Particle-based aerosol/cloud/rain microphysics for LES
Super-Droplet model validation against RICO aircraft observations

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

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

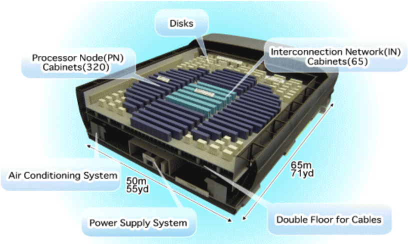
International MetStröm Conference
Berlin, June 9th, 2011

Rain in Cumulus over Ocean (Rauber et al. '07)

(click to start the movie)

NCAR C-130 at the Antigua's airport (photo: B. Stevens)

The Earth Simulator building (Yokohama, Japan)



(click to start the movie)

RICO LES intercomparison (van Zanten et al. '11)

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.)

RICO LES intercomparison

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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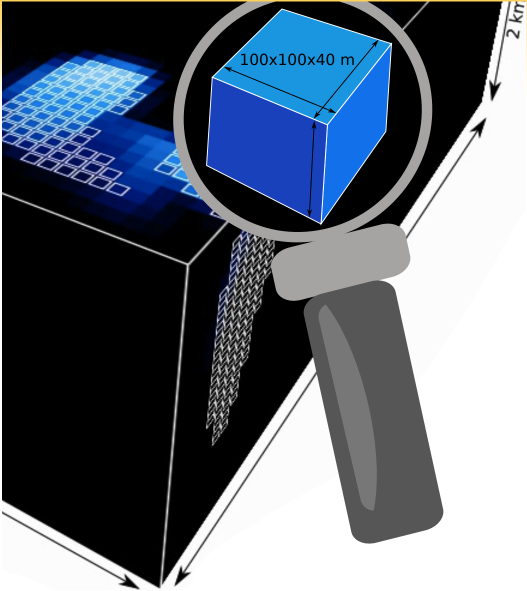
100x100x40 m
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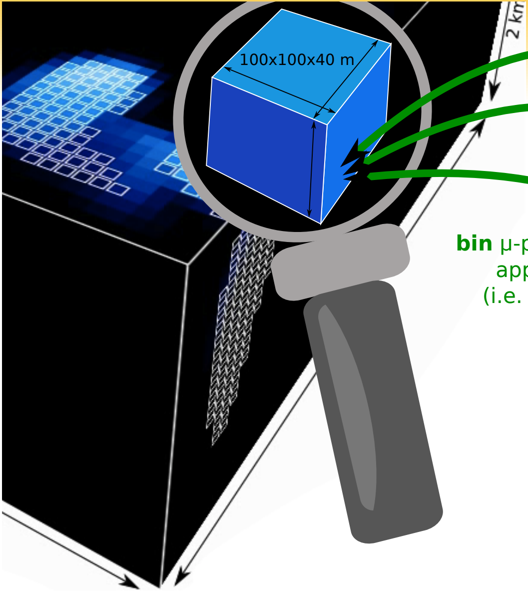

inside each grid box:

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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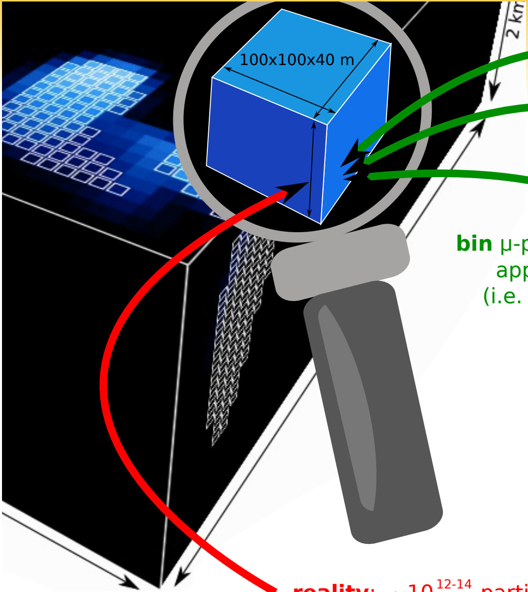

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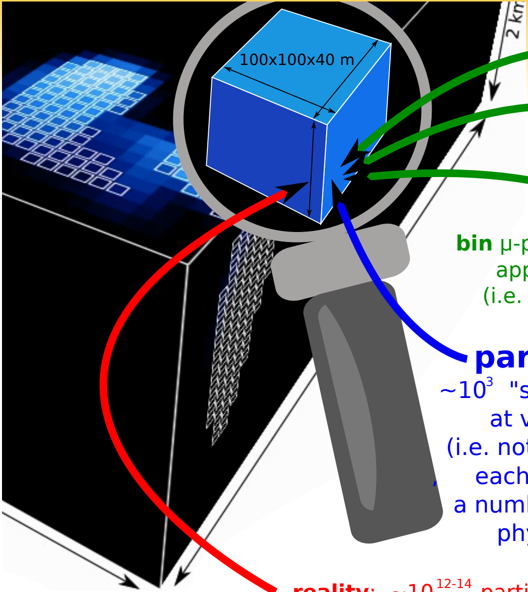
reality: ~$10^{12\text{-}14}$ particles of different sizes
(aerosol, cloud, drizzle, rain particles)



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particle-based μ-physics:

~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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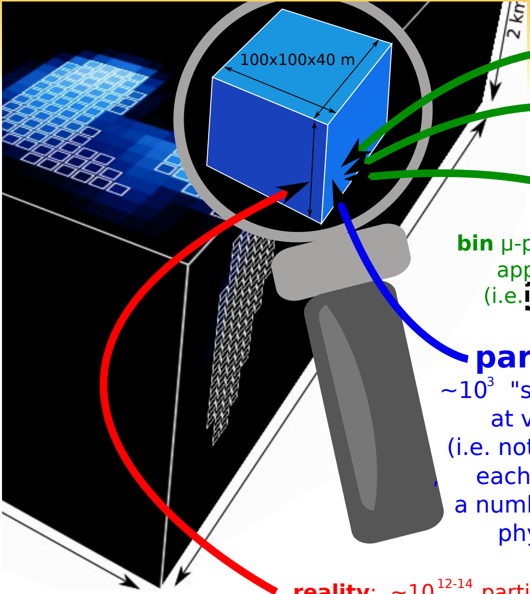

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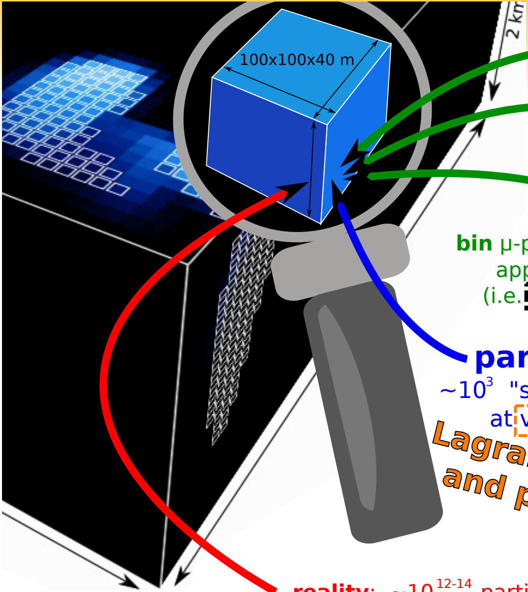

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Lagrangian in both physical and particle-radius space

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

Super-Droplet Method summary:

- particle-based cloud microphysics model describing (in a non-parametrised way):
    - 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

similar formulation (save for the Monte-Carlo collisions) as in e.g.:
– Lagrangian Cloud Model (LCM) by Andrejczuk, Grabowski et al. (2010)
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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 $\min(\xi_i, \xi_j)$ 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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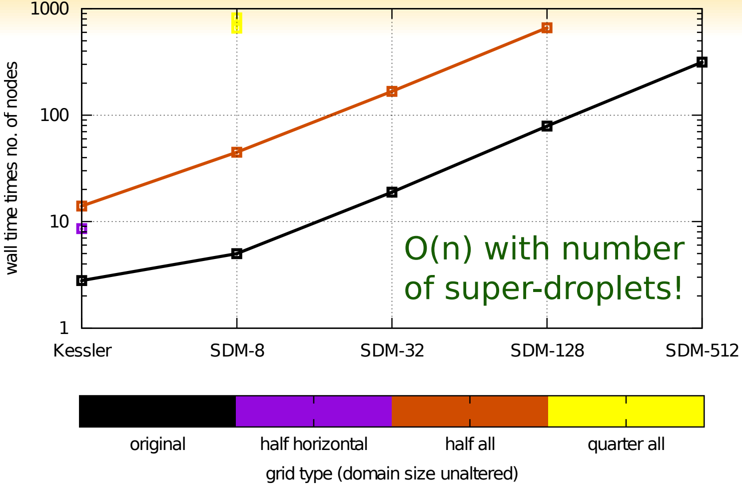
CReSS: bulk vs. SDM computational cost



EARTH SIMULATOR

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...)

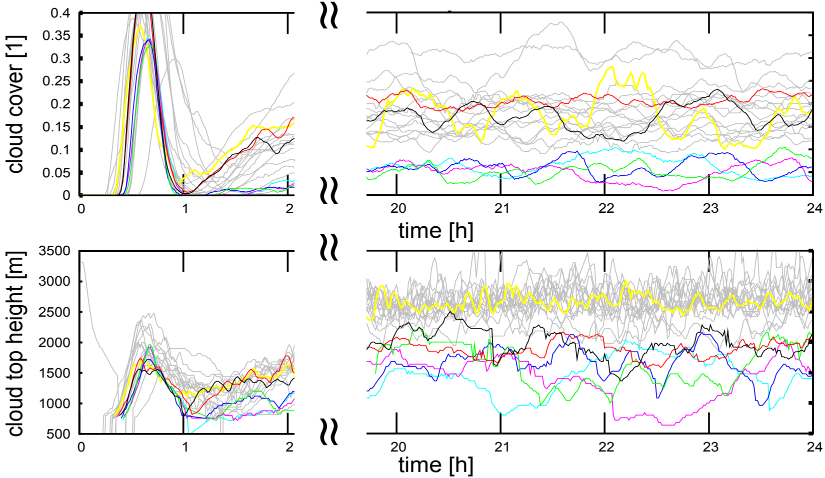
(model domain translated by $[-6, -4]$ m/s)

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 (data: http://knmi.nl/samenw/rico)



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

Particle-based simulation results may be directly compared with particle-counting/sizing measurements!

Fast-FSSP:

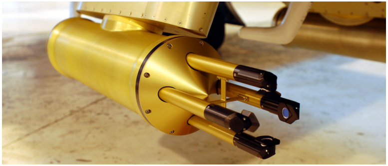
- measures light scattered by single cloud particles
- sizes cloud droplets in the 2-50 μm diameter range

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
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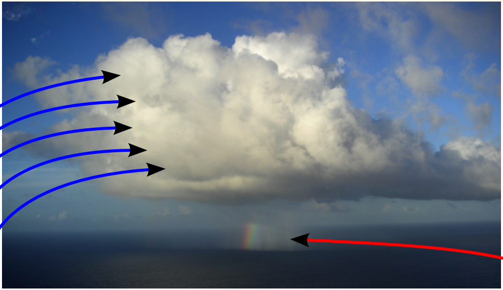

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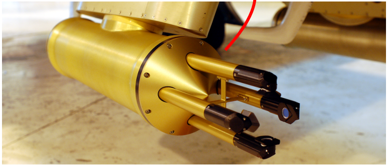

OAP-2DS / SPEC Inc. Boulder CO
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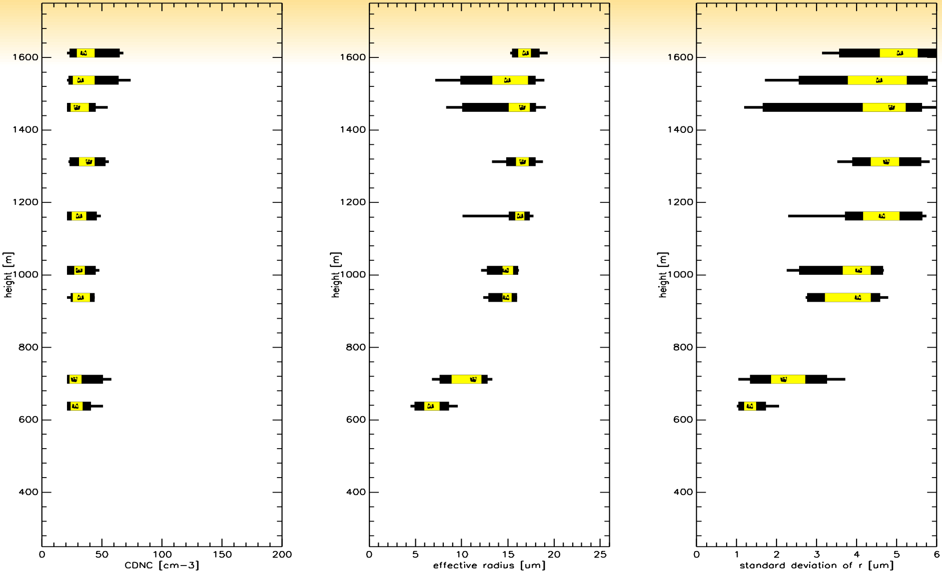
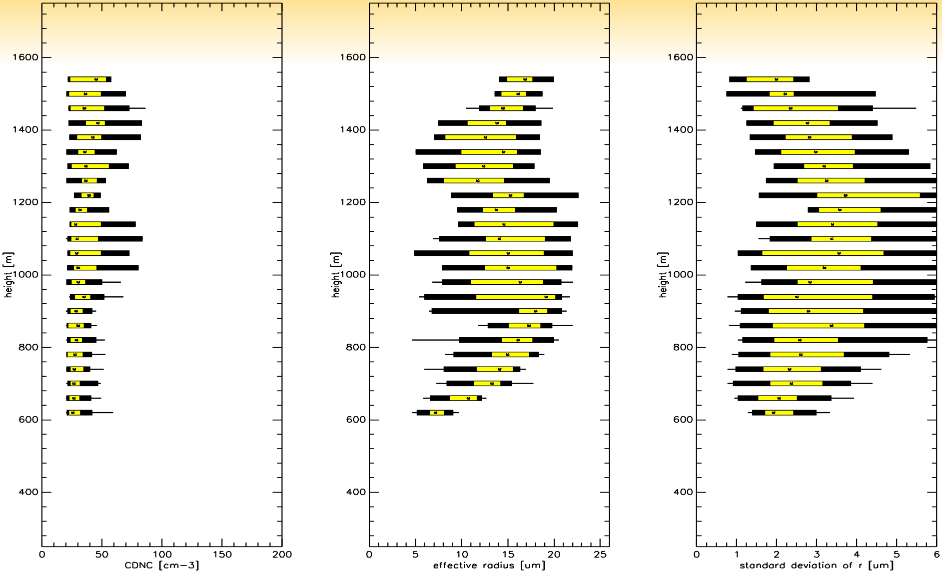
Fast-FSSP height-resolved statistics of CDNC, r_{eff} & σ_r (Arabas et al. 2009, GRL)



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

Baker et al. 2009: OAP-2DS spectra in RICO rain-shafts

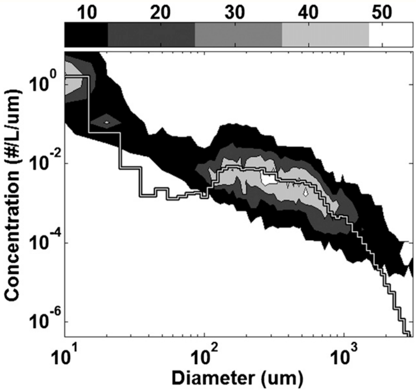


FIG. 4. The mean of 237 rain PSDs is shown on top of density contours of the 237 individual rain PSDs observed at 600-ft (~183 m) altitude over the ocean on 19 Jan 2005. The contours show the number of PSDs passing through the region. Very few individual PSDs have any counts at all between 30 and 100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

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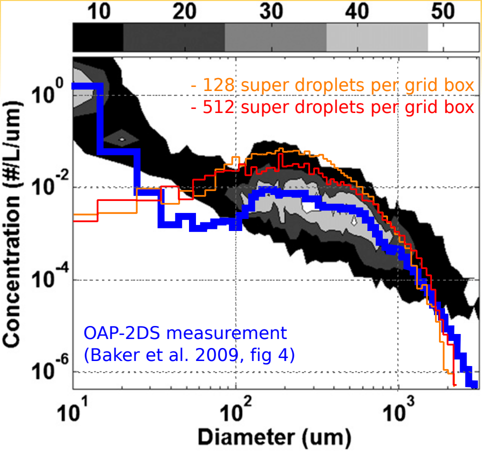
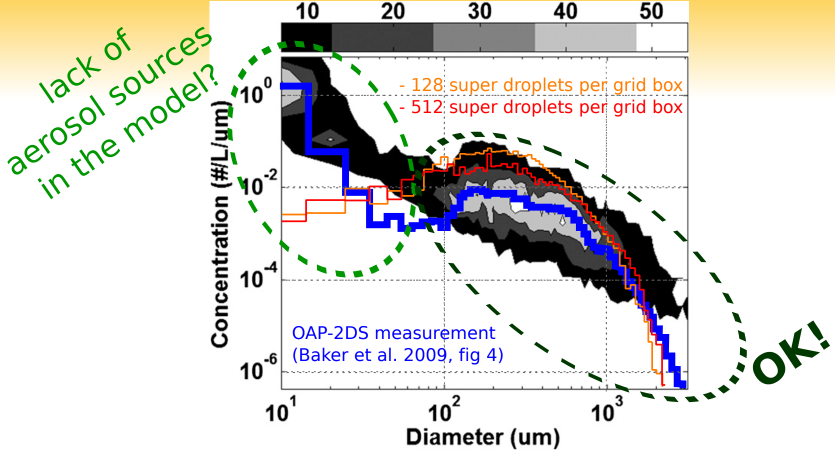


Baker et al. 2009:

- OAP-2DS, RICO RF17 (Jan. 19th 2005)
- 237 size distributions (line=mean)
- observed in rain shafts at 180m (600ft)

Super-droplet simulation:

- 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
- ...

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Thank you for your attention!

(click to start the movie)

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

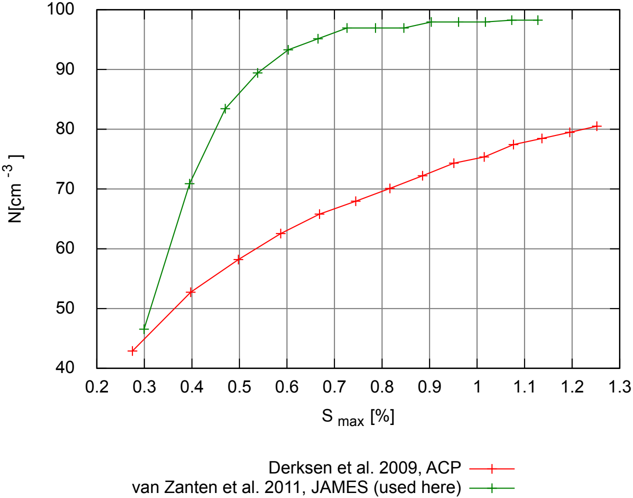
http://www.knmi.nl/samenw/rico/

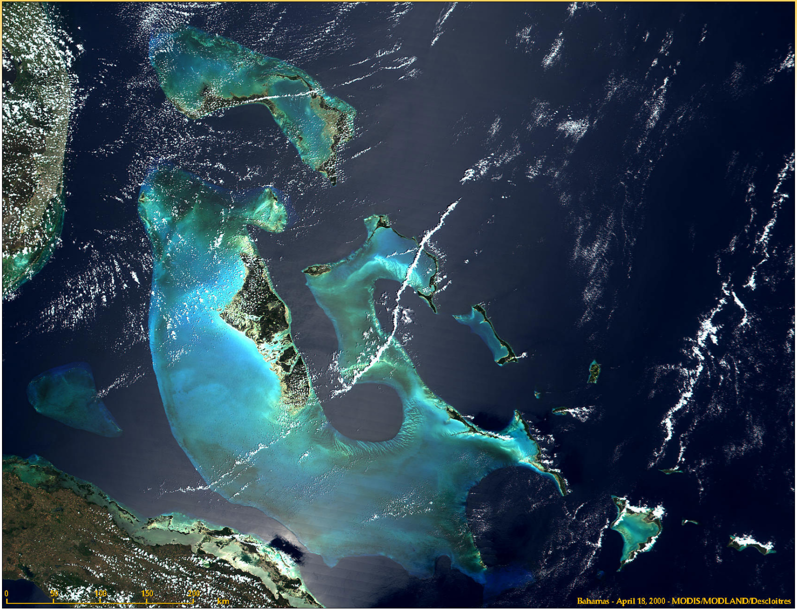
- duration: 24h (analyses mostly over the last 4h)
- domain size: 12.8 × 12.8 × 4.0 km; 128 × 128 × 100 grid points
- boundary conditions:
  - lateral: periodic
  - top: sponge layer 200 m above the mean inversion height
  - bottom: surfaces fluxes parameterised
- initial condition: u, v, q_t, & θ_l 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

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)





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