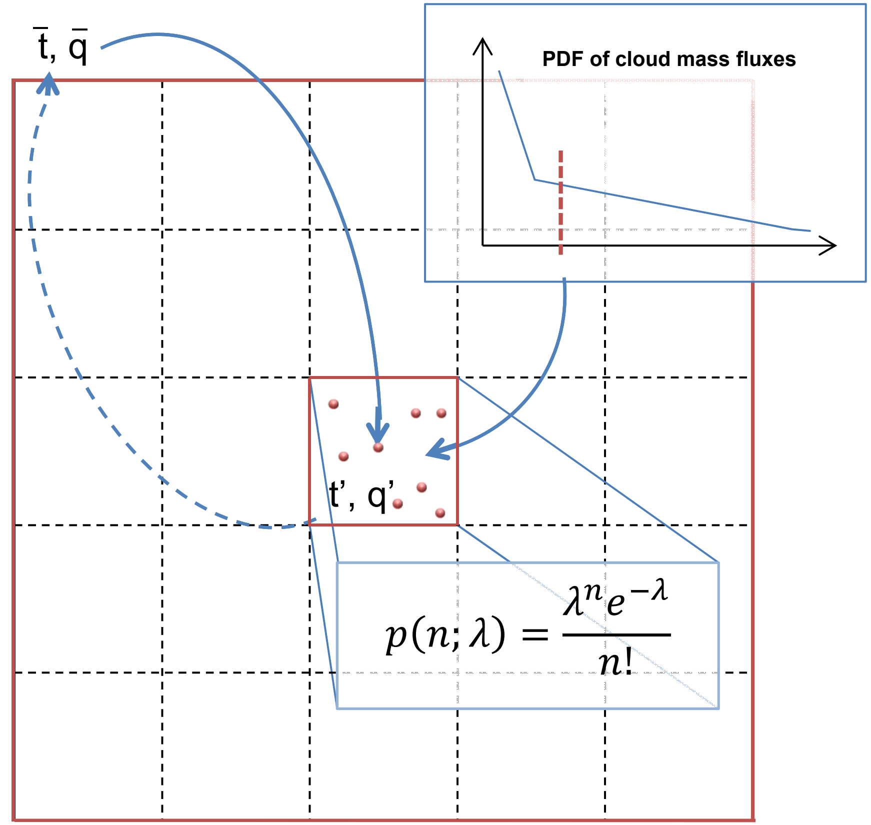
A large grid box contains many clouds, i.e., the full PDF:



a small grid box may contain only a few clouds:



As in the Plant-Craig stochastic convection scheme we define the PDF based on large-scale variables and sample the PDF in the small-scale grid box assuming a Poisson process:



Double-exponential distribution

For the double-exponential we find reasonably simple analytic relations between the ensemble mean ‚bulk' quantities and the parameters of the distribution, e.g.,

$$g(m) = \dot{N}_1 \frac{1}{\langle m_1 \rangle} e^{-\frac{m}{\langle m_1 \rangle}} + \dot{N}_2 \frac{1}{\langle m_2 \rangle} e^{-\frac{m}{\langle m_2 \rangle}}$$

$$\langle N \rangle = \alpha \Gamma(\beta + 1) \left(\dot{N}_1 \langle m_1 \rangle^\beta + \dot{N}_2 \langle m_2 \rangle^\beta \right)$$

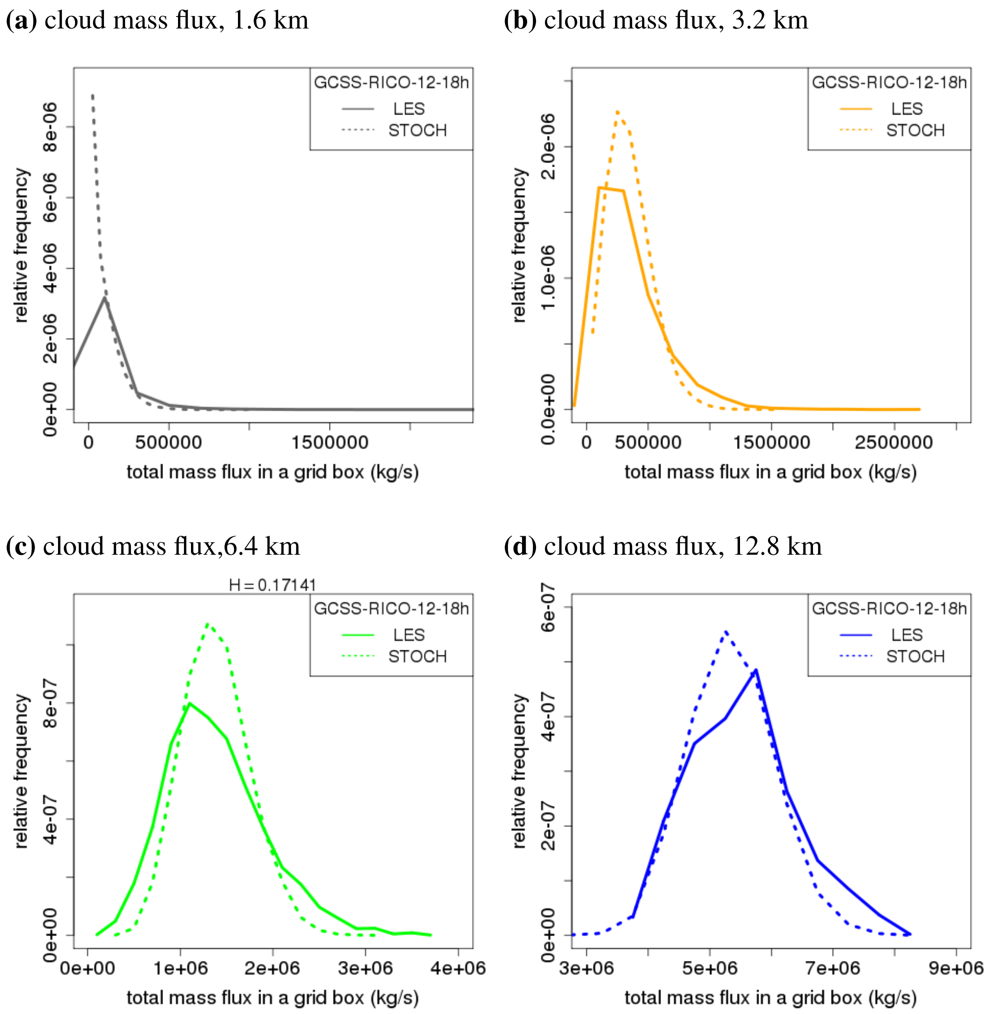
$$\langle C \rangle = \frac{\beta + 1}{\overline{w}_1 \rho} \langle N_1 \rangle \langle m_1 \rangle + \frac{\beta + 1}{\overline{w}_2 \rho} \langle N_2 \rangle \langle m_2 \rangle$$

Here the cloud lifetime is parameterized as a function of cloud mass flux by

$$\tau = \alpha m^\beta$$

Some results of this stochastic model

A main goal is to reproduce the PDF of mass fluxes on various grids:



Variance as function of grid size

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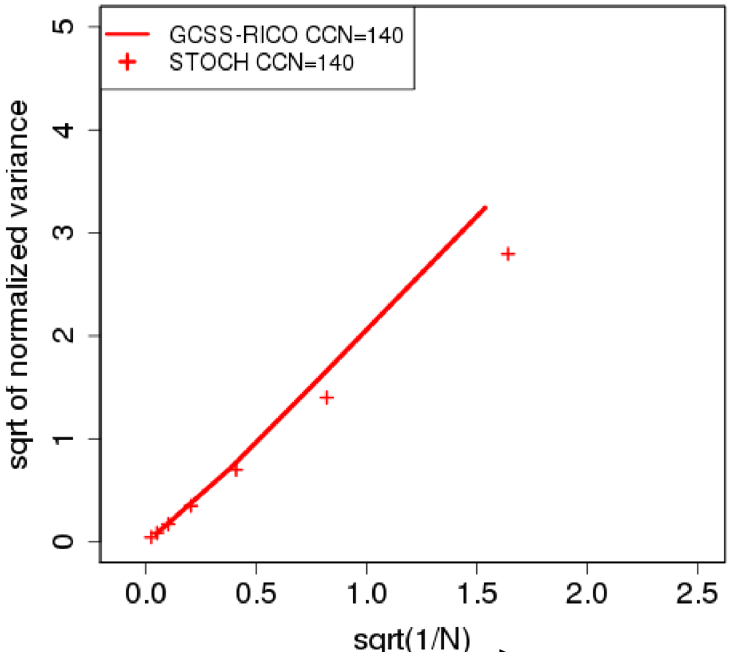
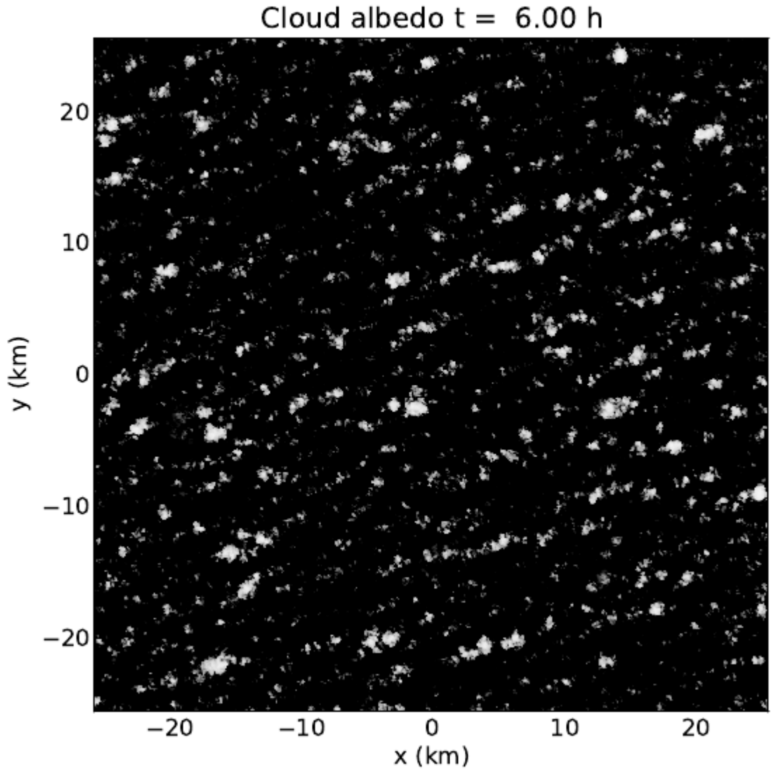
How does the variance scale with mean cloud number or grid spacing?



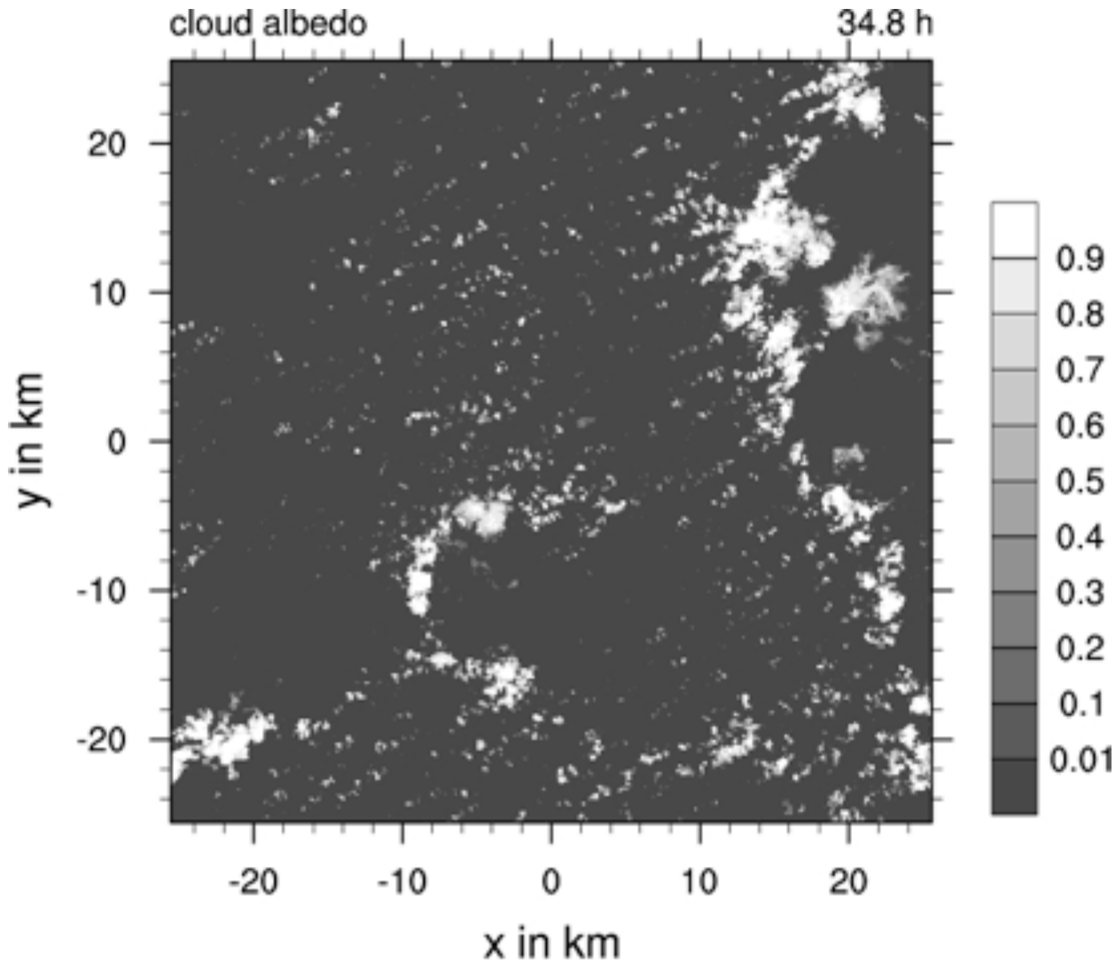
decreasing mesh size



LES of organized shallow convection

LES simulation can reproduce the observed features:

- different cloud sizes which organize in clusters and mesoscale arcs.
- thin ‚high' clouds from convective outflow.
- cloud free areas which could be identified as cold pools.
- cloud tops are well below 3000 m height.
- significant precipitation of about 1 mm/day or 30 W/m^2 starts after 15 hours.



Moist RICO case of Stevens and Seifert (2008) on a 25 m isotropic grid with 50 km domain size (2048x2048x160 grid points).

Variance for organized cloud fields

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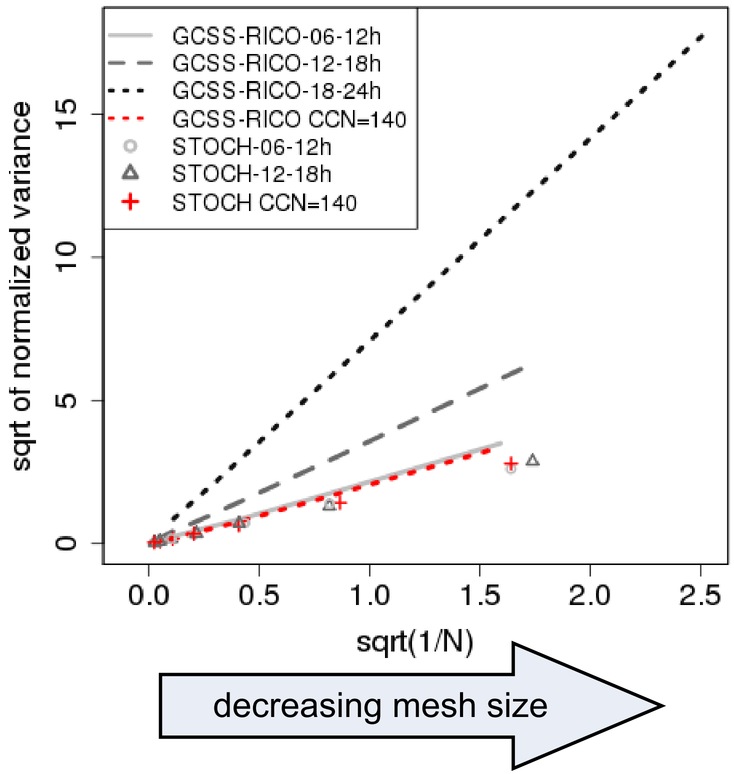
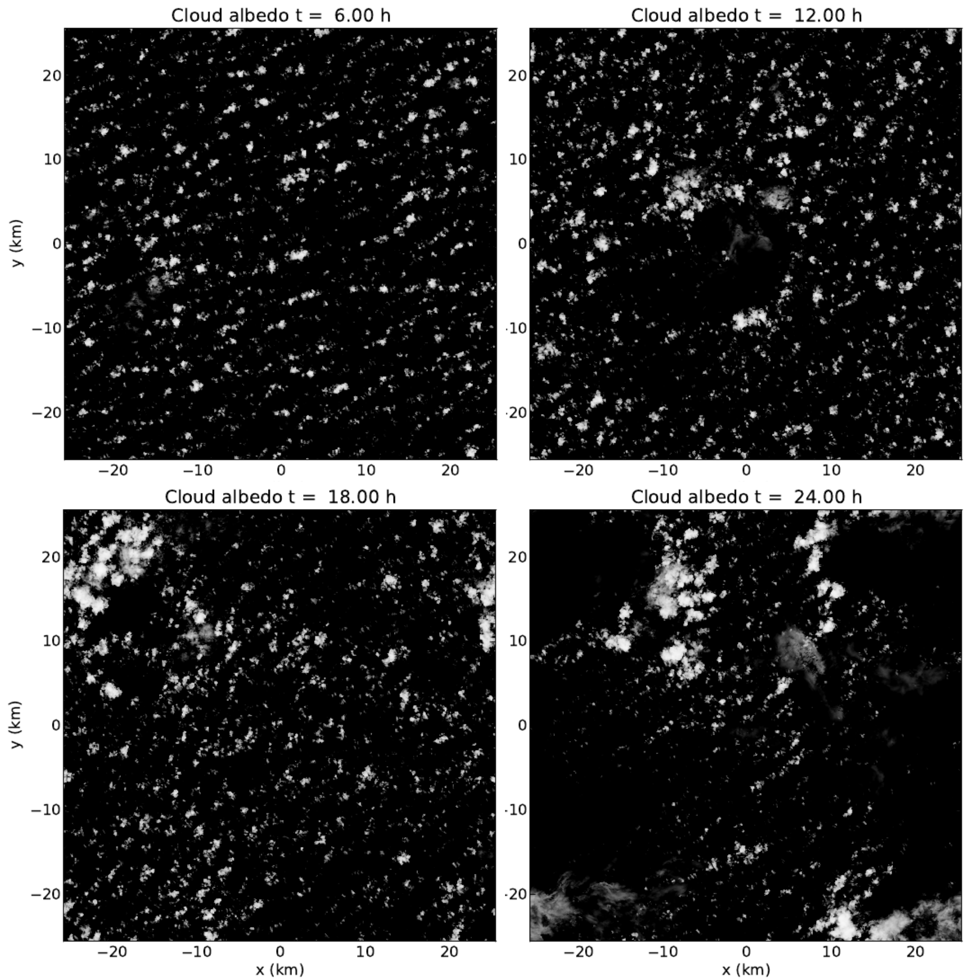
Does the variance scale still hold for organized cloud fields?

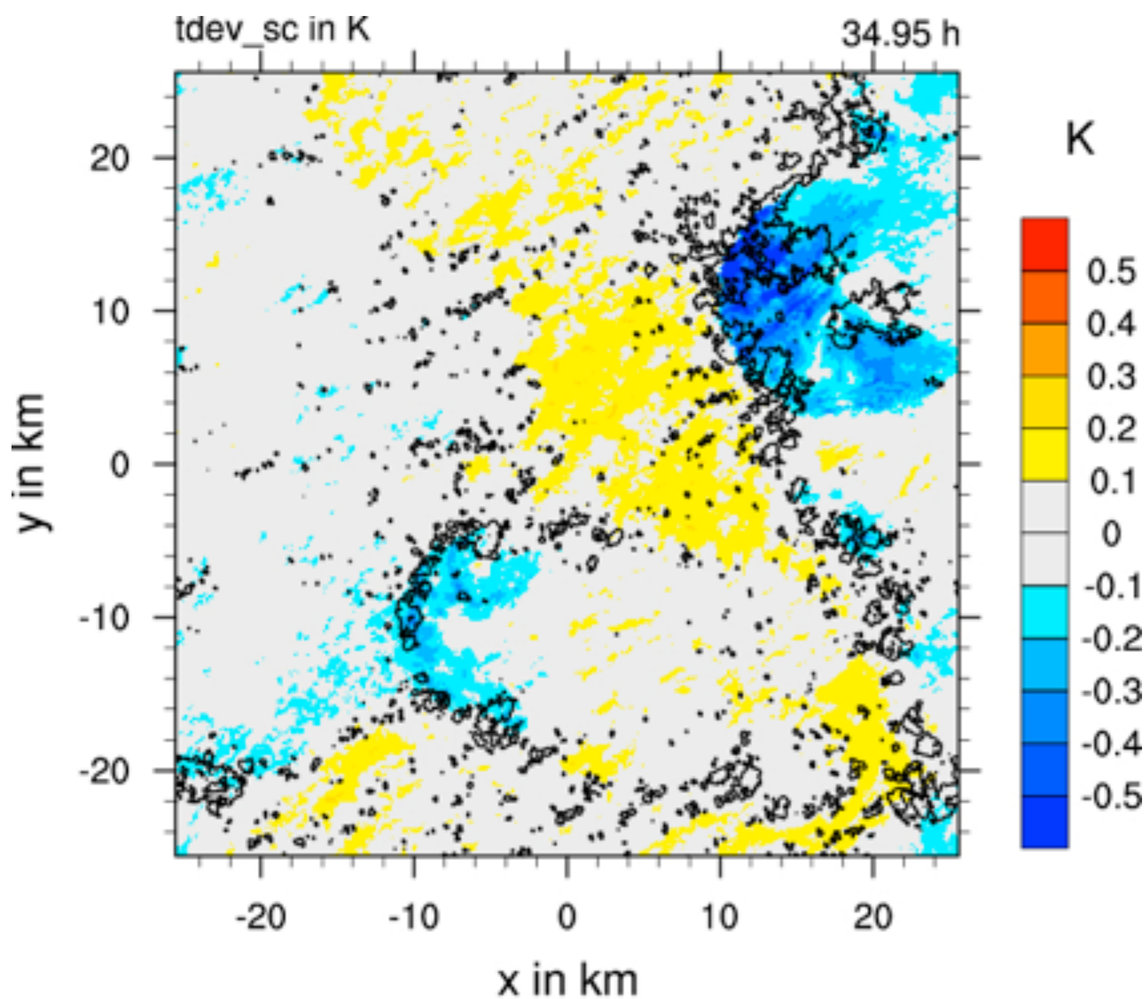




Organization due to cold pools: Sub-cloud layer temperature and clouds

potential temperature averaged over the sub-cloud layer (colors)

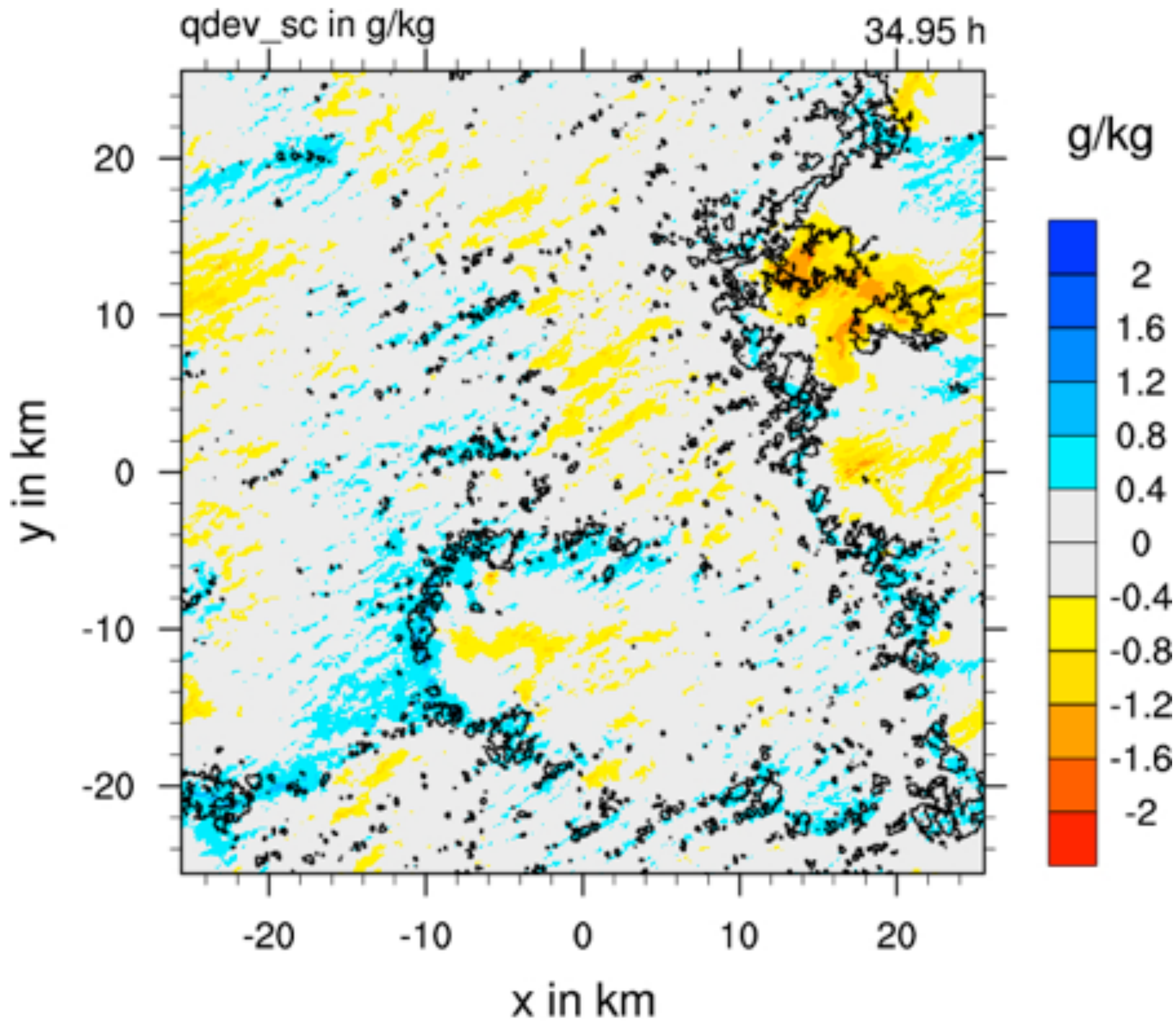
liquid water path (isolines every 1 g/m²)



Mesoscale moisture patches:
Sub-cloud layer moisture and clouds

water vapor mixing ratio vertically averaged over the sub-cloud layer. Shown is the deviation from the horizontal mean (colors)

liquid water path (isolines every 1 g/m^2)



Mesoscale organization

- Precipitating shallow convection does self-organize into mesoscale arcs.
- The main feedback causing organization is the evaporation of rain below cloud base and the corresponding cold pools.
- This leads to the formation of mesoscale structures in the moisture field with scales of O(1 km) and cloud-free areas of O(10 km).

  ➔ Targeting mesh sizes of O(1 km) we hope that the mesoscale moisture structures can be represented by the grid scale, i.e., we keep the stochastic sub-grid model spatially random with a simple Poisson process.

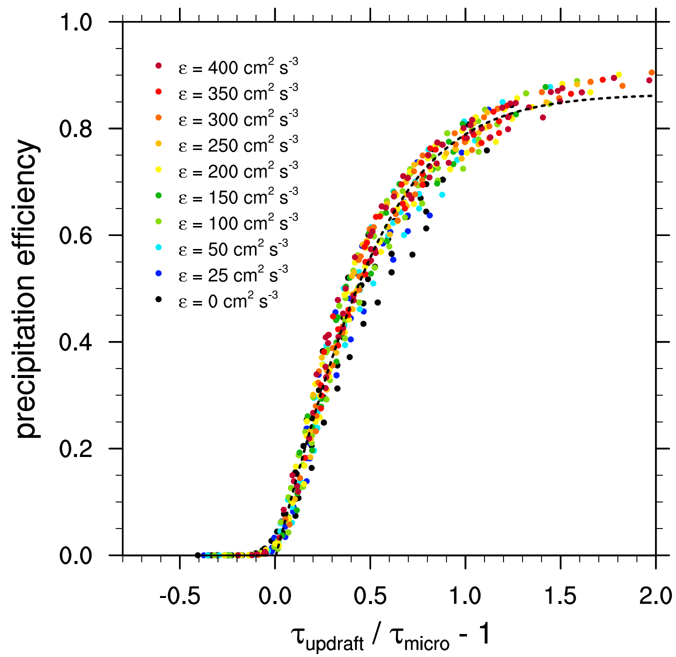
  ➔ But we do need a good representation of rain formation and evaporation in the sub-grid stochastic scheme.

This choice will, of course, depend on the application. For example, on O(10 km) grids the organization should be taken into account in the sub-grid (stochastic) scheme.

Why do clouds rain?

- Most parameterization, including state-of-the-art convection schemes assume a simple threshold behavior as introduced by Kessler (1969). This is an ad-hoc parameterization which cannot be derived for the kinetic equation.
- A more physical formulation is based on time scales, i.e., a Damköhler number which is the ratio of cloud lifetime and a rain formation timescale.

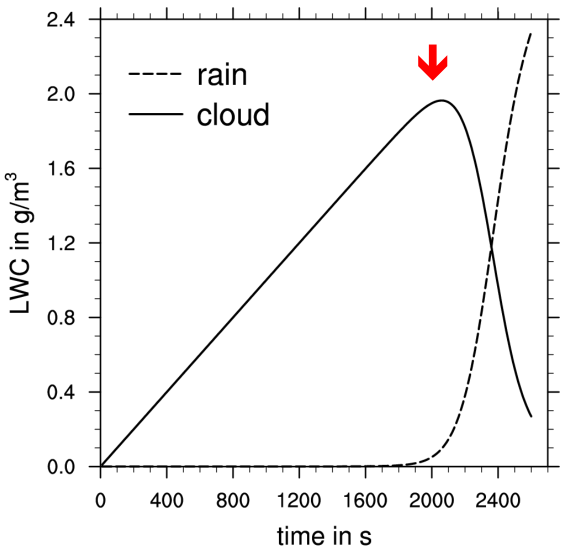
In a simple kinematic framework in can be shown that the precipitation efficiency of shallow clouds is a function of the Damköhler number (Seifert and Stevens 2010, J. Atmos. Sci.)



Microphysical time scale

Define a rain formation timescale based on a simple parcel model with constant condensation rate (Stevens and Seifert 2008):

$$\frac{\mathrm{d}q_c}{\mathrm{d}t} = \frac{1}{\tau_{\mathrm{cond}}} - k_{\mathrm{au}}\, q_c^4\, N_c^{-2}\, \phi_{cc}(\epsilon) - k_{cr}\, q_c\, q_r\, \phi_{cr}(\epsilon)$$



$$\tau_* = \left[\beta_* + \sqrt{\beta_*^2 + \frac{\tau_0^4}{(1-\epsilon_*)^4 \phi_{cc}(\epsilon_*)}}\right]^{1/2}$$

with

$$\beta_* = \frac{k_{cr}\, N_c^2}{2\, k_{\mathrm{au}}} \frac{\epsilon_*\, \phi_{cr}(\epsilon_*)}{(1-\epsilon_*)^3 \phi_{cc}(\epsilon_*)}$$

$$\tau_0 = N_c^{1/2}\, \tau_{\mathrm{cond}}^{3/4}\, k_{\mathrm{au}}^{-1/4}.$$

Time needed for rain formation as a function of condensation time scale τ_{cond} (vertical velocity and lapse rate) as well as droplet number conc. N_c and kernel parameter k_{au}.

Precipitation efficiency of clouds in LES

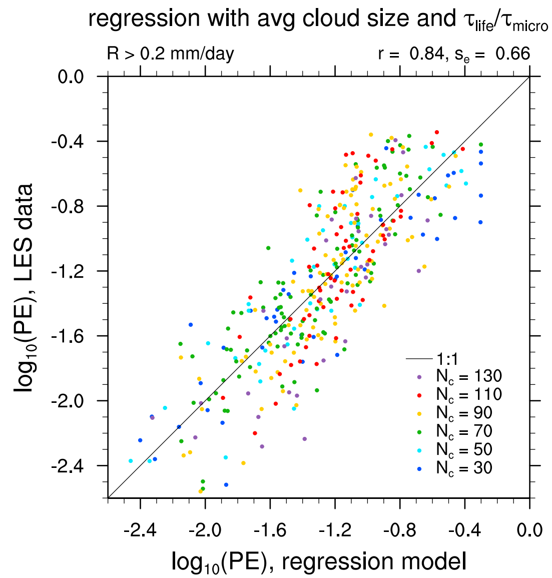
Preliminary results suggest

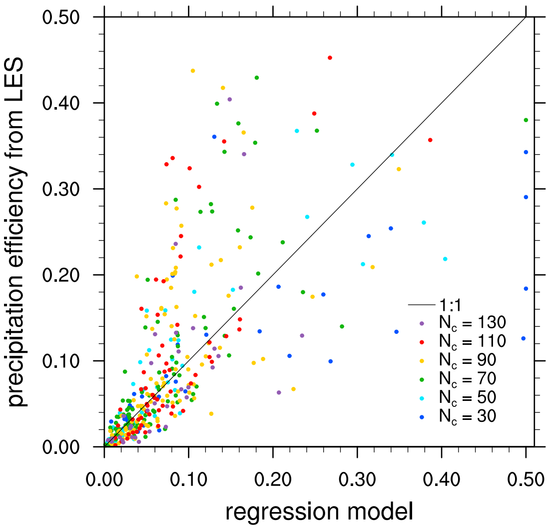
$$PE \sim \frac{\tau_{life}}{\tau_{micro}} \, \ell^2 \sim Da \, \ell^2$$

i.e. the rain rate scales with

$$P \sim Da \, \ell^4 H \sim Da \, \ell^5$$

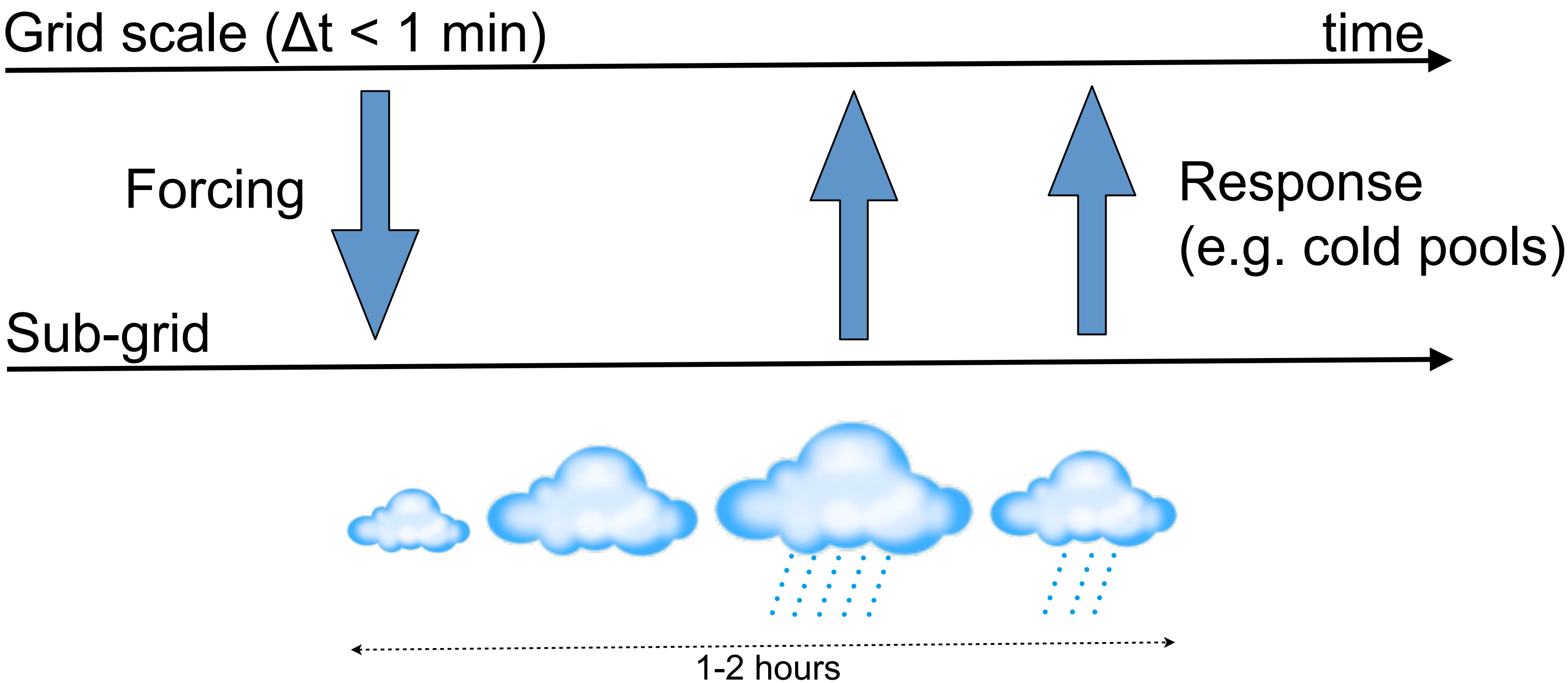
which emphasizes the need to get the tail of the size distribution correct.





A non-Markovian stochastic scheme

Due to the explicit lifecycle of each individual cloud and the delayed formation of rain the final scheme will not only be stochastic but also non-Markovian.



This is an example of the memory effect of sub-grid parameterizations as derived for general systems by Wouters and Lucarini (2012, J. Stat. Mech.).

Conclusions and Outlook

- Stochastic parameterizations offer a new way of looking at the cloud problem.
- With the Plant-Craig-type shallow convection scheme we hope to improve ensemble spread, scale adaptivity, sub-grid convective precipitation etc.
- The next step is to implement this into a 3D NWP model and combine it with an existing shallow convection scheme which provides the ensemble mean properties.
- Important related work would be to derive the corresponding stochastic ODEs, because this microscopic stochastic model might be too expensive for operational applications.

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Related publications:

Seifert, A. and Heus, T.: Large-eddy simulation of organized precipitating trade wind cumulus clouds, Atmos. Chem. Phys., 13, 5631-5645, doi:10.5194/acp-13-5631-2013, 2013.

Heus, T. and Seifert, A.: Automated tracking of shallow cumulus clouds in large domain, long duration large eddy simulations, Geosci. Model Dev., 6, 1261-1273, doi:10.5194/gmd-6-1261-2013, 2013.

Seifert, A. and B. Stevens, 2010: Microphysical Scaling Relations in a Kinematic Model of Isolated Shallow Cumulus Clouds. *J. Atmos. Sci.*, **67**, 1575–1590. doi: 10.1175/2009JAS3319.1

Stevens, B. and Seifert, A., 2008: Understanding macrophysical outcomes of microphysical choices in simluations of shallow cumulus convection, J. Meteorol. Soc. Japan, 86, 143162. 1858, 1870

Movies showing organized shallow convection can be downloaded from

https://dl.dropboxusercontent.com/u/25854302/xy_plots_albedo.avi
https://dl.dropboxusercontent.com/u/25854302/xy_plots_tdev_sc.avi
https://dl.dropboxusercontent.com/u/25854302/xy_plots_qdev_sc.avi

These are higher resolution versions of the movies provided as online supplement with the ACP paper.