Numerical modeling of shallow cumulus convection

Impact of entrainment and mixing on clouds

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Runs:

- 3-dimensional LES
- Eulerian version, cartesian mesh
- anelastic approach
- Supercomputer frost (NCAR)
- Sources: activation, condensation, accretion, evaporation, autoconversion, self-collection ...
- Rain drop fallspeed parameters vary as a function of drop diameter

- One-moment scheme

(Kessler parameterization)

Kessler, E., 1969: On distribution and continuity of water substance in atmospheric circulations. American Meteorological Society, Mereorol. Monogr., 10:32, 84.

$$\frac{d\theta}{dt} = \frac{L\theta_e}{c_p T_e}(C_d - E_r) + D_\theta ,$$

$$\frac{dq_v}{dt} = -(C_d - E_r) + D_{q_v} ,$$

$$\frac{dq_c}{dt} = C_d - A_r - C_r + D_{q_c} ,$$

$$\frac{dq_r}{dt} = \frac{1}{\tilde{\rho}}\frac{\partial}{\partial z}(\tilde{\rho} V_t q_r) + A_r + C_r - E_r + D_{q_r} .$$

MIXING

- Mixing scenario depends on the time scale of mixing and the time scale of evaporation

✓ **extremely inhomogeneous**:

- Time scale of cloud droplet evaporation is significantly larger than time scale of turbulent mixing
- Cloud droplet concentration decreases
- Mean cloud droplet radius does not change

✓ **inhomogeneous:**

- Concentration and mean cloud droplet radius decrease

✓ **homogeneous**:

- Time scale of turbulent mixing is significantly larger than time scale of cloud droplet evaporation
- Cloud droplet concentration “constant” (affected only by dilution)
- Mean cloud droplet radius decreases

Subgrid scale mixing:

- Microphysical adjustment for tendencies due to mixing:

$$N_f = N_i \left(\frac{q_f}{q_i}\right)^{\alpha}$$

i-initial values

f-final values

Mixing scenarios:

- ✓ extremely inhomogeneous: (α =1)
- ✓ inhomogeneous: ($0 < \alpha < 1$)
- ✓ homogeneous: ($\alpha = 0$)

Shallow cumulus convection without precipitation:

BOMEX

Barbados Oceanographic and Meteorological Experiment (1969)

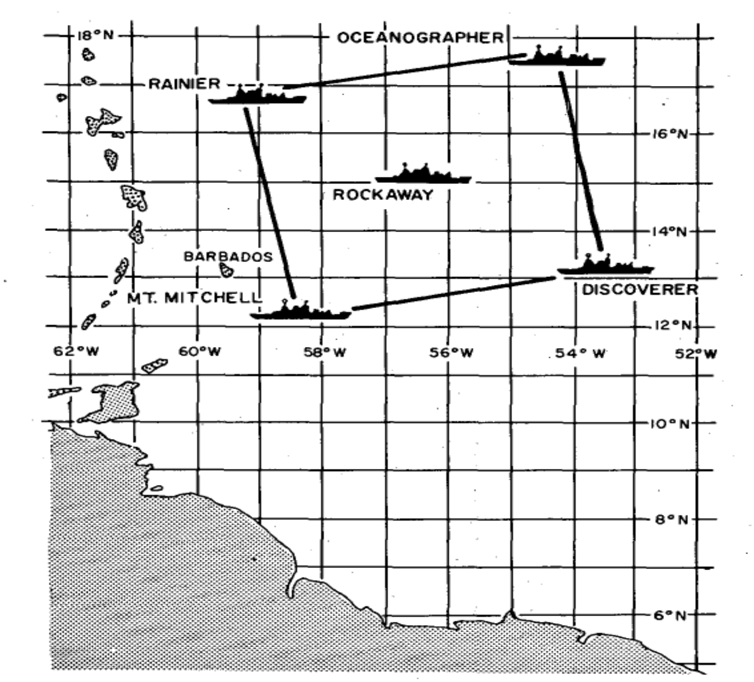
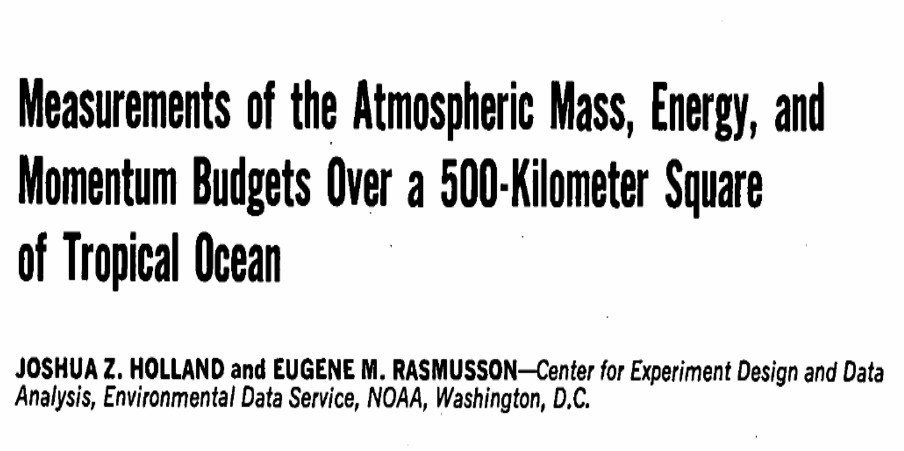


FIGURE 1.—Ship array during BOMEX Observation Periods I, II, and III, May 1–July 1, 1969.

- Date: summer 1969
- Place: Atlantic East of Barbados



Measurements of the Atmospheric Mass, Energy, and Momentum Budgets Over a 500-Kilometer Square of Tropical Ocean

JOSHUA Z. HOLLAND and EUGENE M. RASMUSSON—*Center for Experiment Design and Data Analysis, Environmental Data Service, NOAA, Washington, D.C.*

Monthly Weather Review, 1973,101:44-55

Setup

From: Siebesma et al. JAS (2003): 'A Large Eddy Simulation Intercomparison Study of Shallow Cumulus Convection'

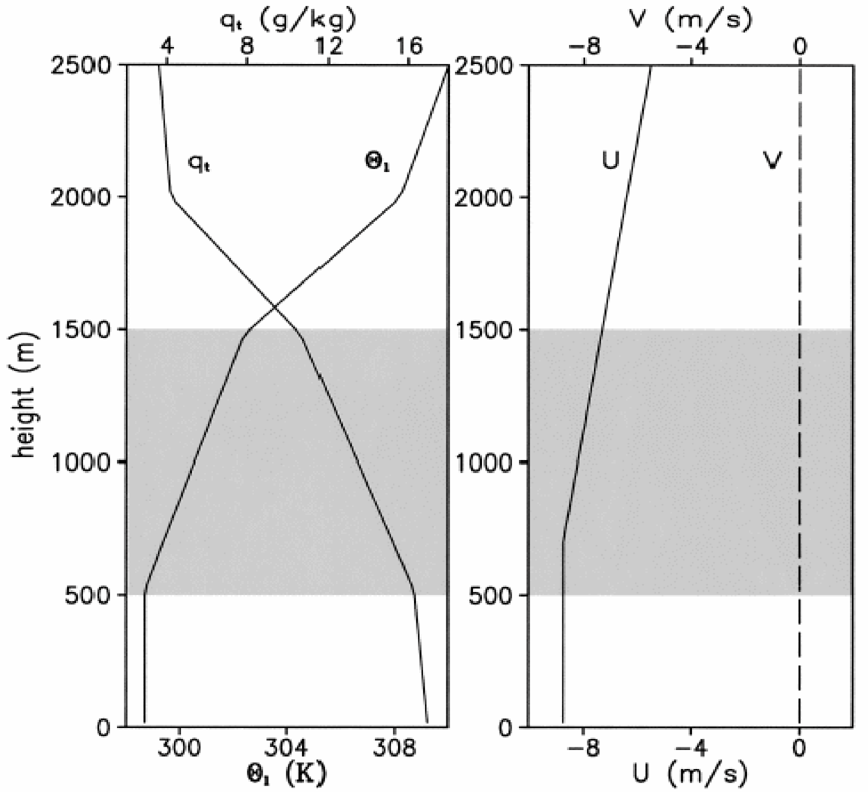


FIG. 1. Initial profiles of the total water specific humidity q_t, the liquid water potential temperature θ_ℓ, and the horizontal wind components u and v. The shaded area denotes the conditionally unstable cloud layer.

<u>Computational domain:</u>
6.4 km * 6.4 km * 3km

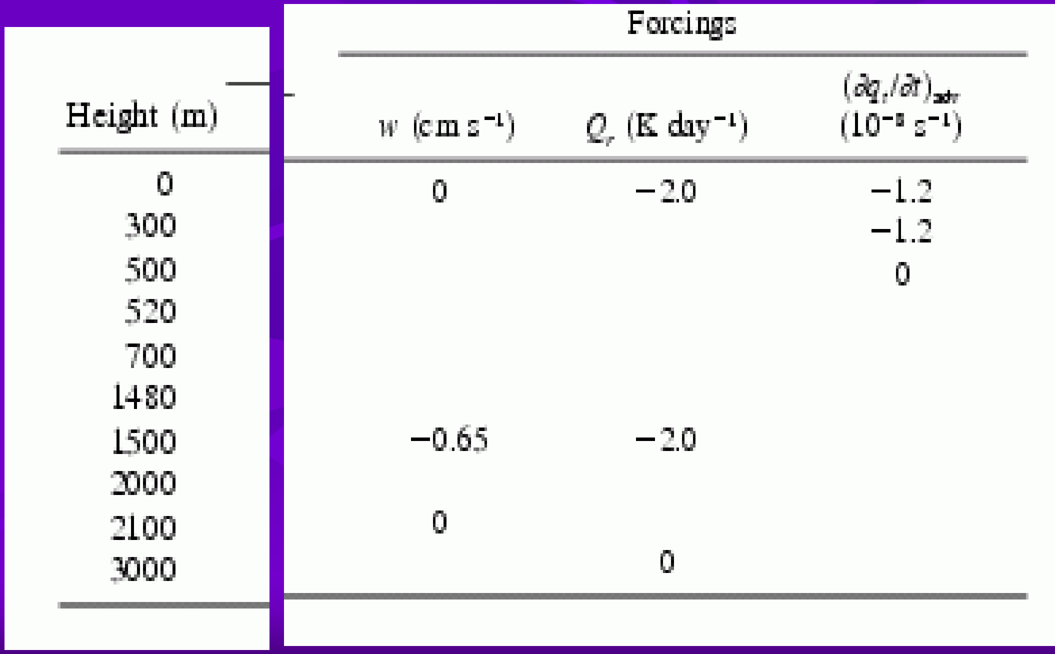
nx=ny=64; nz=75
dx=dy=2.5*dz=100m
dt=1s

The simulations are run for 6 h.
Data are storaged every 10 minutes.
The last 3 hours are used in the analysis.

SHALLOW CONVECTION SIMULATIONS

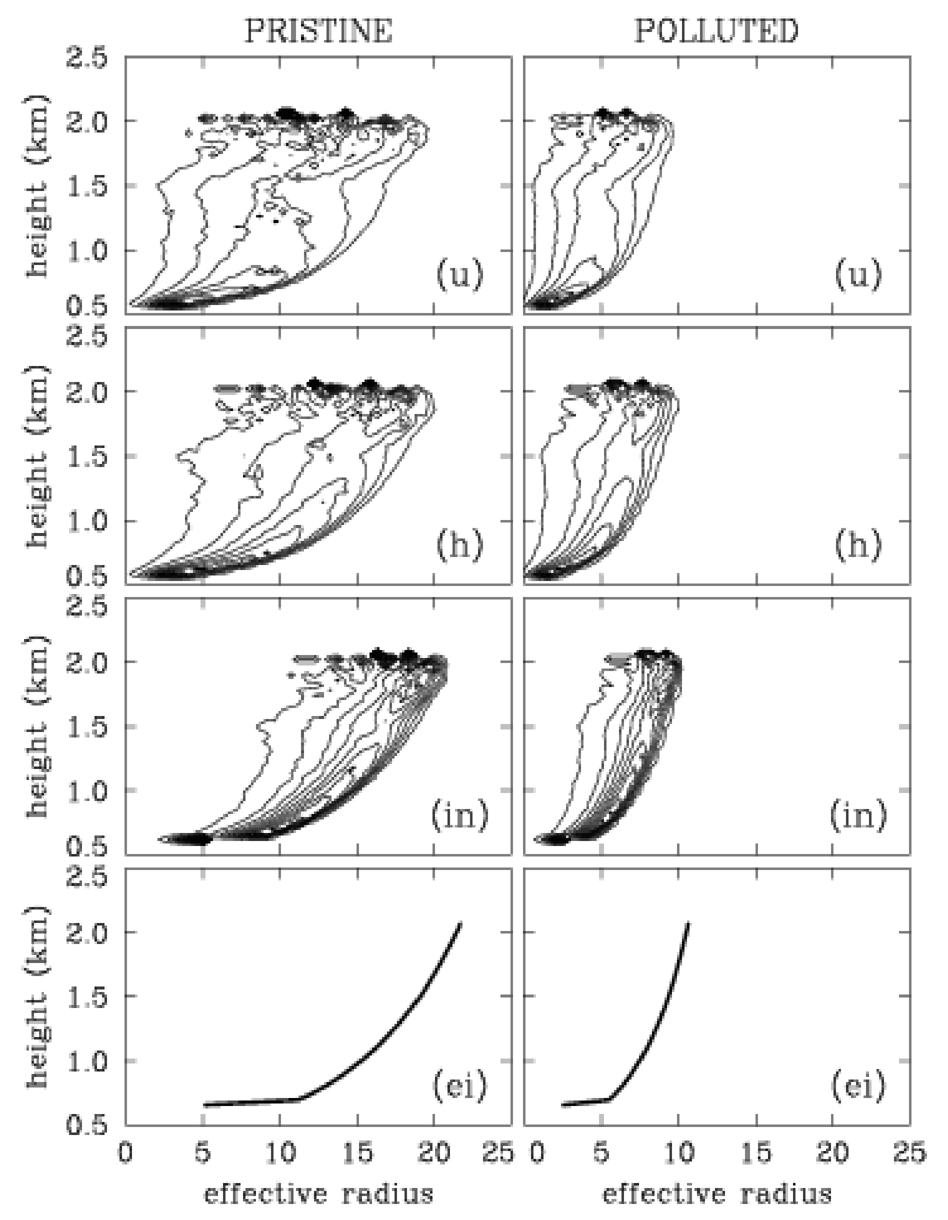
- Surface fluxes:
  - ✓ momentum: $<v'w'> = u_*^2 * \bar{U} * |\bar{U}|^{-1}$, $u_*=0.28$ m s^{-1}
  - ✓ latent heating: $<w'q_l'> = 5.2*10^{-3}$ m s^{-1}
  - ✓ sensible heating: $<w'Q'> = 8*10^{-3}$ K m s^{-1}

- Large-scale forcing:
  - ✓ subsidence
  - ✓ advection of water vapour
  - ✓ advection of temperature
  - ✓ radiative cooling



Height (m)	Forcings		
	w (cm s^{-1})	Q_r (K day^{-1})	$(\partial q_t/\partial t)_{adv}$ (10^{-8} s^{-1})
0	0	−2.0	−1.2
300			−1.2
500			0
520			
700			
1480			
1500	−0.65	−2.0	
2000			
2100	0		
3000		0	

BOMEX, one-moment scheme



Assumed concentration of droplets:

PRISTINE: N= 100 mg-1

POLLUTED: N=1000 mg-1

Mixing scenario:

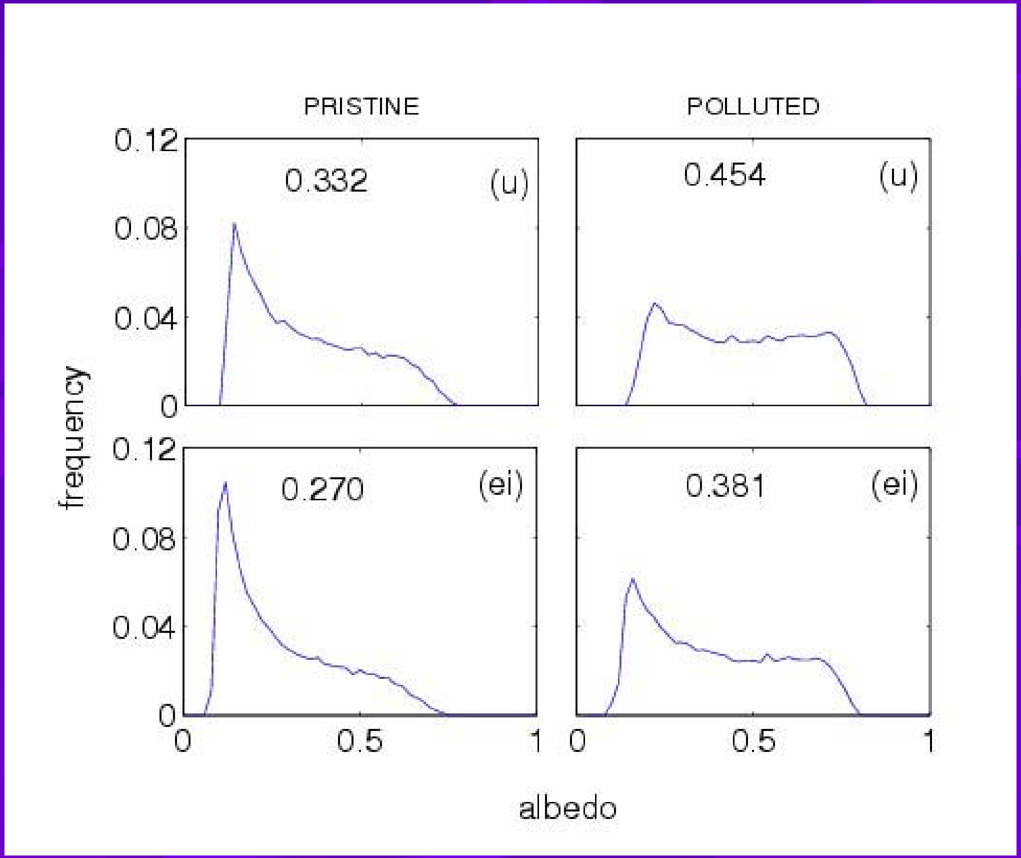
u – uniform

h – homogeneous

in – inhomogeneous

ei – extremely inhomogeneous

CFAD - Contoured Frequency by Altitude Diagram for cloudy grid points: qc > 0.01 g kg^{-1}



Off-line radiative transfer: independent column approximation

Histograms of cloud TOA (top of the atmosphere) albedo for model columns with LWP (liquid water path) larger than 0.005 kg m^{-2}.
Mean albedo is shown in each panel.

Slawinska J, Grabowski WW, Pawlowska H, Wyszogrodzki A; *J. Climate*, **21**, 1639-1647. Optical properties of shallow convective clouds diagnosed from a bulk-microphysics large-eddy simulation.

TWO-MOMENT MICROPHYSICAL SCHEME

(Morrison and Grabowski; JAS, 2007a,b)

Cloud droplet and drizzle/rain drops are predicted.

Assumed gamma size distributions: $N(D)=N_0 D^{\mu} e^{-\lambda D}$

Rain drops are assumed to follow a Marshall-Palmer (exponential) size distribution, implying $\mu=0$.

The parameter $\mu=\eta^{-2}-1$ uses parametrizations of Martin et al. (1994):

$\eta = 0.0005714\, N_c + 0.2714$

Possible three different parametrizations for the coalescence processes:

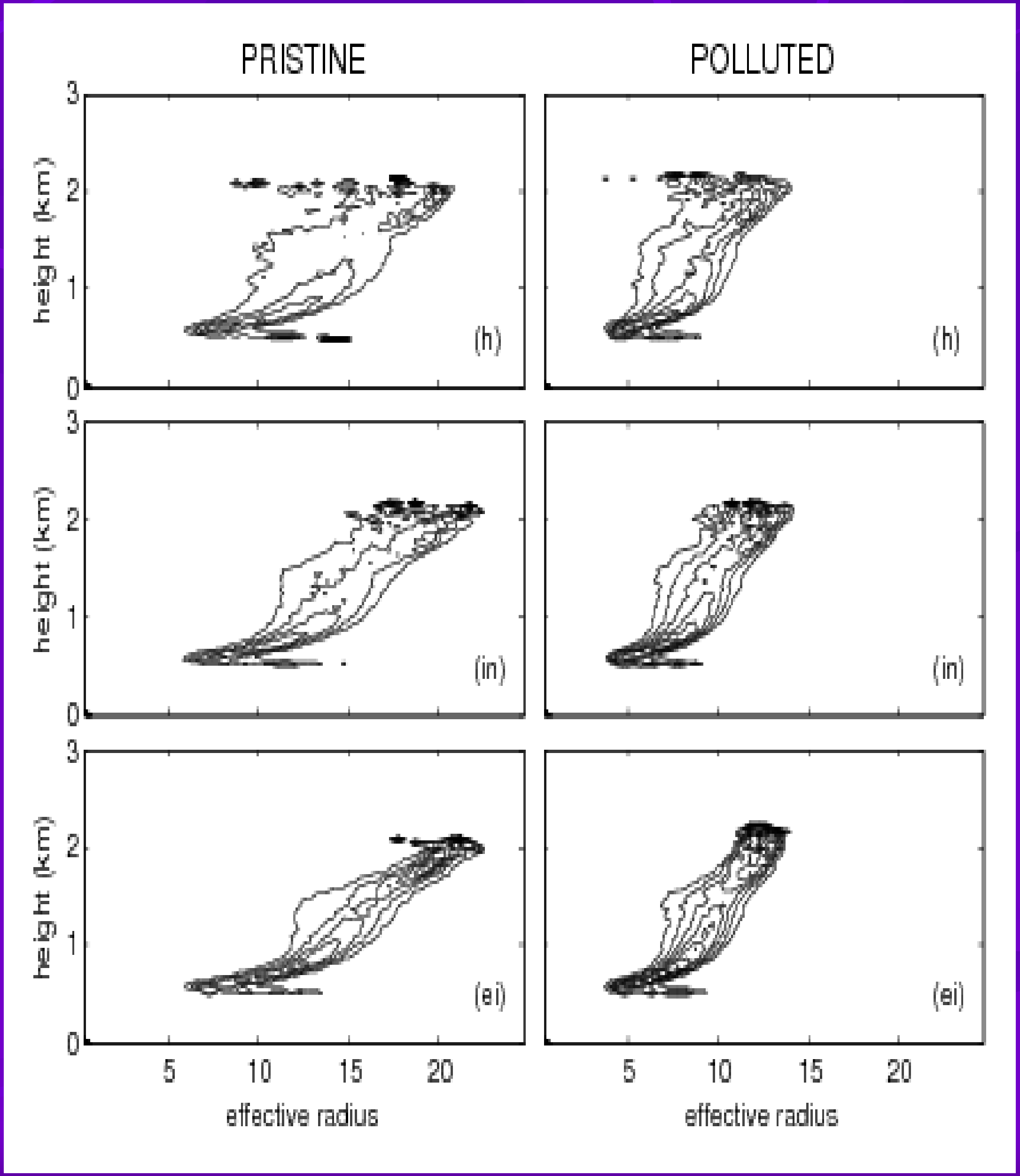
- Beheng (1994)
- Seifert and Beheng (2001)
- Khairoutdinov and Kogan (2000)

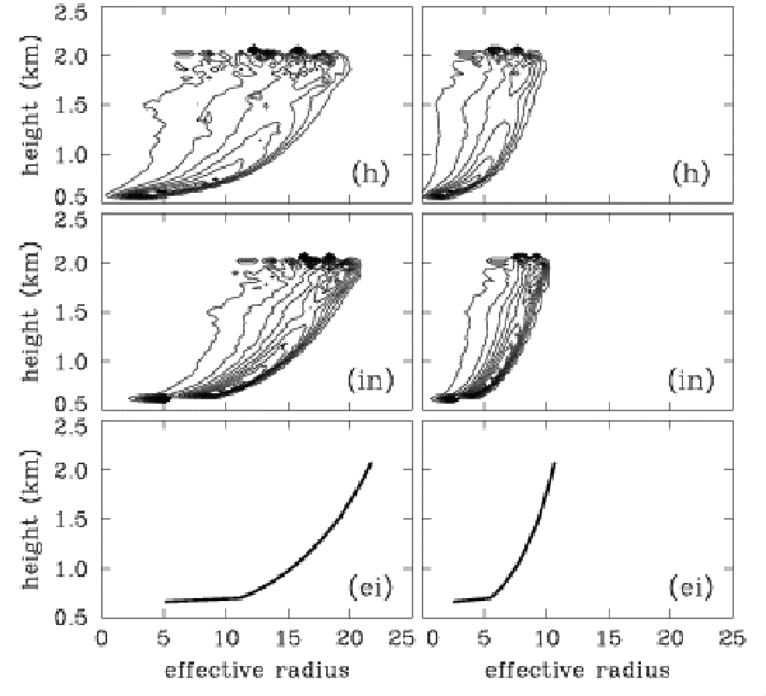
Bomex simulations with two-moment scheme

(in comparison with one-moment scheme)

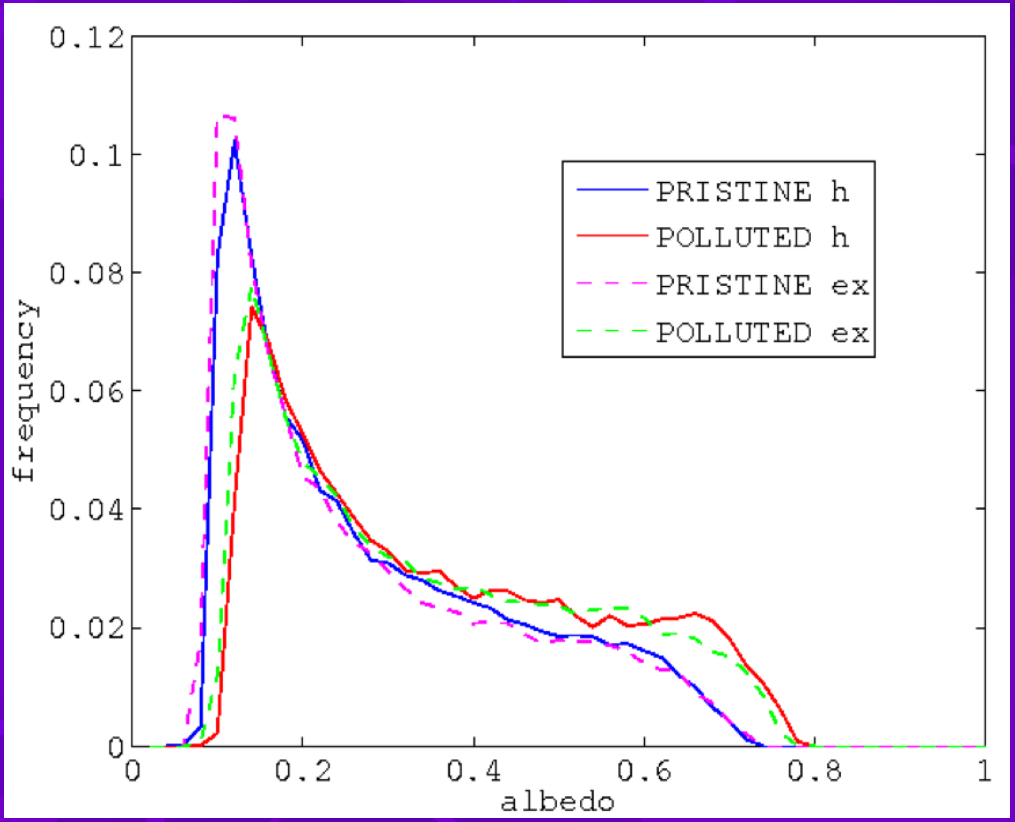
Aerosol characteristics:

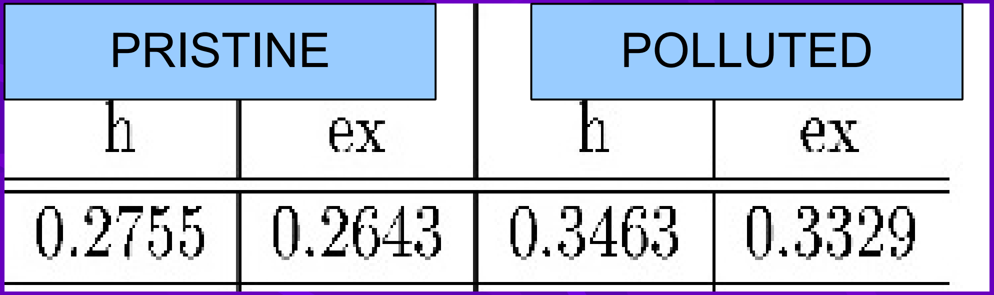
- ➢ Maritime with aerosol concentration of 100 mg^{-1} – the PRISTINE case
- ➢ Continental with aerosol concentration of 1000 mg^{-1} - the POLLUTED case





PDFs (plots) and averages (tables) of albedo for model columns with LWP greater than 5×10^{-3} kg m^{-2}

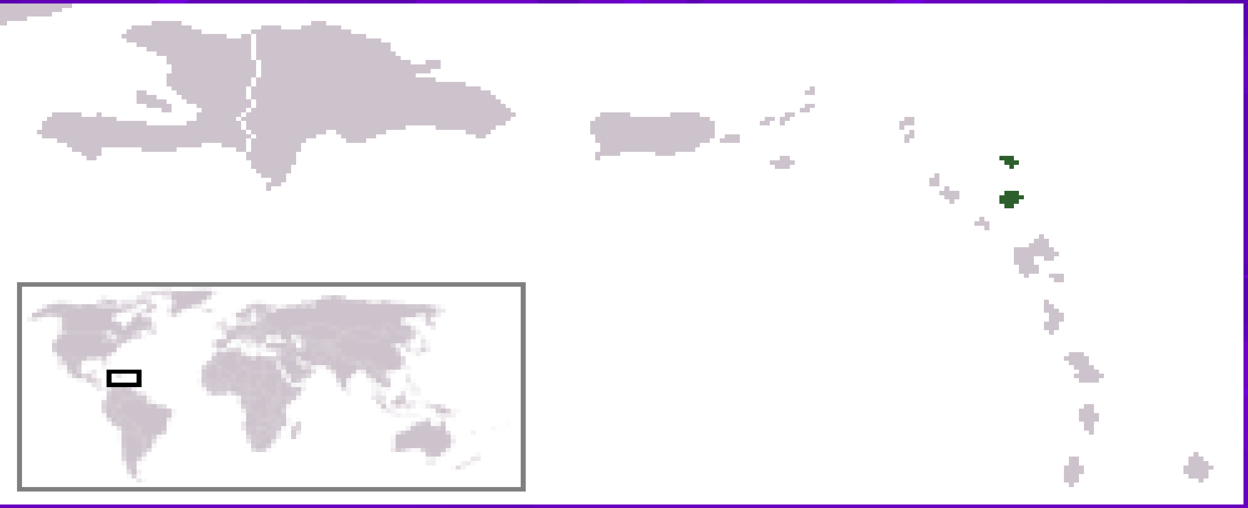




PRISTINE		POLLUTED	
h	ex	h	ex
0.2755	0.2643	0.3463	0.3329

Differences smaller than for one-moment scheme!

Shallow cumulus convection with precipitation



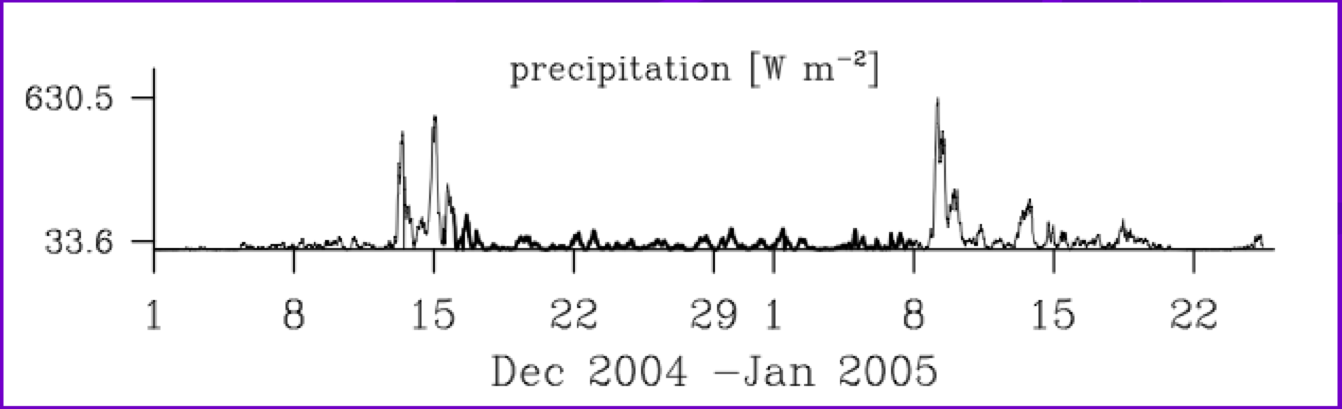
RICO

(Rain In Cumulus over the Ocean)

DATE: winter 2004/2005

PLACE: Antigua i Barbuda

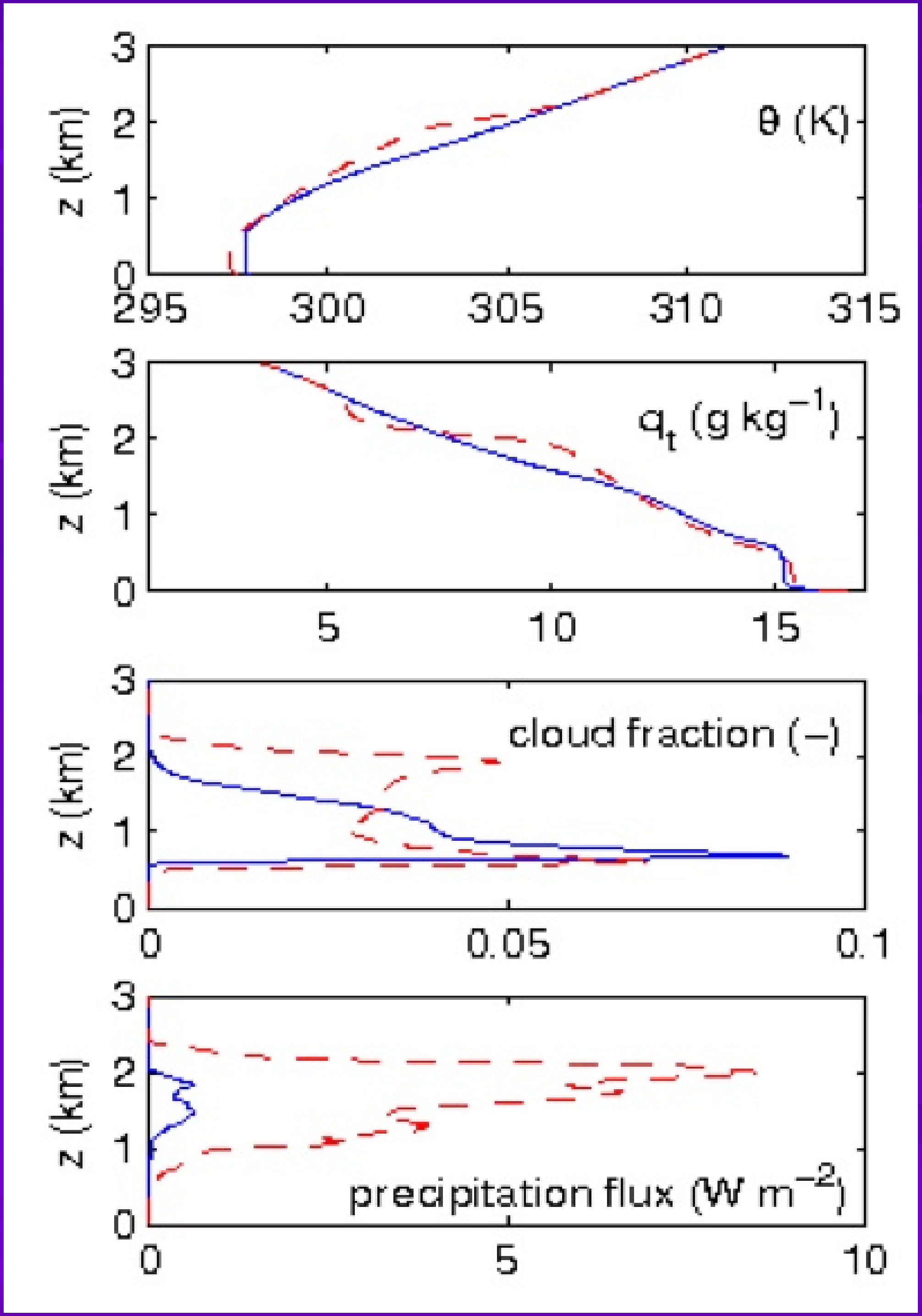
Rauber et al., 2007 *Bull. Amer. Meteor. Soc.*,**88**, 1912-1928



Computational domain:
6.4 km * 6.4 km * 4 km;
50 m * 50 m * 20 m
dt =1s
Simulations are run for 21 hours.

Data are storaged every 10 minutes.
Early state (hours 3 to 6)
and late state (hours 18 to 21)
are used in the analysis.

Profiles of the potential temperature, total water, cloud fraction, and precipitation flux for **PRISTINE extremely inhomogeneous mixing scenario** simulation for the period 3-6 h (blue solid lines) and 18-21 h (red dashed lines)

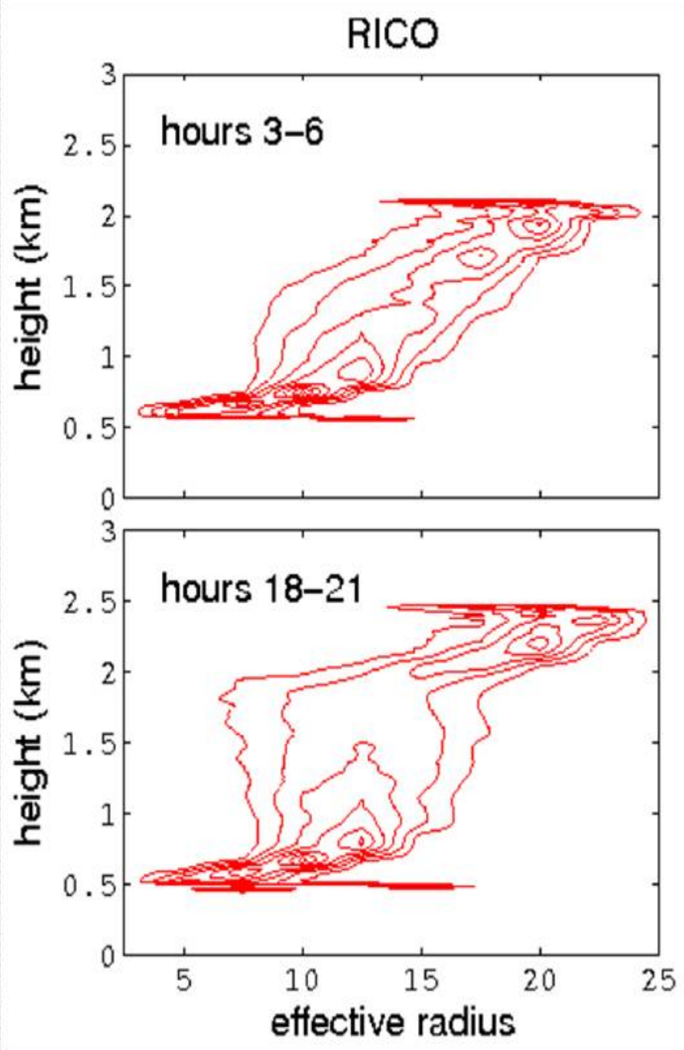


CFADs of the effective radius of cloud droplets assuming **extremely inhomogeneous mixing scenario**.

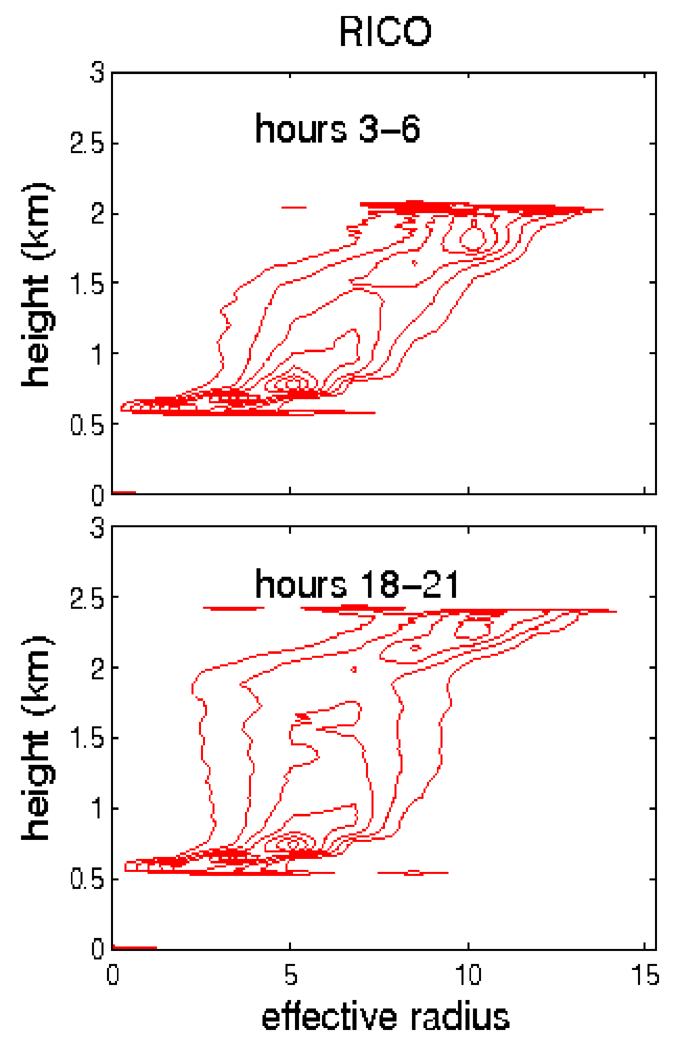
Contour interval is 10%

and the effective radius bin size is:2.5 µm (PRISTINE) / 1.5 µm (POLLUTED)

PRISTINE

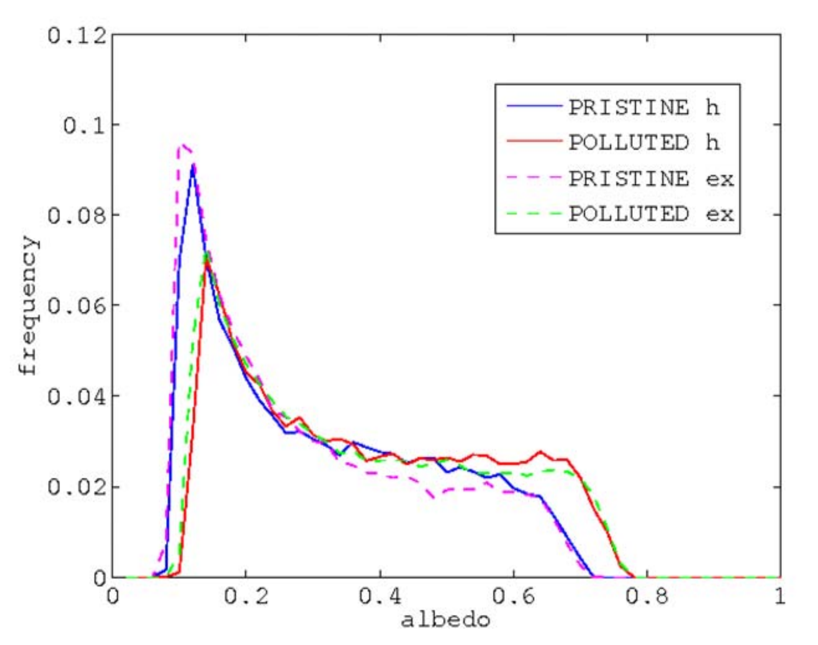


POLLUTED

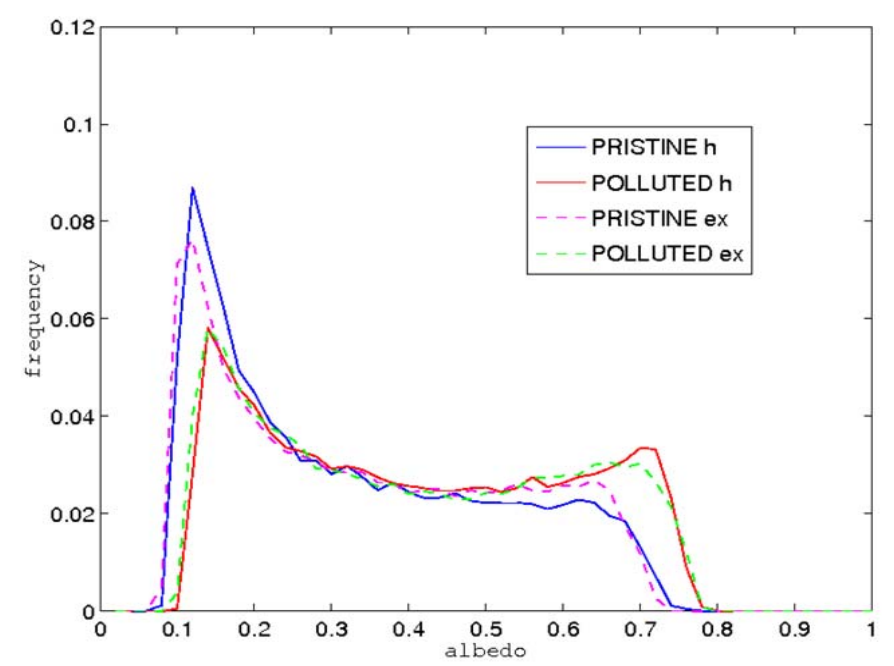


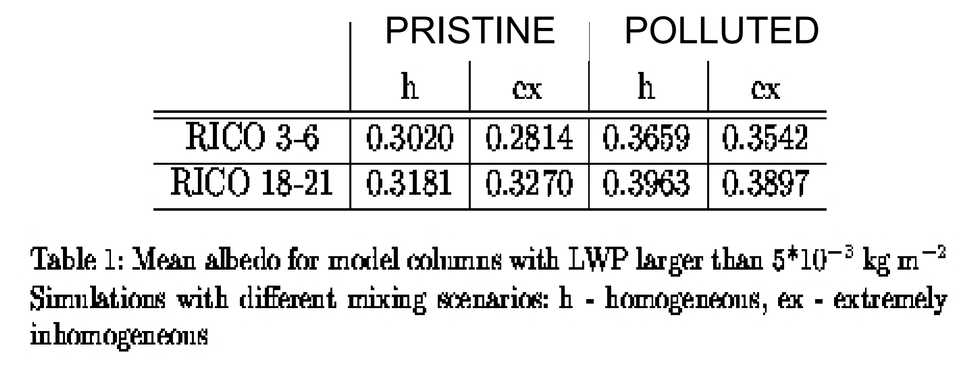
Albedo (for model columns with LWP greater than $5*10^{-3}$ kg m^{-2})

3-6 h



18-21 h





	PRISTINE		POLLUTED	
	h	ex	h	ex
RICO 3-6	0.3020	0.2814	0.3659	0.3542
RICO 18-21	0.3181	0.3270	0.3963	0.3897

Table 1: Mean albedo for model columns with LWP larger than $5*10^{-3}$ kg m^{-2} Simulations with different mixing scenarios: h - homogeneous, ex - extremely inhomogeneous

Summary

- Shallow cumulus convection simulations:
- With and without precipitation
- With one and two-moment microphysical scheme
- Different aerosol loading
- Different mixing scenarios
- Both aerosol content and mixing scenario influence microphysical properties of the cloud.
- Higher aerosol content and more homogeneous mixing lead to widening of the droplet distribution (bimodal at some heights) and reduction of the mean effective radius (possibly because of the entrainment and mixing, and in-cloud activation).
- This is reflected in radiative properties of simulated clouds. The effect is, however, dependent on the microphysical parameterization involved, more pronounced in the case of simple Kessler parameterization and weaker with use of the two-moment scheme.

RICO intercomparison http://www.knmi.nl/samenw/rico/index.html

example of results from individual models

(average profiles over last 4 hours of 24-h simulations)

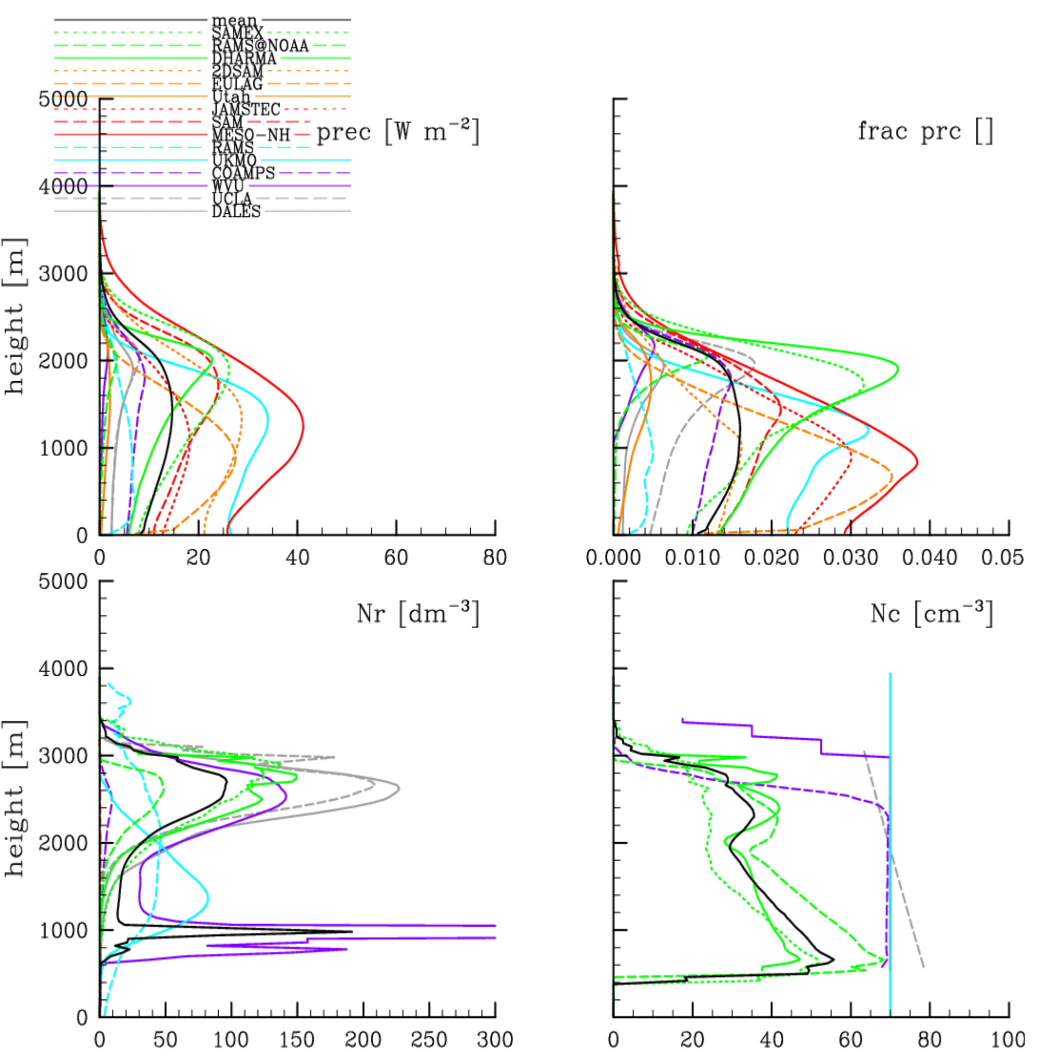
EULAG simulations:
one-moment scheme

Nc - Mean cloud droplet concentration

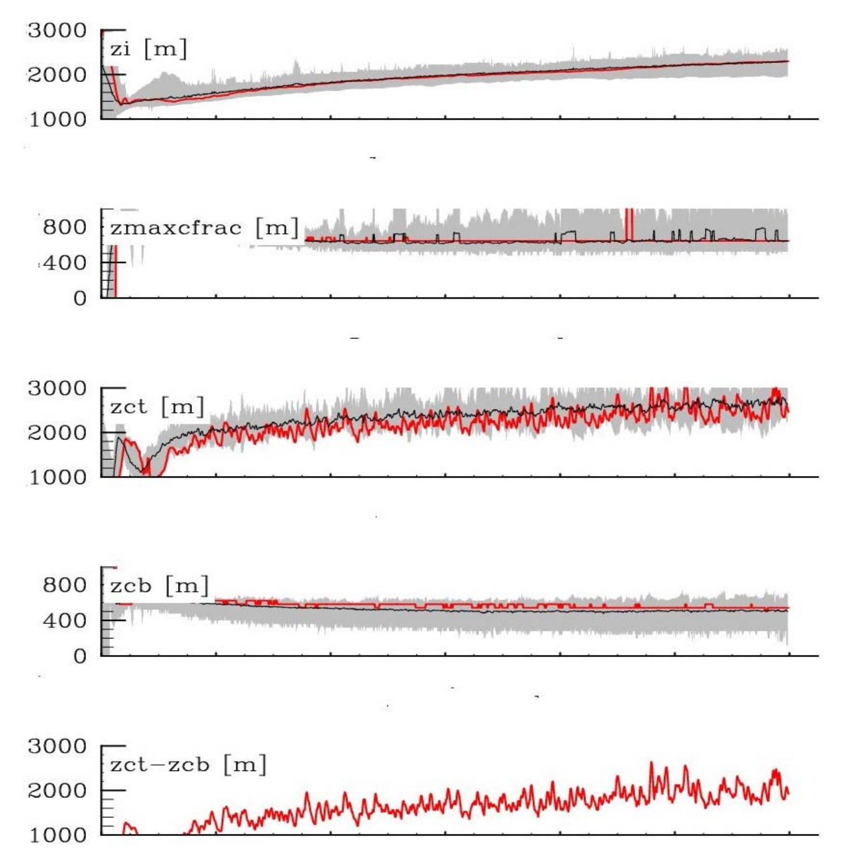
Nr - Mean rain drop concentration

prec - Precipitation flux
(positive downward)

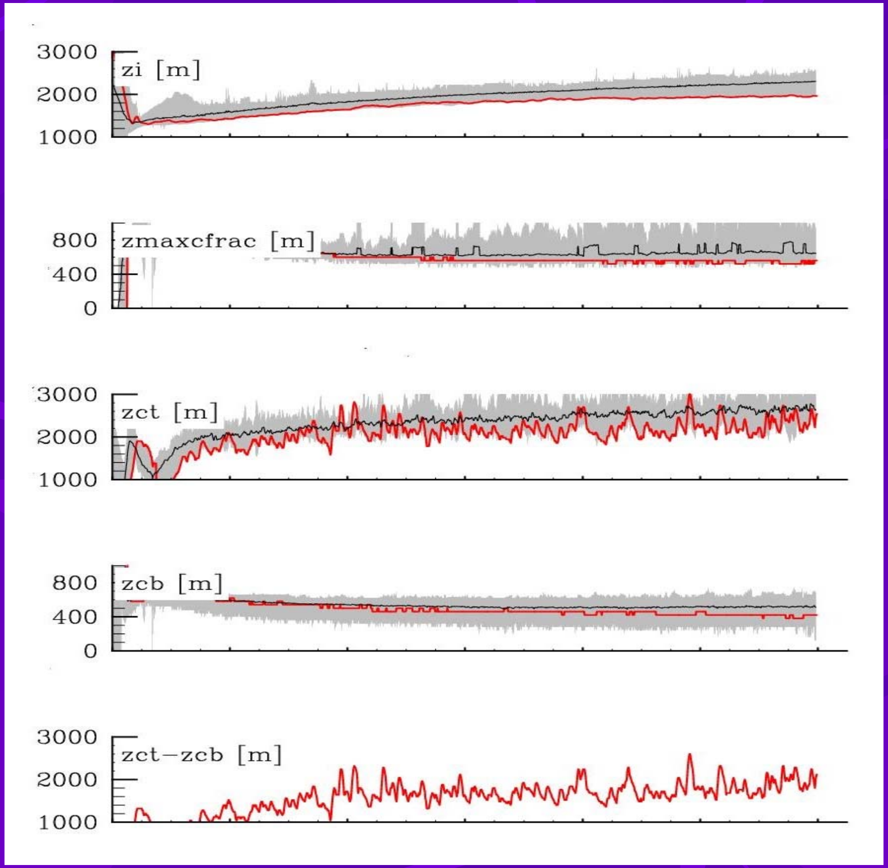
frac_prc - Fraction of precipitating
grid cells with a precipitation flux
of 3.65e-5 kg/kg m/s or higher



RICO, time evolution of scalars, 24 hours of simulations



without precipitation



with precipitation

zi - Mean height of grid cells with largest potential temperature gradient

zmaxcfrac - Height of bottom of gridlevel with highest mean cloud fraction

zct - Height of top of highest cloudy grid cells

zcb - Height of bottom of lowermost cloudy grid cells

The main influence of precipitation is a damping of the growth of the cloud layer height with time