Clouds

LMDz Training – December 2019

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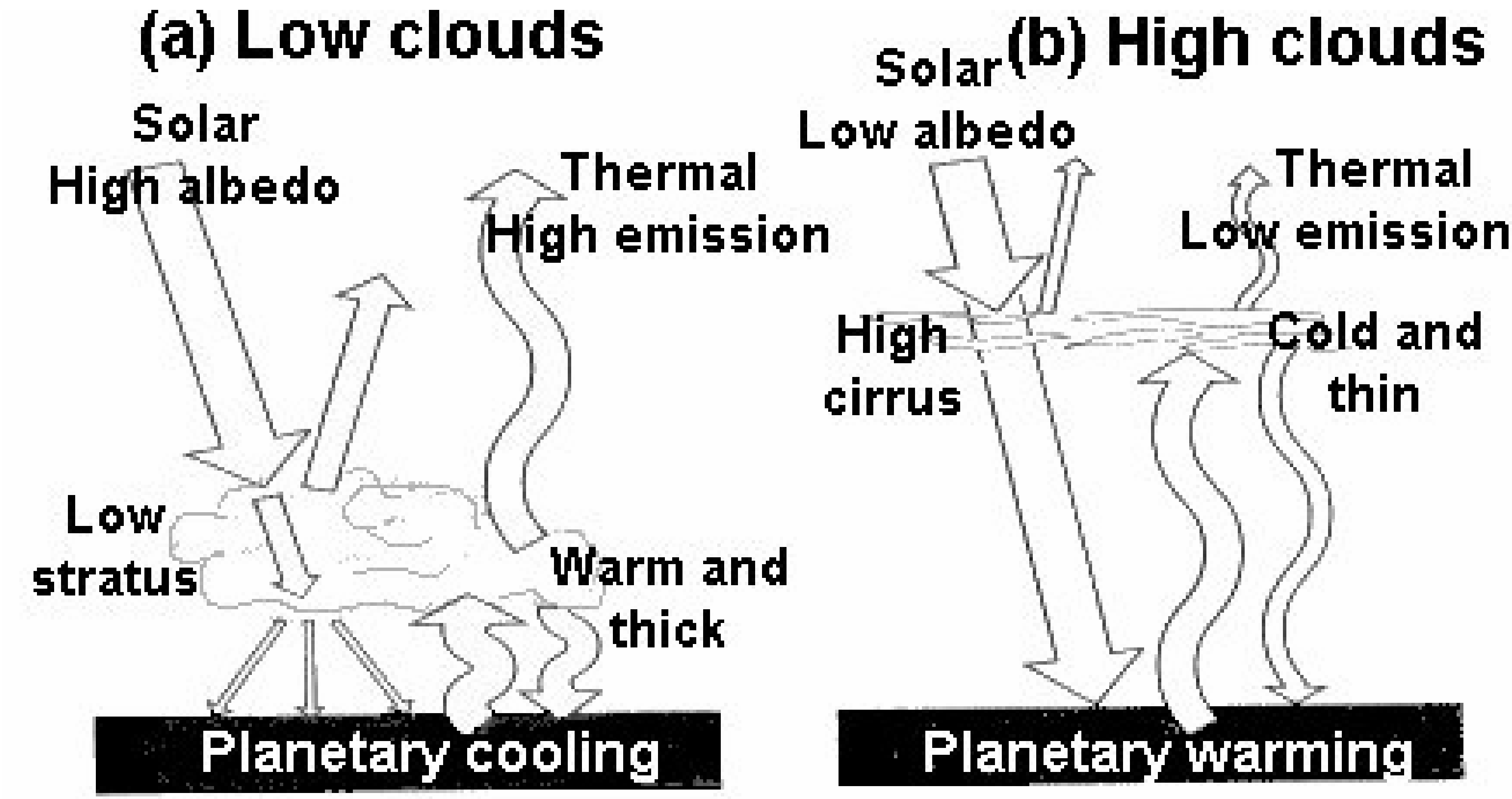
wget ftp://ftp.lmd.jussieu.fr/pub/jbmlmd/transfer/config.def

Picture by Oleg Artemyev taken from the ISS

Radiative impact of clouds



Low clouds
- albedo effect (reflectivity of 40-50%)
- weak greenhouse effect (high temp)

High clouds :
- weak albedo effect
- strong greenhouse effect (cold clouds)

Radiative forcing

LW radiative forcing

Positive : clouds reduce the LW outgoing radiation

Annual mean : +29 W m^{-2}

SW radiative forcing

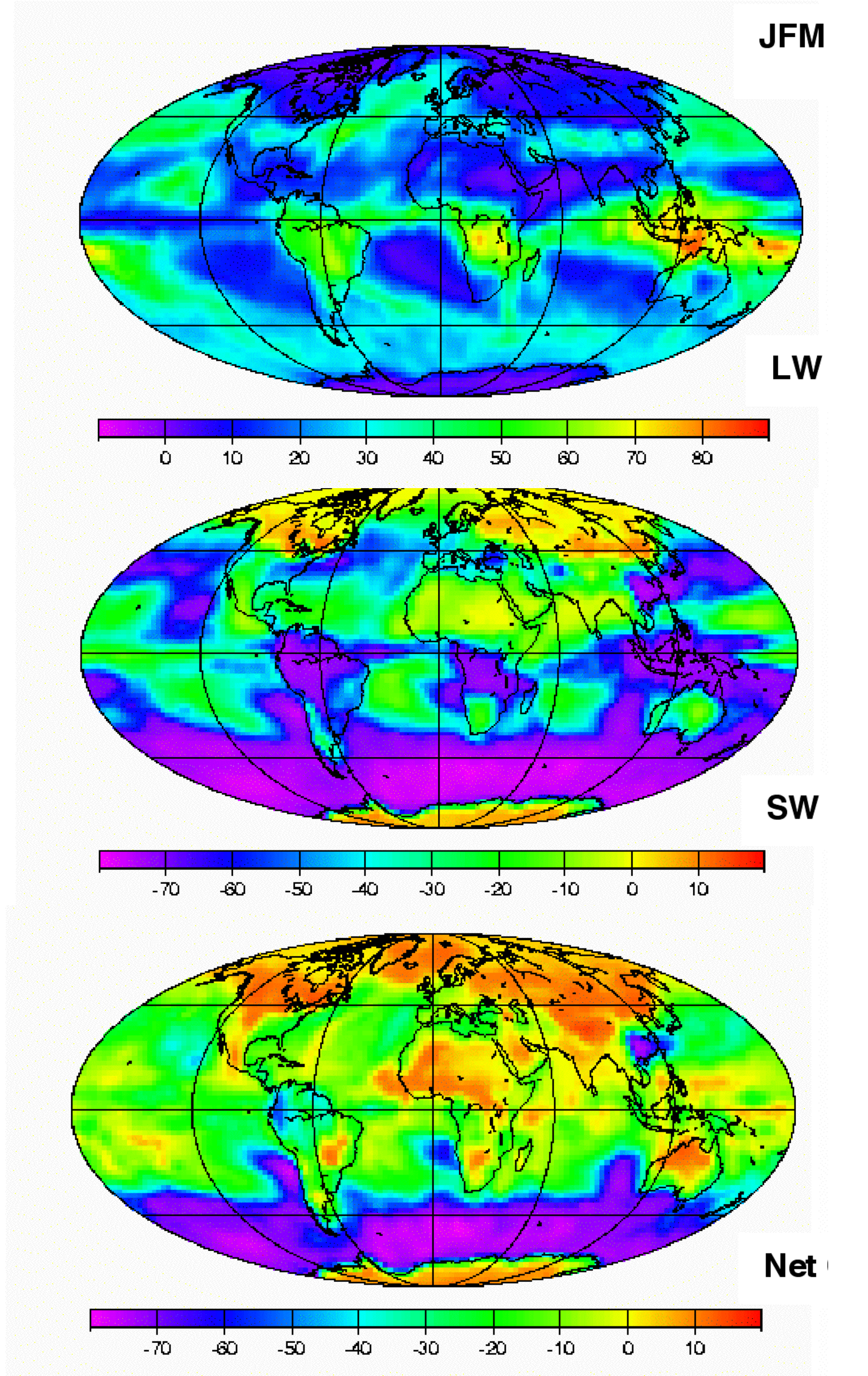
Negative : clouds reflect the incoming SW radiation

Annual mean : -47 W m^{-2}

Net forcing : **Cooling**

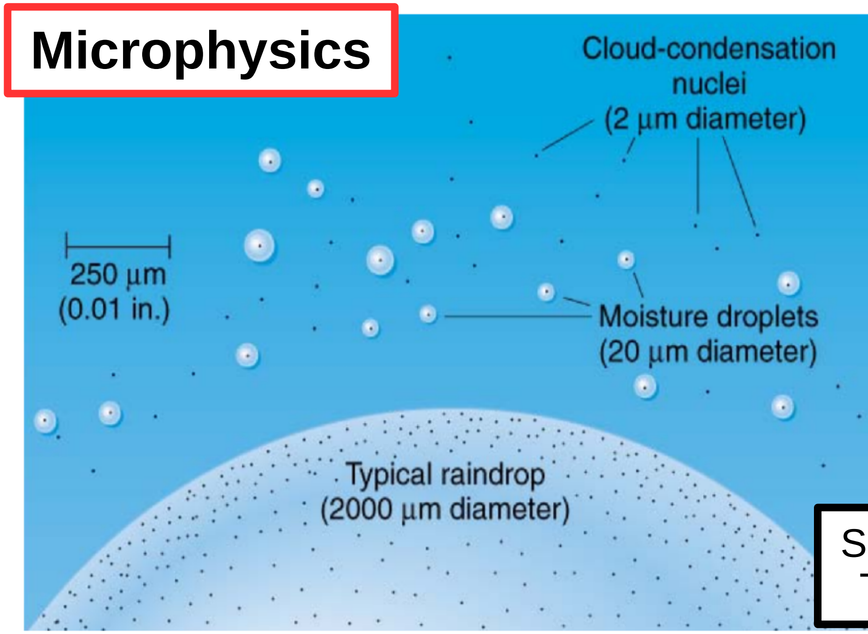
Annual mean : -18 W m^{-2}

« *The single largest uncertainty in determining the climate sensitivity to either natural or anthropogenic changes are clouds and their effects on radiation* » IPCC report



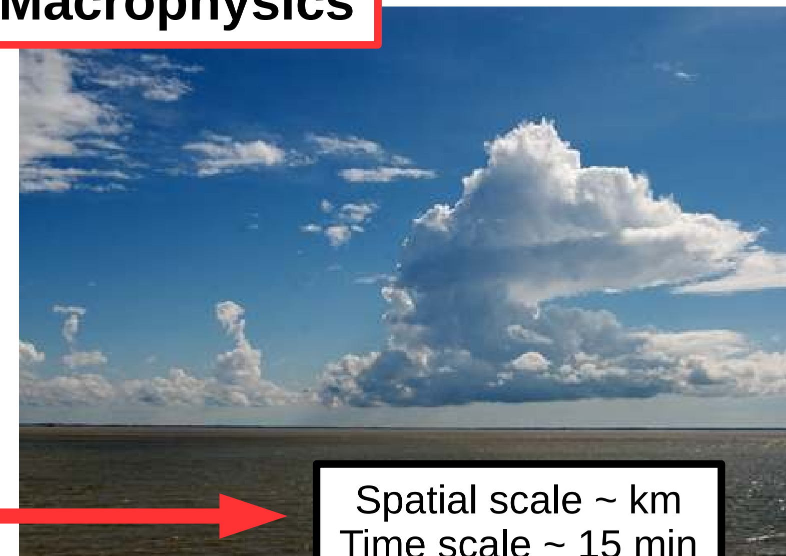
Modeling clouds : a challenge

Microphysics

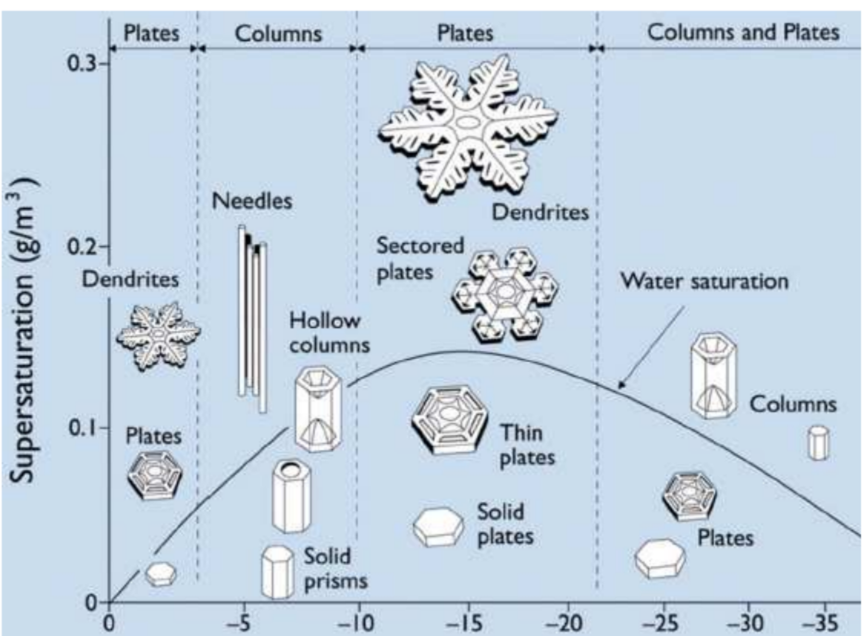


Spatial scale ~ µm
Time scale ~ 1 s

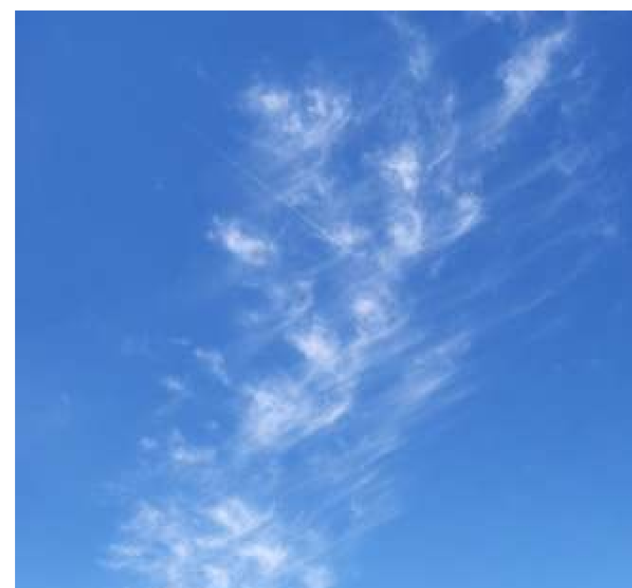
Macrophysics



Spatial scale ~ km
Time scale ~ 15 min



[Libbrecht, 2005]



Fundamental process

- Clausius-Clapeyron equation :

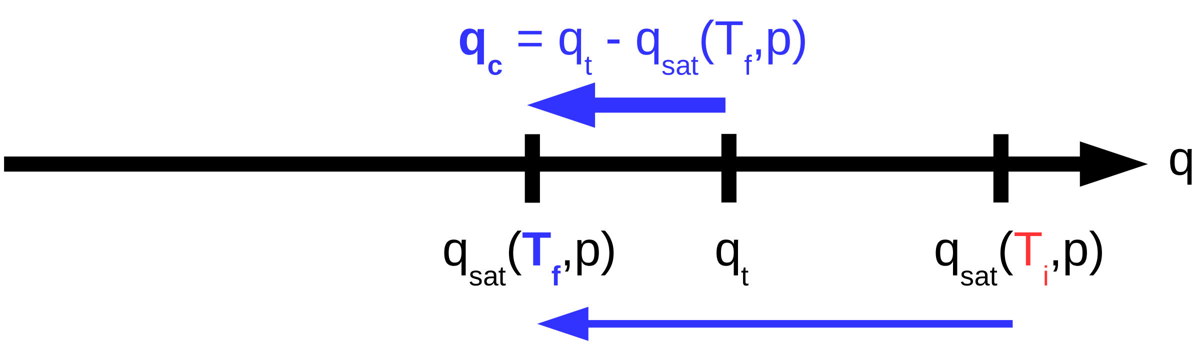
$$\frac{1}{e_{\text{sat}}}\frac{\mathrm{d}e_{\text{sat}}}{\mathrm{d}T} = \frac{L}{R_{\text{vap}}T^2}$$

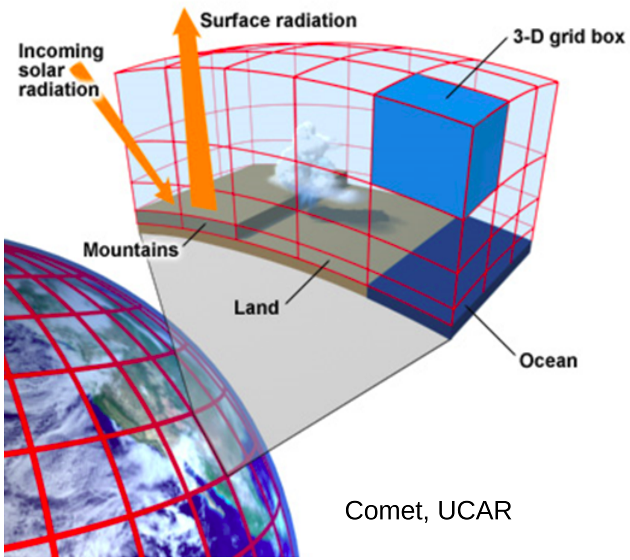
T	0°C	20°C
e_{sat}	6.1 hPa	23.4 hPa
q_{sat}	$3.7\ \text{g kg}^{-1}$	$14.4\ \text{g kg}^{-1}$

- Saturation mass mixing ratio :

$$q_{sat}(T,p) \simeq 0.622\,\frac{e_{sat}(T)}{p}$$, where $e_{sat}(T)$ grows exponentially with temperature

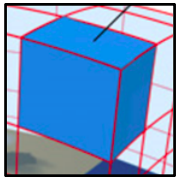
- Clouds form when an air parcel is cooled :



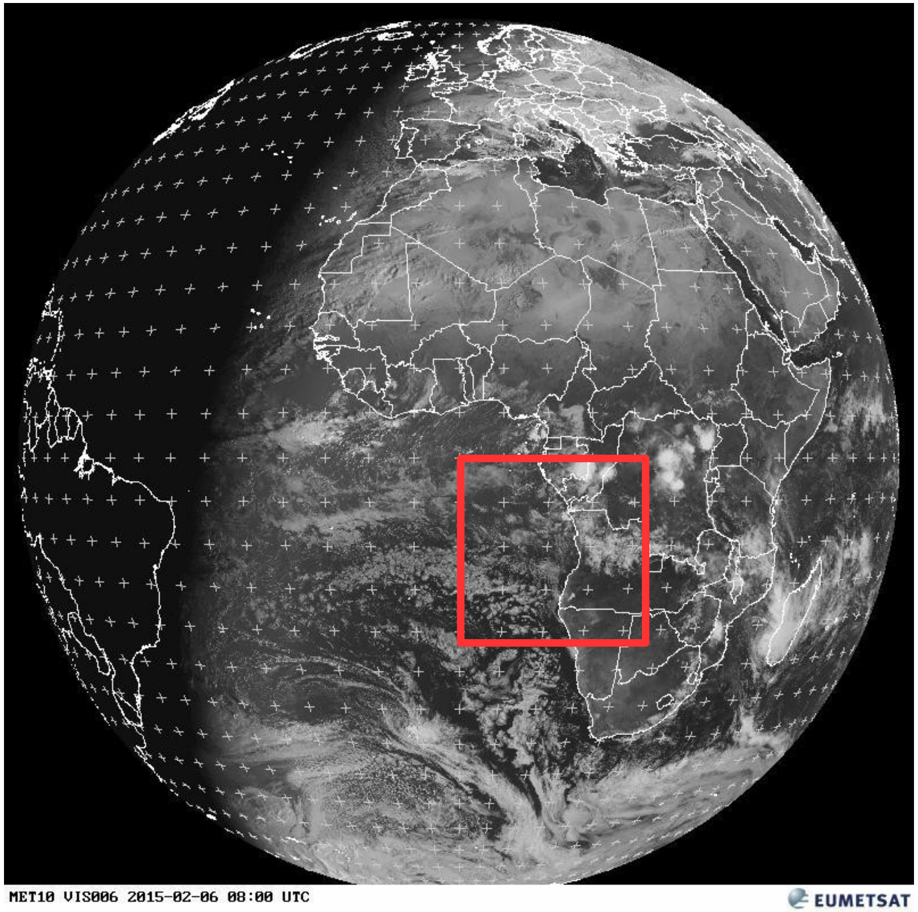


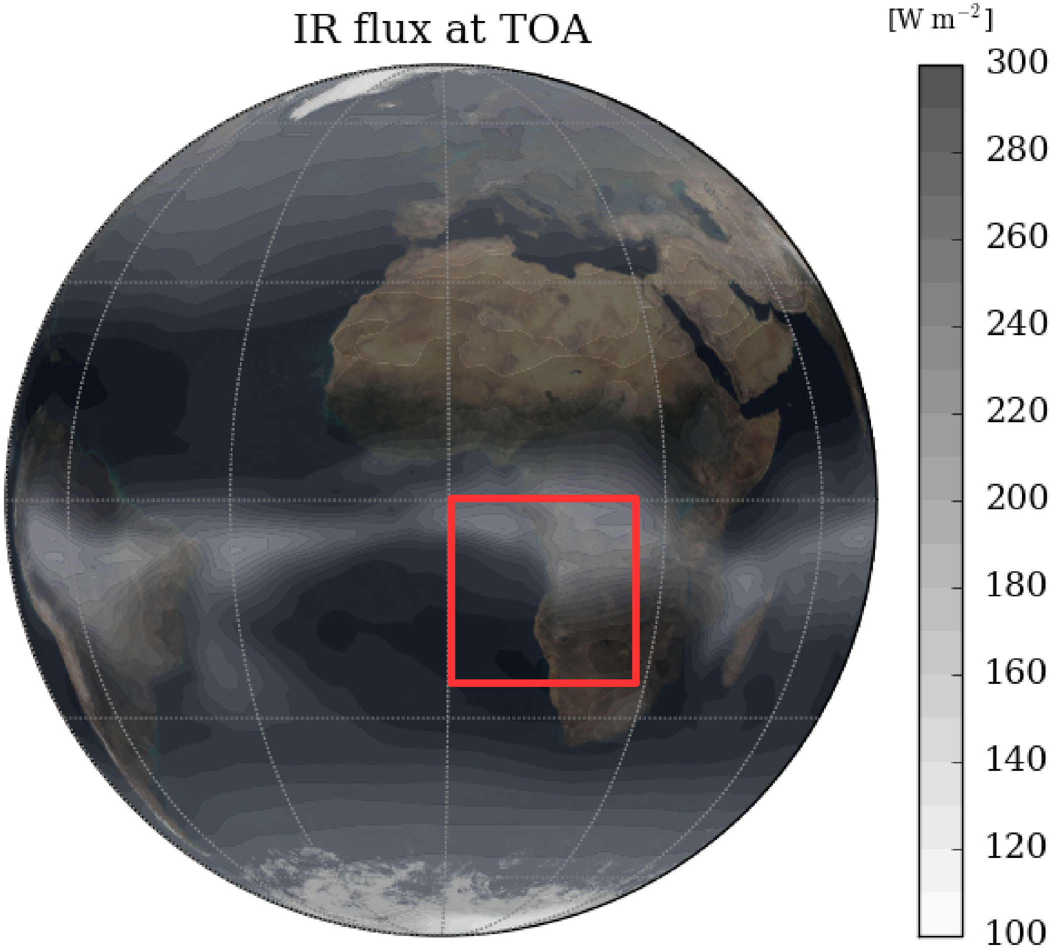
Comet, UCAR

- But clouds do not look like that :



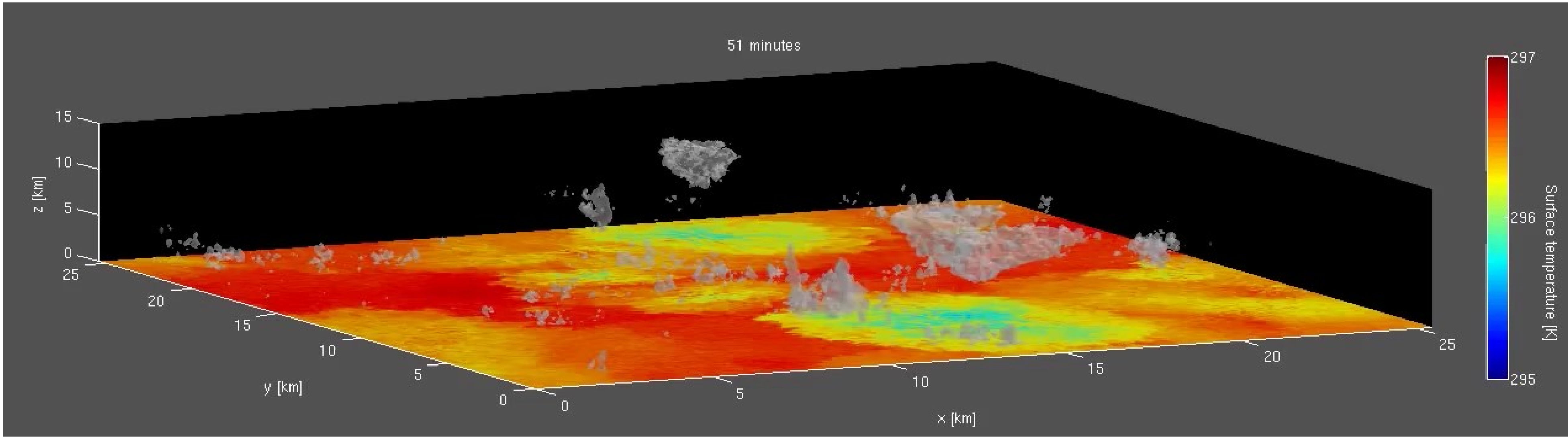
A wide variety of processes





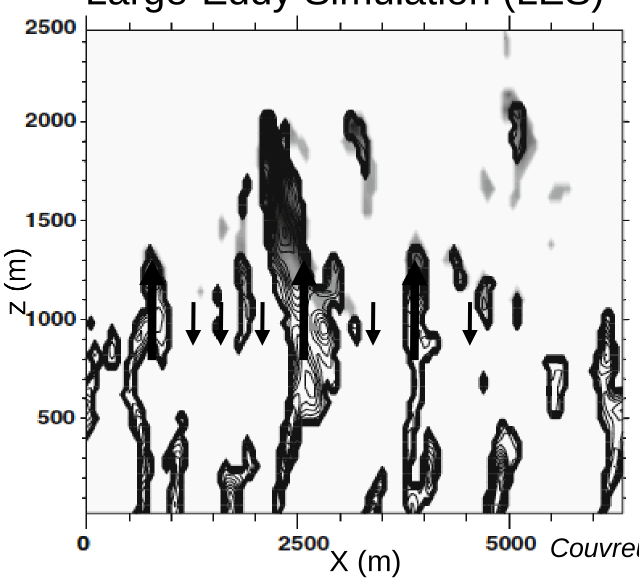
[IPSL Climate Model / 144x142 horizontal resolution / Graphisme: Planetoplot]

Many processes in one grid cell



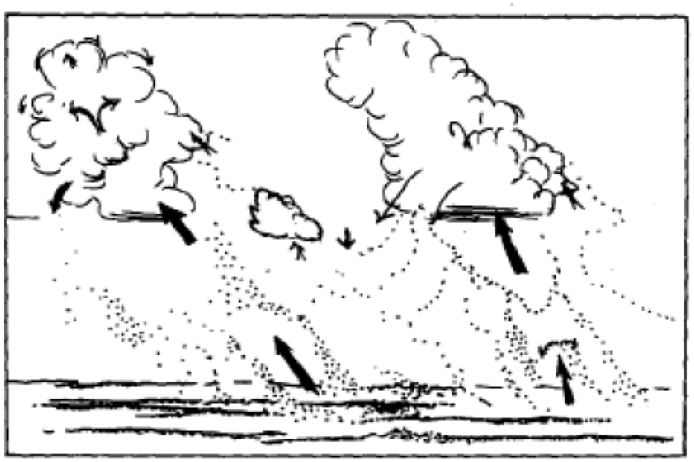
Around 8 hours of simulation by a **Cloud Resolving Model (CRM)** – C. Muller, LMD

Thermals in a
Large-Eddy Simulation (LES)



Couvreux et al., BLM, 2010

Conditional sampling of thermals based on a tracer emitted at the surface.

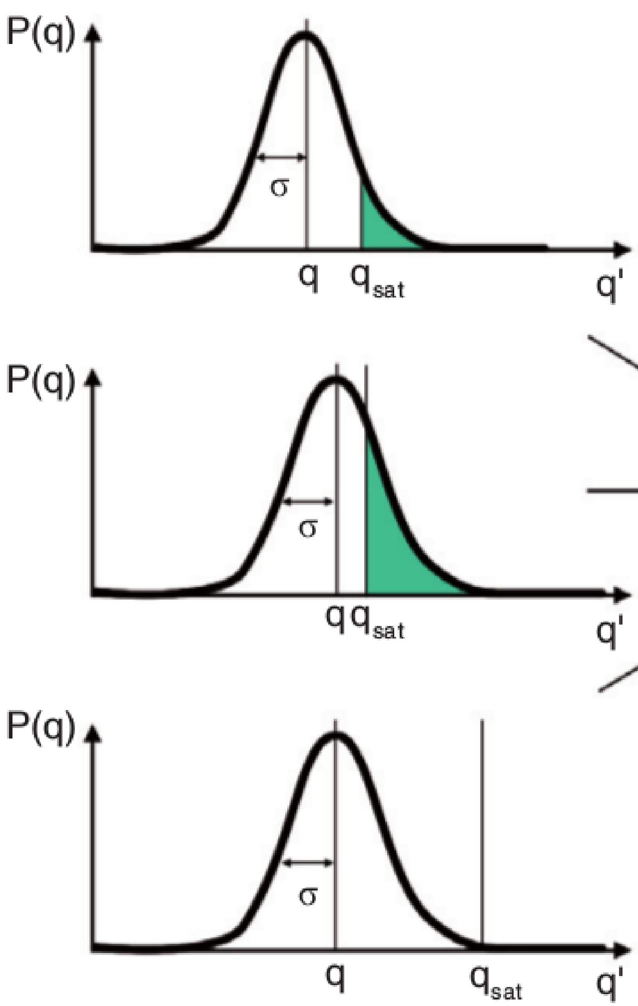


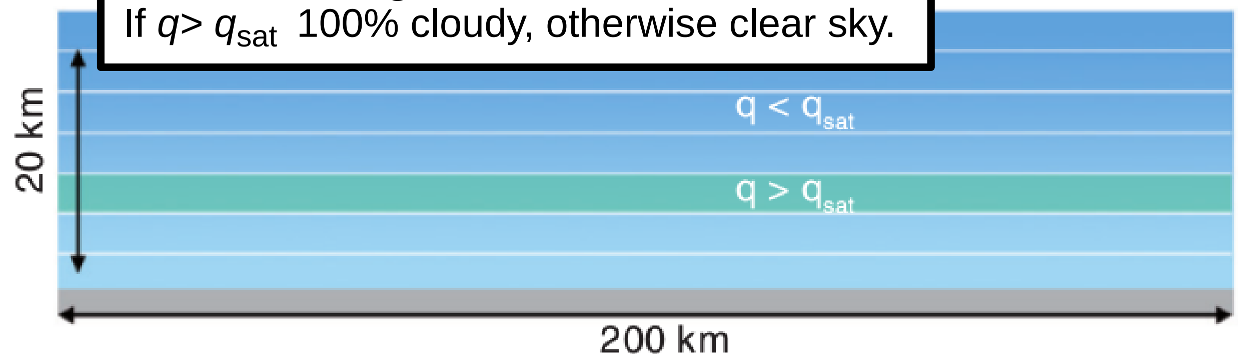
(b)

Lemone et Pennell, MWR, 1976

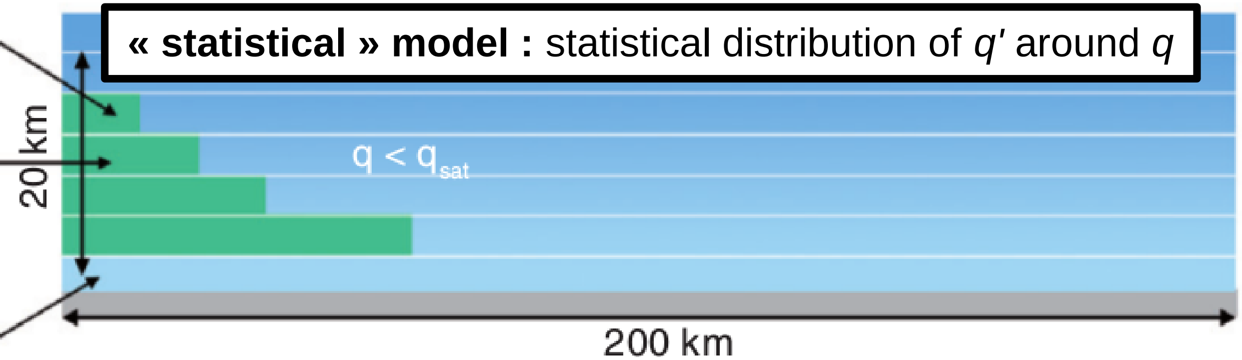
Statistical cloud scheme

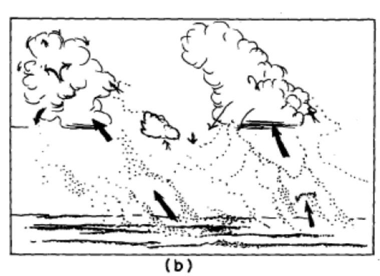
« all or nothing » model :
If $q > q_{sat}$ 100% cloudy, otherwise clear sky.

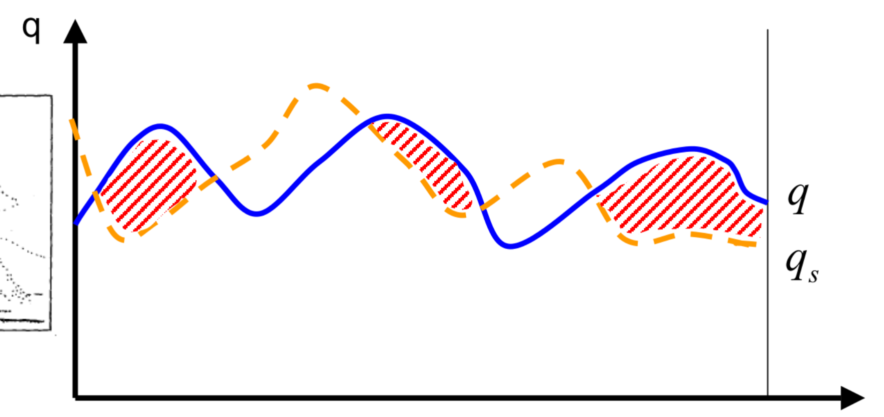




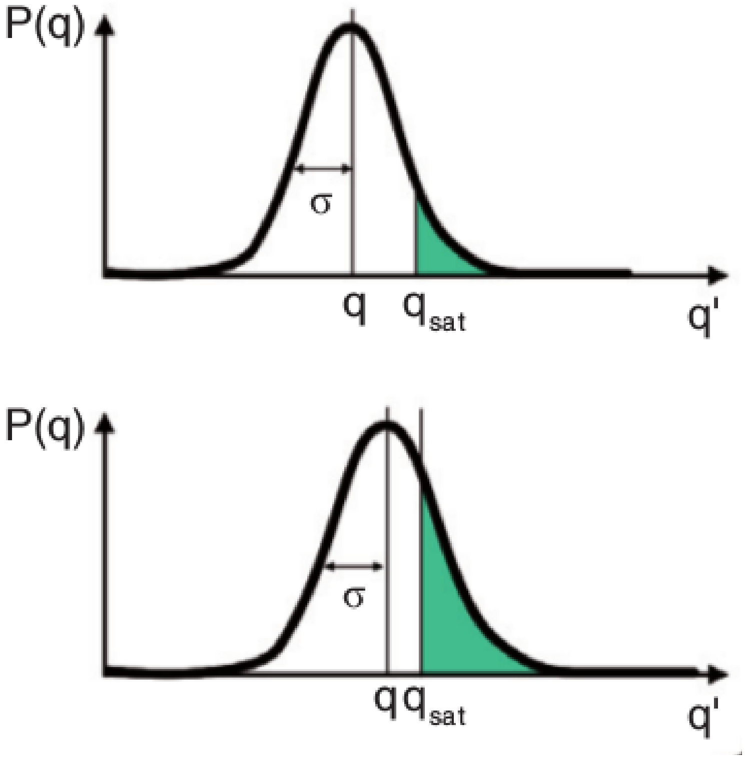
« statistical » model : statistical distribution of *q'* around *q*







Statistical cloud scheme 2/2



The goal of a cloud scheme is therefore to compute q_c^{in} and the cloud fraction based on the different physical parameterizations.

Mean total water content :

$$\bar{q} = \int_0^{\infty} q \; P(q) \; dq$$

Domain-averaged condensed water content :

$$q_c = \int_{q_{sat}}^{\infty} (q - q_{sat}) P(q) dq$$

Cloud fraction :

$$\alpha_c = \int_{q_{sat}}^{\infty} P(q) dq$$

In-cloud condensed water content :

$$q_c^{in} = \frac{q_c}{\alpha_c}$$

physiq_mod.F90 structure - I

Initialization (once) : *conf_phys, phyetat0, phys_output_open*

Beginning *change_srf_frac, solarlong*

Cloud water evap. *reevap*

Vertical diffusion (turbulent mixing) *pbl_surface*

1. **Deep convection** *conflx* (Tiedtke) or *concvl* (Emanuel)
   Deep convection clouds *clouds_gno*

Density currents (wakes) *calwake*

Strato-cumulus *stratocu_if*

2. **Thermal plumes** *calltherm* and *ajsec* (sec = dry)
   Thermal plume clouds *calcratqs*

3. **Large scale condensation** *fisrtilp*

Diagnostic clouds for Tiedtke *diagcld1*

Aerosols *readaerosol_optic*

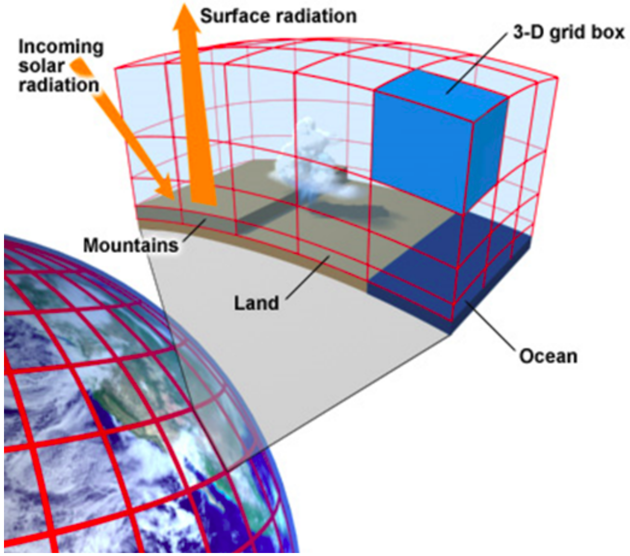
Cloud optical parameters *newmicro* or *nuage*

Radiative processes *radlwsw* (bis)

In blue : subroutines and instructions modifying state variables

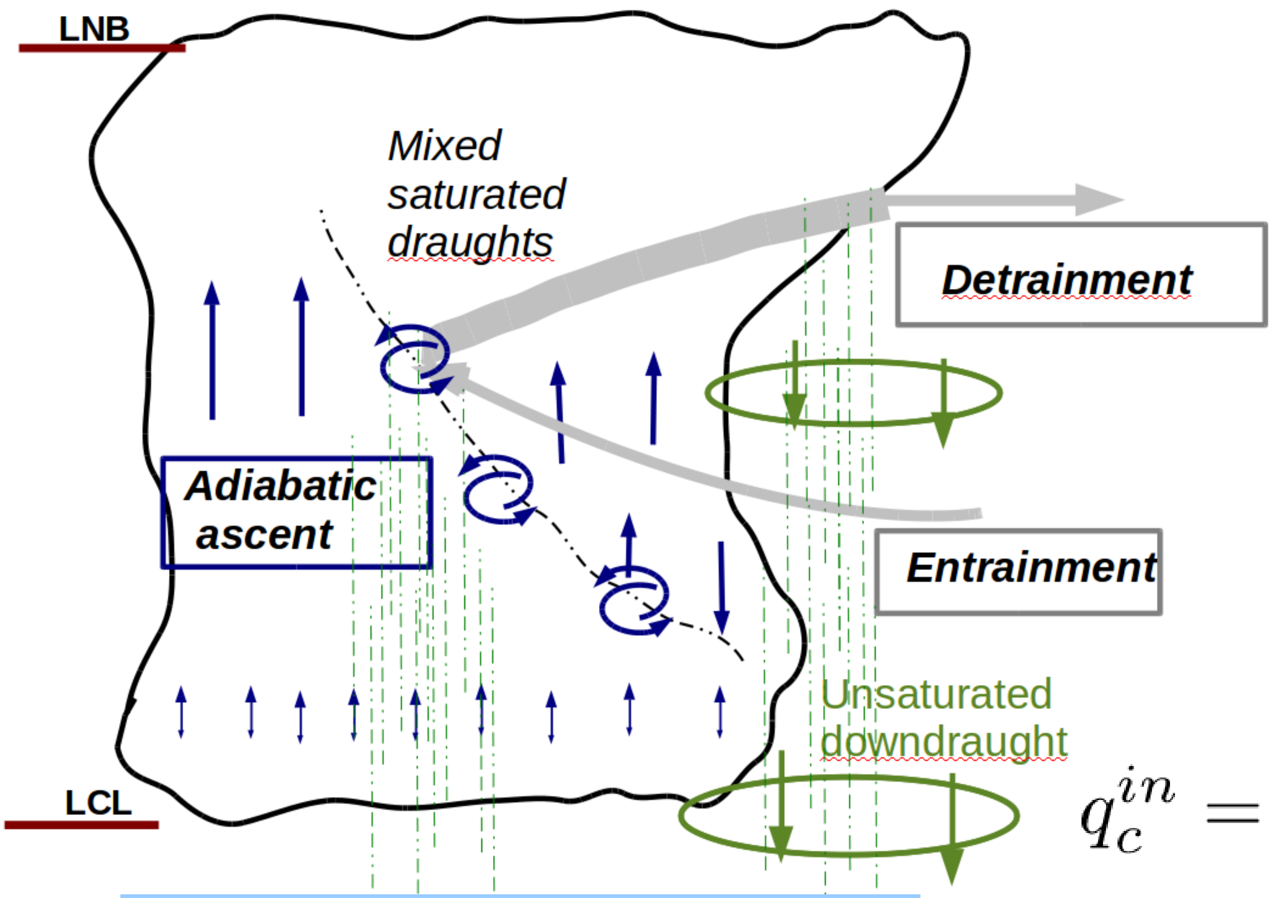
CAREFUL : clouds are evaporated/sublimated at the beginning of each time step (~15 min), but vapor, droplets and crystals are prognostic variables. In other words, **clouds can move but can't last for more than one timestep** (meaning that for example, crystals can't grow over multiple timesteps).

LMDz physics parameterizations

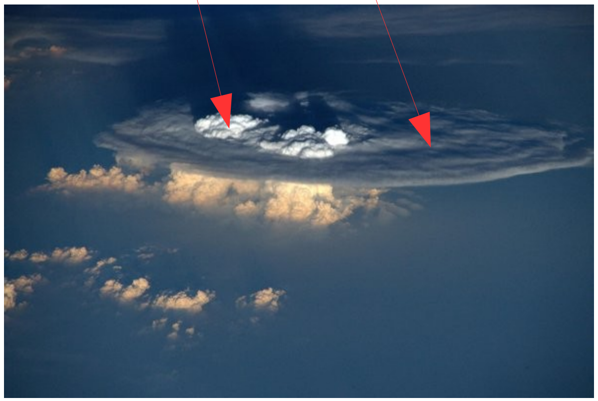


1. Deep convection

Emanuel scheme



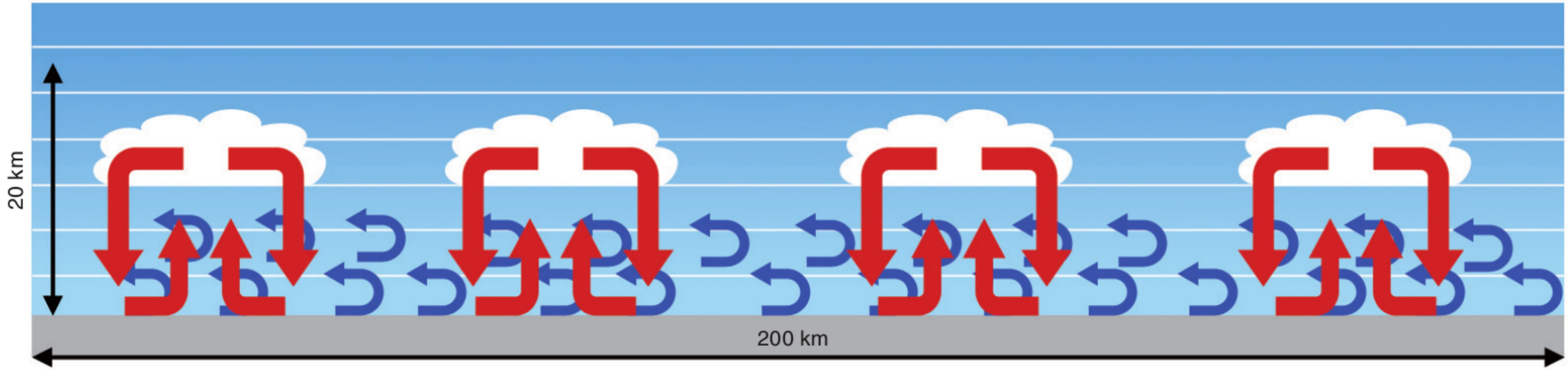
$$q_c^{in} = \frac{\sigma_a \, q_{ca} + \sigma_m \, q_{cm}}{\sigma_a + \sigma_m}$$

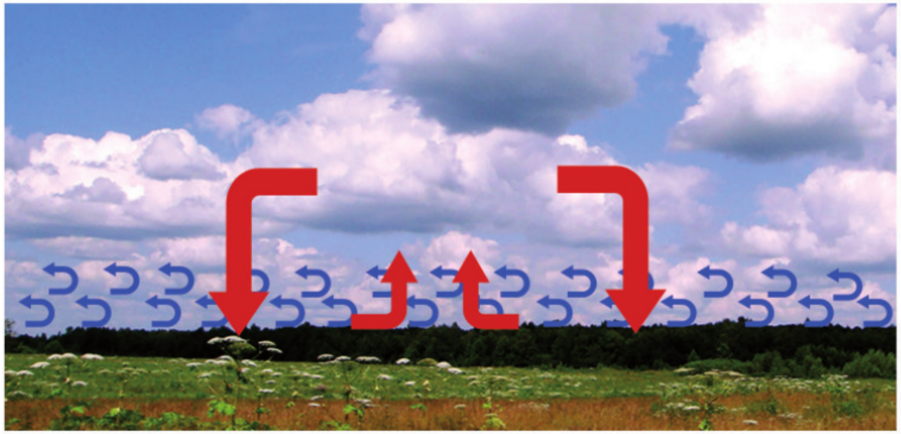


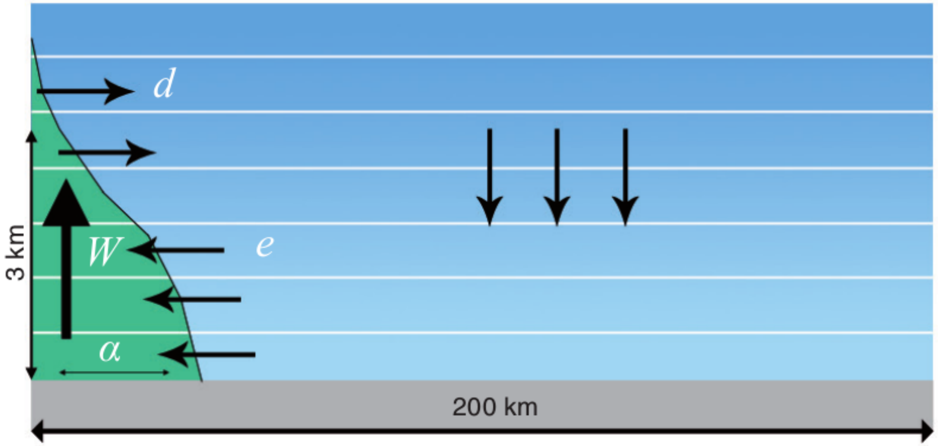
$$q_c^{in} = \frac{\frac{M_a}{\rho \, w_a} \, q_{ca} + \frac{\tau \, M_t \, g}{\delta p} \, q_{cm}}{\frac{M_a}{\rho \, w_a} + \frac{\tau \, M_t \, g}{\delta p}}$$

q_c^{in} is computed by the deep convection scheme and $\bar{q}$ is known → cloud fraction is found

2. Shallow convection 1/2







2. Shallow convection 2/2

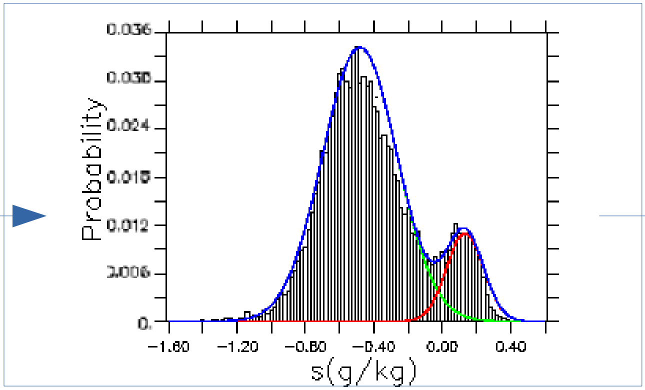
Bi-Gaussian distribution
of saturation deficit s:

$$s = a_1(q_t - q_{sat}(T_l))$$

- One mode associated with thermals s_{th}, σ_{th}
- One mode associated with their environment: s_{env}, σ_{env}

Shallow convection

s_{env}, σ_{env}
s_{th}, σ_{th}, α



q_c, CF

Jam & al., BLM, 2013

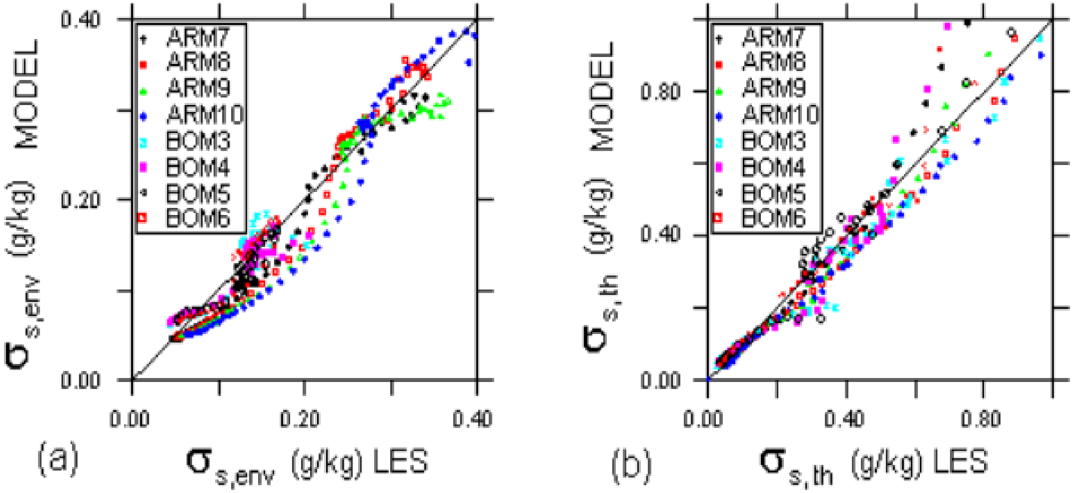
We know:
Mean state: s_{env}
Thermal properties: s_{th}, α

Parameterization of the variances:

$$\sigma_{s,env} = c_{env} \frac{\alpha^{\frac{1}{2}}}{1-\alpha} (\overline{s}_{th} - \overline{s}_{env}) + b\, \overline{q}_{t_{env}}$$

$$\sigma_{s,th} = c_{th}\, \alpha^{-\frac{1}{2}} (\overline{s}_{th} - \overline{s}_{env}) + b\, \overline{q}_{t_{th}}$$

q_c^{in} is deduced from the mean water content of the environment and thermals and the parameterized spreads of the two gaussian distributions

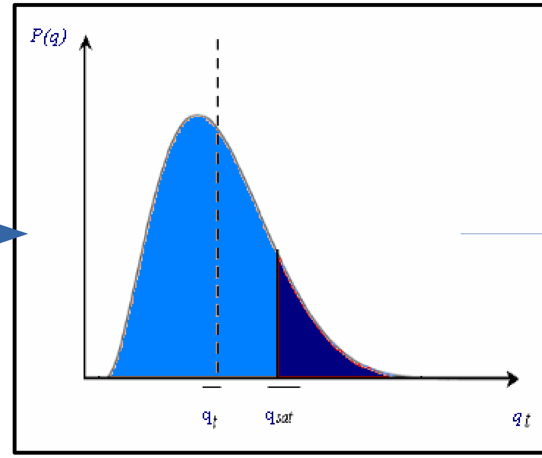


3. Large scale condensation

Log-normal distribution of total water q_t *(Bony & Emanuel, JAS, 2001)*

Grid-cell mean state → q, q_{sat}

σ/q imposed (called "ratqs")

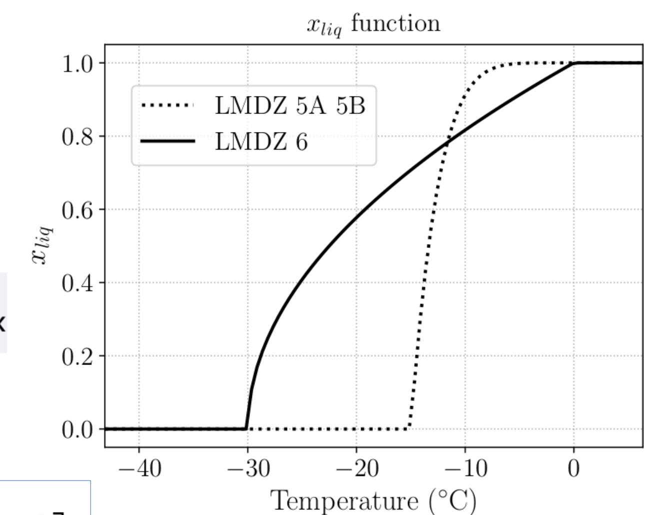


$$\alpha_c = \int_{q_{sat}}^{\infty} P(q)dq$$

$$q_c = \int_{q_{sat}}^{\infty} (q - q_{sat})P(q)dq$$

- condensate: liquid/ice partitioning (function of the temperature) :

$$^{a}\text{Cloud liquid fraction} = \left(\frac{T - T_{\min}}{T_{\max} - T_{\min}}\right)^n, \text{ for } T_{\min} \le T \le T_{\max}$$



- A fraction of the condensate falls as rain (parameters controlling the maximum water content of clouds and the auto-conversion rate) :

$$\frac{dq_{lw}}{dt} = -\frac{q_{lw}}{\tau_{convers}}\left[1 - e^{-(q_{lw}/clw)^2}\right]$$

$$\frac{dq_{iw}}{dt} = \frac{1}{\rho}\frac{\partial}{\partial z}(\rho w_{iw} q_{iw})$$

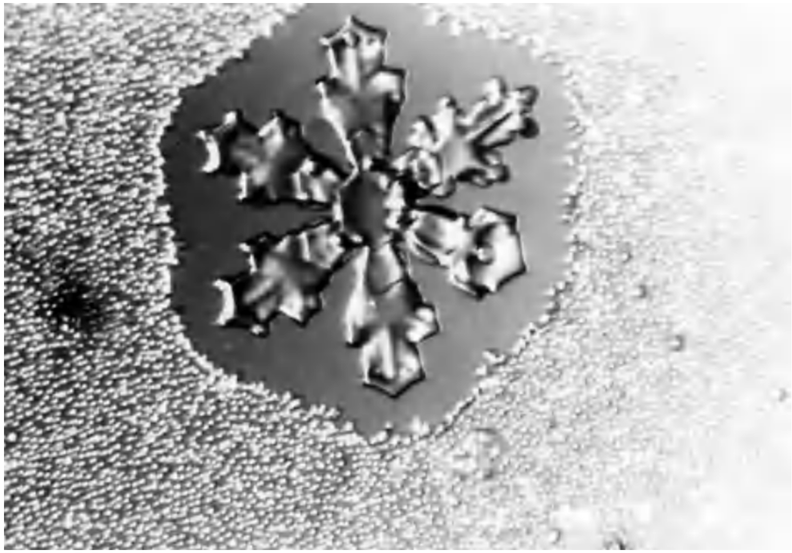
$$w_{iw} = \gamma_{iw} w_0$$

$$w_0 = 3.29(\rho q_{iw})^{0.16}$$

- The rain is partly evaporated in the grid below (parameter controlling the evaporation rate) :

$$\frac{\partial P}{\partial z} = \beta[1 - q/q_{sat}]\sqrt{P}$$

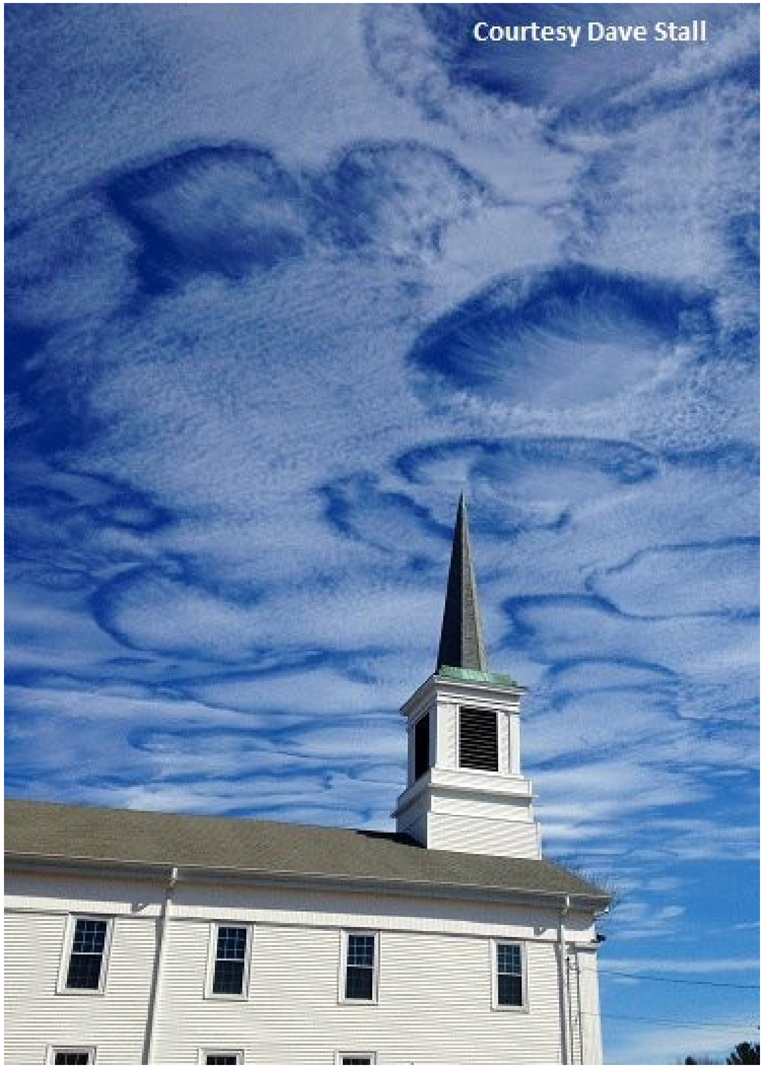
3. “Bergeron” effect



Growth of an ice crystal at the expense of surrounding supercooled water drops [Wallace, 2005]

$$\frac{dq_{lw}}{dt} = -\frac{q_{lw}}{\tau_{convers}}\left[1 - e^{-(q_{lw}/clw)^2}\right]$$

- Can occur under negative temperatures → the resulting liquid precipitation **is converted to ice**
- when freezing, rain releases latent heat, which can potentially bring the temperature back to above freezing. If this is the case, a small amount of rain remains liquid to stay below freezing and stabilize the numerical scheme.

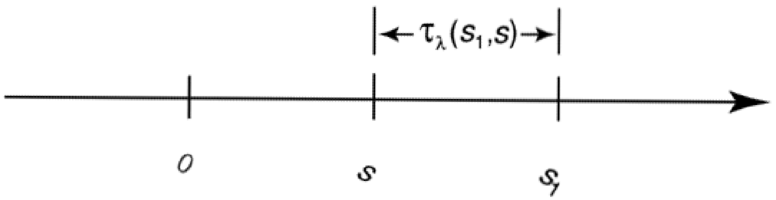


Fallstreak hole (also known as hole punch clouds), Rhode Island, USA

Radiative transfer

Radiative transfer equation :

$$-\mu\frac{\partial I_\lambda}{\partial \tau_\lambda}(\tau_\lambda,\mu,\Phi) = -I_\lambda(\tau_\lambda,\mu,\Phi) + S_\lambda(\tau_\lambda,\mu,\Phi) + \frac{w_{0_\lambda}}{4\pi}\int_0^{2\pi}\int_{-1}^{1} P_\lambda(\mu,\mu',\Phi,\Phi')I_\lambda(\tau_\lambda,\mu',\Phi')d\mu' d\Phi'$$



$q_{c,tot}$ = q_c^{in} (thermals) x CF (thermals) ← bi-gaussian PDF

+ q_c^{in} (convection) x CF (convection)

+ q_c^{in} (large-scale) x CF (large-scale) ← Lognormal PDF

CF_{tot} = min(CF (thermals) + CF (convection) + CF (large-scale), 1.)

Solving the radiative transfer equation requires :

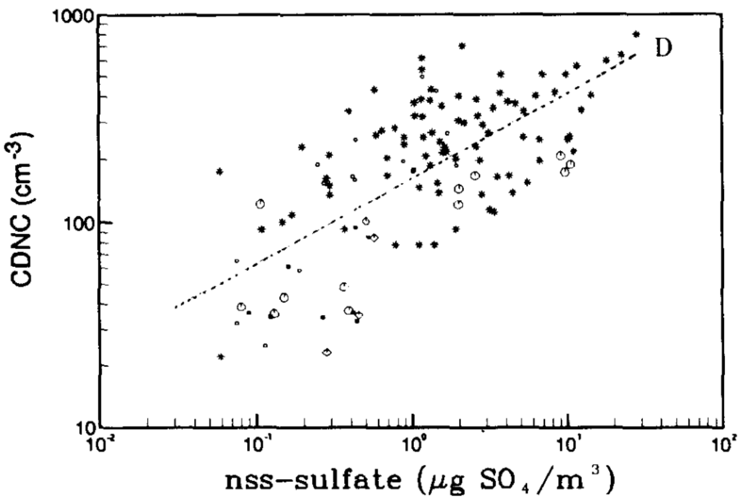
- $q_{c,tot}$ to compute the optical depth ;
- **Cloud droplet and crystal sizes** to compute the optical properties ;
- CF_{tot} to compute the heating rates in the clear-sky (1-CF_{tot}) and cloudy (CF_{tot}) columns.

Optical properties of liquid clouds

(see O. Boucher's talk)

ok_cdnc = y
bl95_b0 = 1.3
bl95_b1 = 0.2

$$CDNC = 10^{\,b0 + b1 \log(m\ SO4)}$$



Link cloud droplet number concentration to aerosol mass concentration (Boucher and Lohmann, Tellus, 1995)
mSO_4 → Now uses mass of all soluble species.

N = CDNC

$$r_3 = \left(\frac{l\, \rho_{\mathrm{air}}}{(4/3)\, \pi \rho_{\mathrm{water}} N} \right)^{1/3}$$

$$r_e = \frac{\int r^3 n(r)\, dr}{\int r^2 n(r)\, dr}$$

$$r_e = 1.1\ r_3$$

Size-dependent computation of cloud optical properties (Fouquart [1988] in the SW, Smith and Shi [1992] in the LW)

Optical properties of ice clouds

Optical properties are computed using Ebert and Curry [1992], based on the computed crystal sizes.

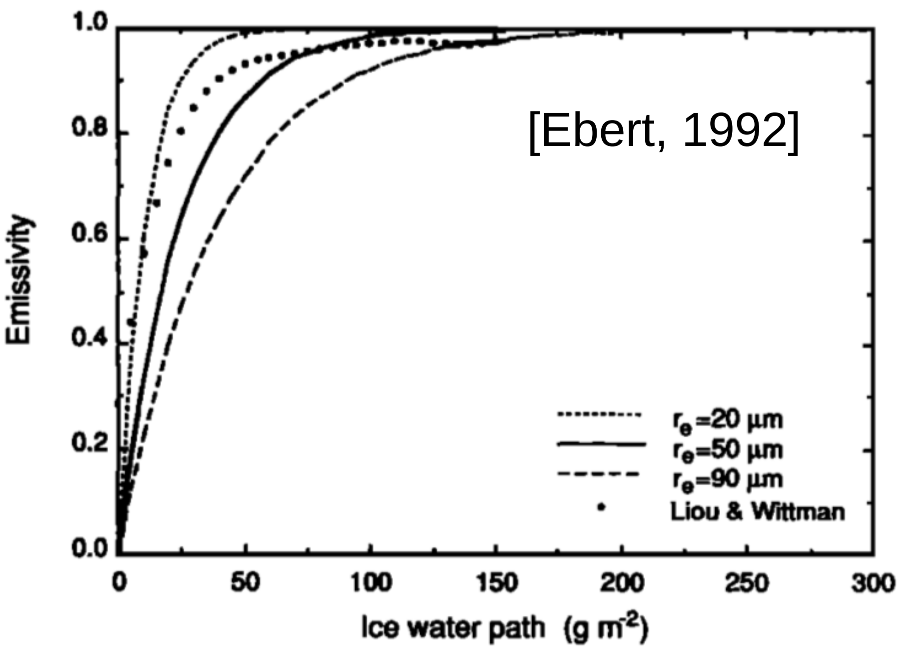
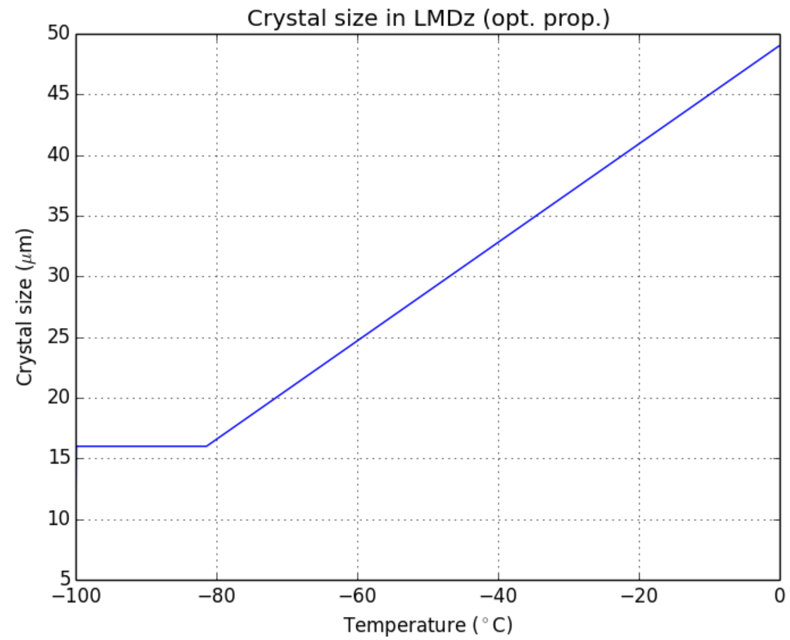


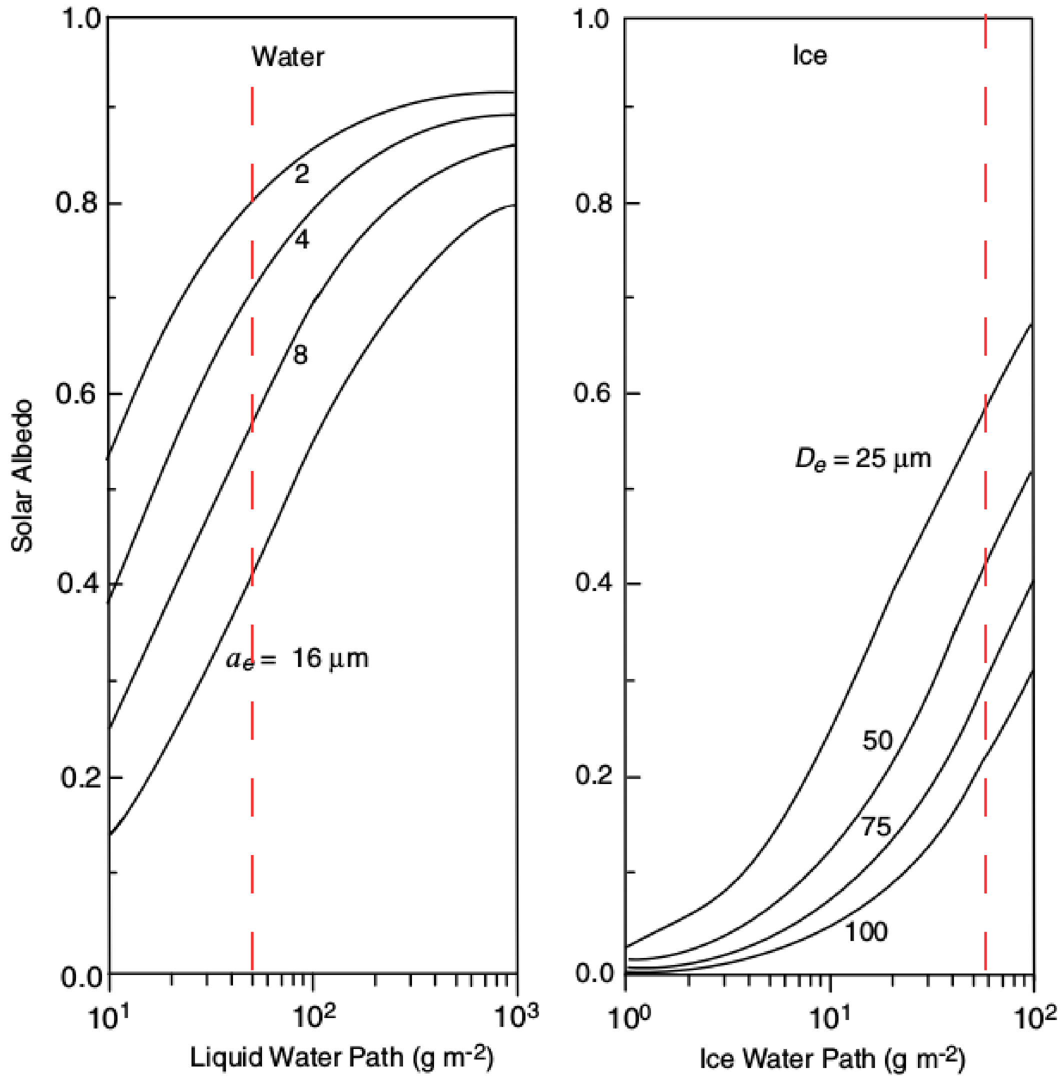
Fig. 5. Cirrus infrared emissivity for r_e = 20, 50, and 90 μm as a function of ice water path. The solid circles represent values computed using the parameterization of *Liou and Wittman* [1979].



Crystal sizes follow
$r = 0.71T + 61.29$ in µm
[Iacobellis et Somerville 2000]
with r_{min} ~ 10 µm (tuneable)
for T < -81.4°C *[Heymsfield et al. 1986]*

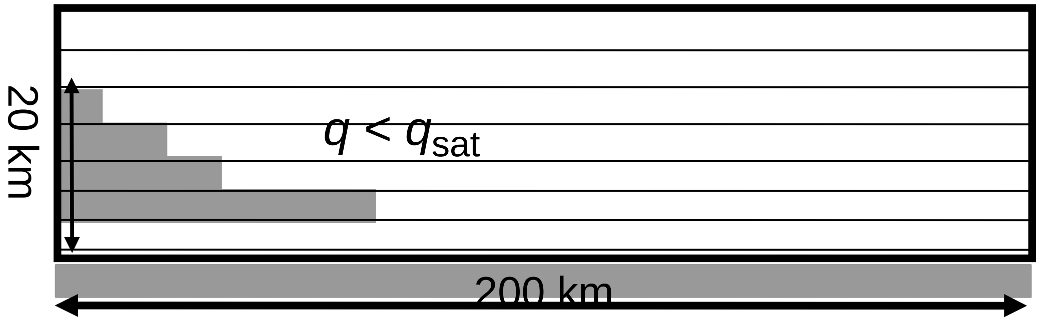
Importance of cloud phase

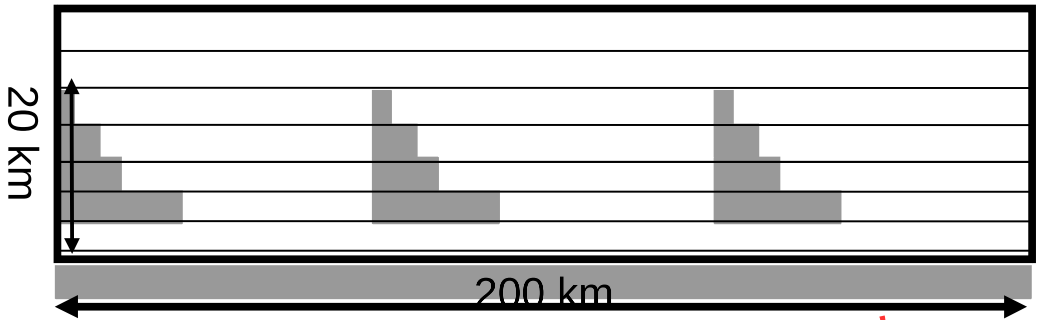
- Clouds reflect sunlight (negative forcing, cooling) and emit in the infrared (positive forcing, warming) ;
- For the same water content, liquid clouds reflect more sunlight than ice clouds ;
- <u>For liquid clouds :</u> if the cloud water content increases, there is a negative forcing (reflection dominates) ;
- <u>For ice clouds :</u> if the cloud water content increases, the forcing depends on the size of the crystals.



[Liou 2002]

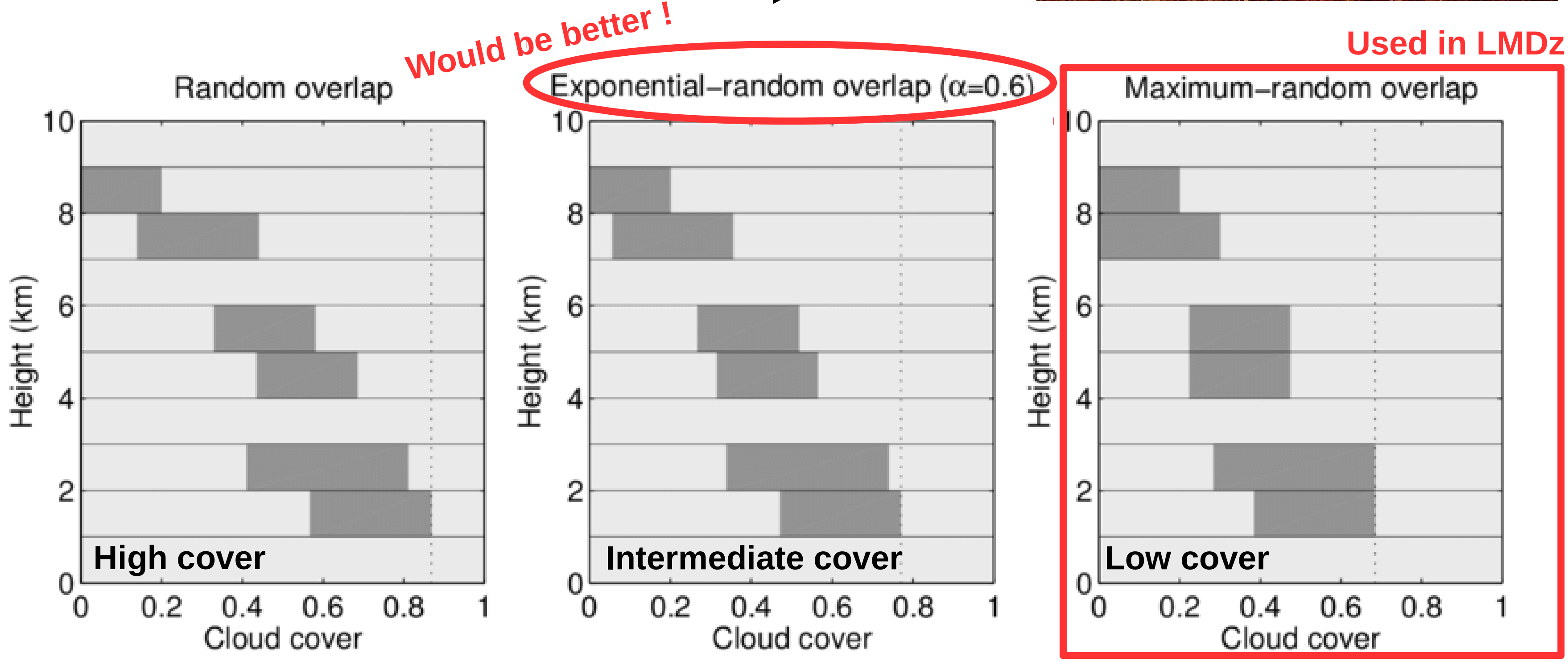
CF versus height is known, but radiation also needs to know the total cloud **cover ;** we therefore parameterize the **cloud overlap**





LMDz : Maximum random overlap

For the GCM, these two scenes are identical ;



[Radiation parameterization and clouds, Hogan, 2009]

Welcome to the LMDz team !