Simulations of a field of precipitating trade-wind cumuli using a particle-based and probabilistic microphysics model coupled with LES

Sylwester Arabas[1] & Shin-ichiro Shima[2]

1: Faculty of Physics, University of Warsaw, Poland
2: Japan Agency for Marine-Earth Science and Technology, Japan

observational data courtesy of
Météo-France (Fred Burnet et al.), SPEC Inc. (Brad Baker et al.) and NCAR

SIAM GS11 MS42: Novel Modelling and Computational Techniques for Atmospheric Aerosols and Clouds
Long Beach, CA, USA, March 23rd, 2011

Plan of the talk

1. Introduction: RICO and the trade-wind cumuli
2. The Super-Droplet Method (SDM) and its Monte Carlo scheme for particle coalescence
3. RICO cloud macrophysics: SDM vs. other LES
4. RICO cloud microphysics: SDM vs. observations

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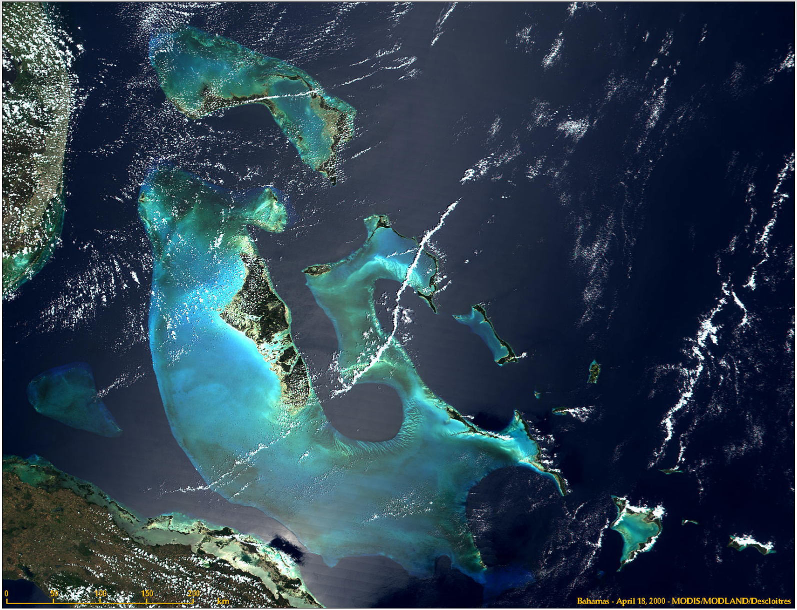
1. **Introduction: RICO and the trade-wind cumuli**
2. The Super-Droplet Method (SDM) and its Monte Carlo scheme for particle coalescence
3. RICO cloud macrophysics: SDM vs. other LES
4. RICO cloud microphysics: SDM vs. observations



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

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 Rain in Cumulus Over Ocean (RICO) campaign

(Loading movie...)

- 2 months of intensified observations (Dec 2004 – Jan 2005)
- 3 aircraft, 1 research vessel, 410 soundings
- . . . Rauber et al. 2007 MWR

The „RICO" LES set-up

van Zanten et al. 2011, (JAMES, in press):

- definition of the model benchmark case – the „RICO" set-up
- 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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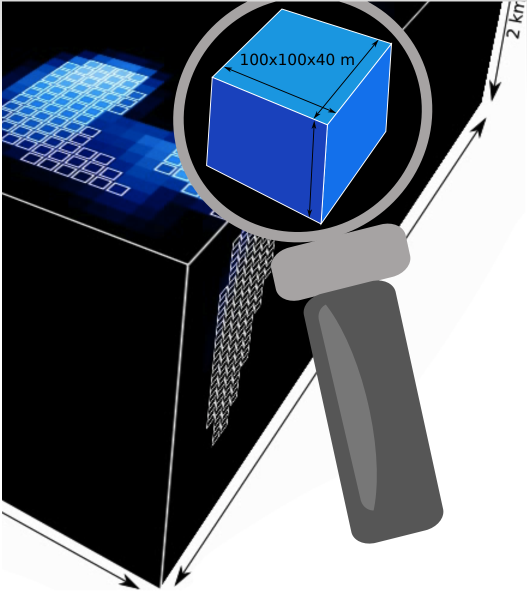
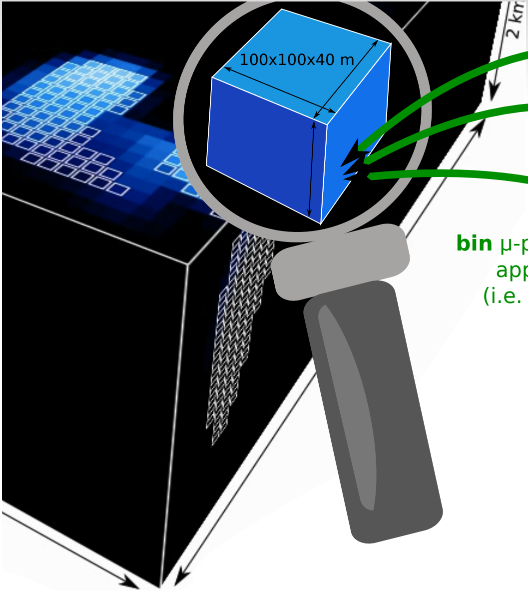
RICO set-up modelled with CReSS-bulk (Kessler param.)

(Loading movie...)

(model domain translated by $[-6, -4]$ m/s)

CReSS: Cloud Resolving Storm Simulator (Tsuboki and Sakakibara, 2006, Lect. Not. Comp. Sci.)


100x100x40 m
2 km

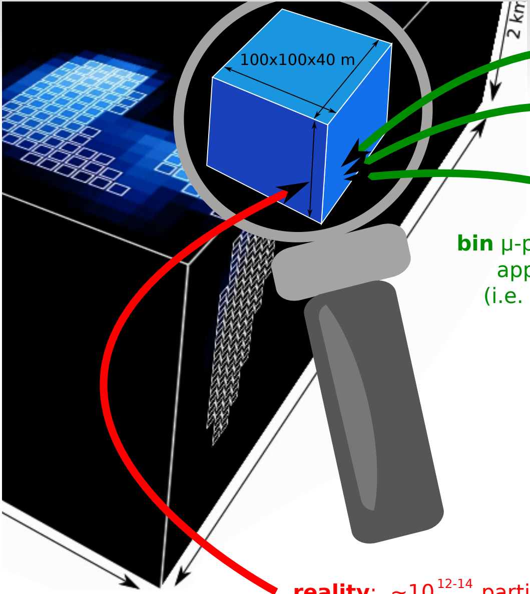


inside each grid box:

bulk μ-physics: q_c , q_r

2-moment μ-physics:
q_c, N_c, q_r, N_r

bin μ-physics: concentration density N(r)
approximated with a histogram
(i.e. defined for discrete drop radii r)



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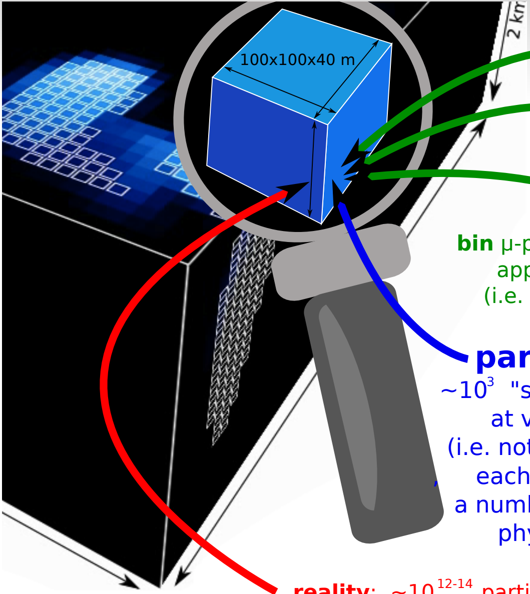
reality: ~$10^{12\text{-}14}$ particles of different sizes (aerosol, cloud, drizzle, rain particles)



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particle-based μ-physics:
$\sim 10^3$ "super-droplets" of variable radii,
at variable coordinates (x,y,z)
(i.e. not assigned to a given grid box)
each "super-droplet" representing
a number of real particles of the same
physico-chemical properties

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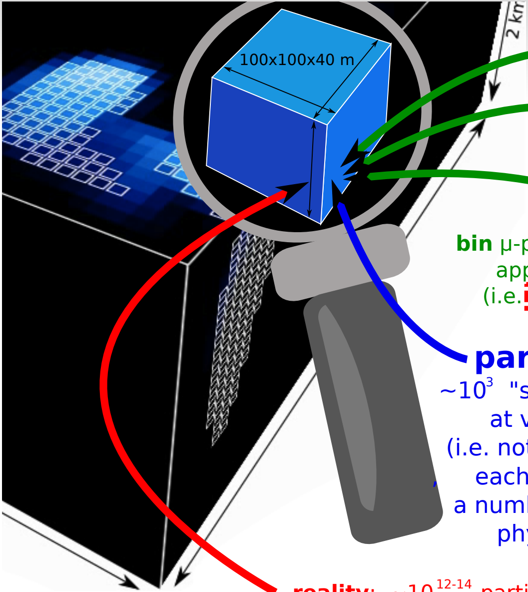

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The Super-Droplet Method (Shima et al, 2009, QJRMS)

Super-Droplet Method summary:

- particle-based cloud microphysics model in which basic physical principles (i.e. not parametrisations) are used to describe:
  - condensational growth (incl. CCN activation)
  - collisional growth (incl. rain initiation and aerosol wet deposition)
  - gravitational sedimentation (incl. drizzle and rain precipitation and aerosol dry deposition)
- Monte-Carlo type probabilistic scheme for numerically solving the droplet collision-coalescence process
- Method of coupling particle-based simulation with an LES

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SDM: Monte Carlo scheme the droplet coalescence process

- 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 following the latter of the two (consistent) scenarios:
  - a part of ξ real particles (defined by P_{ij}) coalesce every timestep
  - all of min(ξ_i,ξ_j) droplets coalesce once in a number of timesteps (defined by P_{ij}) $\rightsquigarrow$ 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}
- [n/2] random non-overlapping (i,j) pairs examined instead of all (i,j) pairs 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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Plan of the talk

CReSS-SDM (8 super-droplets per grid box)

(Loading movie...)

(model domain translated by $[-6, -4]$ m/s)

CReSS-SDM (32 super-droplets per grid box)

(Loading movie...)

(model domain translated by $[-6, -4]$ m/s)

CReSS-SDM (128 super-droplets per grid box)

(Loading movie...)

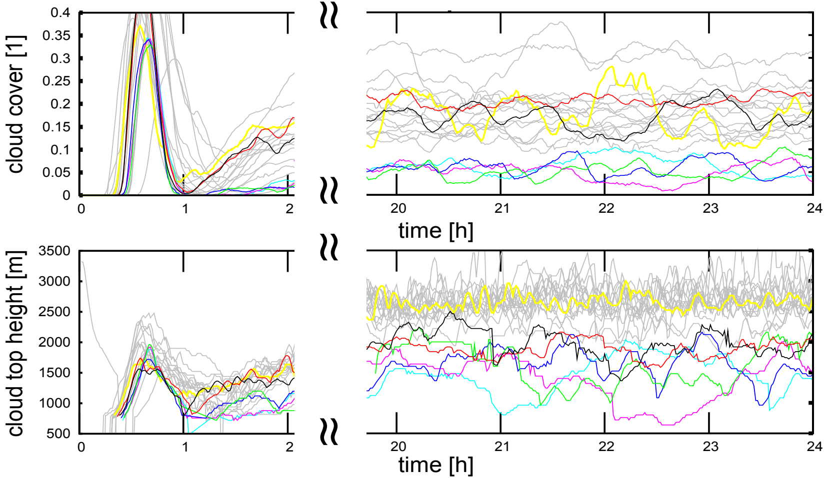
(model domain translated by $[-6, -4]$ m/s)

CReSS-SDM (512 super-droplets per grid box)

(Loading movie...)

(model domain translated by $[-6, -4]$ m/s)

- original RICO set-up grid: CReSS-bulk, 8 SD, 32 SD, 128 SD, 512 SD
- half grid size for all directions: 8 SD, 32 SD
- 13 LES models from van Zanten et al. 2011



- sensitivity to vertical grid resolution (supersaturation!)
- 24h simulation vs. lack of super-droplet sources (precipitation is a sink)

Plan of the talk

Fast-FSSP
(Forward Scattering Spectrometer Probe)

- measures laser light scattered by cloud droplets
- single-particle counter
- range: $2 - 50\,\mu m$ in diameter
- developed by Météo-France (Brenguier et al. 1998, JOAT)
- modified version of the FSSP-100
- key derived quantities:
  - cloud droplet number conc. (CDNC)
  - effective radius ($r_{eff} = \langle r^3 \rangle / \langle r^2 \rangle$)
  - radius standard deviation (σ_r)

(FSSP under the SPEC Learjet fuselage)

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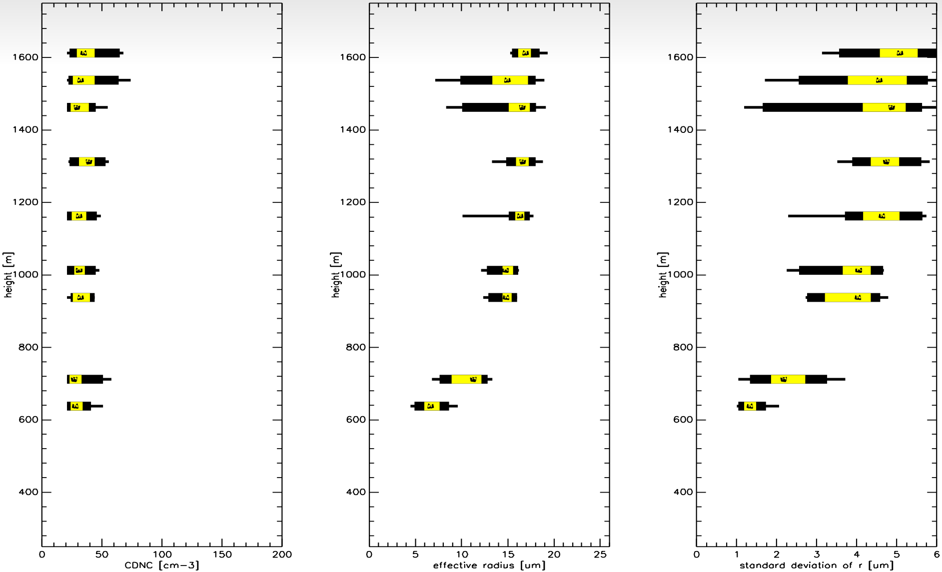
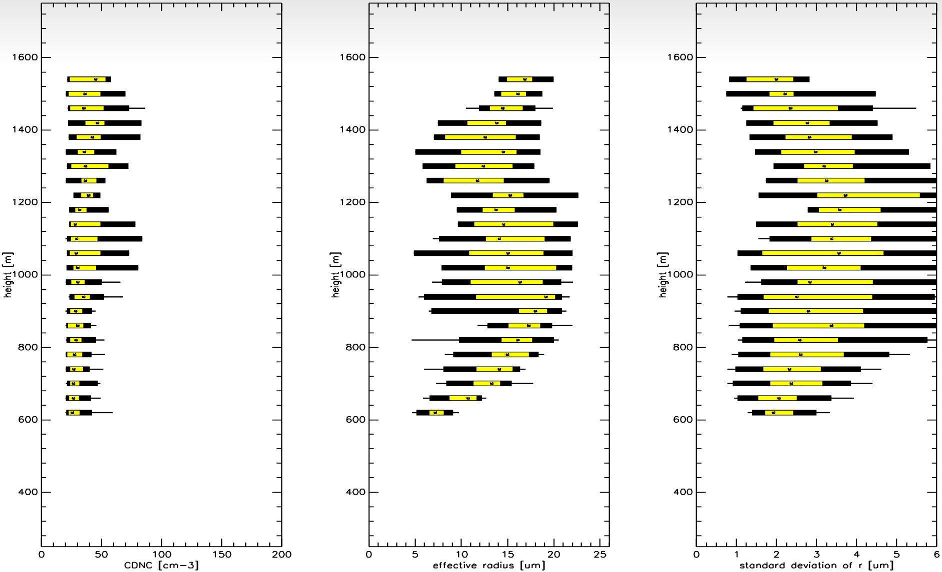
(FSSP under the SPEC Learjet fuselage)

Fast-FSSP height-resolved statistics of CDNC, r_{eff} & σ_r (Arabas et al. 2009, GRL)



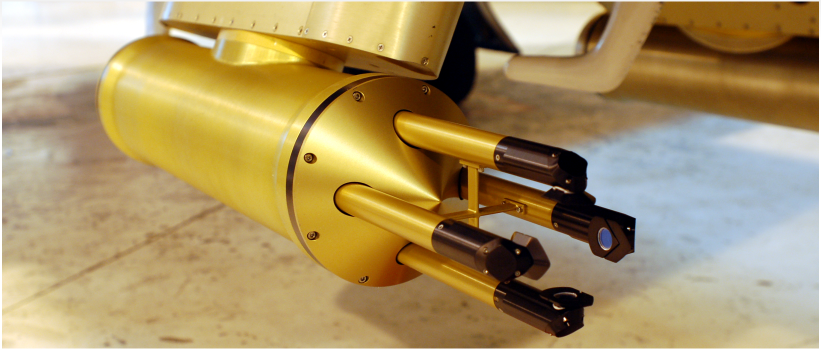
RICO RF07 (Dec. 17th 2004), frequency distributions at a given altitude: 0th, 5th, 25th, 50th, 75th, 95th and 100th percentiles

CReSS-SDM height-resolved statistics of CDNC, r_{eff} & σ_r (512 SD/gridbox)



domain-wide stats (t=5h) over Fast-FSSP spectral range, freq. dist. at a given alt.: 0^{th}, 5^{th}, 25^{th}, 50^{th}, 75^{th}, 95^{th} and 100^{th} percentiles

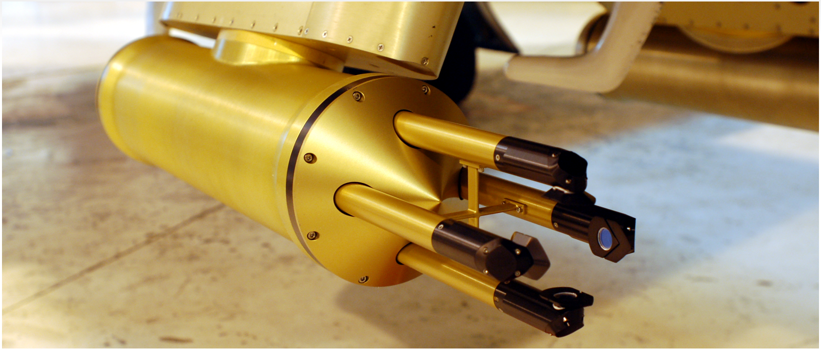
OAP-2DS (2-dimensional "stereo" optical array probe)



(OAP-2DS under the SPEC Learjet fuselage, thanks Brad for the visit to the hangar!)

- registers shadows of particles on two photodiode arrays
- multiple droplets at a time, particle spectra via image analysis
- sizes cloud, drizzle and rain particles (5–3000 μm diam.)
- developed by SPEC Inc., Boulder CO (Lawson et al. 2006, JAOT)
- RICO was one of the first campaigns for this instrument

OAP-2DS (2-dimensional "stereo" optical array probe)



(OAP-2DS under the SPEC Learjet fuselage, thanks Brad for the visit to the hangar!)

- registers shadows of particles on two photodiode arrays
- multiple droplets at a time, particle spectra via image analysis
- sizes cloud, drizzle and rain particles (5–3000 μm diam.)
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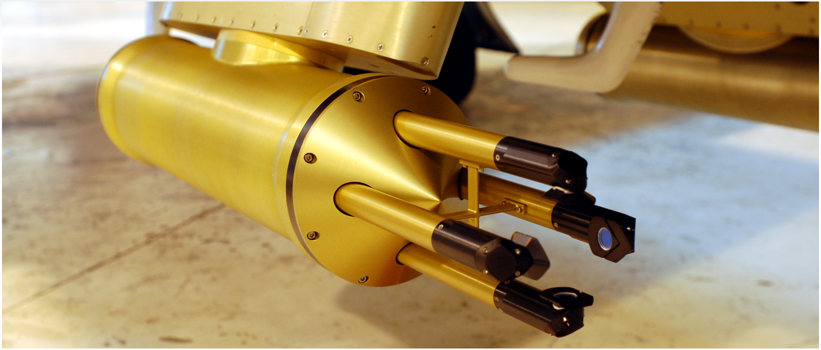

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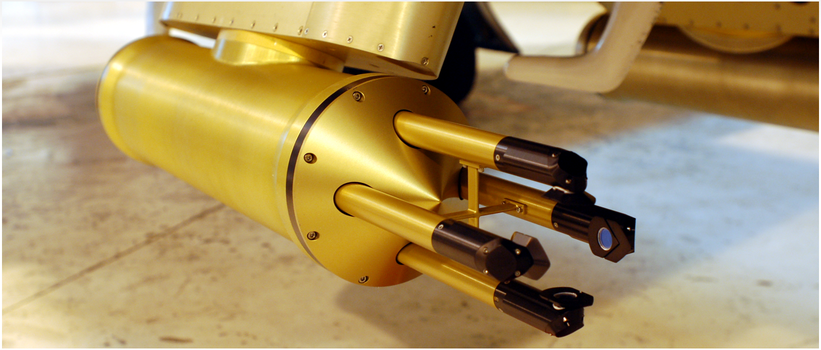

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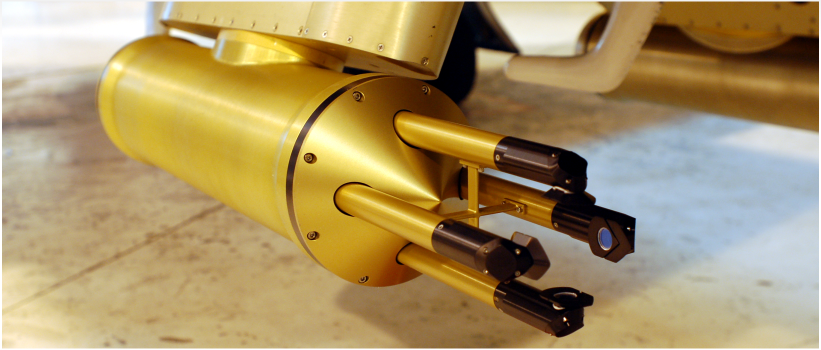

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OAP-2DS particle spectra in RICO rain-shafts

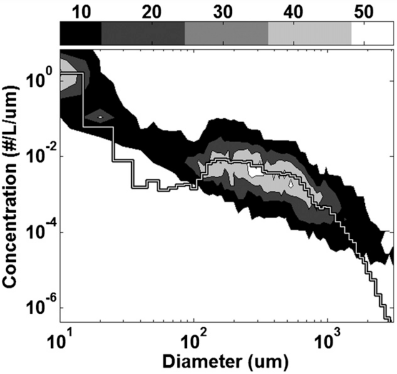

FIG. 4. The mean of 237 rain PSDs is shown on top of density contours of the 237 individual rain PSDs observed at 600-ft (~183 m) altitude over the ocean on 19 Jan 2005. The contours show the number of PSDs passing through the region. Very few individual PSDs have any counts at all between 30 and 100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

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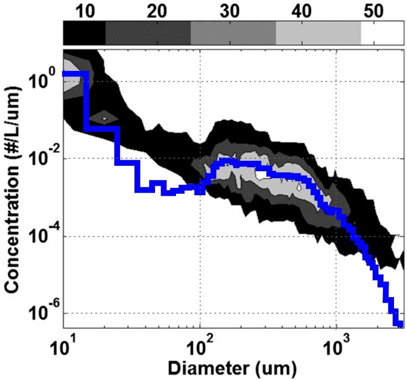
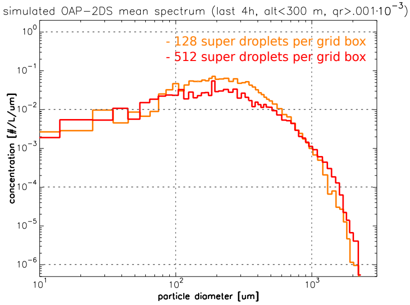
Baker et al. 2009, J. Appl. Meteor. Clim.

OAP-2DS spectra vs. RICO SDM simulations

- RF17 (Jan. 19th 2005)
- 237 size distributions (line=mean)
- observed in rain shafts at 180m (600ft) cloud base at ca. 500m (1600ft)

- means over the last 4h of simulation
- altitude < 300 m, $q_r > 0.001 g/kg$
- OAP-2DS bin layout





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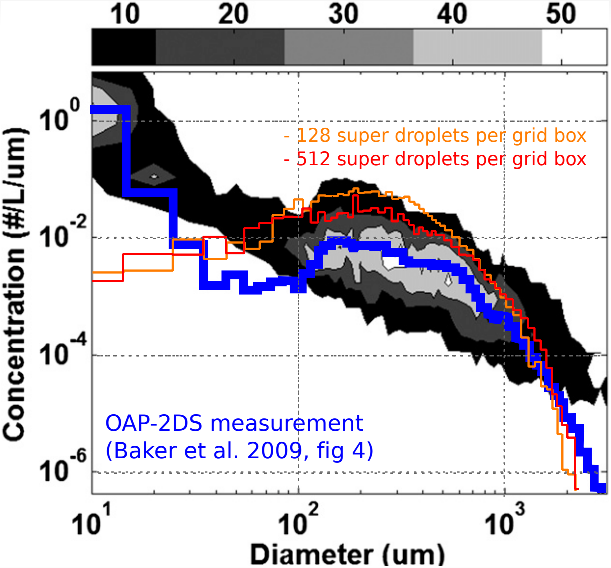

Summary and outlook

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- Monte-Carlo type cloud μ-physics coupled with LES
- 24h simulations of a field of precipitating trade-wind cumuli
- prediction of detailed features of aerosol/cloud/drizzle/rain spectrum
- encouraging results from comparison with aircraft observations

Outlook

- perturbing initial aerosol spectrum $\rightsquigarrow$ impact on precip/albedo
- tracing back above-cloud base CCN activation
- ...
- turbulent coalescence kernel; aerosol processing

Acknowledgements: JAMSTEC, The Earth Simulator; Akira T. Noda & Kanya Kusano; CReSS model developers; Hanna Pawlowska

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The Feynman Lectures on Physics, 1964

Thank you for your attention!

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The Feynman Lectures on Physics, 1964

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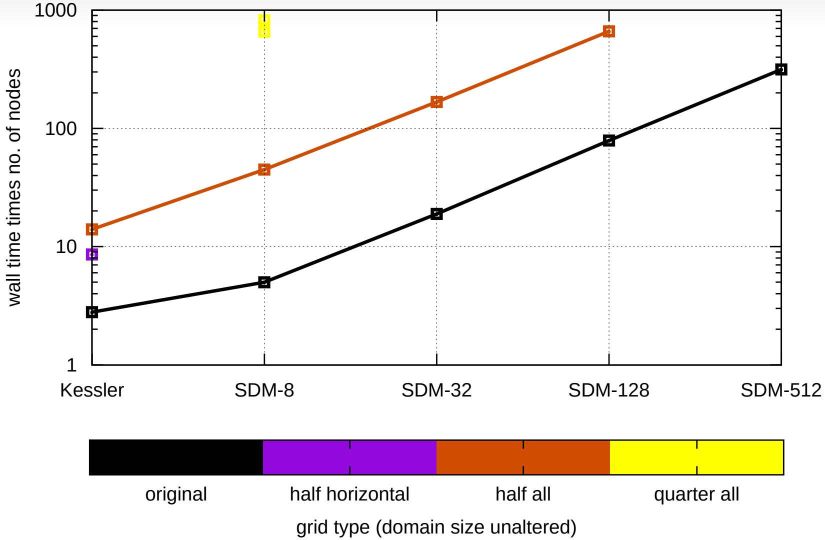
RICO set-up (van Zanten et al. 2011, JAMES)

http://www.knmi.nl/samenw/rico/

- duration: 24h (analyses mostly over the last 4h)
- domain size: 12.8 $\times$ 12.8 $\times$ 4.0 km; 128 $\times$ 128 $\times$ 100 grid points
- boundary conditions:
  - lateral: periodic
  - top: sponge layer 200 m above the mean inversion height
  - bottom: surfaces fluxes parameterised
- initial condition: u, v, q_t, & θ_l profiles based on observations/reanalysis
- initial random q_v and θ perturbations
- surface: constant SST of 299.8 K, prescribed drag coefficients
- large-scale forcings (subsidence & large-scale advection)
- other: domain translation by mean wind (SDM less sensitive than Kessler)
- CReSS/SDM options:
  - coalescence kernel: Hall
  - subgrid-scale model: Smagorinsky
  - advection scheme: semi-Lagrangian / Cubic Lagrange interpolation

CReSS: bulk vs. SDM computational cost



CCN activation spectrum for the RICO set-up

predictions for lognormal fits to RICO aerosol aircraft observations

(using adaptive moving-sectional air-parcel model, Arabas & Pawlowska 2011, GMD)