Model physics part II

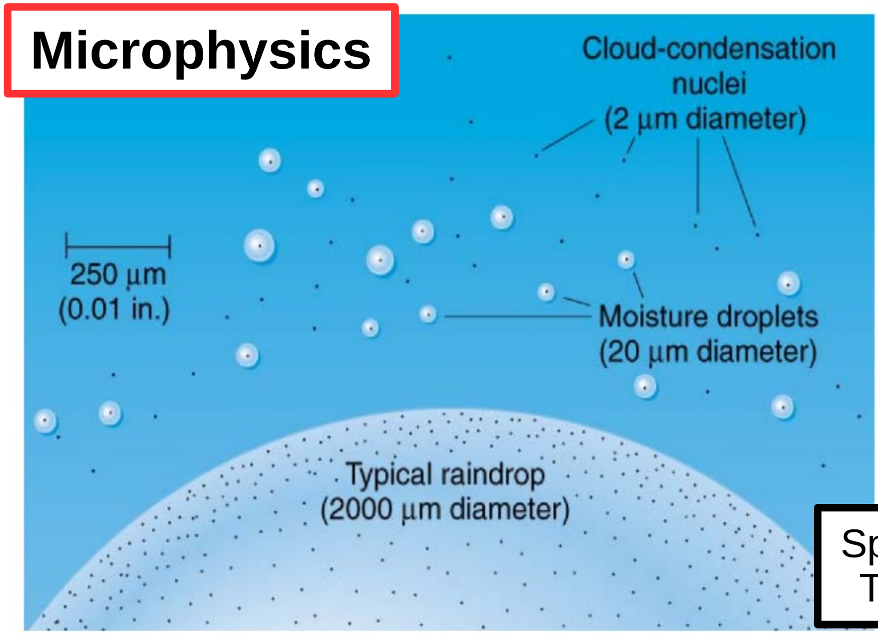
Convective and large-scale clouds

LMDZ Training – December 2024
J-B Madeleine and the LMDZ team

Picture by Oleg Artemyev taken from the ISS

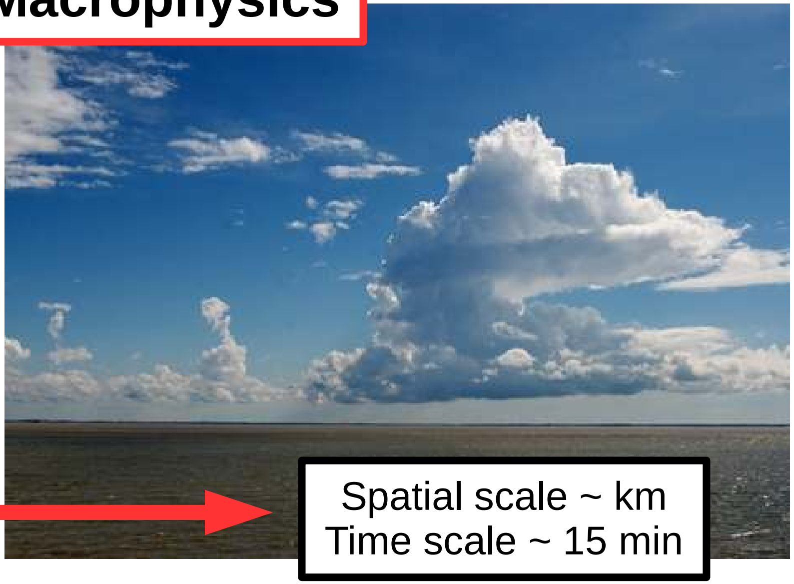
Modeling clouds : a challenge

Microphysics

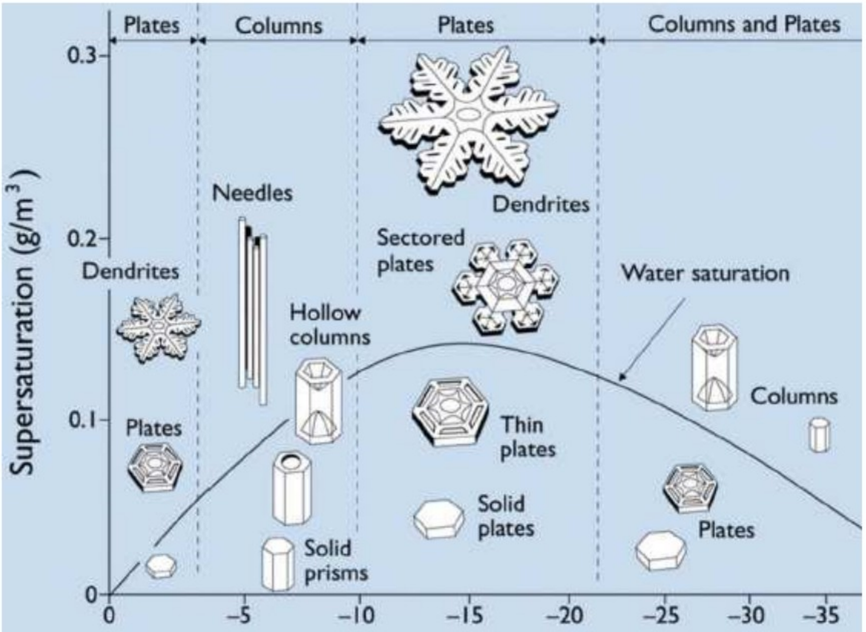


Spatial scale ~ µm
Time scale ~ 1 s

Macrophysics



Spatial scale ~ km
Time scale ~ 15 min



[Libbrecht, 2005]

Fundamental process

- Clausius-Clapeyron equation :

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

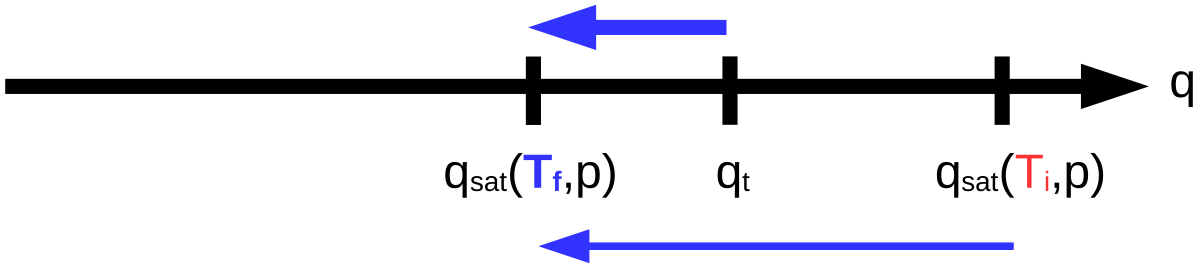
T	0°C	20°C
$e_{\rm sat}$	6.1 hPa	23.4 hPa
$q_{\rm sat}$	3.7 g kg^{-1}	14.4 g kg^{-1}

- Saturation mass mixing ratio :

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

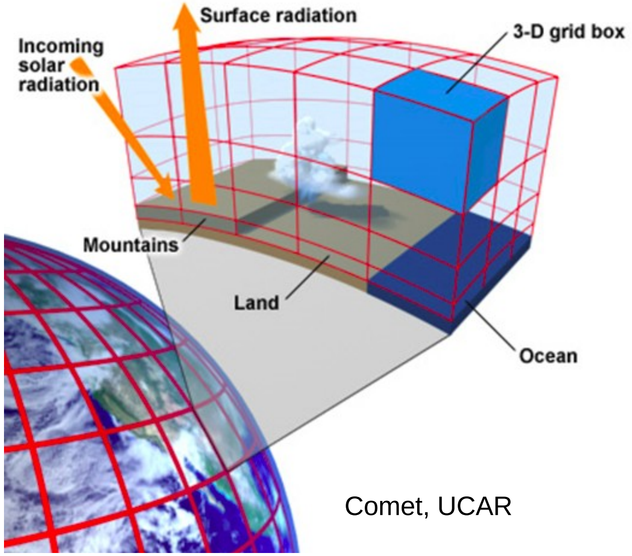
- Clouds form when an air parcel is cooled :

$\mathbf{q_c} = q_t - q_{sat}(T_f,p)$



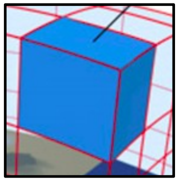
q

$q_{sat}(T_f,p)$ q_t $q_{sat}(T_i,p)$

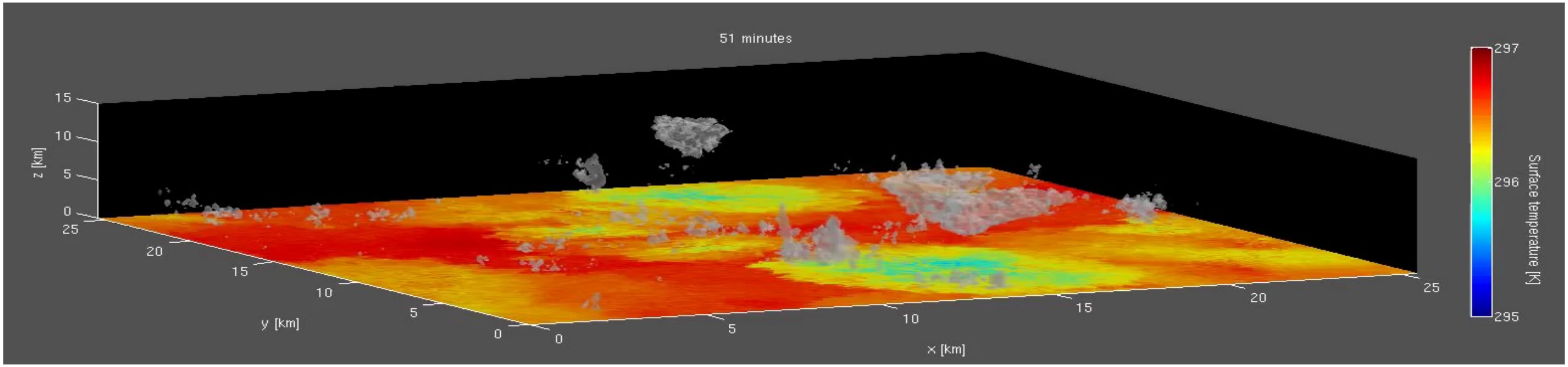


Comet, UCAR

- But clouds do not look like that :

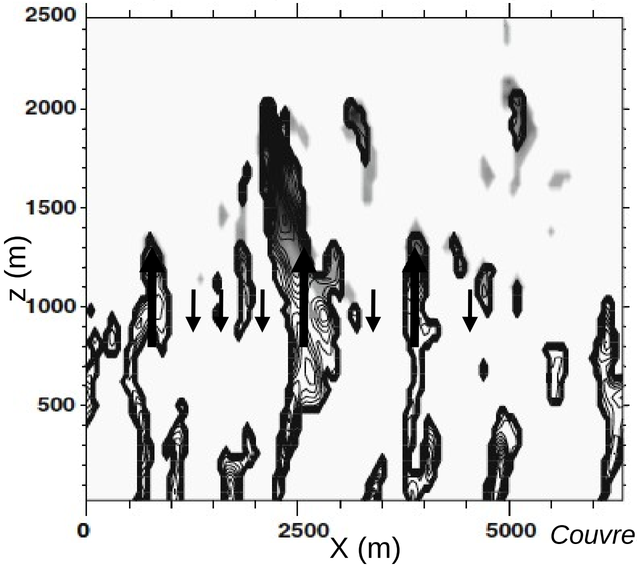


Many processes in one grid cell



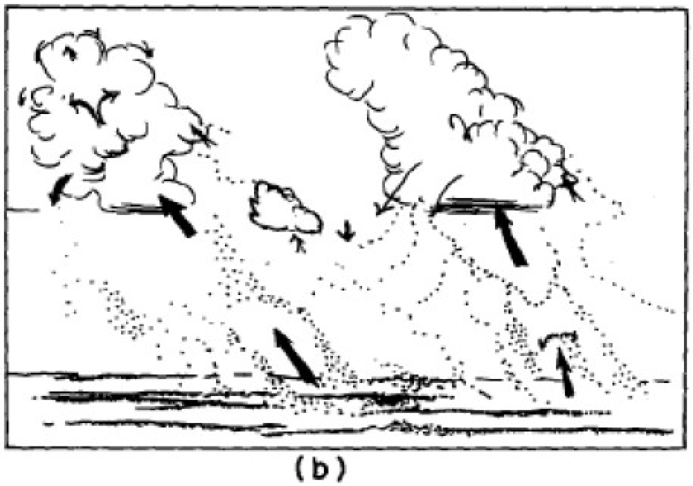
Around 8 hours of simulation by a **Cloud Resolving Model (CRM)** – C. Muller, LMD

Thermals in a
Large-Eddy Simulation (LES)



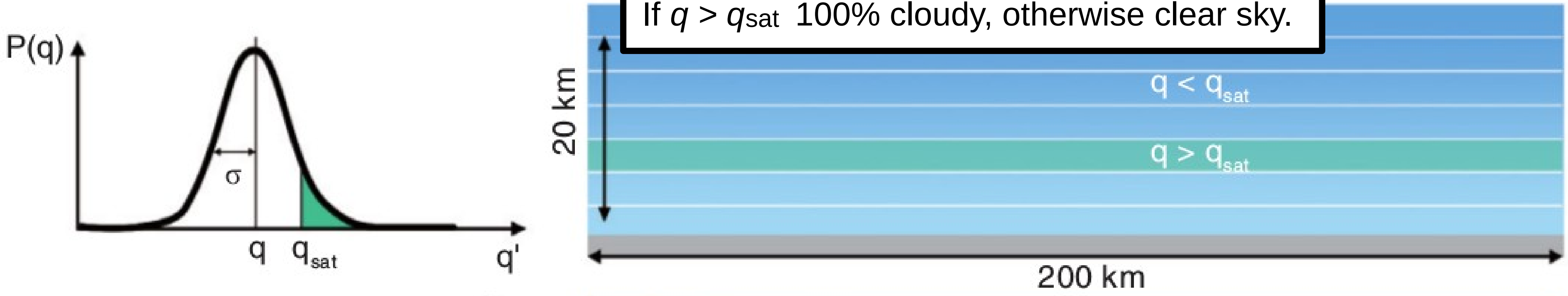
Couvreux et al., BLM, 2010

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



Lemone et Pennell, MWR, 1976

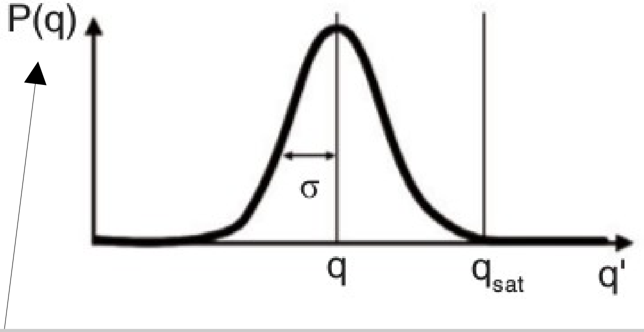
Statistical cloud scheme 1/2

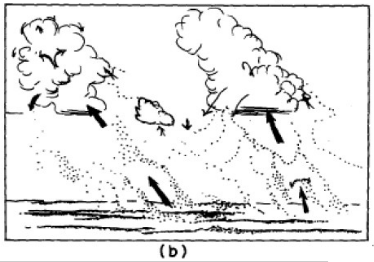


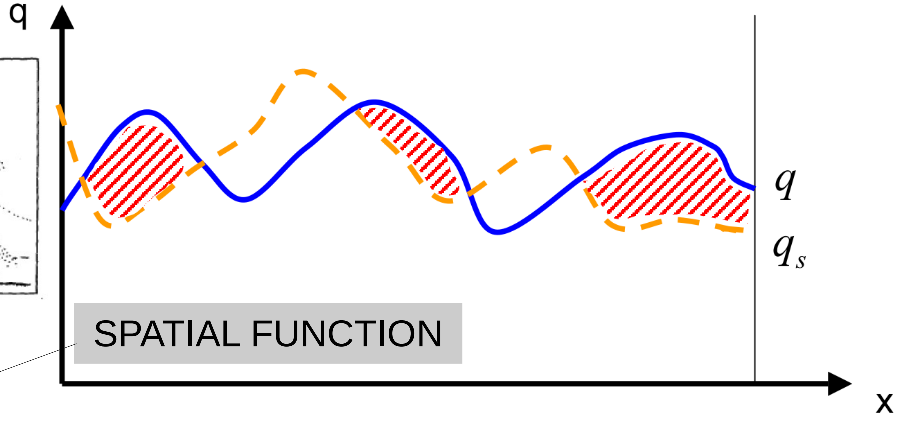
« all or nothing » model :
If $q > q_{sat}$ 100% cloudy, otherwise clear sky.

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

PROBA. DENSITY FUNCTION



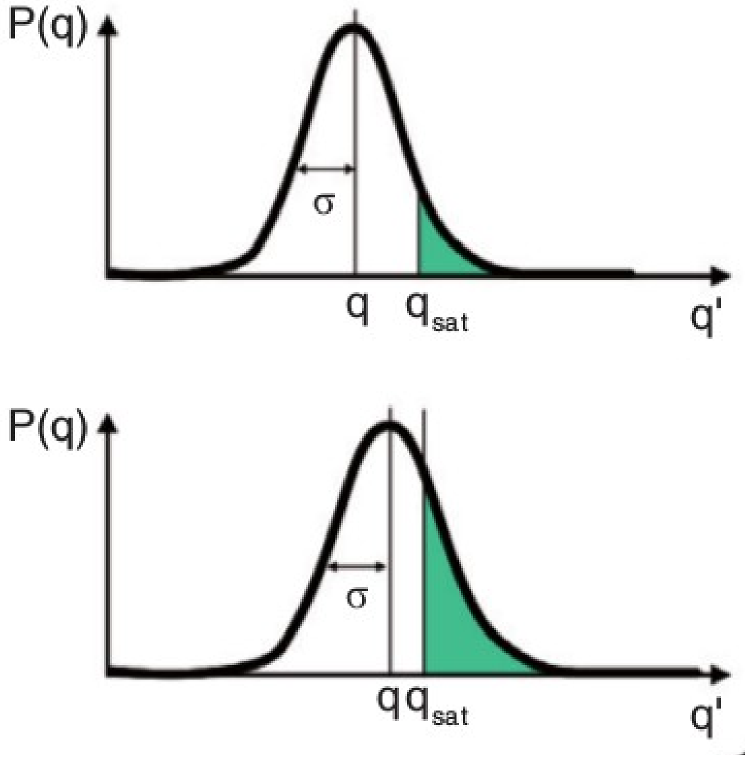




SPATIAL FUNCTION

ergodicity (statistical stationarity) : for turbulent flow, the property of having the spatial, temporal and ensemble averages all converge to the same mean (AMS dictionary)

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 :

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

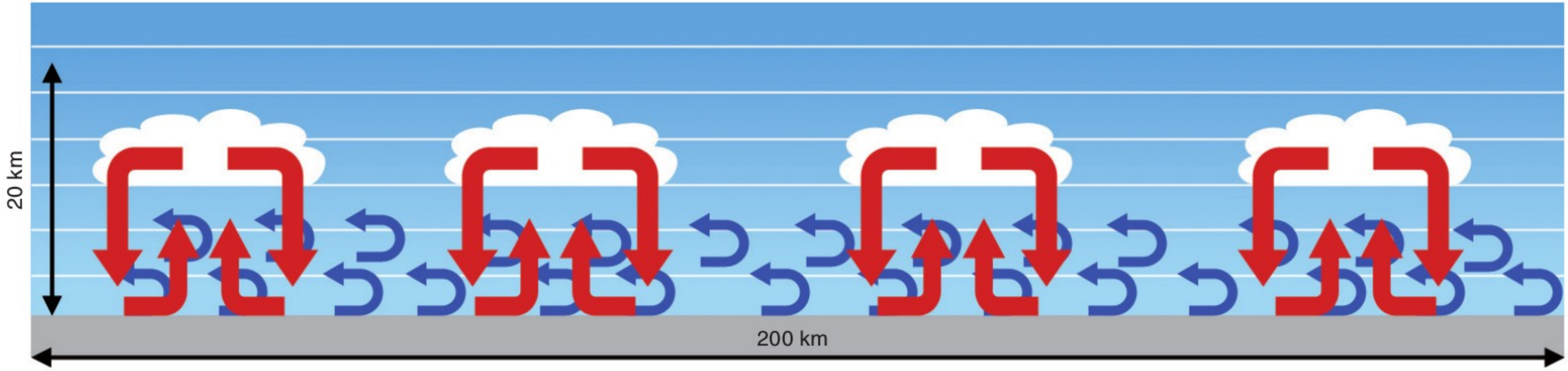
In-cloud condensed water content :

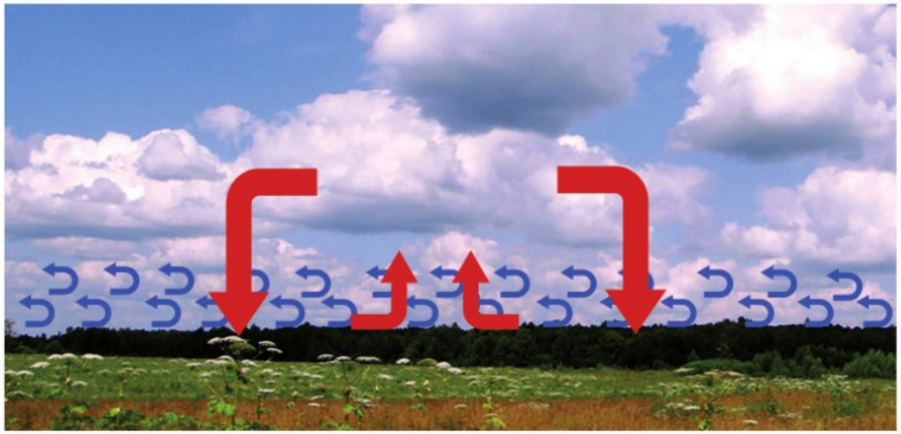
$$q_c^{in} = \frac{q_c}{\alpha_c}$$

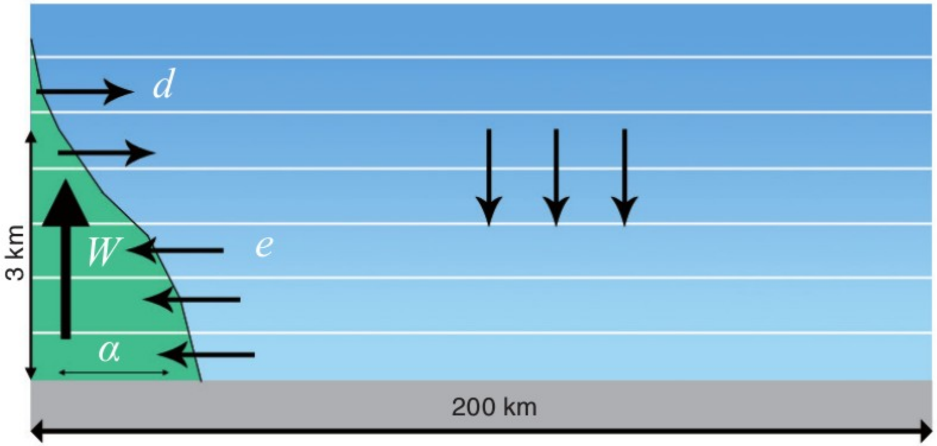
Shallow convective clouds

Clouds over the southern ocean with the Antarctic ice sheet in the distance (Thomas Pesquet, ISS)

Shallow convection 1/2







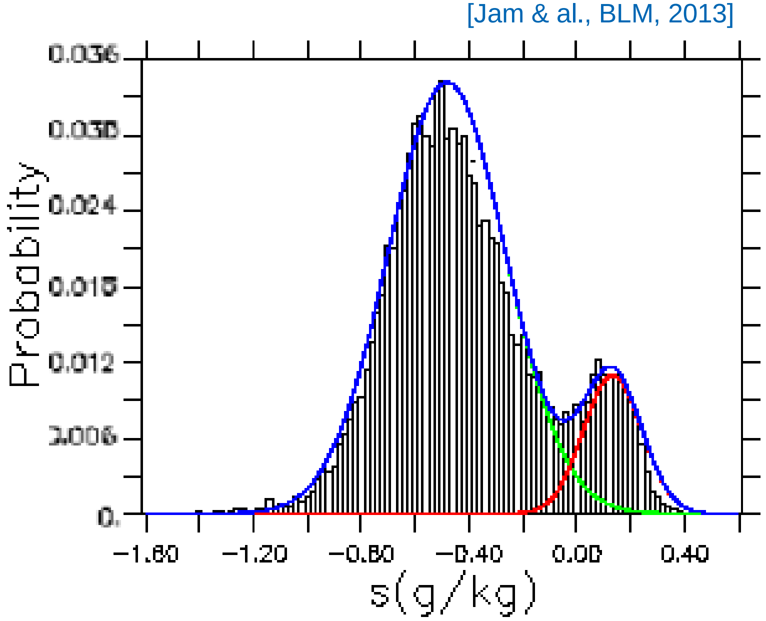
Shallow convection 2/2

Bi-Gaussian distribution of saturation deficit s:

$$Q(s) = (1-\alpha_{th})f(s,\, s_{env},\, \sigma_{env}) + \alpha_{th} f(s,\, s_{th},\, \sigma_{th})$$

One mode for thermals : s_{th}, σ_{th}

One mode for their environment : s_{env}, σ_{env}


[Jam & al., BLM, 2013]

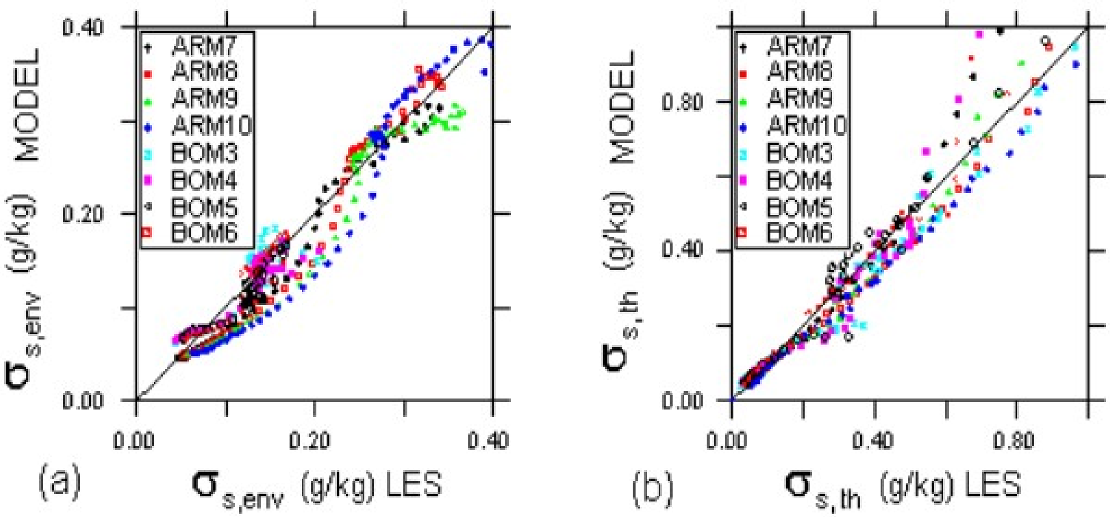
S_{env}, s_{th}, and α are given by the shallow convection scheme, and the distribution's variances are parameterized following :

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

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

q_c^{in} and the cloud fraction can be computed following :

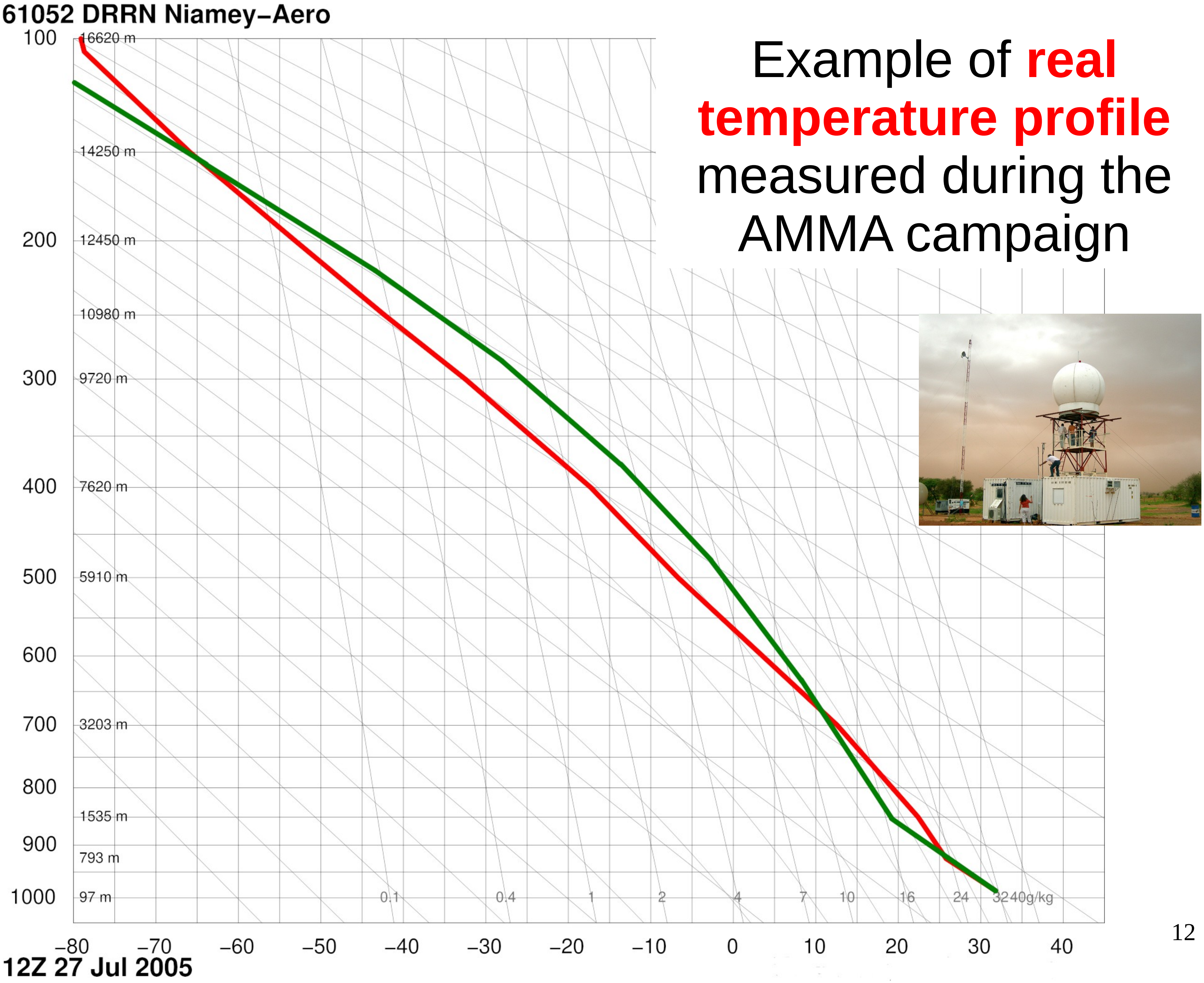
$$q_c^{in} = \int_0^{\infty} s\, Q(s)\, ds \qquad \alpha_c = \int_0^{\infty} Q(s)\, ds$$


[Jam & al., BLM, 2013]

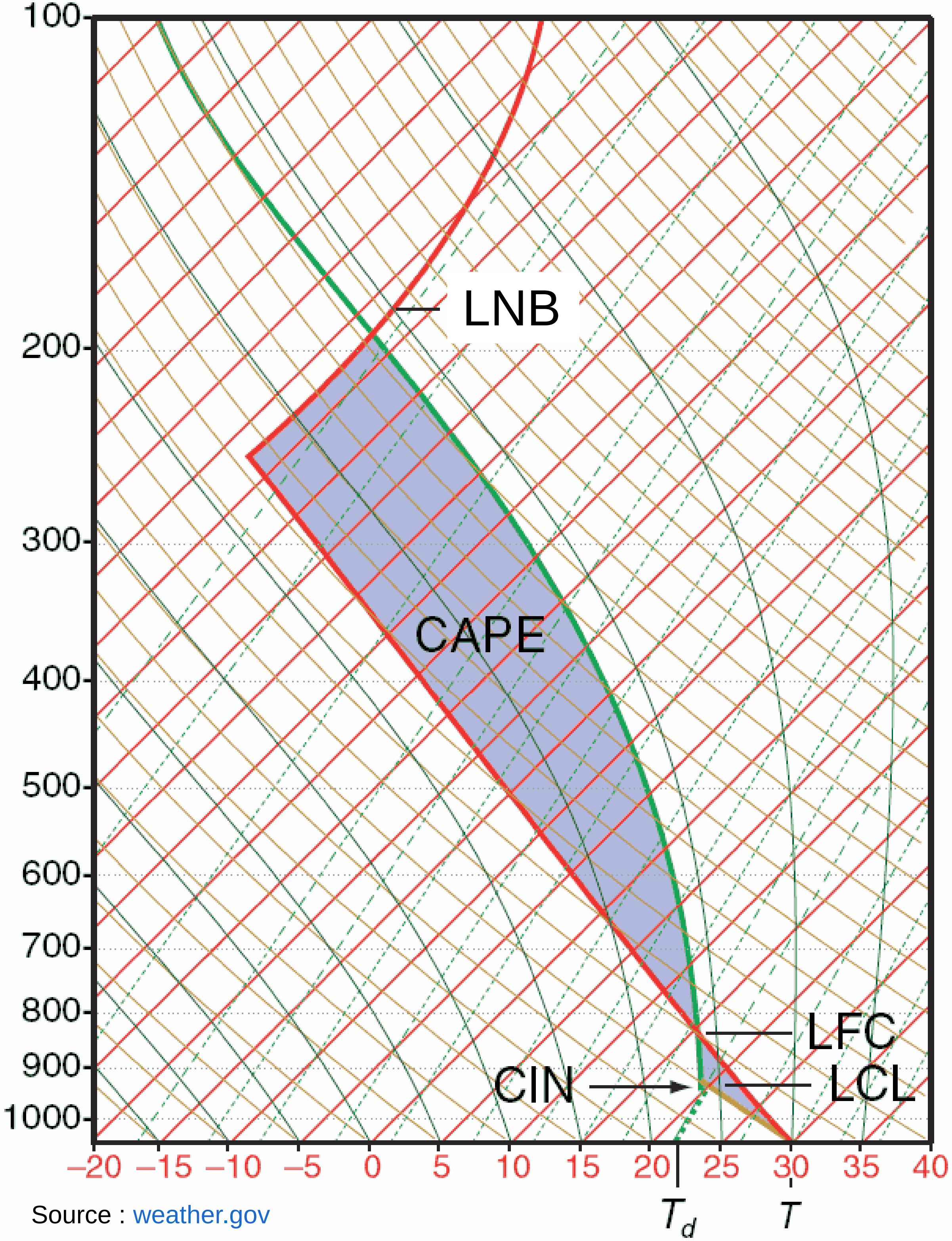
Deep convective clouds

International Space Station

Example of **real temperature profile** measured during the AMMA campaign



Theory



Source : weather.gov

Main variables shown on a skew-T diagram :

Red profile : Environment
Green profile : Adiabatic ascent

LCL : Lifted Condensation Level
LFC : Level of Free Convection

CIN : Convective INhibition
CAPE : Convective Available Potential Energy

CAPE = (J/kg) $$\int_{z_{LFC}}^{z_{LNB}} \boxed{g\left(\frac{T}{T_{env}} - 1\right)} \cdot dz$$

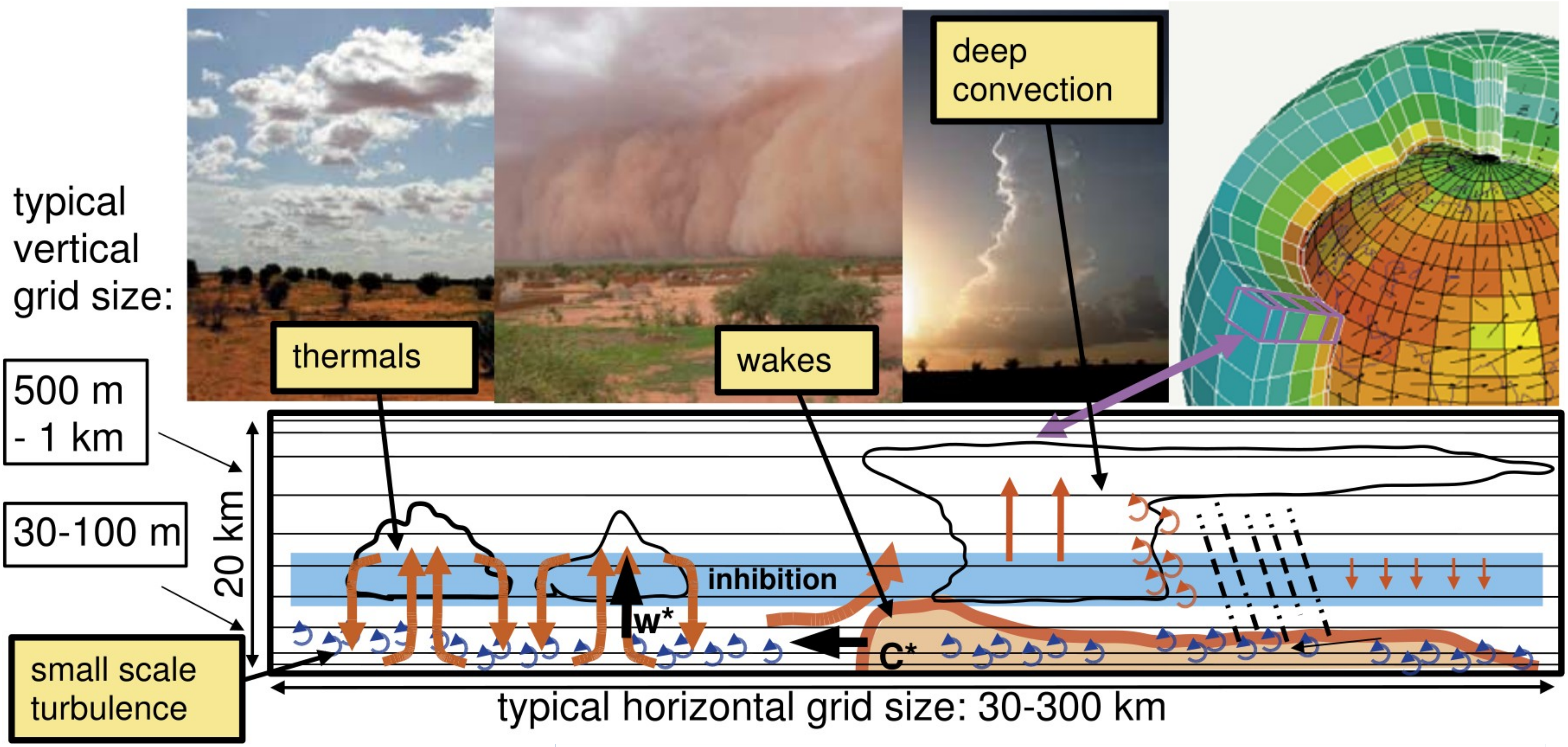
Buoyancy (N/kg)

$$E_c = \frac{1}{2} \cdot w^2$$ and therefore :

CAPE = $\boxed{\Delta_{LFC \rightarrow LNB} E_c}$

LMDZ framework

Source : Rio et al., 2009



$$\mathrm{ALE}^{\mathrm{th}} = w_*^2/2$$

$$\mathrm{ALE}^{\mathrm{wk}} \simeq C_*^2$$

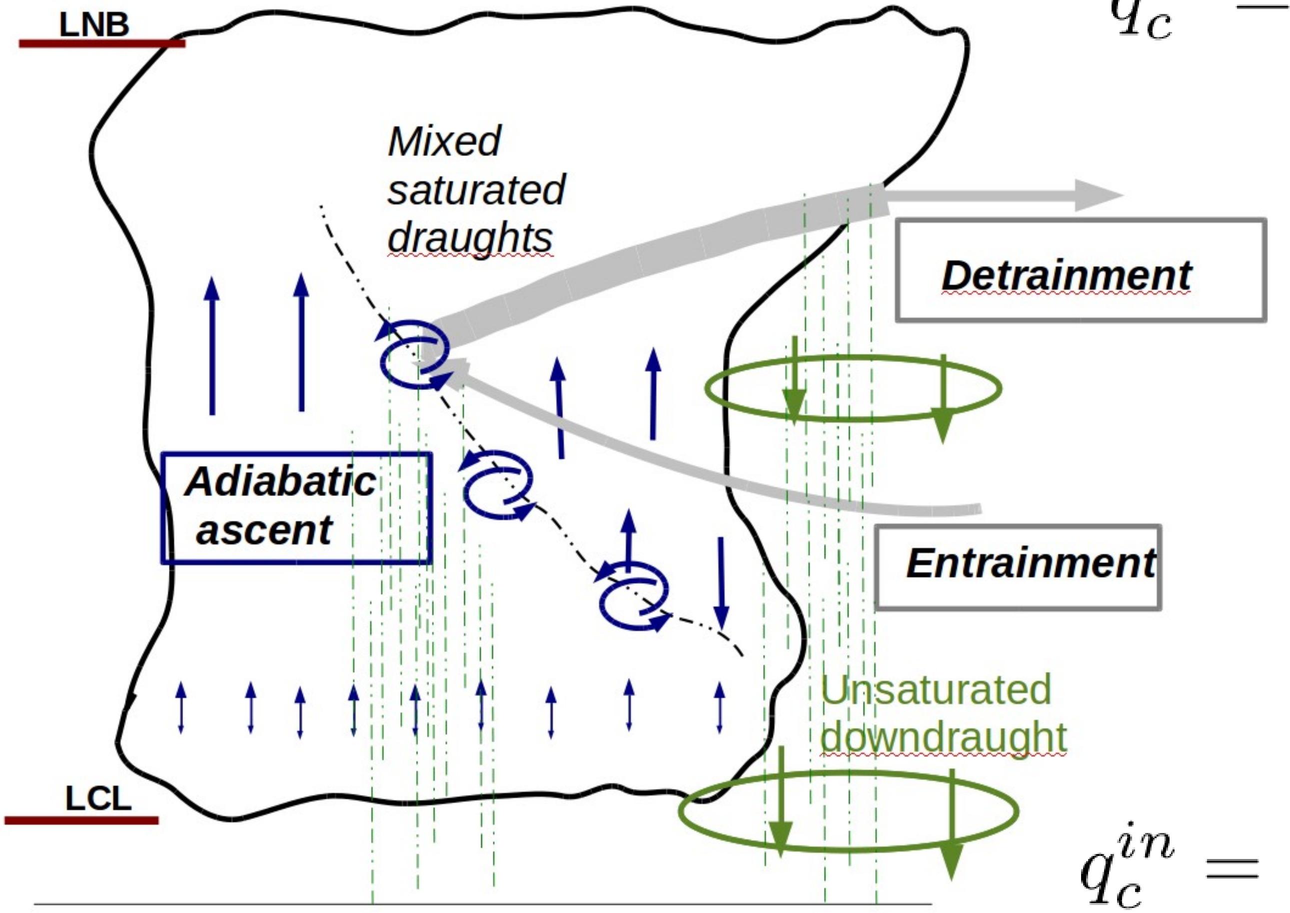
Deep convection is triggered :

- **IF :** $\max(\mathrm{ALE}^{\mathrm{th}}, \mathrm{ALE}^{\mathrm{wk}}) > |\mathrm{CIN}|$
- **AND IF** : at least one cloud reaches a given threshold size (stochastic triggering scheme, Rochetin et al., 2014)

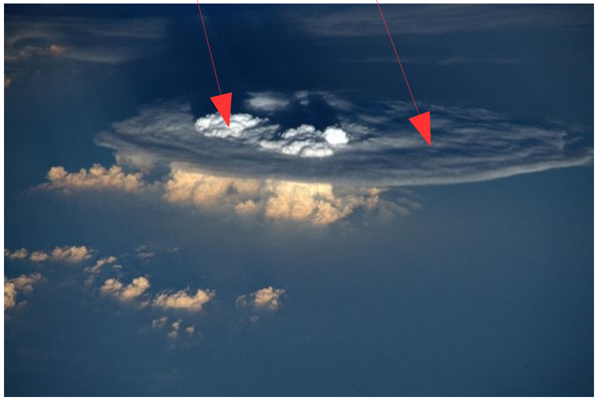
Deep convection cloud scheme

(JAS 1991)

Emanuel scheme



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



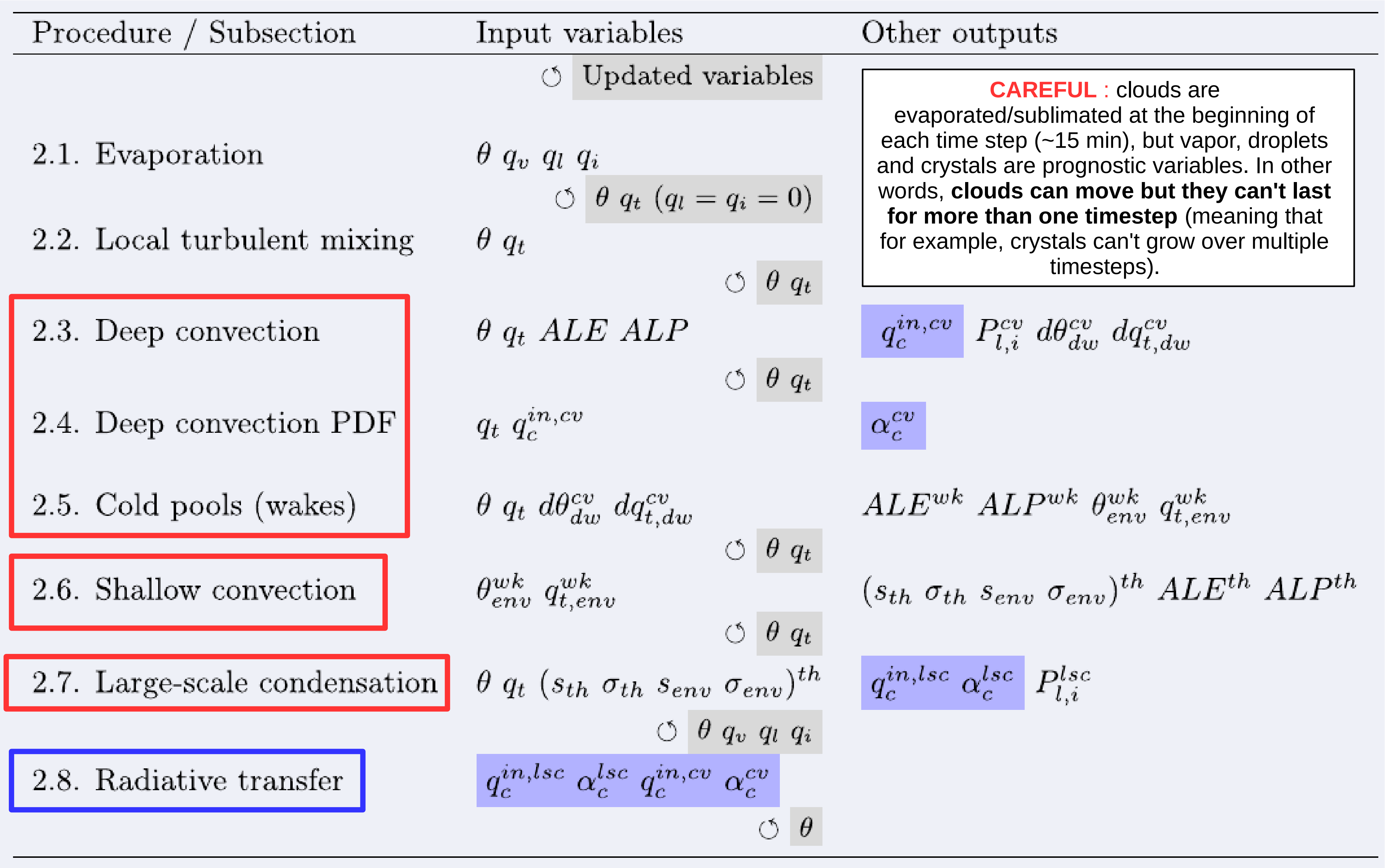
$$q_c^{in} = \frac{\frac{M_a}{\rho \; w_a} q_{ca} + \frac{\tau \; M_t \; g}{\delta p} q_{cm}}{\frac{M_a}{\rho \; w_a} + \frac{\tau \; M_t \; g}{\delta p}}$$

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

Large-scale clouds

International Space Station

Architecture of the physical scheme

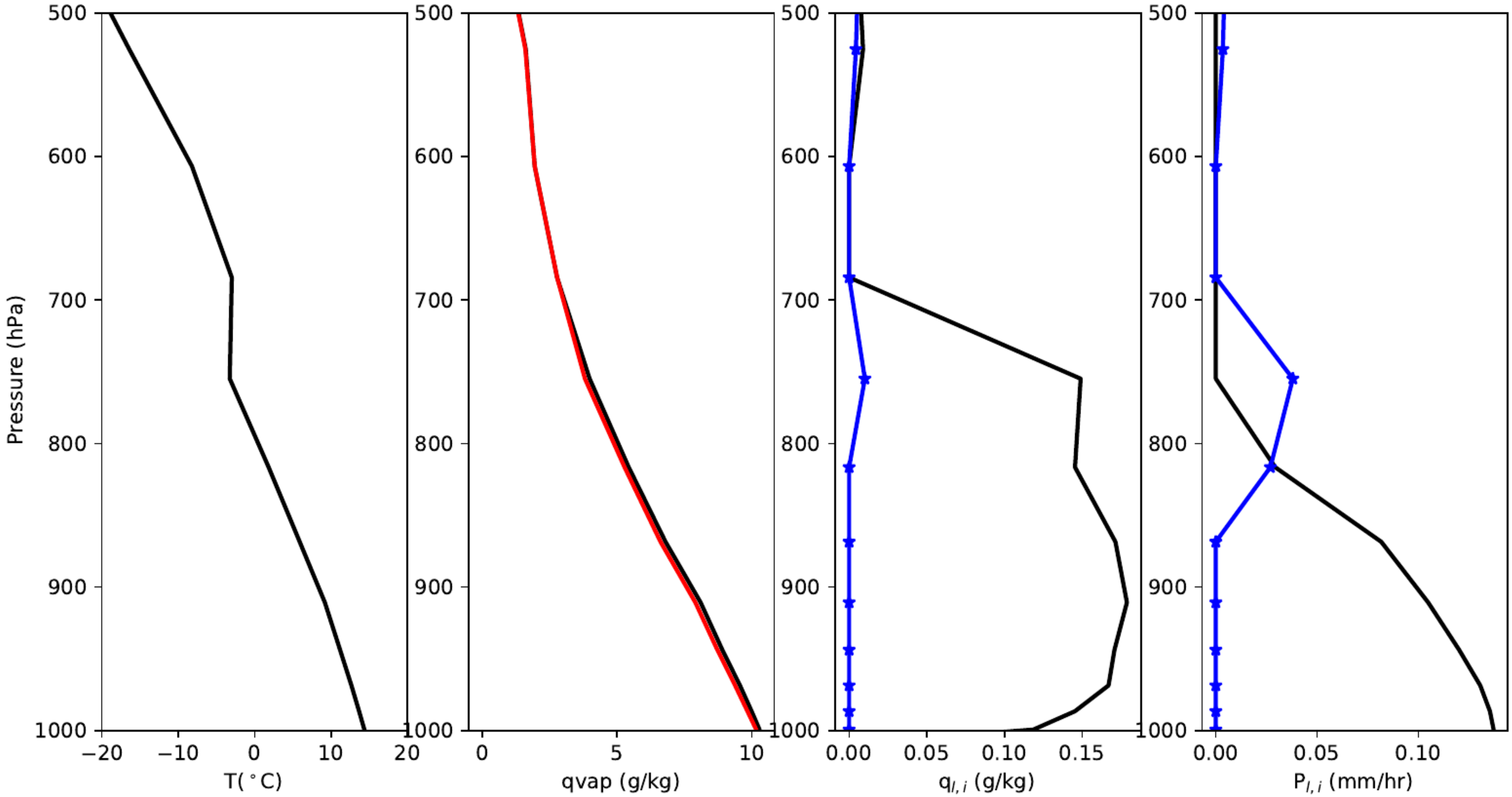


Procedure / Subsection	Input variables	Other outputs
	↻ Updated variables	
2.1. Evaporation	$\theta\ q_v\ q_l\ q_i$	
	↻ $\theta\ q_t\ (q_l = q_i = 0)$	
2.2. Local turbulent mixing	$\theta\ q_t$	
	↻ $\theta\ q_t$	
2.3. Deep convection	$\theta\ q_t\ ALE\ ALP$	$q_c^{in,cv}\ \ P_{l,i}^{cv}\ \ d\theta_{dw}^{cv}\ \ dq_{t,dw}^{cv}$
	↻ $\theta\ q_t$	
2.4. Deep convection PDF	$q_t\ q_c^{in,cv}$	α_c^{cv}
2.5. Cold pools (wakes)	$\theta\ q_t\ d\theta_{dw}^{cv}\ dq_{t,dw}^{cv}$	$ALE^{wk}\ \ ALP^{wk}\ \ \theta_{env}^{wk}\ \ q_{t,env}^{wk}$
	↻ $\theta\ q_t$	
2.6. Shallow convection	$\theta_{env}^{wk}\ q_{t,env}^{wk}$	$(s_{th}\ \sigma_{th}\ s_{env}\ \sigma_{env})^{th}\ \ ALE^{th}\ \ ALP^{th}$
	↻ $\theta\ q_t$	
2.7. Large-scale condensation	$\theta\ q_t\ (s_{th}\ \sigma_{th}\ s_{env}\ \sigma_{env})^{th}$	$q_c^{in,lsc}\ \ \alpha_c^{lsc}\ \ P_{l,i}^{lsc}$
	↻ $\theta\ q_v\ q_l\ q_i$	
2.8. Radiative transfer	$q_c^{in,lsc}\ \alpha_c^{lsc}\ q_c^{in,cv}\ \alpha_c^{cv}$	
	↻ θ	

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 they can't last for more than one timestep** (meaning that for example, crystals can't grow over multiple timesteps).

Large scale condensation 1/3

Temperature, water vapor, clouds and precipitation over one timestep



1 **REEVAPORATION** **2** **CLOUD FORMATION** **3** **PRECIPITATION**

Large scale condensation 2/3

- Rain/snow is partly evaporated in the grid below (parameter controlling the evaporation rate) :

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

1 **REEVAPORATION**

2 **CLOUD FORMATION**

If there is shallow convection

q_c^{in} and the cloud fraction can be computed following :

$$q_c^{in} = \int_0^{\infty} s\,Q(s)\,ds$$

$$\alpha_c = \int_0^{\infty} Q(s)\,ds$$

If there is no shallow convection

q_c^{in} and the cloud fraction can be computed following :

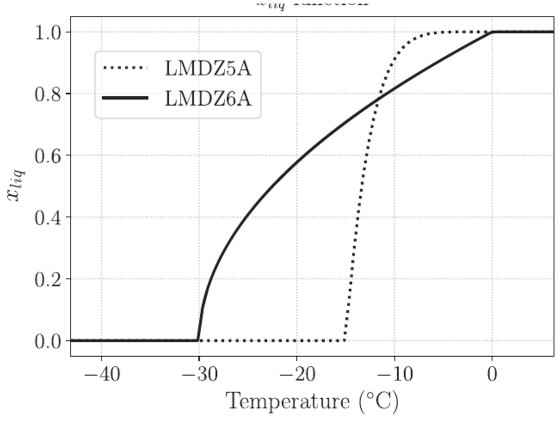
$$q_c = \int_{q_{sat}}^{\infty} (q - q_{sat})P(q)dq$$

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

Log-normal distribution of total water q_t using a prescribed variance $\sigma = \xi q_t$

In both cases, cloud phase is parameterized using a simple function of temperature :

$$x_{liq} = \left(\frac{T - T_{min}}{T_{max} - T_{min}}\right)^n$$



Large scale condensation 3/3

3 **PRECIPITATION**

- A fraction of the condensate falls as rain (parameters controlling the maximum water content of clouds and the auto-conversion rate)
- For clouds, it corresponds to a sink term written as :

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

[Kessler 1969, Sundqvist 1988]

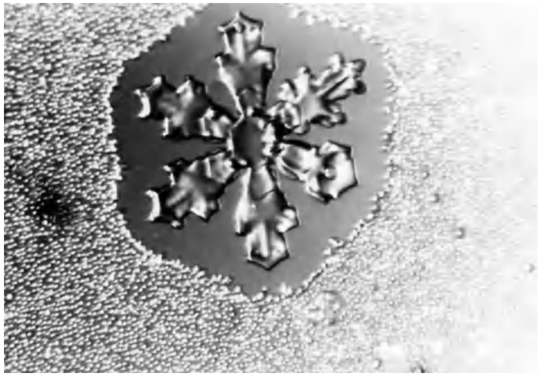
- Another fraction is converted to snow ; the corresponding sink term for ice clouds depends on the divergence of the ice crystal mass flux :
- This fraction depends on the same temperature function as clouds → rain can be created below freezing
- When this occurs, the resulting liquid precipitation **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.

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

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

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

[Heymsfield, 1977; Heymsfield & Donner, 1990]



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

Tuning parameters

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

coef_eva=0.0001

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

cld_lc_lsc=0.00065
cld_tau_lsc=900

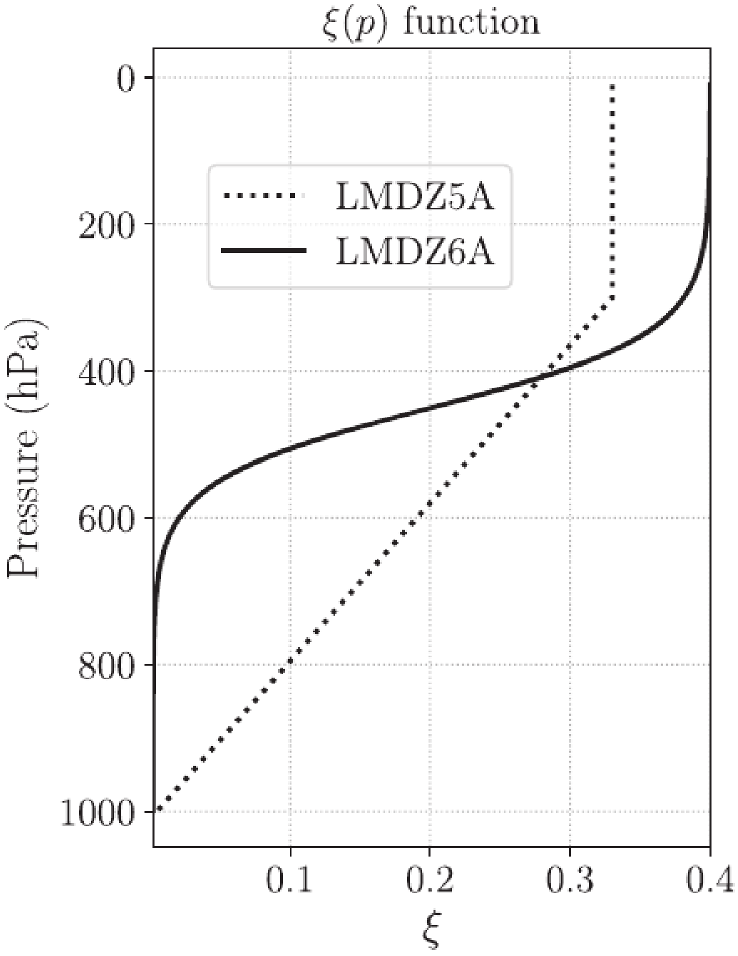
$$\frac{dq_{iw}}{dt} = \frac{1}{\rho}\frac{\partial}{\partial z}(\rho w_{iw} q_{iw})$$

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

ffallv_lsc=0.8

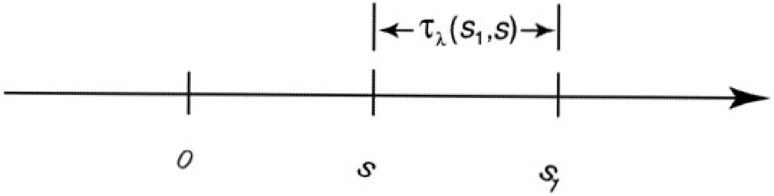
$$\sigma = \xi q_t$$

ratqsp0=45000
ratqsdp=10000
ratqsbas=0.002
ratqshaut=0.4



Radiative transfer

Radiative transfer equation :



$$-\mu\frac{\partial I_\lambda}{\partial\tau_\lambda}(\tau_\lambda,\mu,\Phi) = -I_\lambda(\tau_\lambda,\mu,\Phi) + S_\lambda(\tau_\lambda,\mu,\Phi)$$

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

Solving the radiative transfer equation requires :

- $\boldsymbol{q_{rad}}$ to compute the optical depth ;
- **Cloud droplet and crystal sizes** to compute the optical properties ;
- The cloud fraction **α** to compute the heating rates
  in the clear-sky (1-α) and cloudy (α) columns.

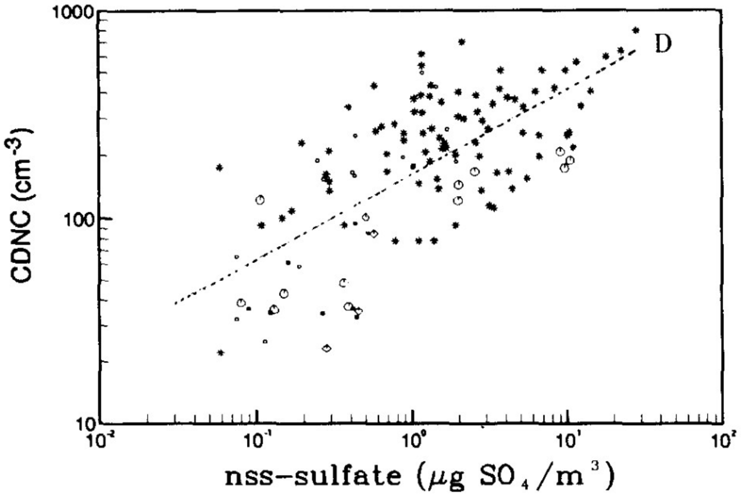
$$q_{rad} = q_c^{in,\,cv}\alpha_c^{cv} + q_c^{in,\,lsc}\alpha_c^{lsc}$$

$$\alpha_c = \min\left(\alpha_c^{cv} + \alpha_c^{lsc},\ 1\right)$$

Optical properties of liquid clouds

$$\mathrm{CDNC} = 10^{1.3 + 0.2\log(m_{\mathrm{aer}})}$$

Link cloud droplet number concentration to soluble aerosol mass concentration (Boucher and Lohmann, Tellus, 1995)



N = CDNC

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

$$r_\mathrm{e} = \frac{\int r^3 n(r)\,\mathrm{d}r}{\int r^2 n(r)\,\mathrm{d}r}$$

$$r_\mathrm{e} = 1.1\; r_3$$

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.

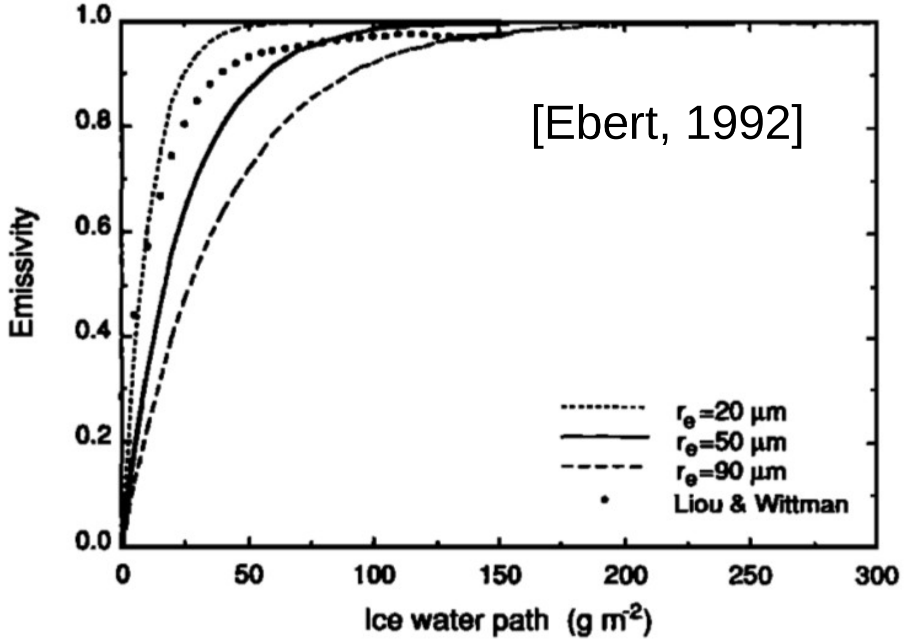
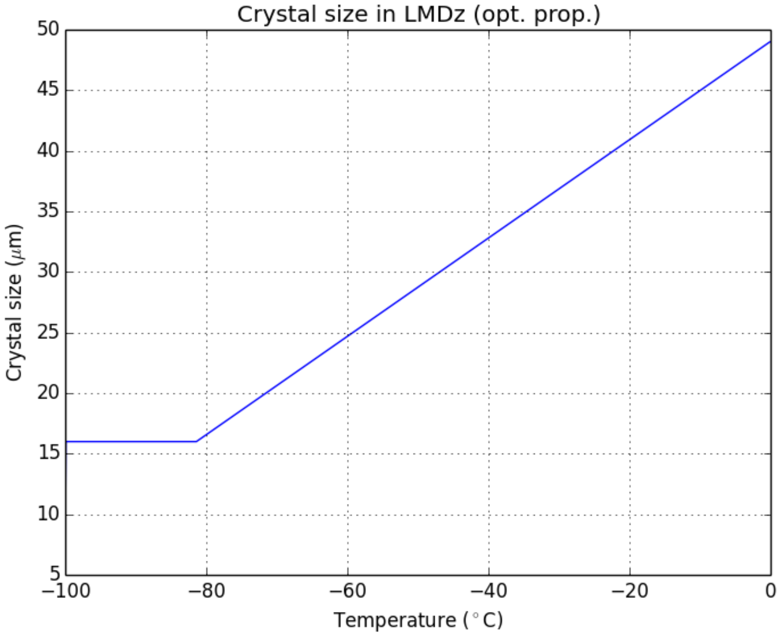
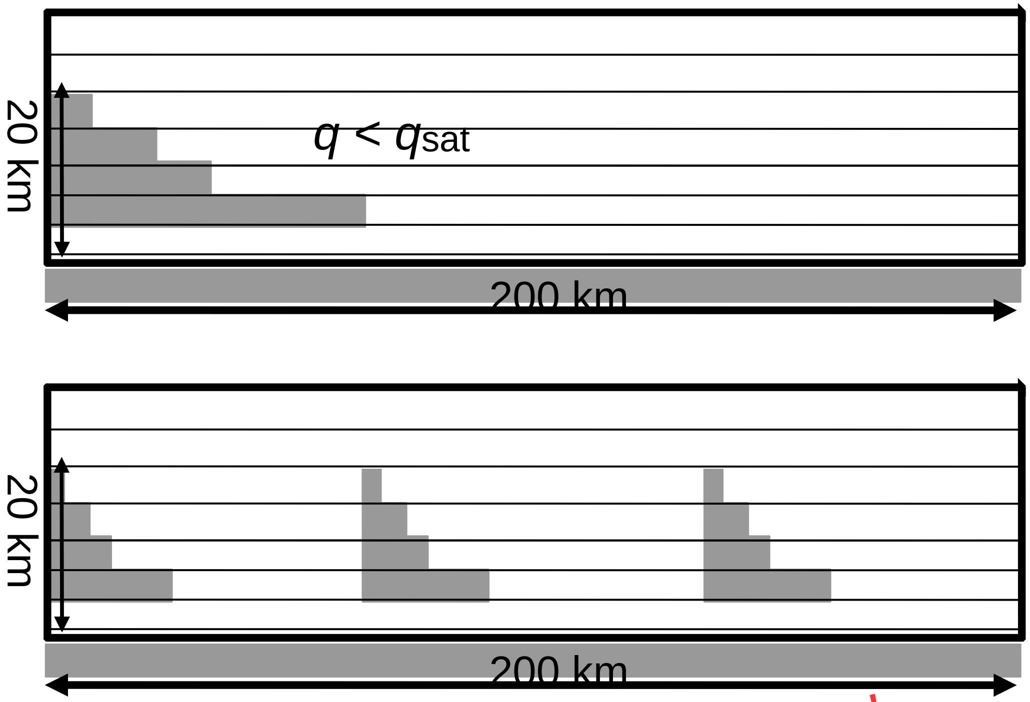


Fig. 5. Cirrus infrared emissivity for r_e = 20, 50, and 90 µm as a function of ice water path. The solid circles represent values computed using the parameterization of *Liou and Wittman* [1979].



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]*

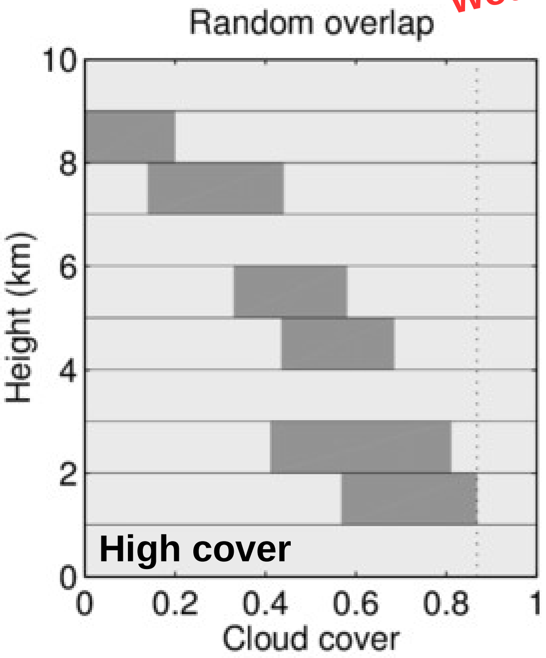
CF versus height is known, but radiation also needs to know the total cloud **cover ;** we therefore parameterize the **cloud overlap**



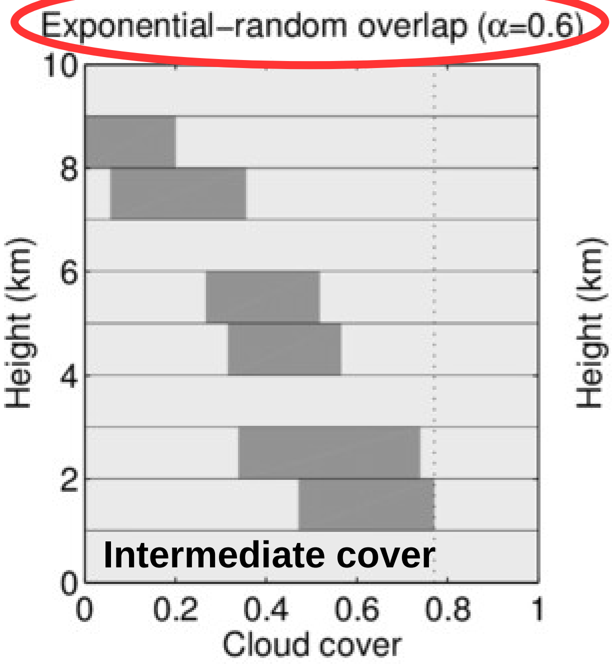
For the GCM, these two scenes are identical ;

Would be better !

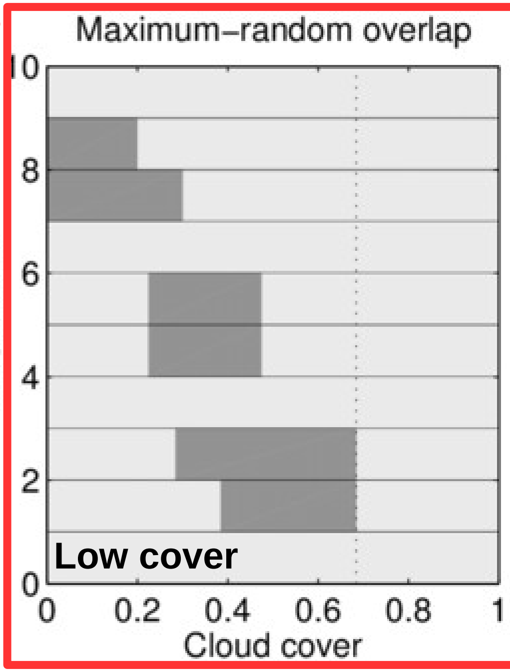
Used in LMDz



High cover



Intermediate cover



Low cover

[Radiation parameterization and clouds, Hogan, 2009]

Radiative forcing

LW radiative forcing

Positive : clouds reduce the LW outgoing radiation

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

SW radiative forcing

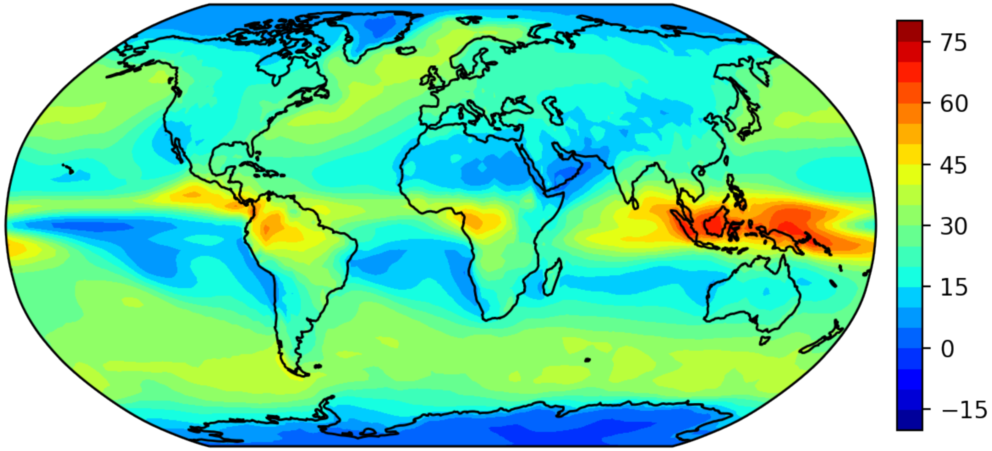
Negative : clouds reflect the incoming SW radiation

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

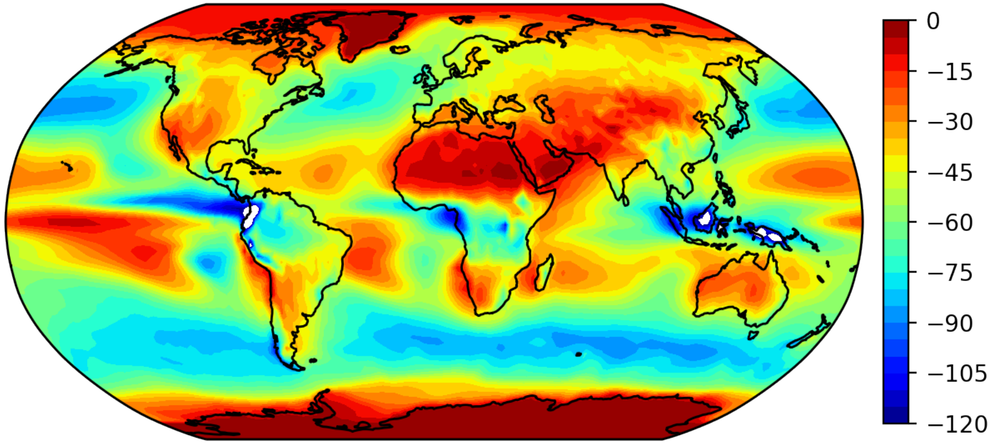
Net forcing : **Cooling**

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

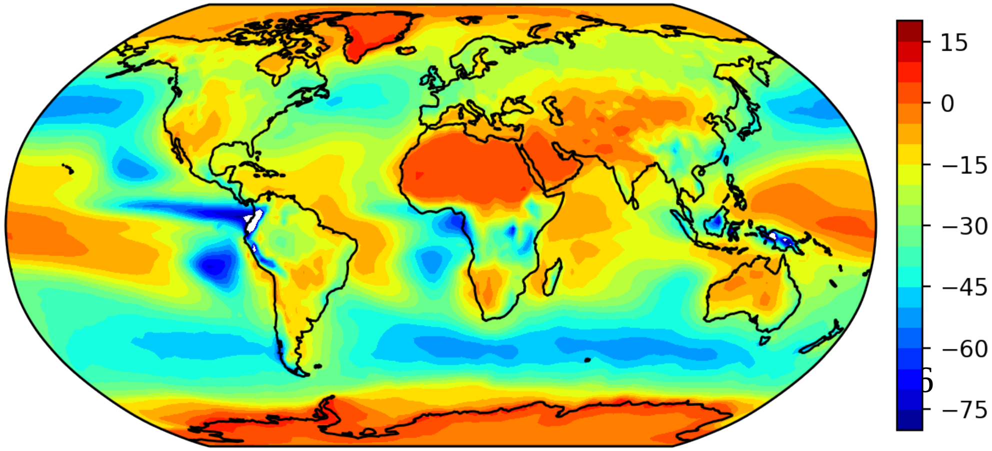
LW Cloud Radiative Forcing (W m^{-2}) - LMDZ6A



SW Cloud Radiative Forcing (W m^{-2}) - LMDZ6A



Net Cloud Radiative Forcing (W m^{-2}) - LMDZ6A



Cloud scheme : toward LMDZ v.7

- **Improved reevaporation** (Ludovic Touzé-Peiffer 2021 PhD thesis p117)
- **Prognostic variances for cloud PDFs** (Louis d’Alençon et al. in prep)
- **Mixed-phase clouds** (Lea Raillard et al. in prep)
- **Supersaturation** with respect to ice in high clouds (A. Borella et al. in prep)
- **New ice precipitation scheme** (N. Dutrievoz et al. in prep)
- **Tuning of the ecRad radiative transfer scheme** inside LMDZ using LES simulations (Maëlle Coulon-Decorzens et al. submitted)

3D effect of clouds

- **New radiative transfer scheme ecRad** ECMWF (Abderrahmane Idelkadi et al.)
  - McICA (Monte-Carlo Independent Column Approximation, Pincus et al. 2005) → subgrid scale heterogeneities
  - SPARTACUS (3D effects at cloud sides, Hogan et al., 2016)

Cloud variables in LMDZ

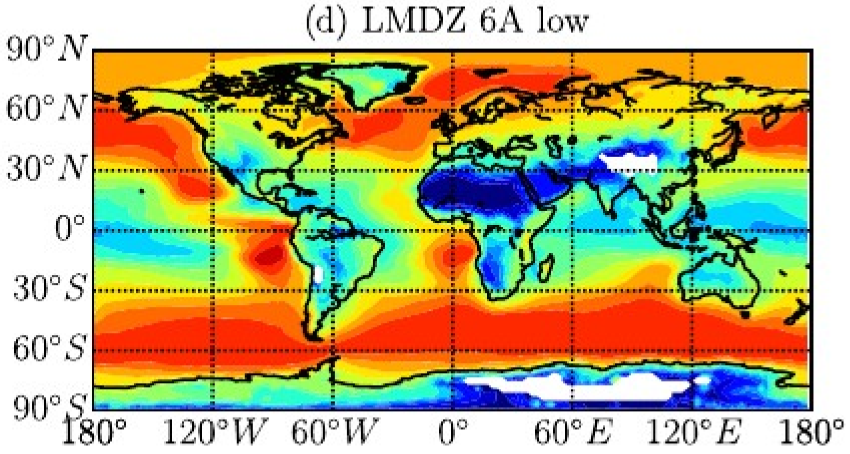
prw (2D) : Precipitable water (kg/m^2)
pluc/plul (2D) : Convective/lsc rainfall (kg/m^2/s)
snow (2D) = surface snowfall (kg/m^2/s)
lwp (2D) : Cloud liquid water path (kg/m^2)
iwp (2D) : Cloud ice water path (kg/m^2)

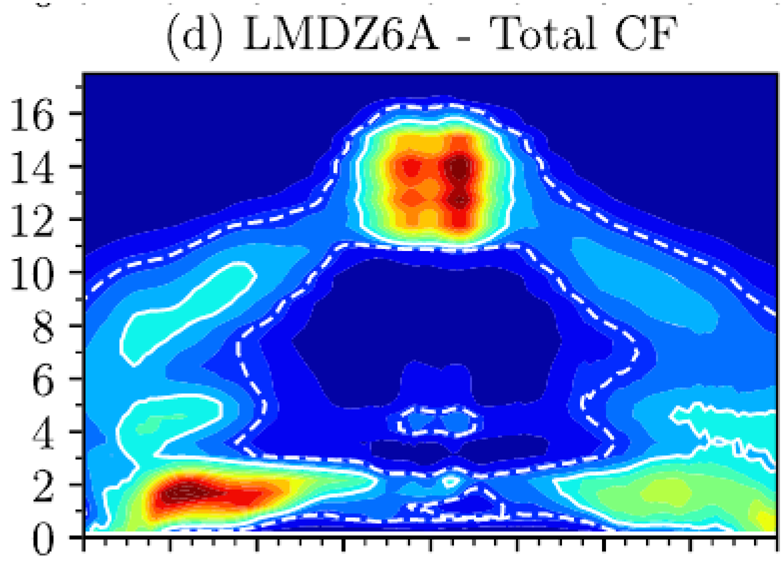
ovap (3D) : water vapor content (kg/kg)
oliq (3D) : cloud liquid water content (kg/kg)
ocond (3D) : cloud liq+ice water content (kg/kg)

pr_lsc_l (3D) : lsc rain mass fluxes (kg/m^2/s)
pr_lsc_i (3D) : lsc snow mass fluxes (kg/m^2/s)

rneb (3D) : cloud **fraction** (%)
cldh (2D) : High-level cloud **cover** (%)
cldm (2D) : Mid-level cloud **cover** (%)
cldl (2D) : Low-level cloud **cover** (%)
cldt (2D) : Total cloud **cover** (%)

low-level clouds = below 680 hPa or ~3 km
mid-level clouds = between 680 and 440 hPa
high-level clouds = above 440 hPa or ~6.5 km





Useful links and references

- **On the general LMDZ v.6 cloud scheme :**
  - Madeleine et al. 2020 : https://doi.org/10.1029/2020MS002046
  - Supplementary material : https://zenodo.org/record/3942031
- **On the deep convection scheme :**
  - Grandpeix et al., 2004 : https://doi.org/10.1256/qj.03.144
  - Rio et al., 2009 : https://doi.org/10.1029/2008GL036779
- **Process animations :**
  - Satellite animation using the SEVIRI instrument : http://pmm.nasa.gov/education/videos/water-vapor-animation
  - Animations of updrafts and triggering of deep convection over the mountains of Arizona : https://animations.atmos.uw.edu, sections 15.1 and 16.5
  - Animation of the cloud field in high resolution LMDZ simulations : https://lmdz.lmd.jussieu.fr/pub/Training/Presentations/LMDZ_animation-highres.mp4