CELS cloud physics

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VILLUM FONDEN

- Modeling dynamics
- Atmospheric stability
- Radiative convective equilibrium
- Aerosol and cloud microphysics
- Microbes as ice nucleation particles

Model equations

momentum equation

$$\frac{\partial \bar{u}_i}{\partial t} = -\bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} - c_p \Theta_0 \frac{\partial \bar{\pi}}{\partial x_i} + \frac{1}{\rho_0} \frac{\partial(\rho_0 \tau_{ij})}{\partial x_j} + \mathcal{F}_i$$

scalars, e.g.: q_t, Θ, etc.

$$\frac{\partial \bar{\phi}}{\partial t} = -\bar{u}_j \frac{\partial \bar{\phi}}{\partial x_j} + \frac{1}{\rho_0} \frac{\partial(\rho_0 \gamma_{\phi j})}{\partial x_j} + \mathcal{S}_\phi$$

buoyancy and external forces

sources/sinks

Anelastic continuity

$$\frac{\partial(\rho_0 u_i)}{\partial x_i} = 0$$

Ideal gas law equation of state

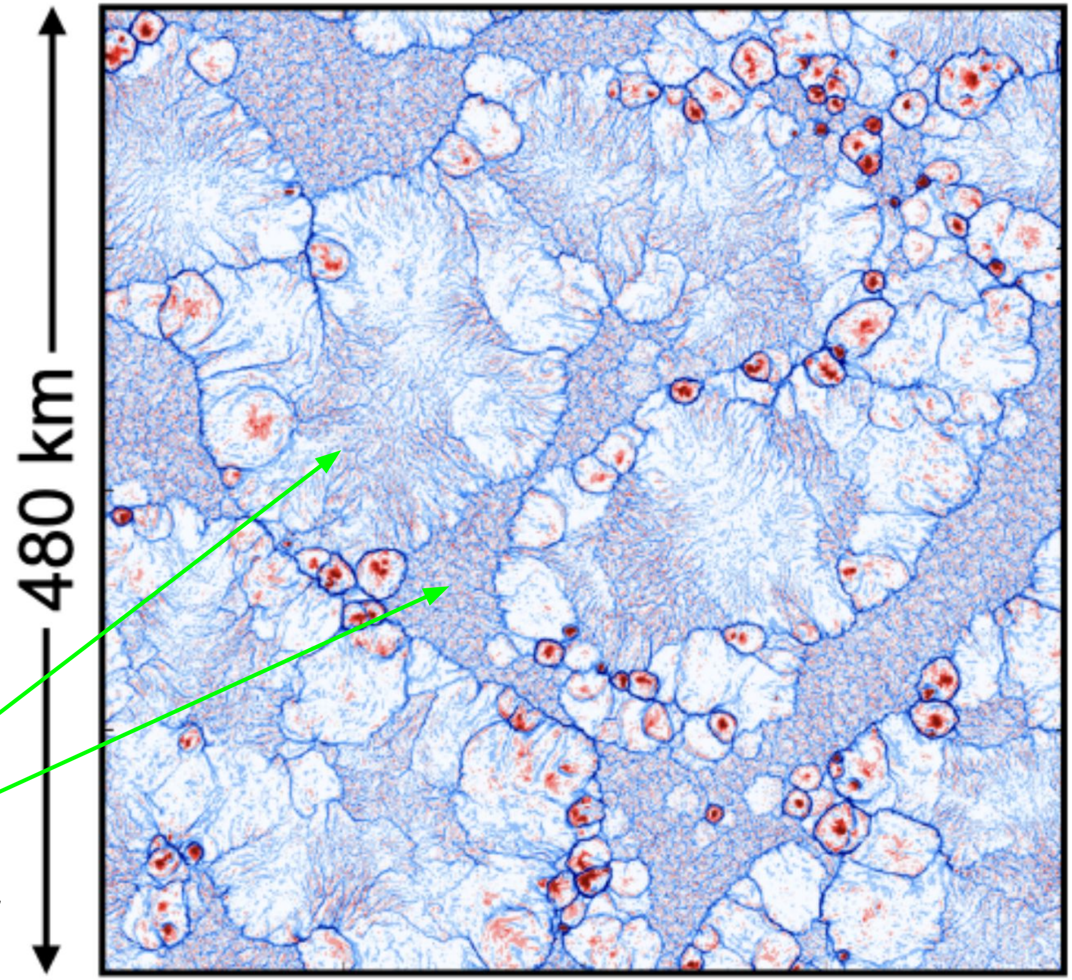
$$\theta_v = \theta\left(1 + (R_v/R_d - 1)q_t - (R_v/R_d)q_l\right).$$

Surface boundary conditions: bulk scheme
Lateral boundary conditions: cyclic
Timestepping: Runge Kutta (third order)
Advection: 4th order central differencing

Our research

Why do clouds organize?

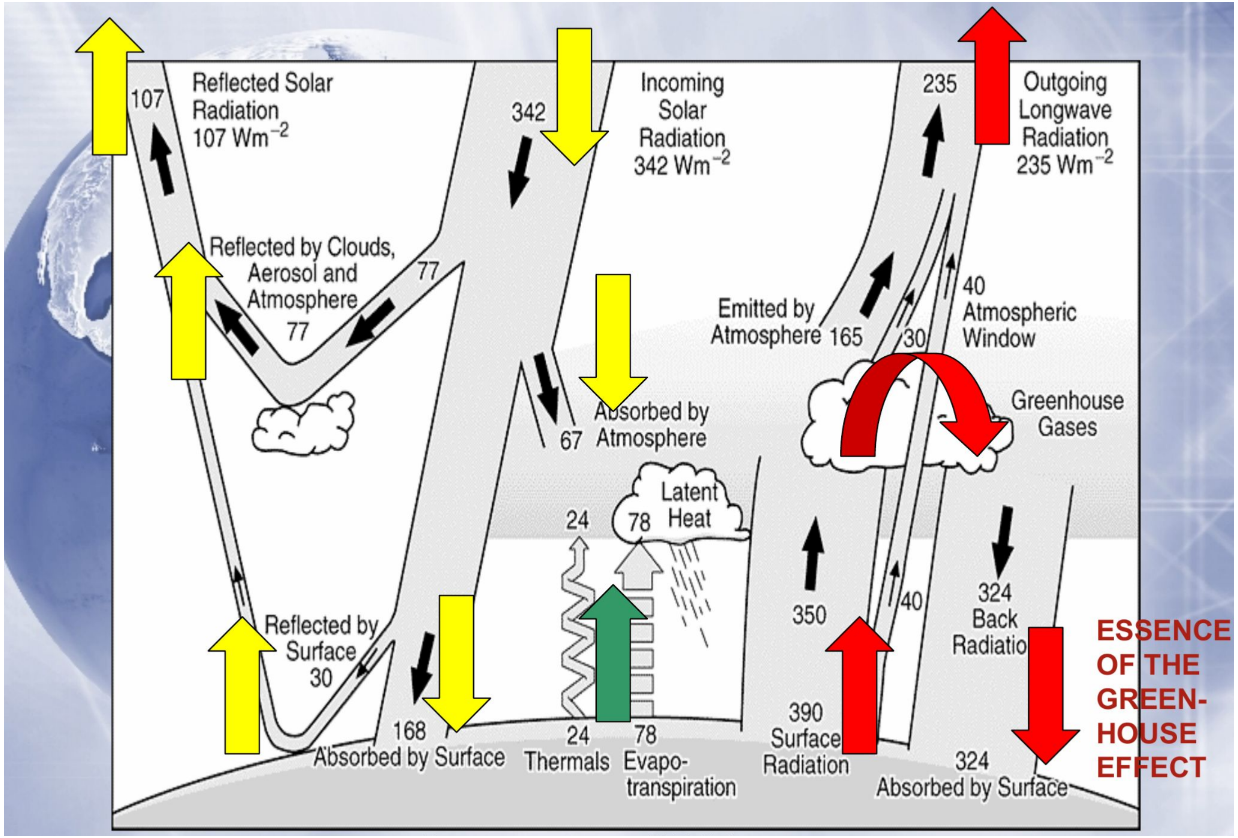
How does this impact on radiation and precipitation?



system-scale symmetry breaking

w (100m), vertical velocity

Energy balance in the climate system



source: IPCC

Radiative equilibrium

$$S_0 \equiv \frac{L_0}{4\pi d^2} = 1370\, Wm^{-2}$$

$$\text{Absorption per unit area} = \frac{S_0}{4}\left(1 - a_p\right)$$

Effective emission temperature:

Stefan-Boltzmann Equation: $F = \sigma T^4$

$\sigma = 5.67 \times 10^{-8}\ Wm^{-2} K^{-4}$

$$\sigma T_e^4 \equiv \frac{S_0}{4}\left(1 - a_p\right)$$

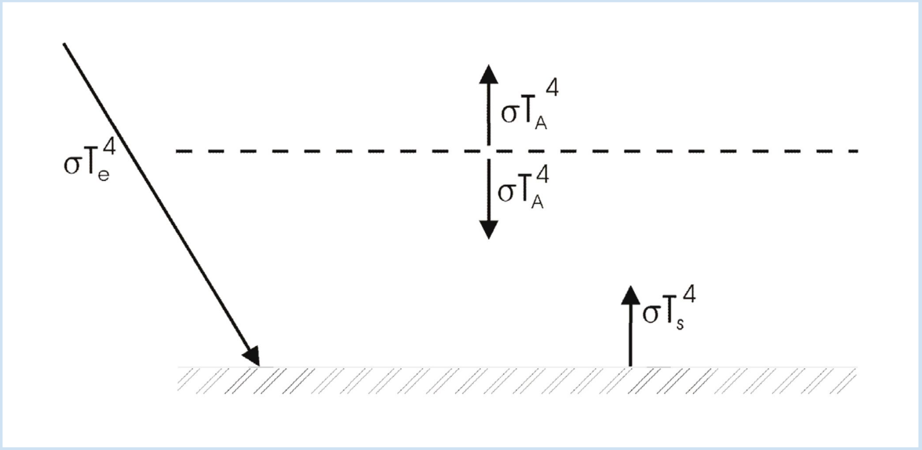
Sun: $\sigma T^4 = 6.4 \times 10^7\ Wm^{-2}$

$\rightarrow \quad T \simeq 6{,}000\, K$

Earth: $T_e = 255K = -18°C$

Observed average surface temperature $= 288K = 15°C$

Strongly reduced model



Radiative Equilibrium:

Top of Atmosphere:

$$\sigma T_A^{\;4} = \frac{S_0}{4}\left(1 - a_p\right) = \sigma T_e^{\;4}$$

$$\rightarrow \boxed{T_A = T_e}$$

Surface:

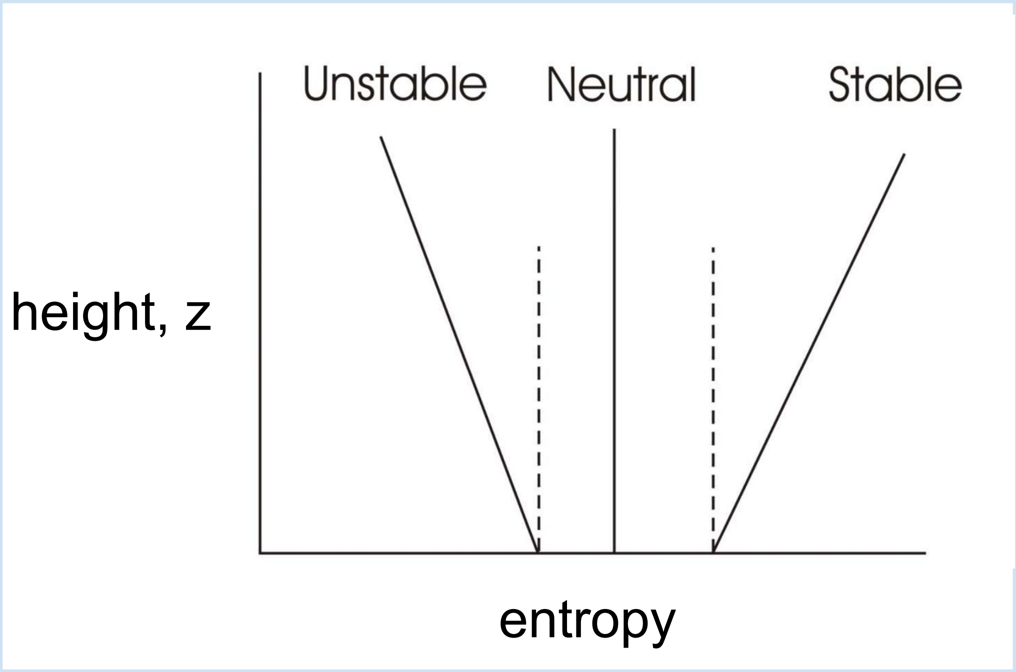
$$\sigma T_s^{\;4} = \sigma T_A^{\;4} + \frac{S_0}{4}\left(1 - a_p\right) = 2\sigma T_e^{\;4}$$

$$\rightarrow \boxed{T_s = 2^{1/4} T_e} = 303\ K$$

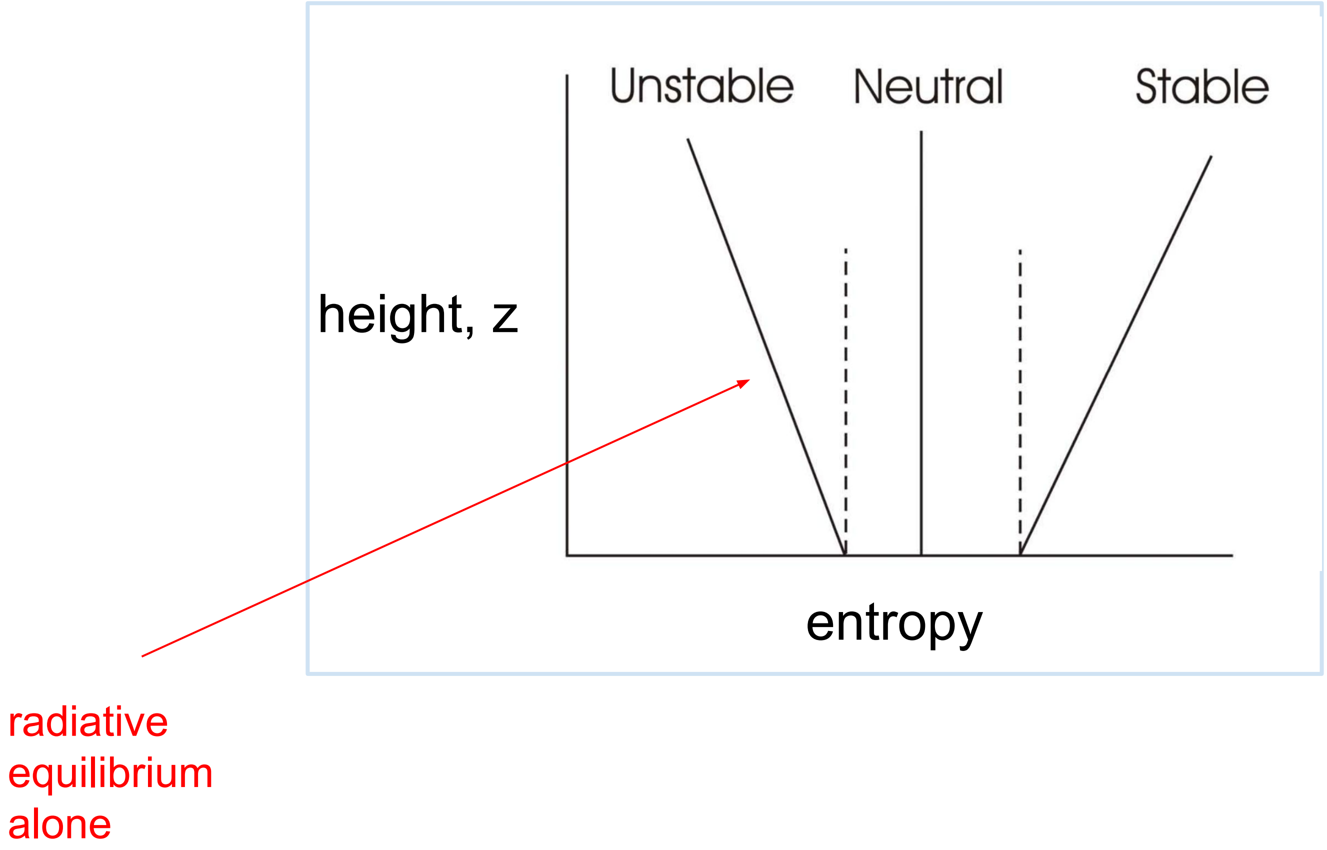
surface temperature too large:

- real atmosphere not opaque
- heat transported by convection and radiation

Atmospheric stability



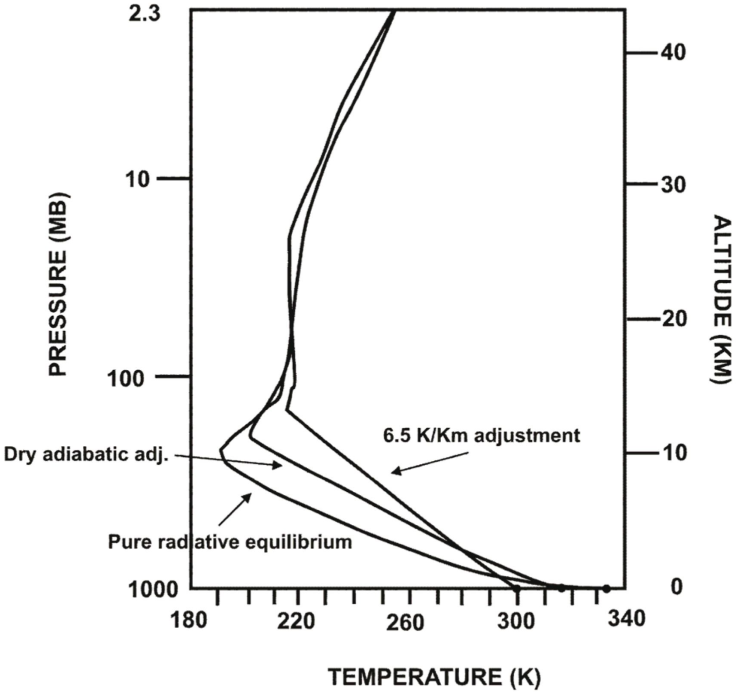
Atmospheric stability



Radiative convective equilibrium (RCE)

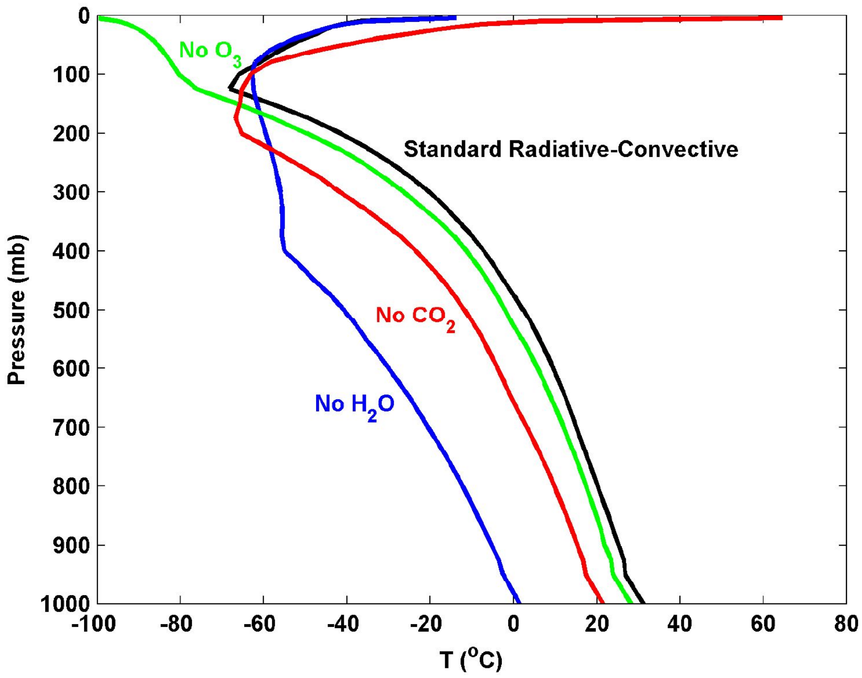
convective heating = radiative cooling

- radiative equilibrium alone: very steep vertical temperature decline
- radiative dry-convective equilibrium: still too steep, but better
- radiative convective equilibrium: moist-adiabatic lapse rate



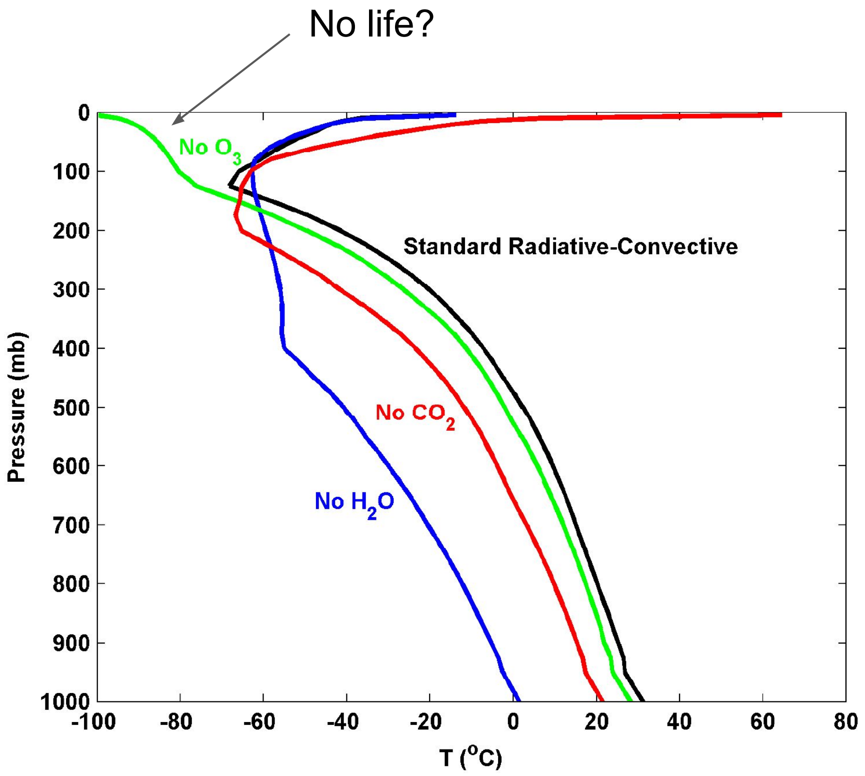
Manabe & Strickler, 1964 calculation

Contributions from various absorbers



Gas Name	Chemical Formula	Percent Volume
Nitrogen	N_2	78.08%
Oxygen	O_2	20.95%
*Water	H_2O	0 to 4%
Argon	Ar	0.93%
*Carbon Dioxide	CO_2	0.0360%
Neon	Ne	0.0018%
Helium	He	0.0005%
*Methane	CH_4	0.00017%
Hydrogen	H_2	0.00005%
*Nitrous Oxide	N_2O	0.00003%
*Ozone	O_3	0.000004%

Contributions from various absorbers



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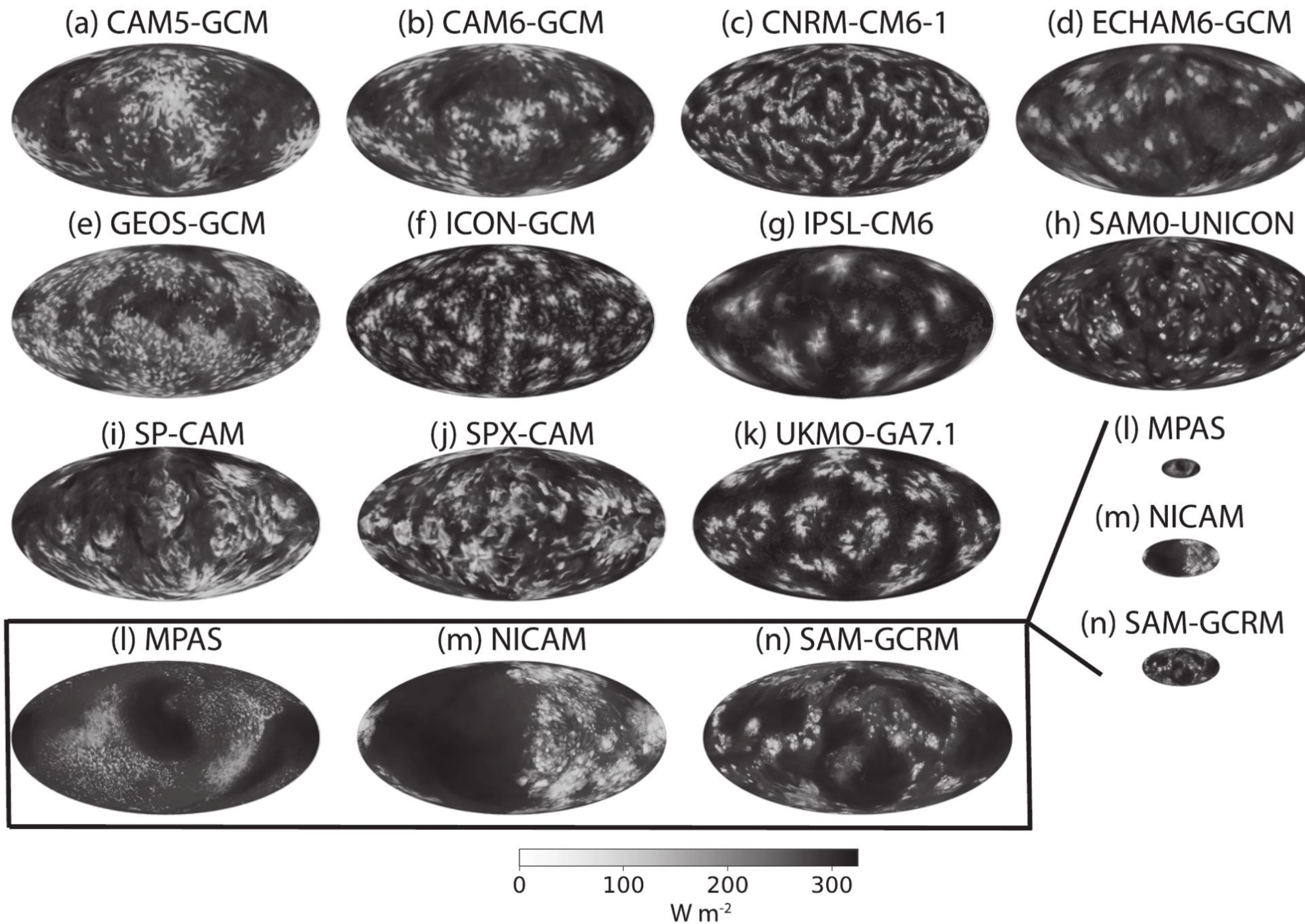
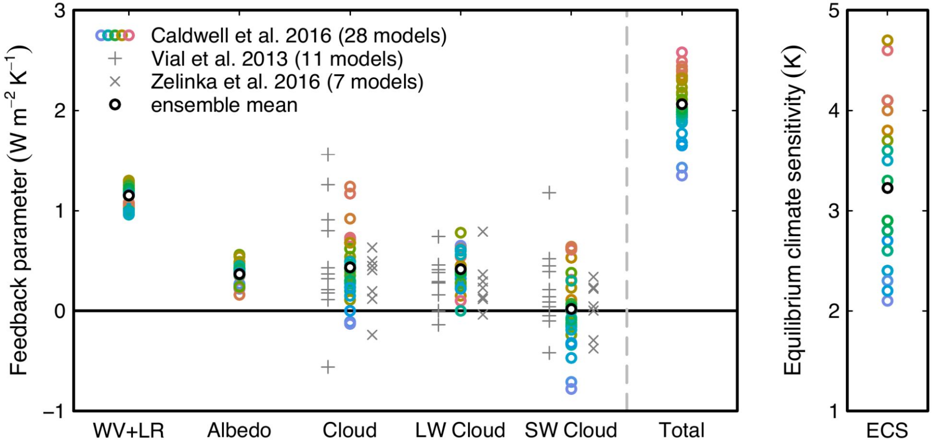
Moist convection tends to *aggregate* in RCE

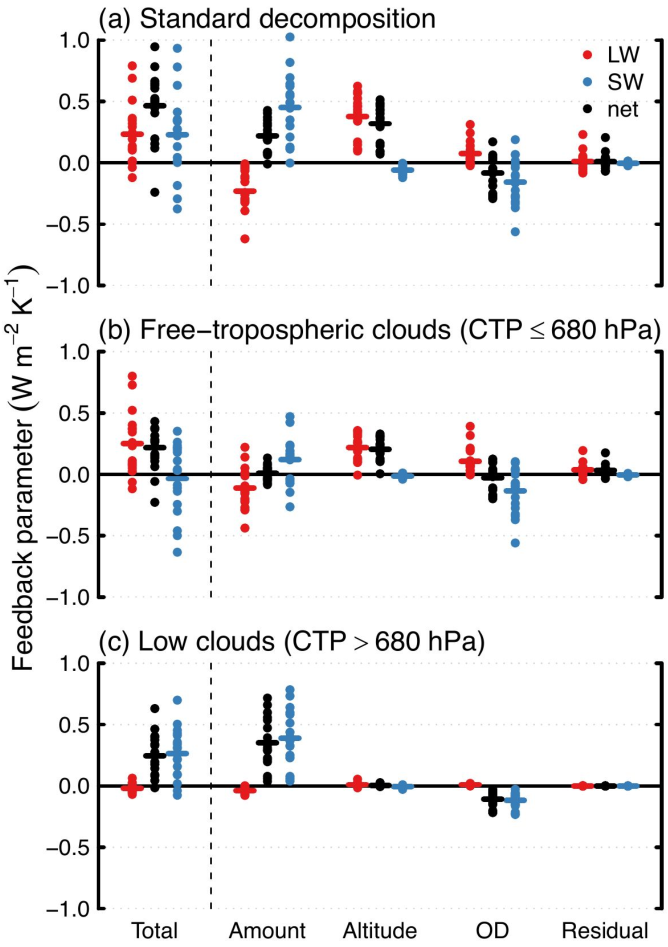


Cloud feedbacks

$$N = F + \lambda \Delta T$$

feedback parameter

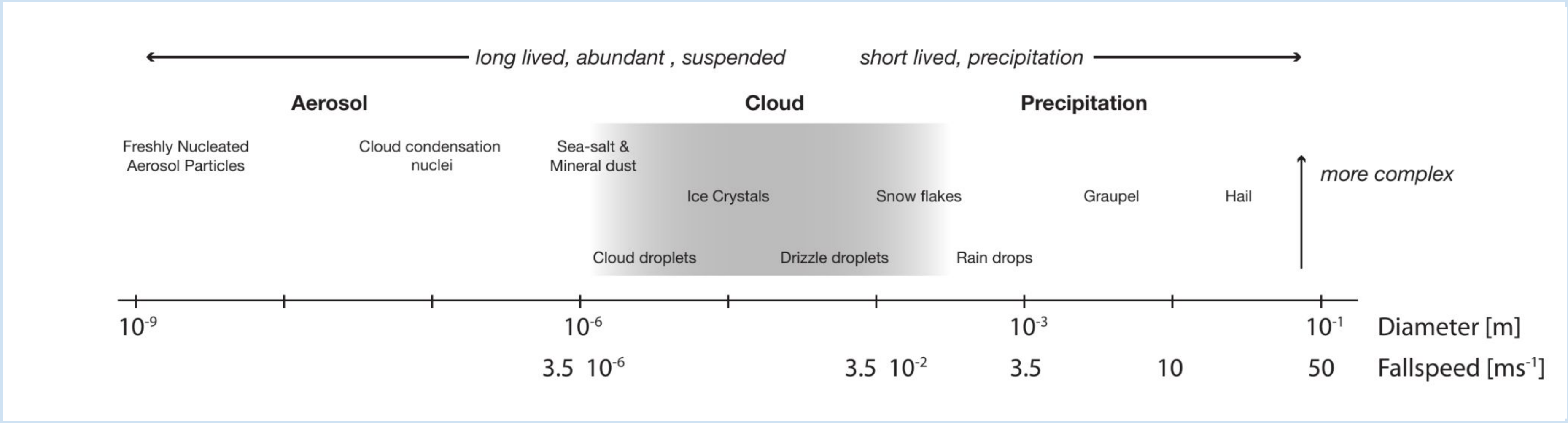




Features of RCE

- convective updrafts widely spaced
- surface heat fluxes = vertically integrated radiative cooling
- precipitation = evaporation = radiative cooling
- radiation and convection *highly* interactive

Clouds rarely develop out of clear blue sky

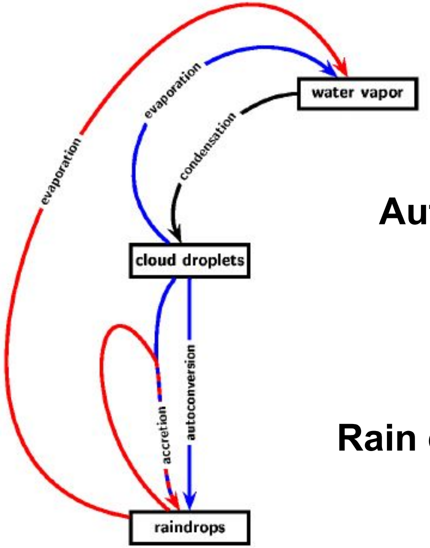


difficult to form ice in the atmosphere

common to find super-cooled liquid water

- talking about ice phase implies talking about liquid phase as well
- many processes depend on the nucleating substrate: Ice Nuclei.

Cloud microphysical processes (warm clouds)



Evaporation and condensation of cloud droplets

parameterized by saturation adjustment

Autoconversion

difficult, artificial process to separate cloud droplets and rain

Rain evaporation

very important: determines strength of cold pools

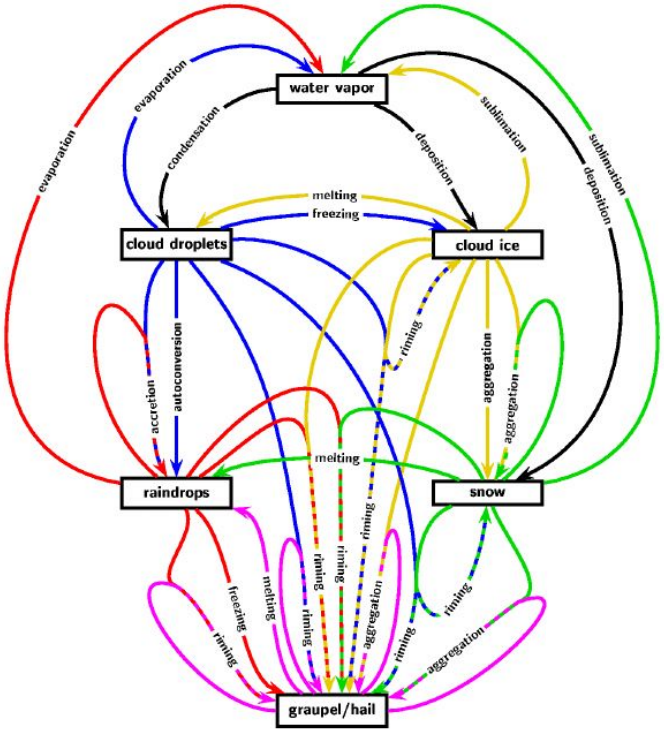
parameterization not easy: size dependence

conclusion

many unknowns, even for warm rain processes

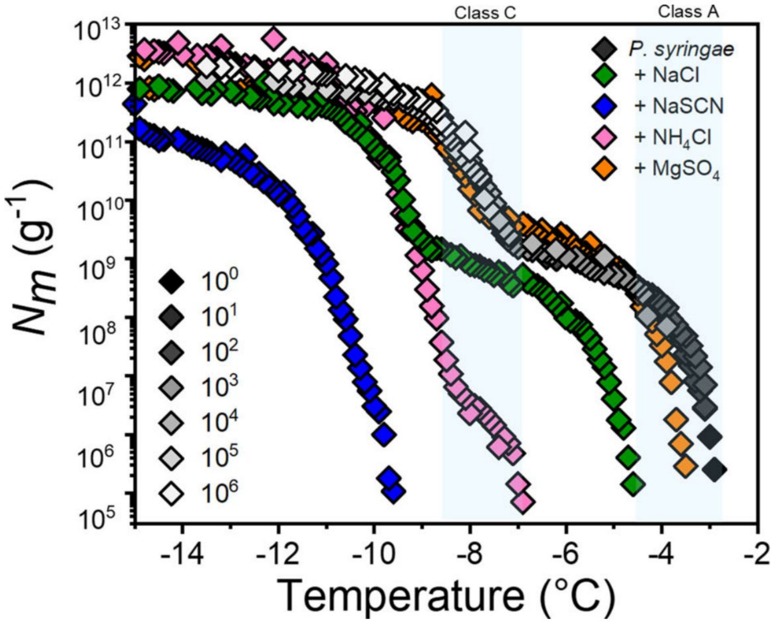
(mixing/entrainment, turbulence, coalescence, nucleation processes)

Cloud microphysical processes (including ice clouds)



Ice nucleation-active bacteria

- most efficient ice nucleators known
- enabling the crystallization of water at temperatures close to 0 deg C
- overcome kinetically hindered phase transition process

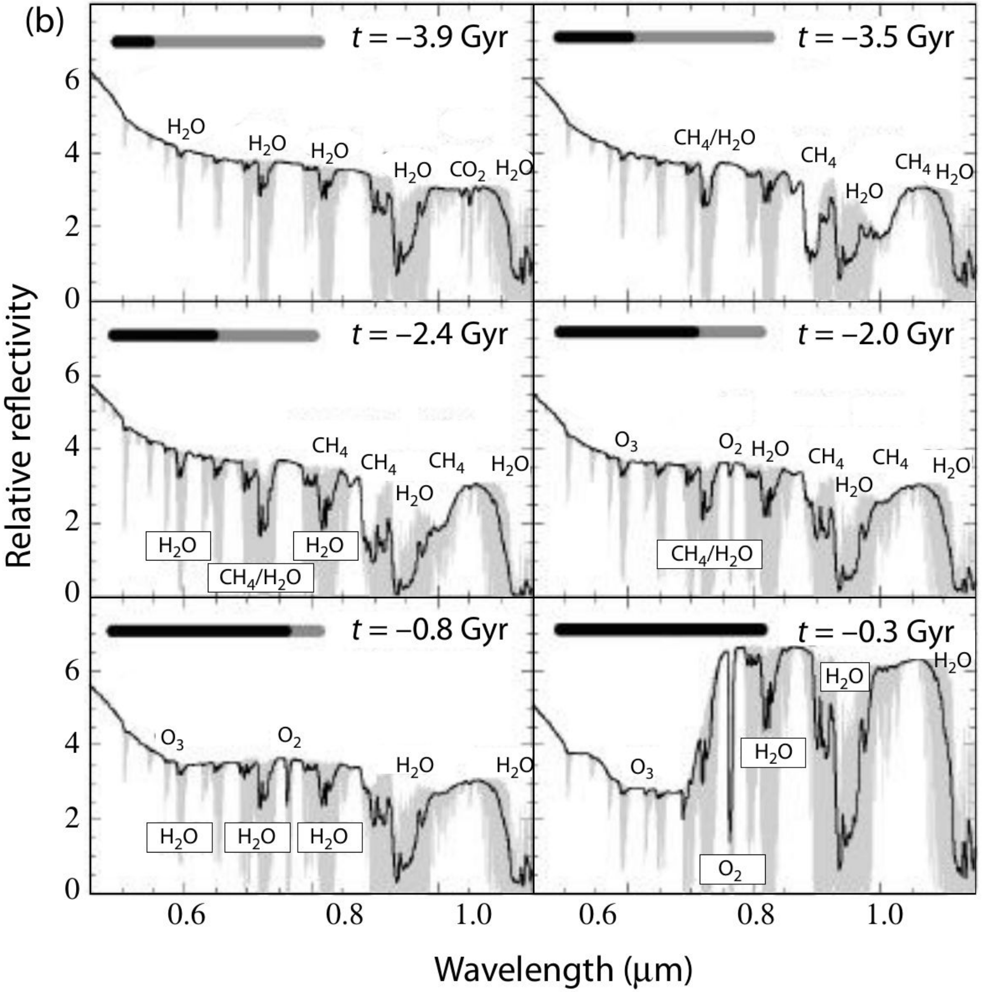


Schwidetzki et al., 2021

Microbial influence on planetary climate

- Miguel Garrido’s project

- which role can microbes play in ice nucleation?
- how do they influence cloud dynamics?
- how does cloud dynamics influence bacterial evolution?
- which role does the inversion play?
- are clouds relevant to life?



(b) visible and near-infrared spectra of an Earth-like
planet at six distinct geological epochs, again in the absence of clouds. The spectral lines (grey) change significantly as the planet evolves from CO2-rich (−3.9 Gyr), through CO2 /CH4 -rich (−2.4 Gyr), to a present-day atmosphere (lower right). Solid curves show
a spectral resolution of 70, comparable to the proposed TPF–C mission concept. From Kaltenegger et al. (2007, Figures 1 and 9), reproduced by permission of the AAS.