Large Eddy Simulations of Trade-Wind Cumuli using Particle-Based Microphysics with Monte-Carlo Coalescence

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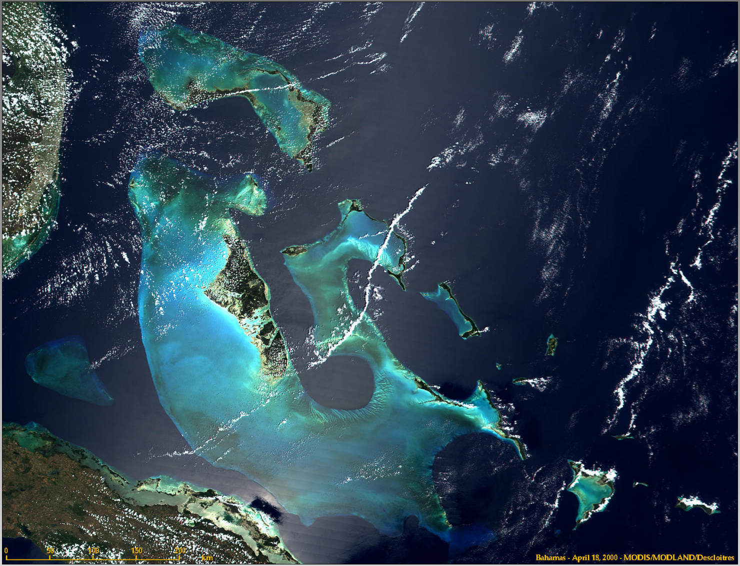
Trade-wind cumuli



MODIS image by Robert Wood: http://www.atmos.washington.edu/~robwood/

Trade-wind cumuli: why to study them?

- important for the Earth climate due to contrasting effects on solar and thermal radiation:
  - shortwave: significant change of albedo if clouds present
  - longwave: small impact on outgoing thermal radiation (low level)
- often treated in models as non-precipitating clouds while...

Figure 1. from Rauber et al. 2007 (MWR)

The „RICO" LES set-up

van Zanten et al. 2011, JAMES:

- definition of a shallow-convection model benchmark case inspired by the RICO field campaign (Rauber et al. 2007, MWR)
- comparison of results from 13 different LES models
- selected conclusions:
  - *"simulations agree on the broad structure of the cloud field ... plausibly reproduces many features of the observed layer"*
  - *"simulations do show considerable departures from one another in the representation of the cloud microphysical structure"*
  - *"simulations differ substantially in the amount of rain they produce"*
  - *"these differences appear to be related to microphysical assumptions made in the models"*

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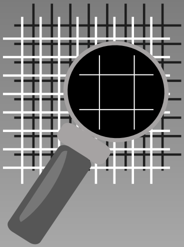
Cloud μ-physics: options for LES



features of the Lagrangian (in size) approach:

- diffusive error-free particle growth schemes (condensational "moving sectional", collisional: Monte-Carlo)
- scales better than ND-bin with number of particle attributes
- fewer parameterisation in comparison with bulk or bin models
- coupled with Lagrangian-in-space $\rightsquigarrow$ particle tracking
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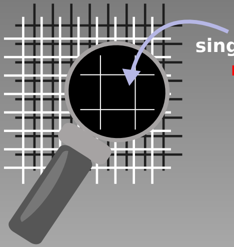

single-moment bulk:
no influence of aerosol on cloud

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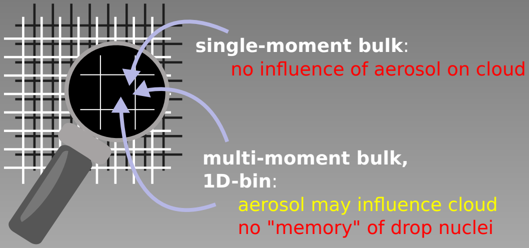

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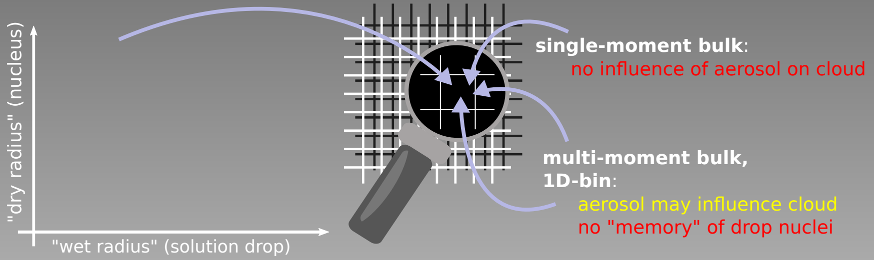

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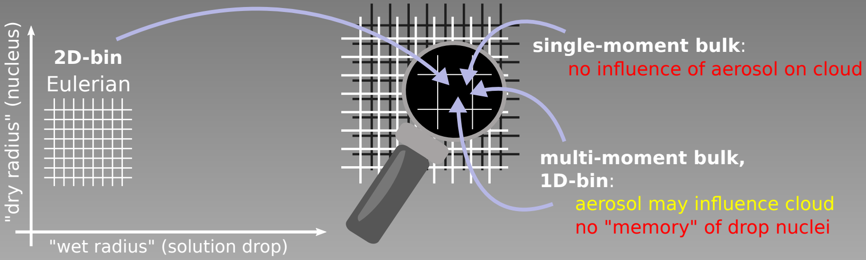

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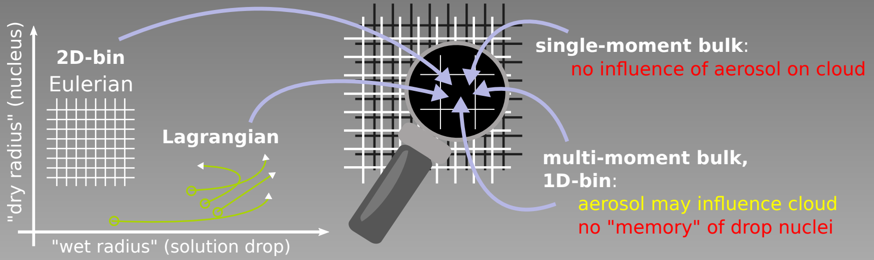

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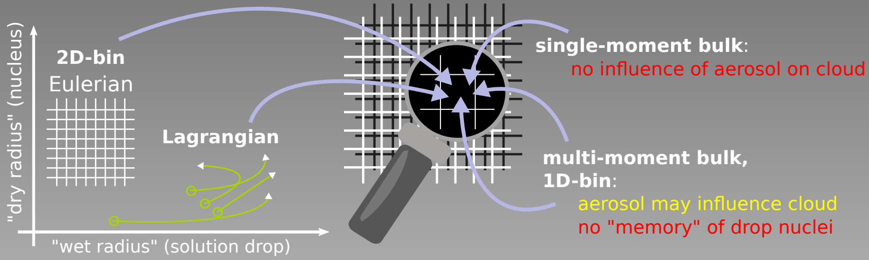

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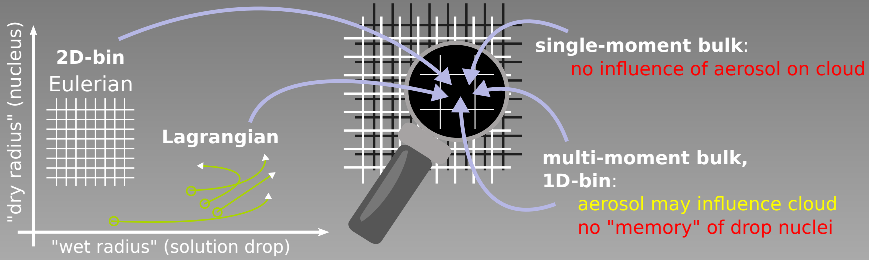

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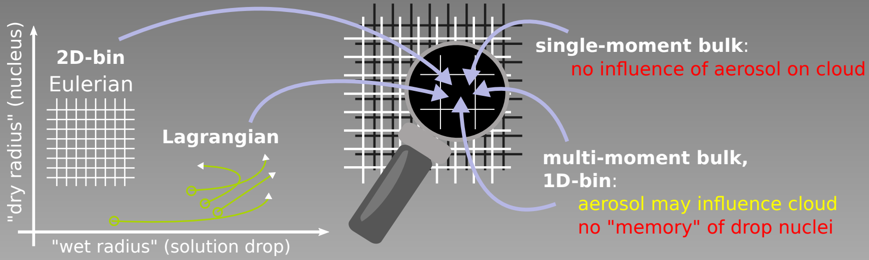

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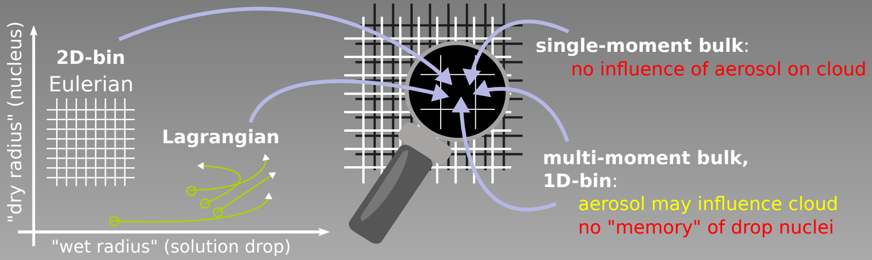

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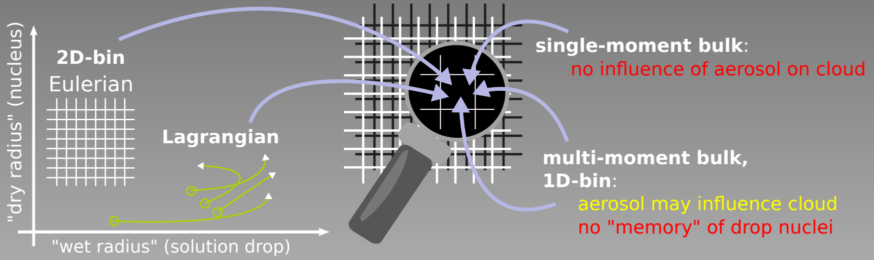

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Lagrangian μ-physics: key elements

- each particle (aka super-droplet) $\rightsquigarrow$ many "similar" real-world particles
- attributes: multiplicity, dry radius, wet radius, nucleus type, ...
- aerosol, cloud, precip. particles not distinguished, subject to same processes

Eulerian / PDE	Lagrangian / ODE
advection of heat	particle transport by the flow
advection of moisture	condensational growth
	collisional growth
	sedimentation
$\partial_t(\rho_d r) + \nabla(\vec{v}\rho_d r) = \rho_d \dot{r}$	$\dot{r} = \sum_{\text{particles} \in \Delta V} \ldots$
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Monte-Carlo coalescence scheme (Shima et al. 2009)

- for all n super-droplets in a grid box of volume ΔV in timestep Δt
- each representing ξ real particles (aerosol/cloud/drizzle/rain)
- the probability of coalescence of i-th and j-th super-droplets is:

$$P_{ij} = max(\xi_i, \xi_j) \cdot \underbrace{E(r_i, r_j) \cdot \pi (r_i + r_j)^2 \cdot |v_i - v_j|}_{\text{coalescence kernel}} \cdot \frac{\Delta t}{\Delta V} \cdot \frac{n \cdot (n-1)}{2} / \left[\frac{n}{2}\right]$$

  where r – drop radii, $E(r_i, r_j)$ – collection efficiency, v – drop velocities
- coalescence takes place once in a number of timesteps (def. by P_{ij})
- all min(ξ_i,ξ_j) droplets coalesce
  $\rightsquigarrow$ there's always a "bin" of the right size to store the collided particles
- collisions triggered by comparing a uniform random number with P_{ij}
- extensive parameters summed ($\rightsquigarrow$ conserved), intensive averaged
- [n/2] random non-overlapping (i,j) pairs examined only
  cost: $O(n^2) \rightsquigarrow O(n)$, probability upscaled by $\frac{n \cdot (n-1)}{2} / \left[\frac{n}{2}\right]$

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  where r – drop radii, $E(r_i, r_j)$ – collection efficiency, v – drop velocities
- coalescence takes place once in a number of timesteps (def. by P_{ij})
- all min(ξ_i,ξ_j) droplets coalesce
  $\rightsquigarrow$ there's always a "bin" of the right size to store the collided particles
- collisions triggered by comparing a uniform random number with P_{ij}
- extensive parameters summed ($\rightsquigarrow$ conserved), intensive averaged
- [n/2] random non-overlapping (i,j) pairs examined only
  cost: $O(n^2) \rightsquigarrow O(n)$, probability upscaled by $\frac{n \cdot (n-1)}{2} / \left[\frac{n}{2}\right]$

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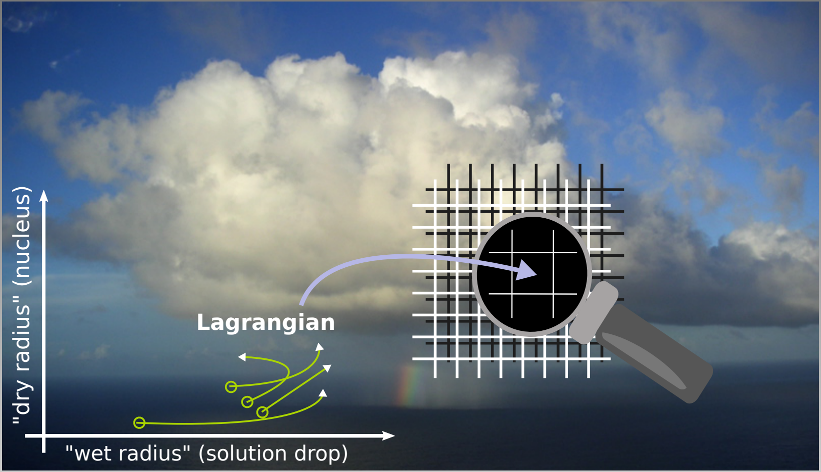

background: Figure 1. from Rauber et al. 2007 (MWR)

Simulation set-up[s]

- LES solver: Nagoya Univ. CReSS (Tsuboki et al.) at the Earth Simulator 2
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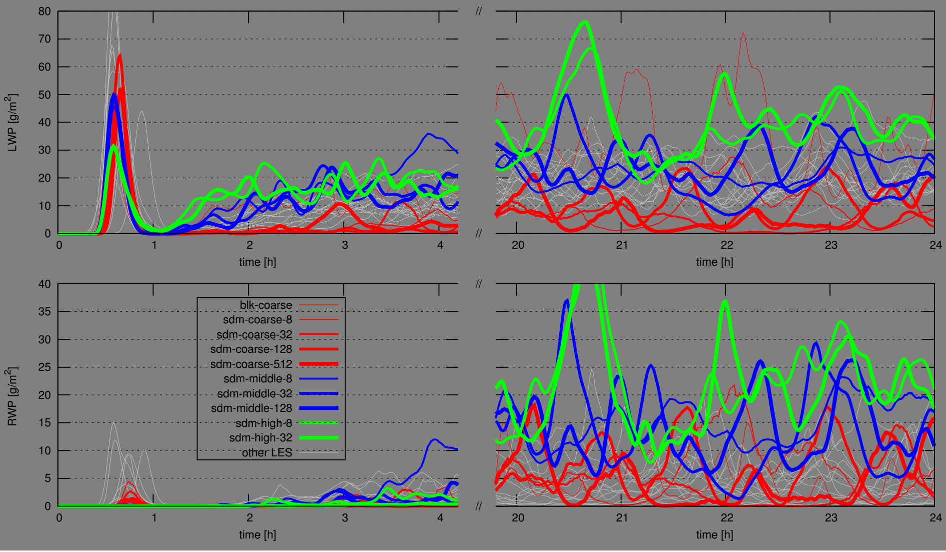
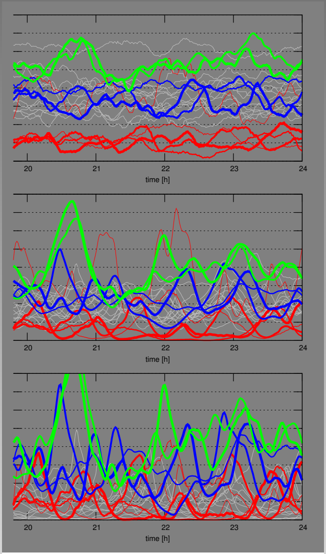
Particle-based LES vs. other LES (van Zanten et al. 2011)



less sensitive to super-droplet density than to grid resolution

Particle-based LES vs. other LES (Matheou et al. 2011)

← Δx=25,50,100 m   Δx=20,40,80 m ↓



cloud cover, LWP, RWP
last 4 hours

Matheou et al. 2011, MWR: Fig. 8

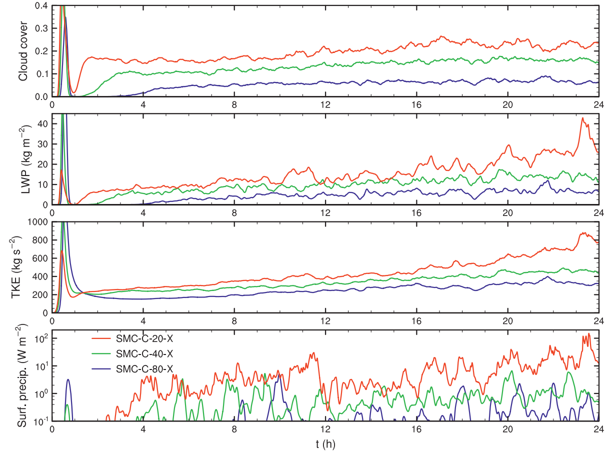


FIG. 8. Time evolution of cloud cover, LWP, vertically integrated resolved-scale TKE, and surface precipitation rate for precipitating runs at different resolutions.

Focus of the analysis: mimicking particle-counting probes

Fast-FSSP:

- measures light scattered by single cloud particles

- sizes cloud droplets in the 2-50 μm diameter range

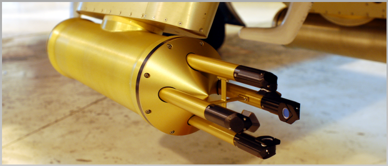
Figure 1. from Rauber et al. 2007 (MWR)

OAP-2DS:

- measures light shadowed by cloud/drizzle/rain drops

- sizes multiple particles at a time in the 5-3000 μm diameter range

Fast-FSSP / Meteo-France, Toulouse
Brenguier et al. 1997, JAOT



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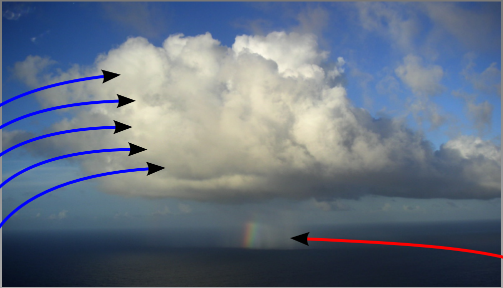

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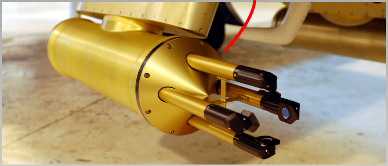

OAP-2DS / SPEC Inc. Boulder CO
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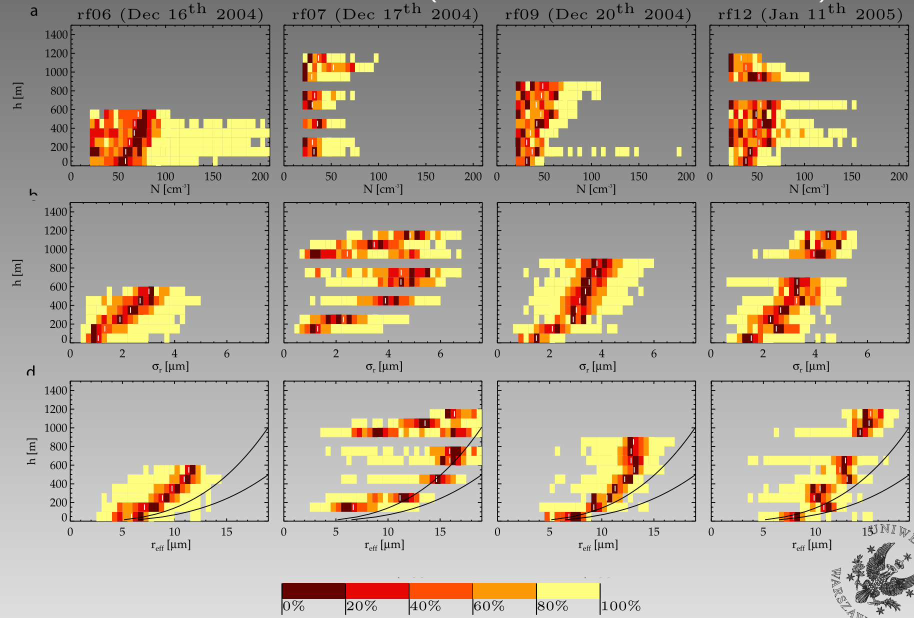
RICO Fast-FSSP statistics (Arabas et al. 2009, GRL)



Super-Droplet LES: Fast-FSSP-mimicking analysis

- Fast-FSSP spectral range (1-24 μm in radius)
- Fast-FSSP concentration threshold (20 cm^{-3})
- 5^{th}-95^{th} percentile, interquartile, 45^{th}-55^{th} percentile ranges vs. height

- caveats:
  - last 4h of the LES vs. flight-long statistics
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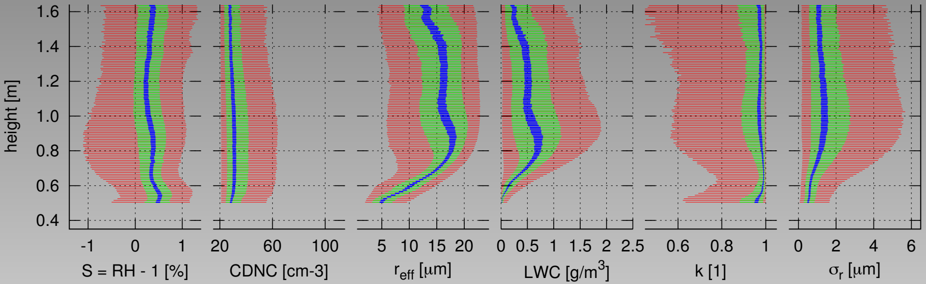

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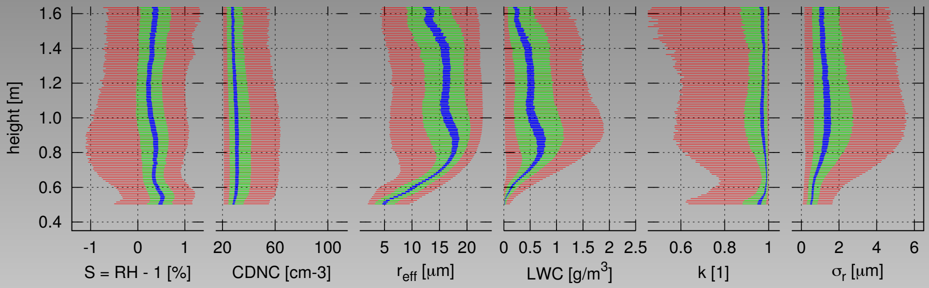

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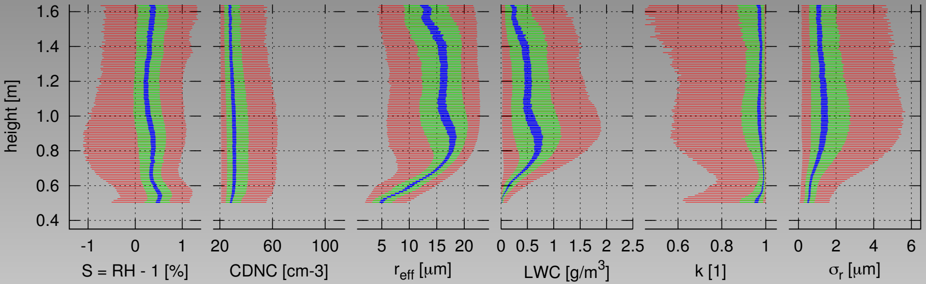

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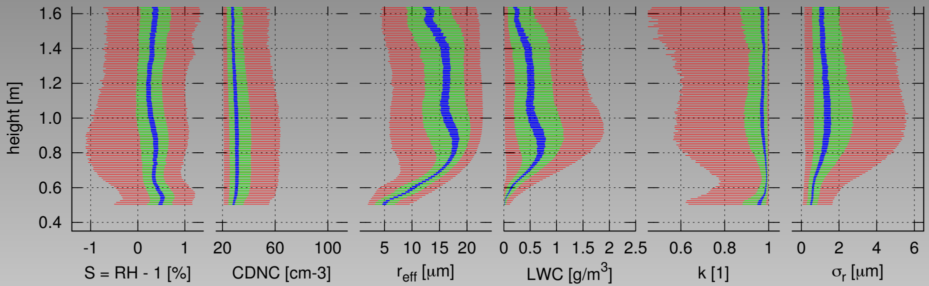

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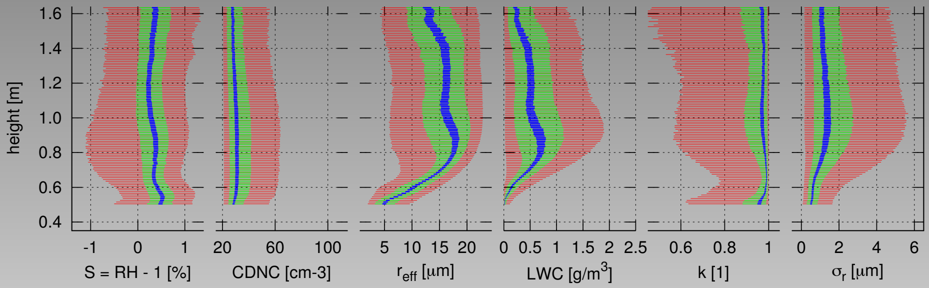

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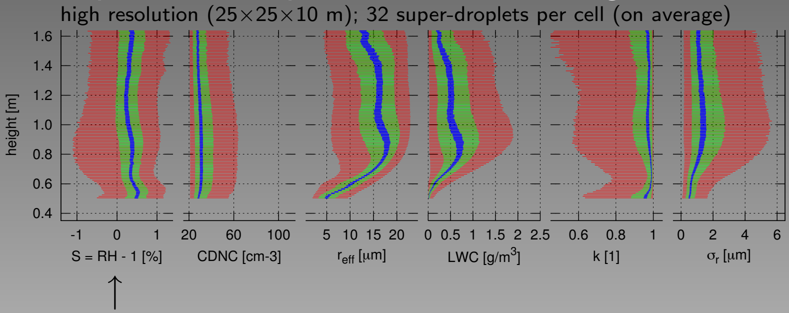
Super-Droplet LES: supersaturation vs. height



- lowest quartile subsaturated
- maximum near cloud base (median profile) ⇝ CCN activation kinetics
- condensational growth integrated implicitly ⇝ $\Delta t \sim 0.2$ s
- values: lack of measurements to compare to?

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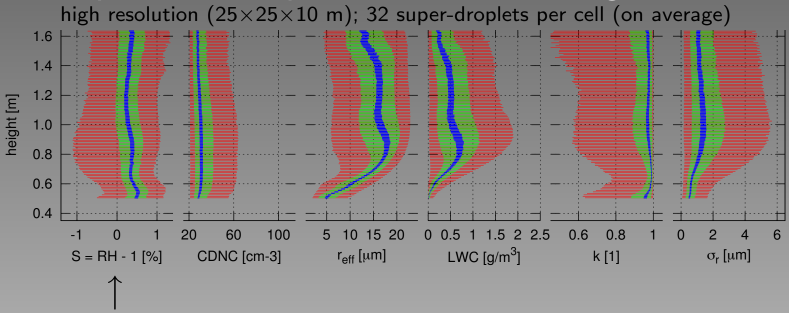

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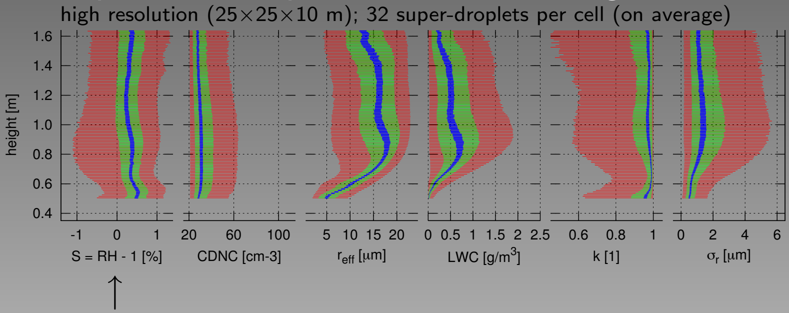

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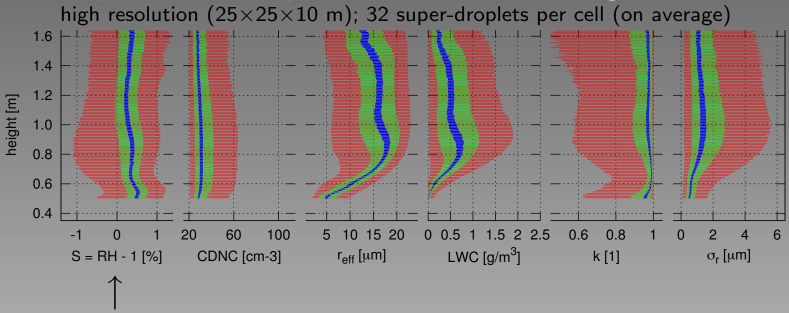

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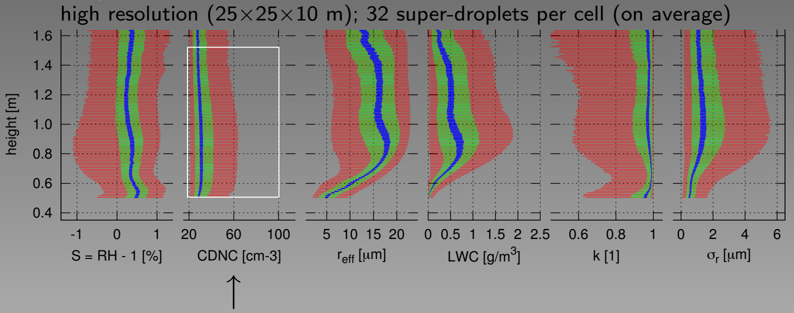
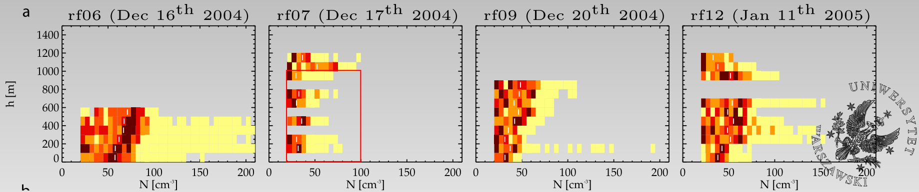
Super-Droplet LES vs. RICO Fast-FSSP measurements

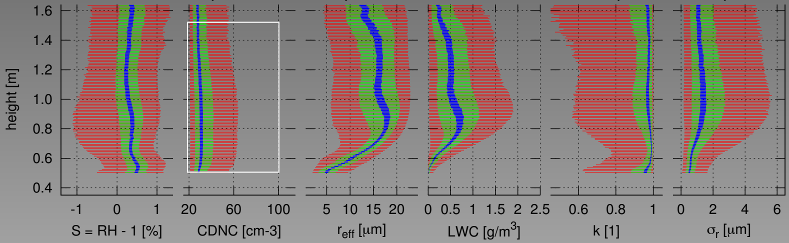


- values comparable with RICO data (measurements: day-to-day variability!)
- roughly constant with height (precip sink in the upper part)
- measurements: increase with height? (vigorous updraft ⇝ deeper & higher conc.)



Super-Droplet LES vs. RICO Fast-FSSP measurements

high resolution (25×25×10 m); 32 super-droplets per cell (on average)



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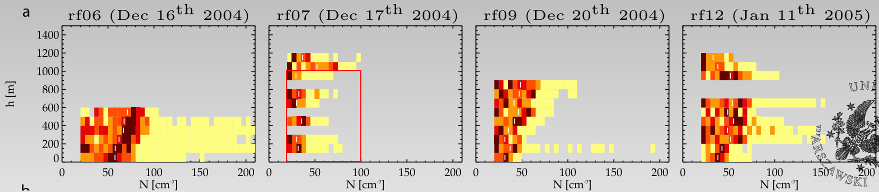

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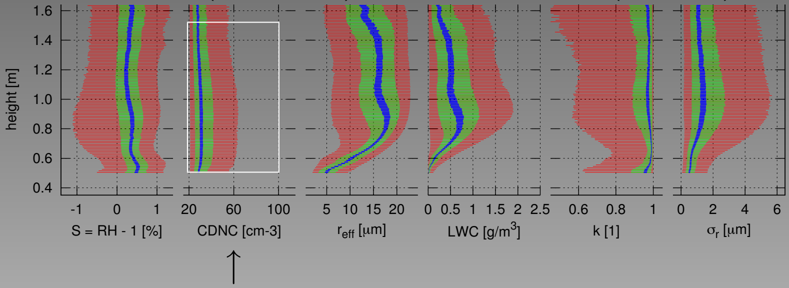

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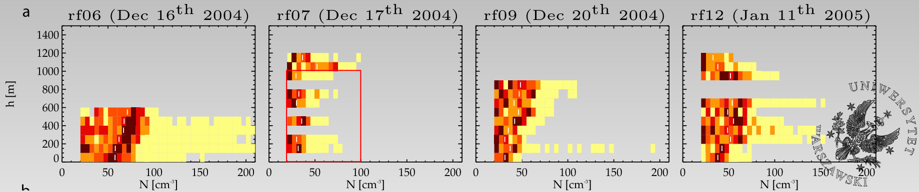

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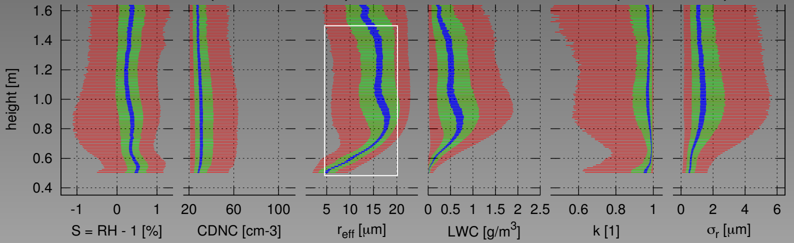

- reasons for the reduced slope in the upper part of the cloud field:
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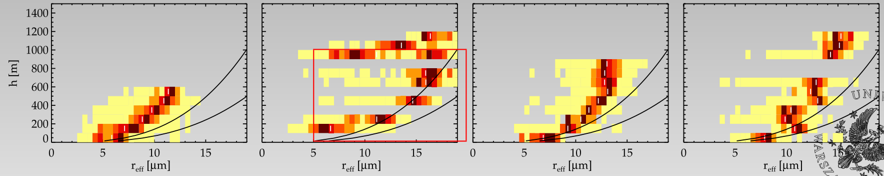

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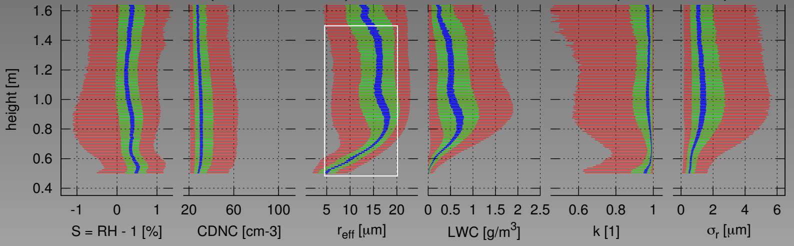

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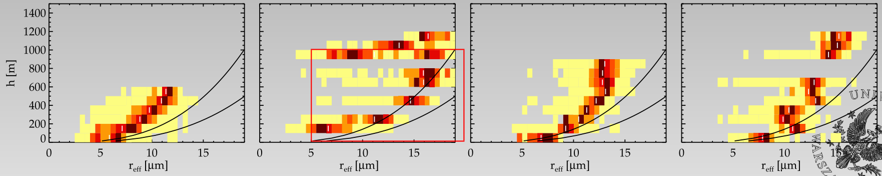

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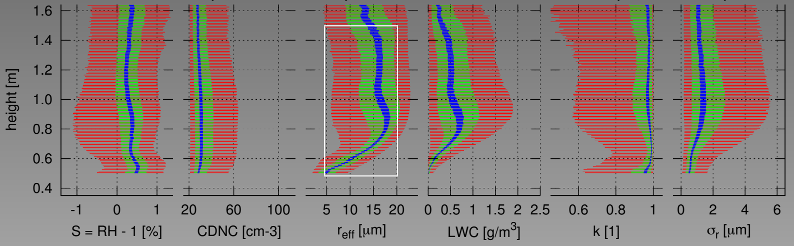

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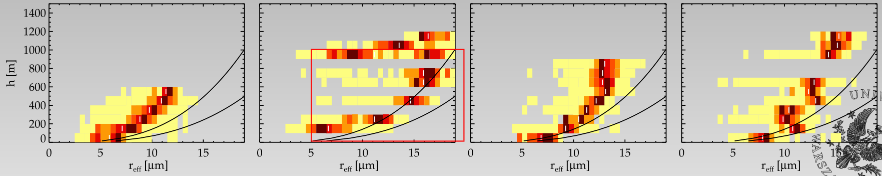
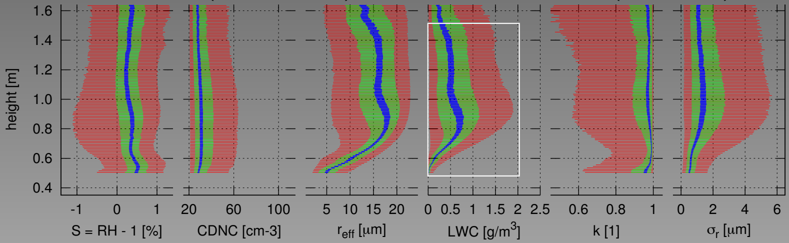
  - increased probability of drop collisions and coalescence

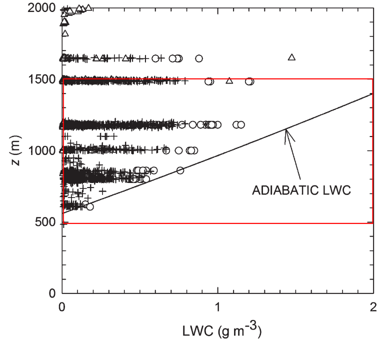


Super-Droplet LES vs. RICO Fast-FSSP measurements

high resolution (25×25×10 m); 32 super-droplets per cell (on average)



Gerber et al. 2008, JMSJap: Fig. 1



↑

- significant spread: zero . . . ca. adiabatic
- mixing in SDM?
  - not homogeneous (supersaturation interpolated to SD positions)
  - super-droplets ∼ parcels
- sensitive to sampling volume choice (both measurements & model)

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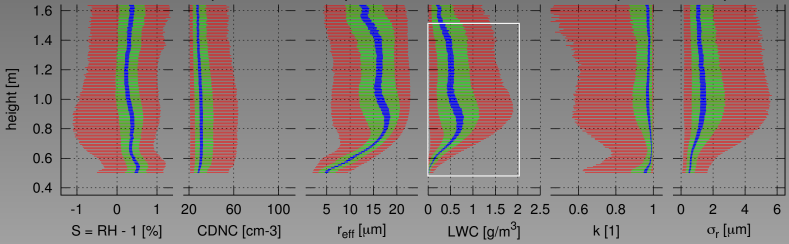
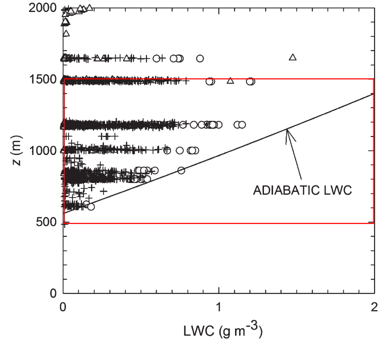


Gerber et al. 2008, JMSJap: Fig. 1



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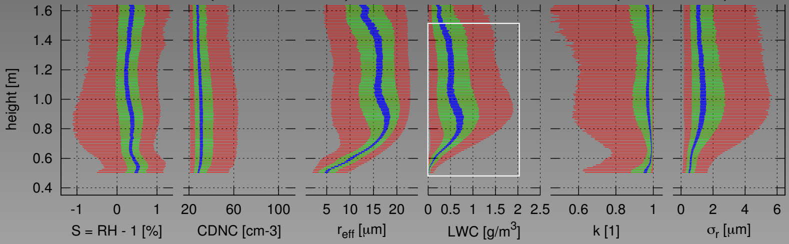

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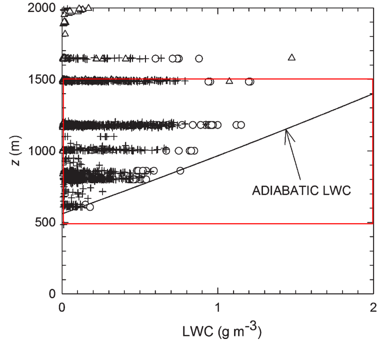

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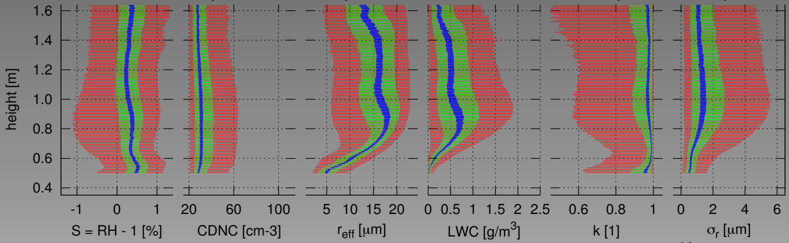
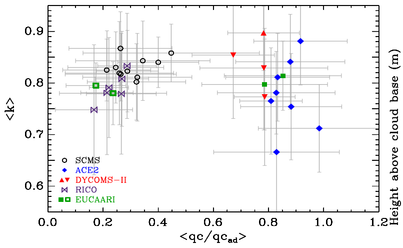


$$k = \frac{\langle r^3 \rangle}{r_{eff}^3}$$

used in GCMs to parameterise cloud droplet spectrum width

Brenguier et al. 2011: Figs 4, 5



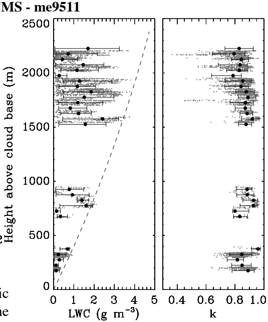
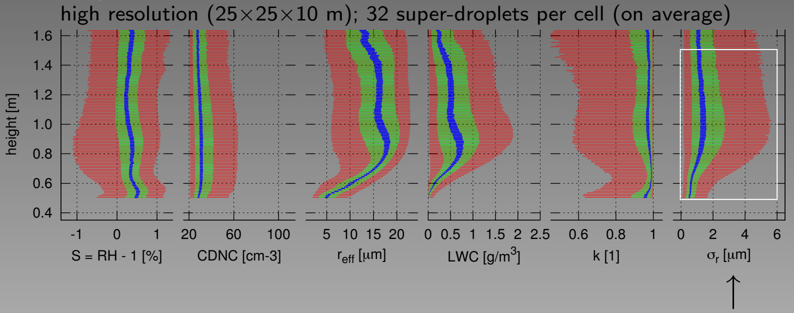
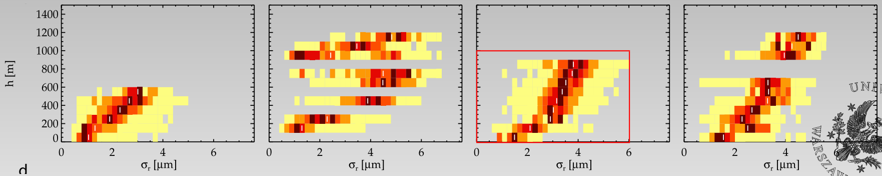


Fig. 4. Scatterplot of $\langle k \rangle$ values as function of the LWC adiabatic fraction. For the LWC adiabatic fraction, the difference between the 80th and the 20th percentile of the frequency distribution is used

Super-Droplet LES vs. RICO Fast-FSSP measurements



- values larger than in adiabatic growth (⇝ mixing-induced broadening)
- highest percentile profiles correspond to measurements (increase with height)
- drop breakup and influences of turbulence not represented in the model



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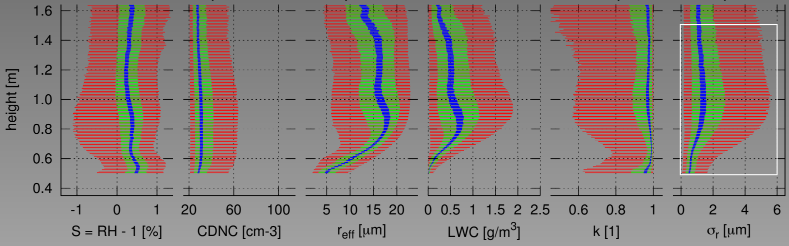

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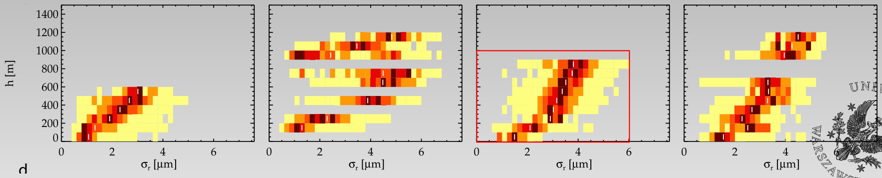

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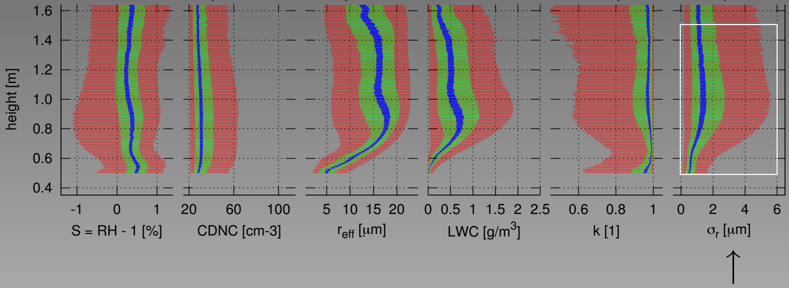

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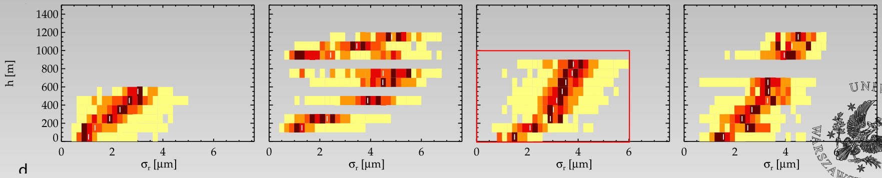


Focus of the analysis: mimicking particle-counting probes

Fast-FSSP:

- measures light scattered by single cloud particles

- sizes cloud droplets in the 2-50 μm diameter range

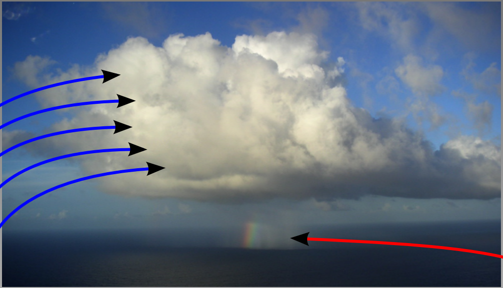


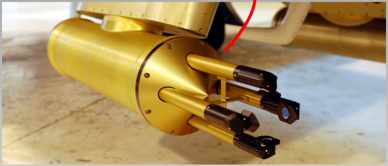
Figure 1. from Rauber et al. 2007 (MWR)

OAP-2DS:

- measures light shadowed by cloud/drizzle/rain drops

- sizes multiple particles at a time in the 5-3000 μm diameter range

Fast-FSSP / Meteo-France, Toulouse
Brenguier et al. 1997, JAOT



OAP-2DS / SPEC Inc. Boulder CO
Lawson et al. 2006, JAOT

OAP-2DS-mimicking analysis vs. RICO OAP-2DS statistics

Baker et al. 2009, JAMC

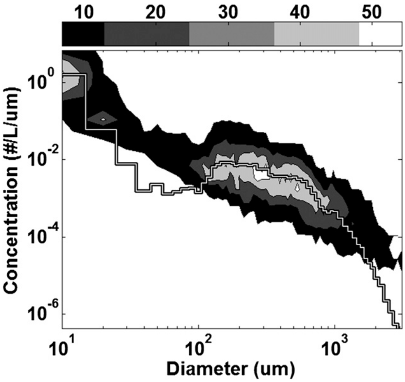


FIG. 4. The mean of 237 rain PSDs is shown on top of density contours of the 237 individual rain PSDs observed at 600-ft (~183 m) altitude over the ocean on 19 Jan 2005. The contours show the number of PSDs passing through the region. Very few individual PSDs have any counts at all between 30 and 100 μm. These do not appear on the contour plot because zero values are not included on log–log plots.

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- RF17 (Jan. 19th 2005)
- 237 size distributions (line=mean)
- observed in rain shafts at 180 m (600 ft)
  cloud base at 0.5 km (1.6 kft)

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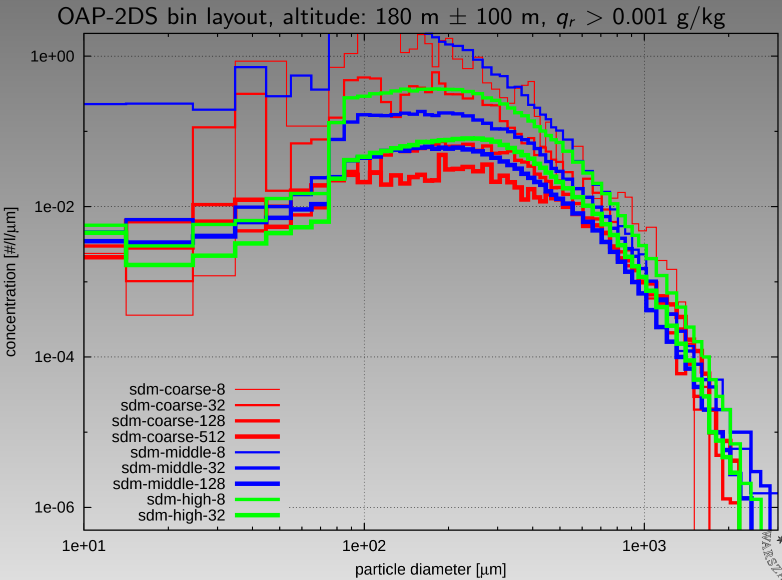
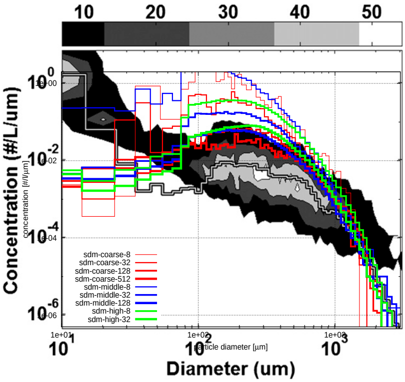
OAP-2DS-mimicking analysis vs. RICO OAP-2DS statistics



OAP-2DS-mimicking analysis vs. RICO OAP-2DS statistics

Baker et al. 2009, JAMC

MARCH 2009 BAKER ET AL.



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- fair agreement for d>100 μm (best for highest SD densities)
- no agreement for 10–20 μm where the OAP-2DS measured: *"most likely deliquesced aerosols"*

- no aerosol sources in the model (analysis: last 4h of 24h runs)
- no drop breakup in the model

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Summary

- salient features of the Super-Droplet μ-physics:
  - diffusive error-free computational schemes for both condensational and collisional growth
  - linear scaling of computational cost with the number of particles
  - persistence of arbitrary number of scalar quantities assigned to a super-droplet (e.g. chemical properties)
- (arguably) reasonable agreement with in-situ measurements
  $\rightsquigarrow$ set-up includes the key players in aerosol-cloud-precip interactions
- fewer parameterisation in comparison with bulk or bin models (e.g. Köhler curve and aerosol size spectrum instead of activation parameterisations or autoconversion thresholds)

ongoing work: super-droplets & aerosol processing

- interactions: aerosol —▷ cloud & precipitation —▷ aerosol
- processed CCN formed by evaporation of
  - collisionally-grown drops
  - drops within which irreversible oxidation occurred
- CCN spectrum modification by wet deposition
- simulations using a 2D kinematic framework with Wojciech Grabowski & Zach Lebo @ NCAR and Anna Jaruga @ Univ. Warsaw (visiting NCAR in January)

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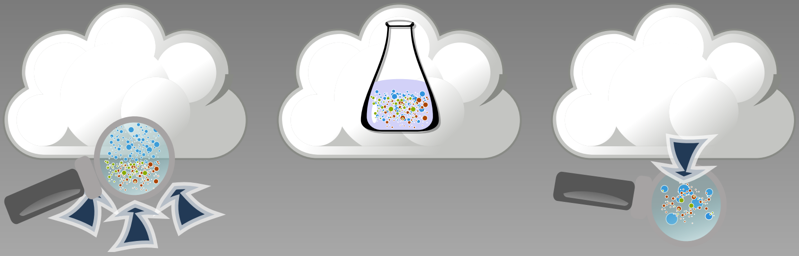

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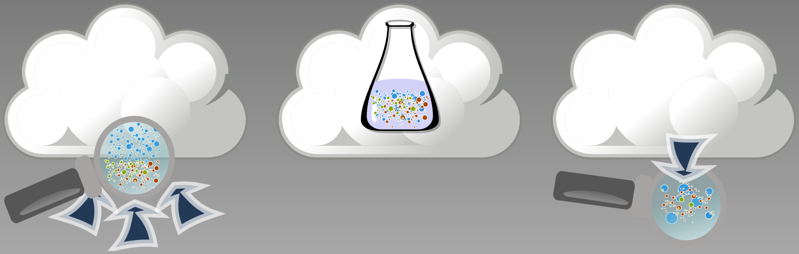

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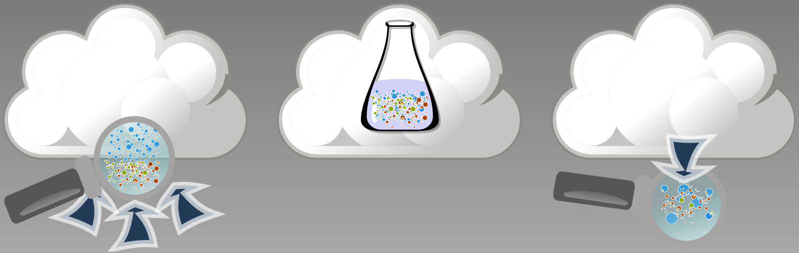

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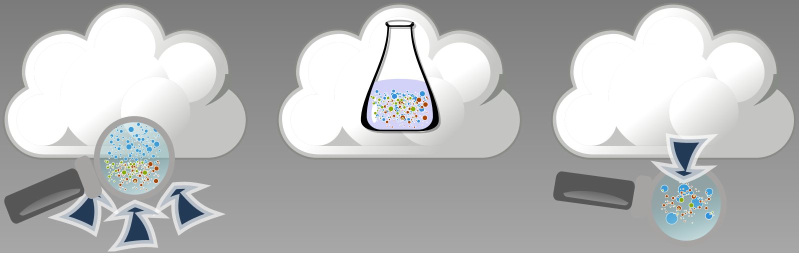

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Thanks for your attention!

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Hanna Pawłowska (University of Warsaw)

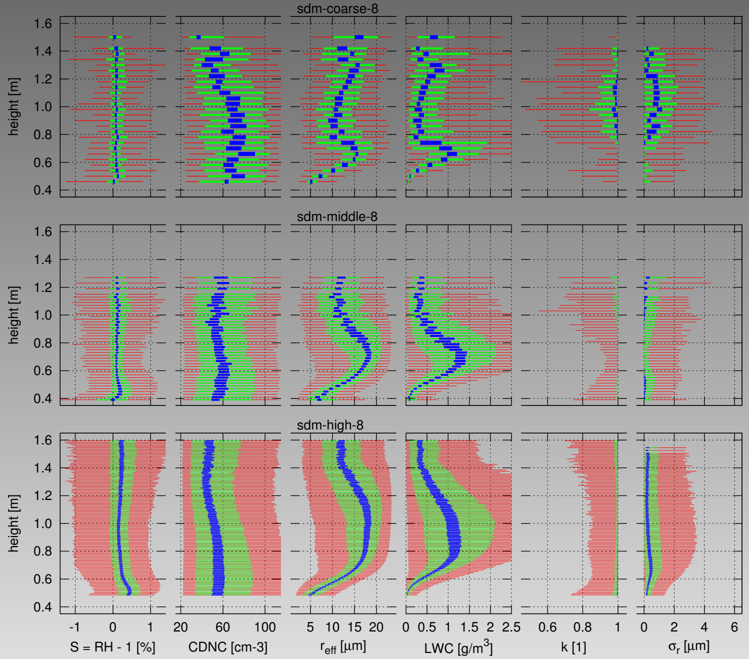
Kanya Kusano (JAMSTEC & Nagoya University)

Kozo Nakamura (JAMSTEC)

Computer time on the Earth Simulator 2 provided by JAMSTEC

Visit to NCAR funded by the Foundation for Polish Science

run label	grid	dx=dy	dz	time-steps [s]	SD density [cm^{-3}]
blk-coarse	$64 \times 64 \times 100$	100m	40m	1.00/0.100 n/a	n/a
sdm-coarse-8	$64 \times 64 \times 100$	100m	40m	1.00/0.100/0.25/1.0/1.0	2.0×10^{-11}
sdm-coarse-32	$64 \times 64 \times 100$	100m	40m	1.00/0.100/0.25/1.0/1.0	8.0×10^{-11}
sdm-coarse-128	$64 \times 64 \times 100$	100m	40m	1.00/0.100/0.25/1.0/1.0	3.2×10^{-10}
sdm-coarse-512	$64 \times 64 \times 100$	100m	40m	1.00/0.100/0.25/1.0/1.0	1.3×10^{-09}
sdm-middle-8	$128 \times 128 \times 200$	50m	20m	0.50/0.050/0.25/1.0/1.0	1.6×10^{-10}
sdm-middle-32	$128 \times 128 \times 200$	50m	20m	0.50/0.050/0.25/1.0/1.0	6.4×10^{-10}
sdm-middle-128	$128 \times 128 \times 200$	50m	20m	0.50/0.050/0.25/1.0/1.0	2.6×10^{-09}
sdm-high-8	$256 \times 256 \times 400$	25m	10m	0.25/0.025/0.25/1.0/0.5	1.3×10^{-09}
sdm-high-32	$256 \times 256 \times 400$	25m	10m	0.20/0.020/0.20/1.0/0.2	5.1×10^{-09}


sdm-coarse-8
sdm-middle-8
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height [m]
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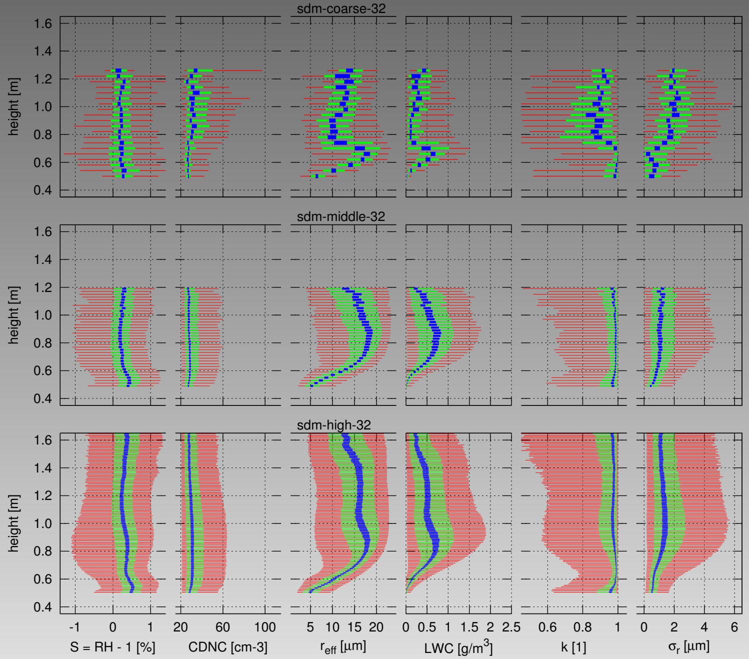
sdm-coarse-32
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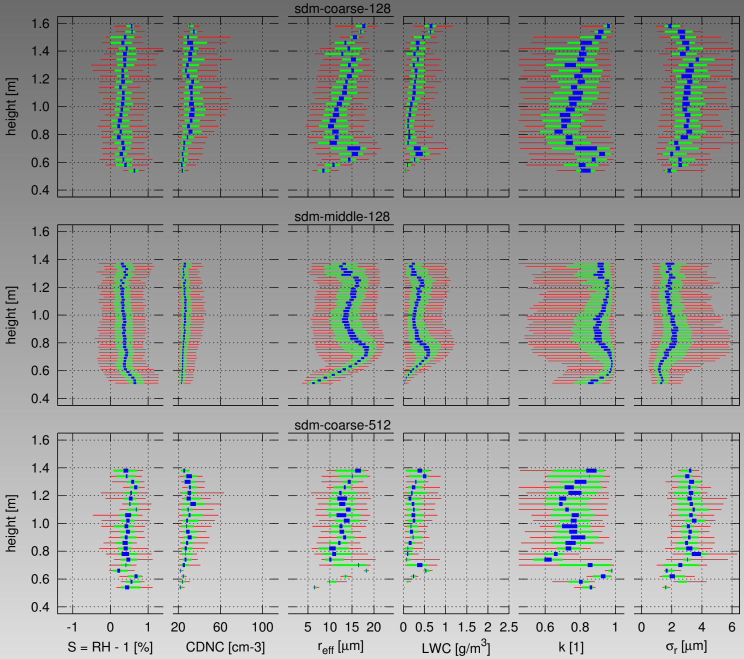

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