Overview of Cloud Microphysics and Aerosol-Cloud Interactions in GCMs

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Cloud microphysics important for

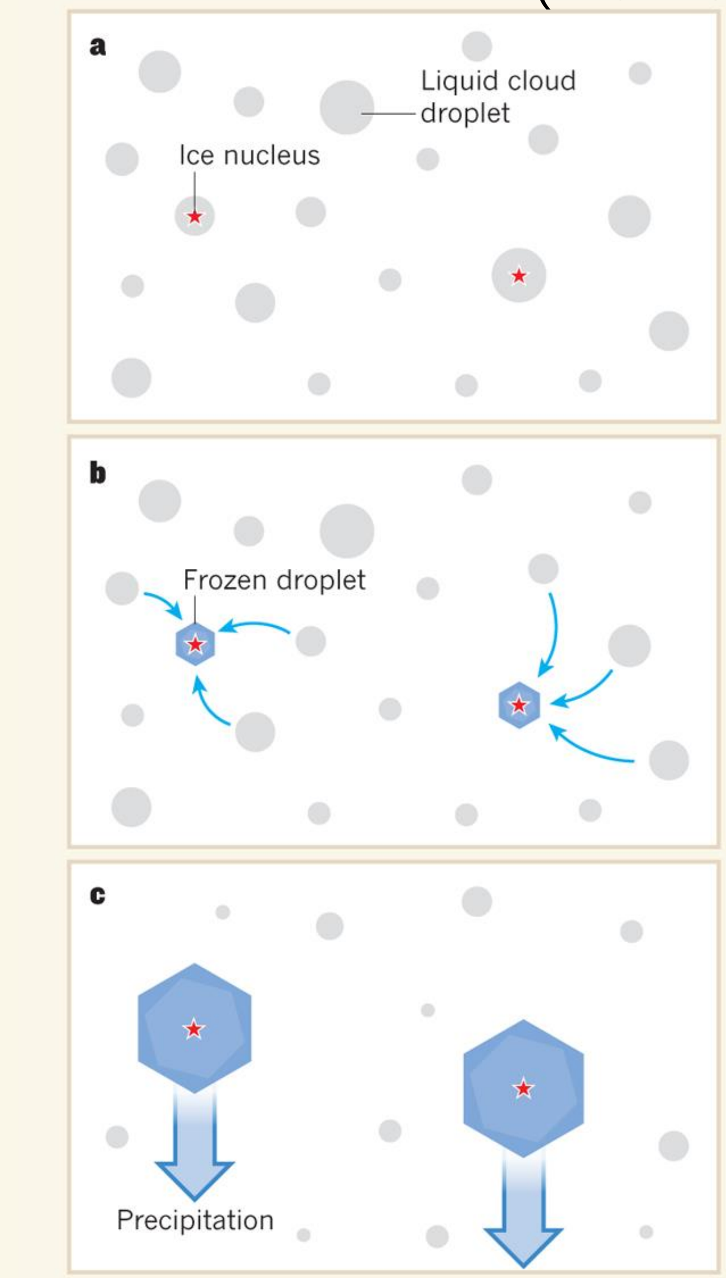
- radiation,
- precipitation formation,
- chemistry/aerosol,
- climate

Ice Nucleation

Bergeron-F. Process

Precipitation Initiation

(T<0 ° C)



Koop, Nature (2013)

Development of cloud microphysics in GCMs

Single-Moment Microphysics
IPCC AR4 (2007)

CAM3/CAM4

- Single moment (M)
- No ice nucleation
- Phase partitioning prescribed as f(T)

GFDL AM2

- Single moment (M)
- Ice nucleation f(T, RH)
- Phase partitioning calculated

Two-Moment Microphysics
IPCC AR5 (2013)

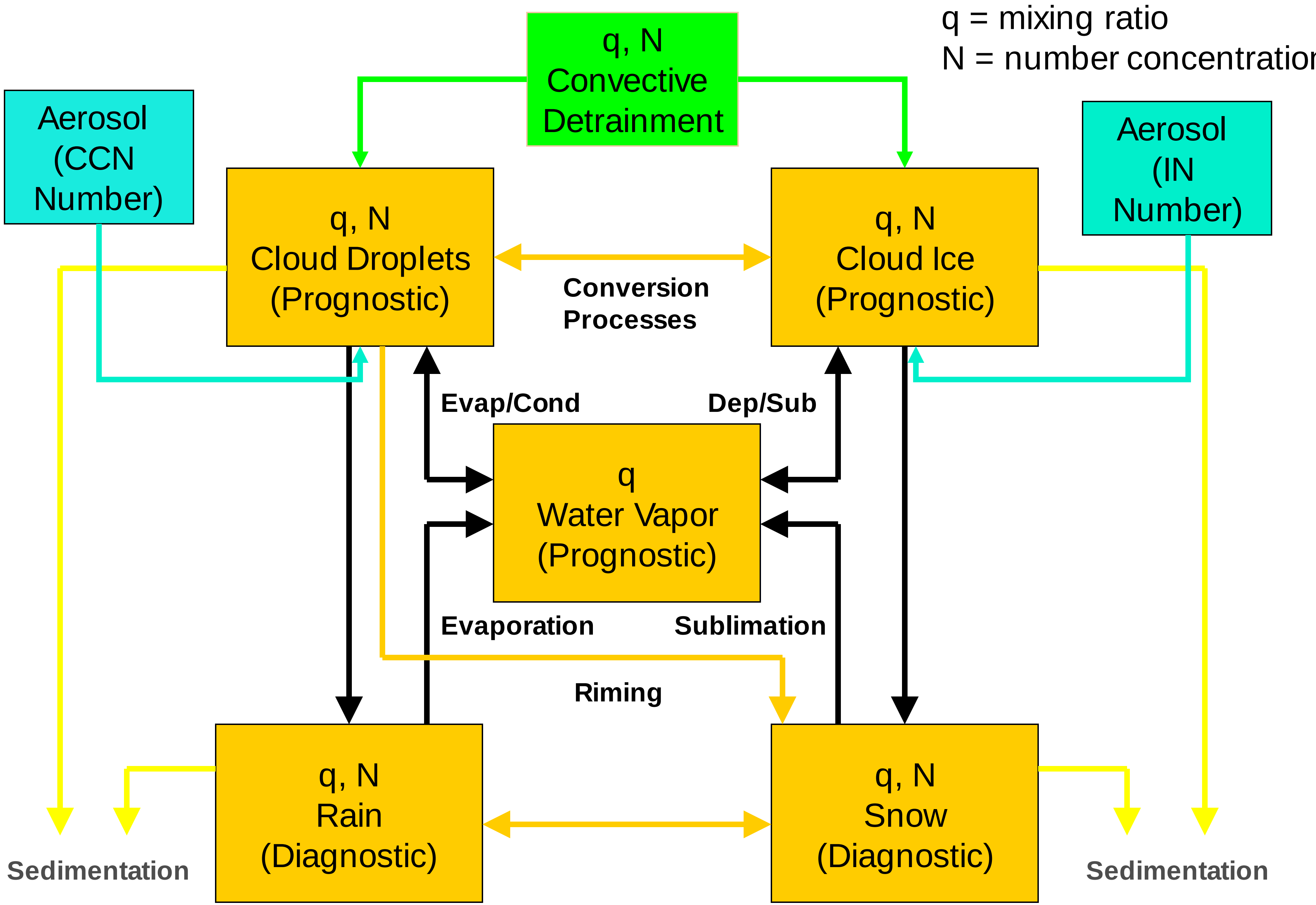
CAM5, ECHAM5

- Two moment (M,N) for liquid/ice
- Aerosol-cloud interactions (warm & cold clouds)
- Phase partitioning calculated

GFDL AM3

- Two moment (M,N) for liquid
- Aerosol-cloud interactions (warm clouds)
- Phase partitioning calculated

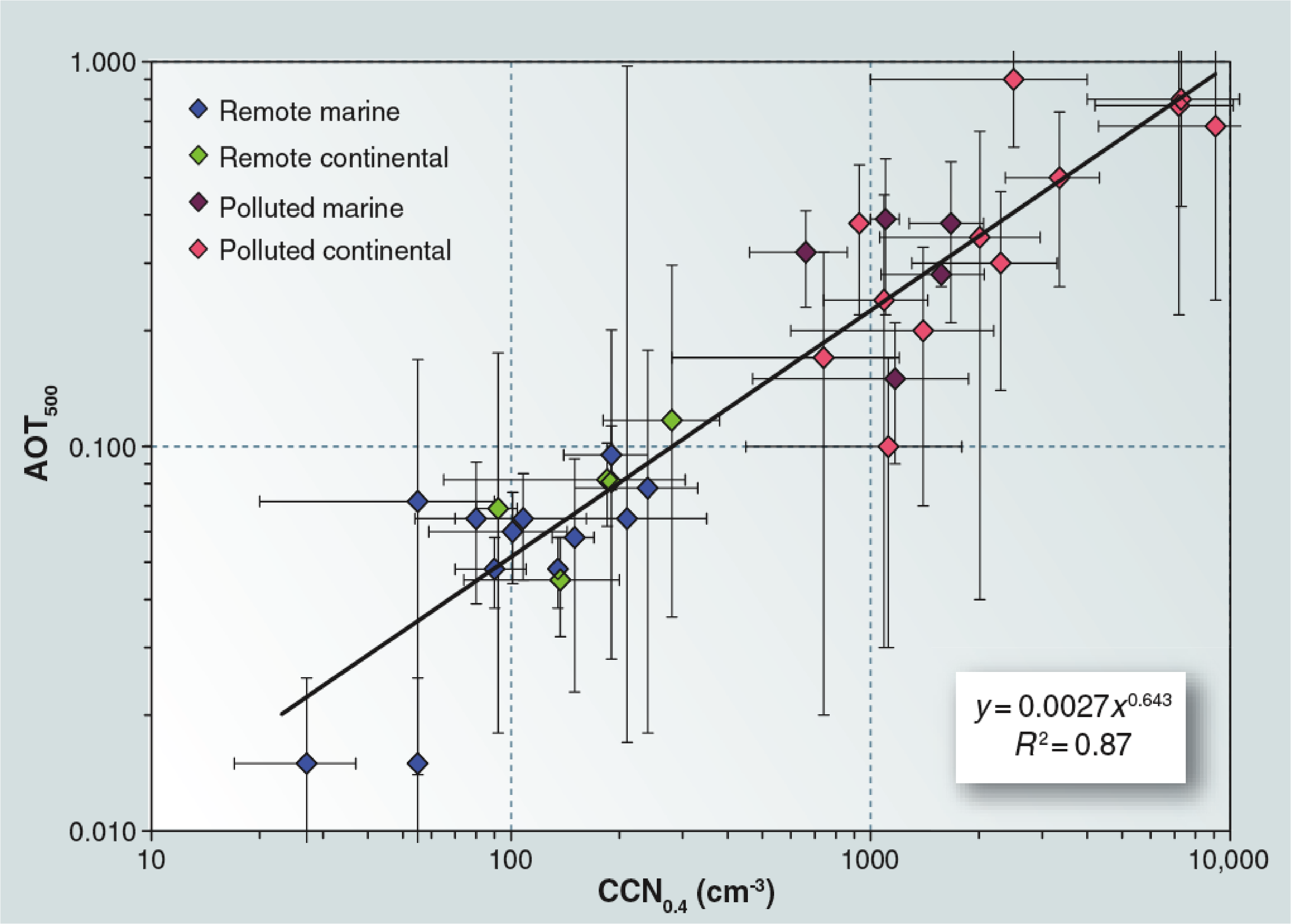
Cloud microphysics in advanced GCMs



Warm Cloud Microphysics Process

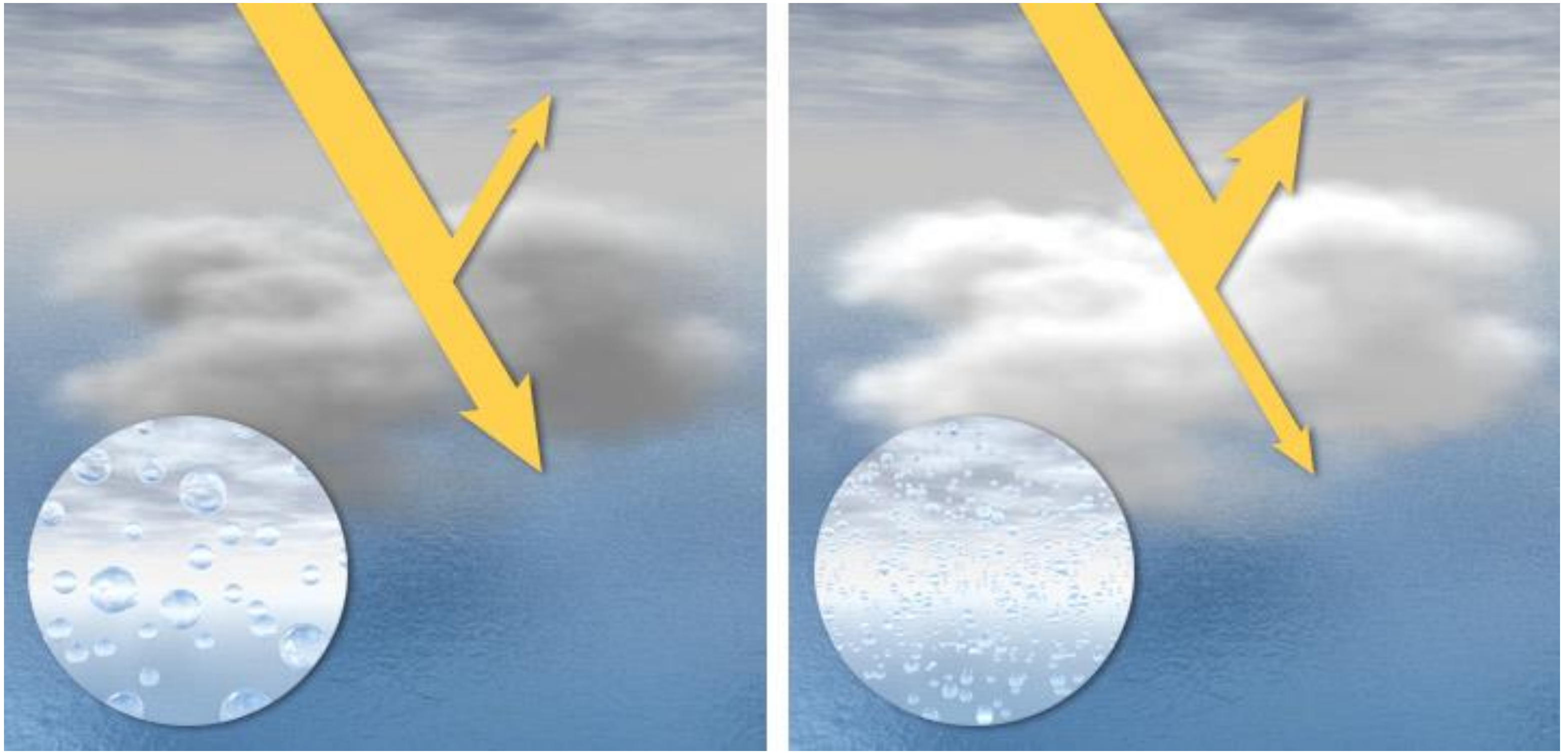
- Droplet formation ⟹ aerosol first indirect effect
- Vapor condensation/evaporation
- Autoconversion of cloud droplets to rain ⟹ aerosol second indirect effect
- Accretion of cloud droplets by rain
- Convective detrainment

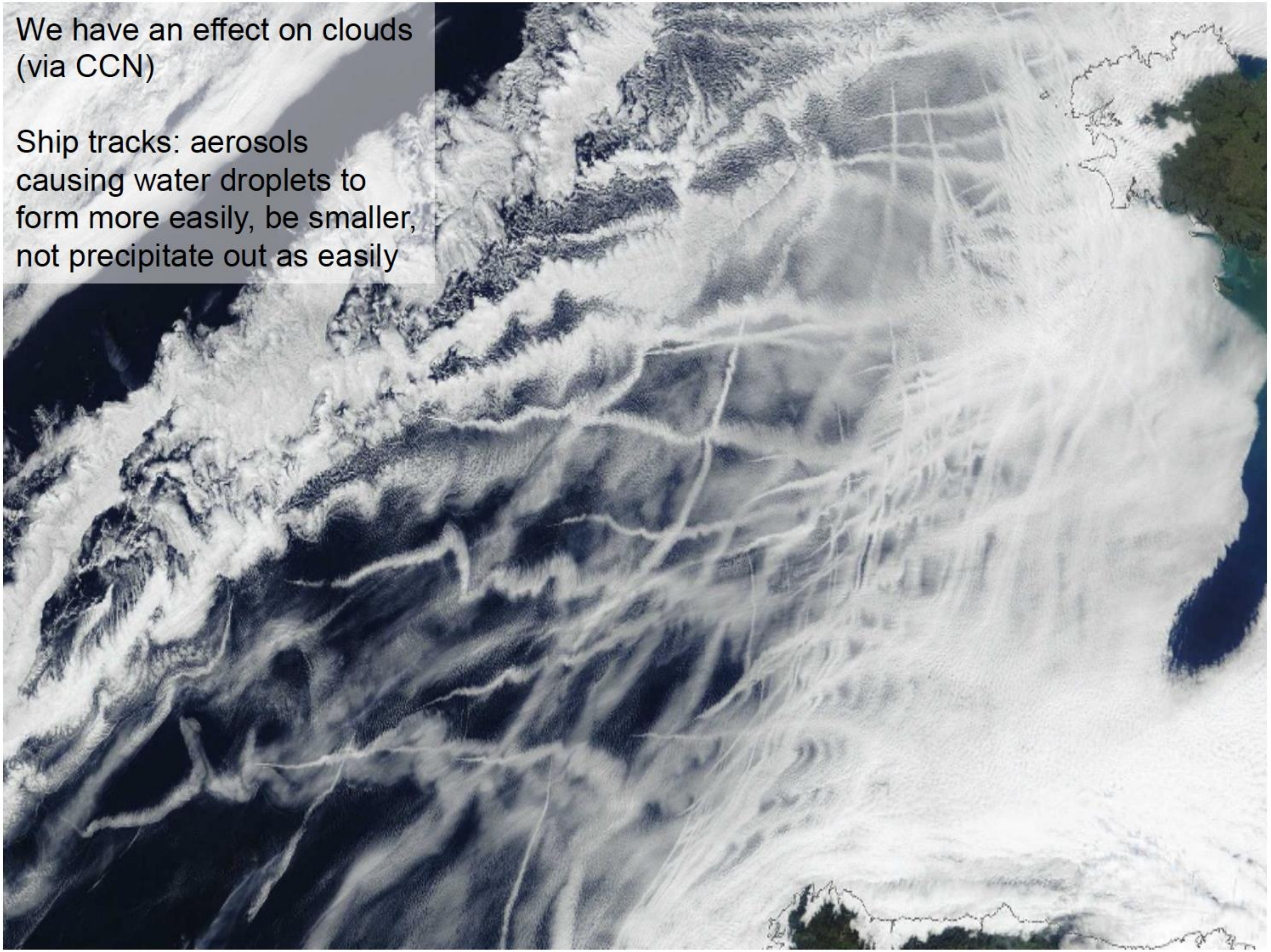
CCN vs. Aerosol Optical Thickness



Andrea 2009

Polluted vs. clean cloud droplets




We have an effect on clouds
(via CCN)
Ship tracks: aerosols
causing water droplets to
form more easily, be smaller,
not precipitate out as easily

Aerosol modification of marine clouds observed during the Monterey Area Ship Track experiment

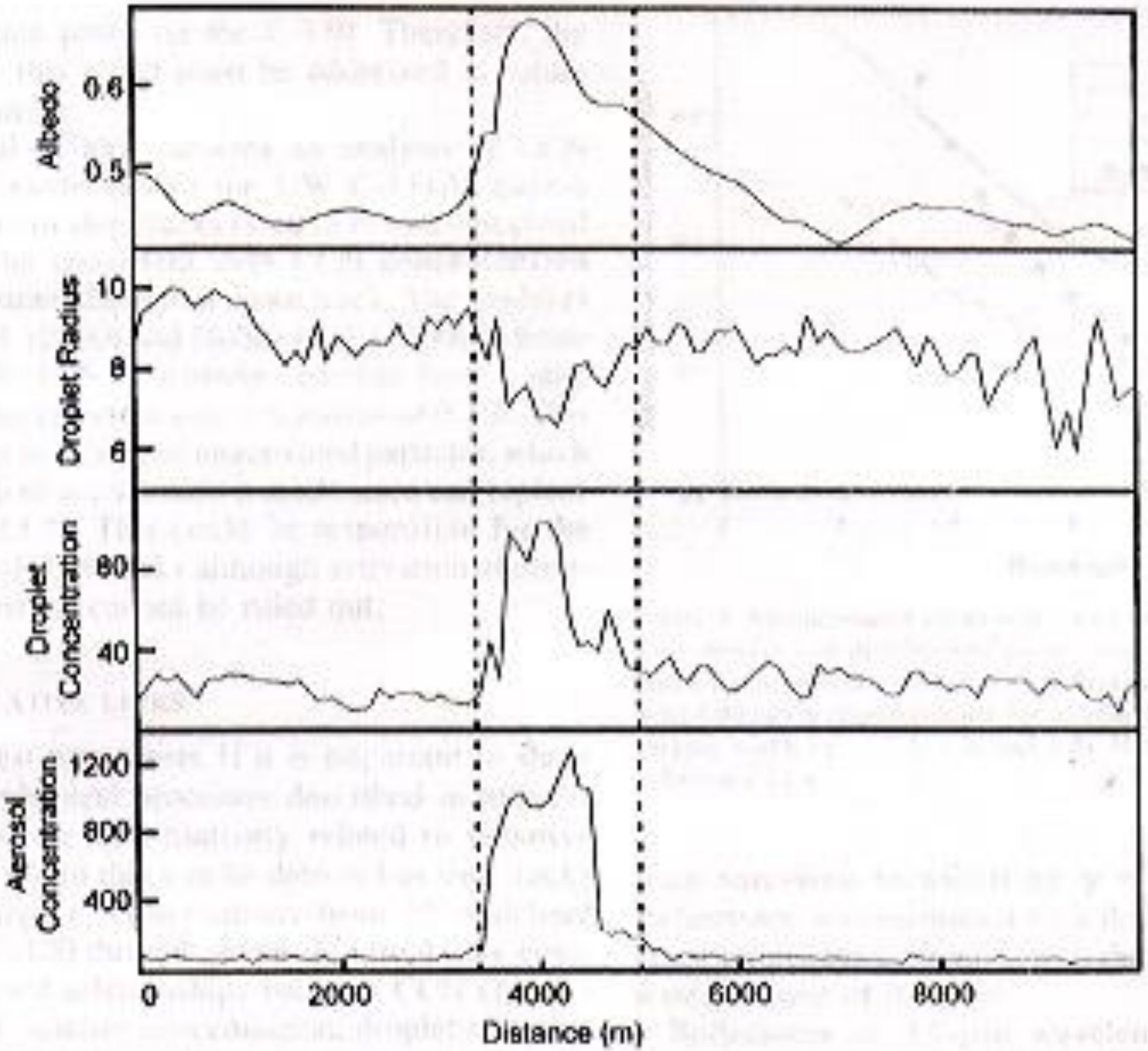
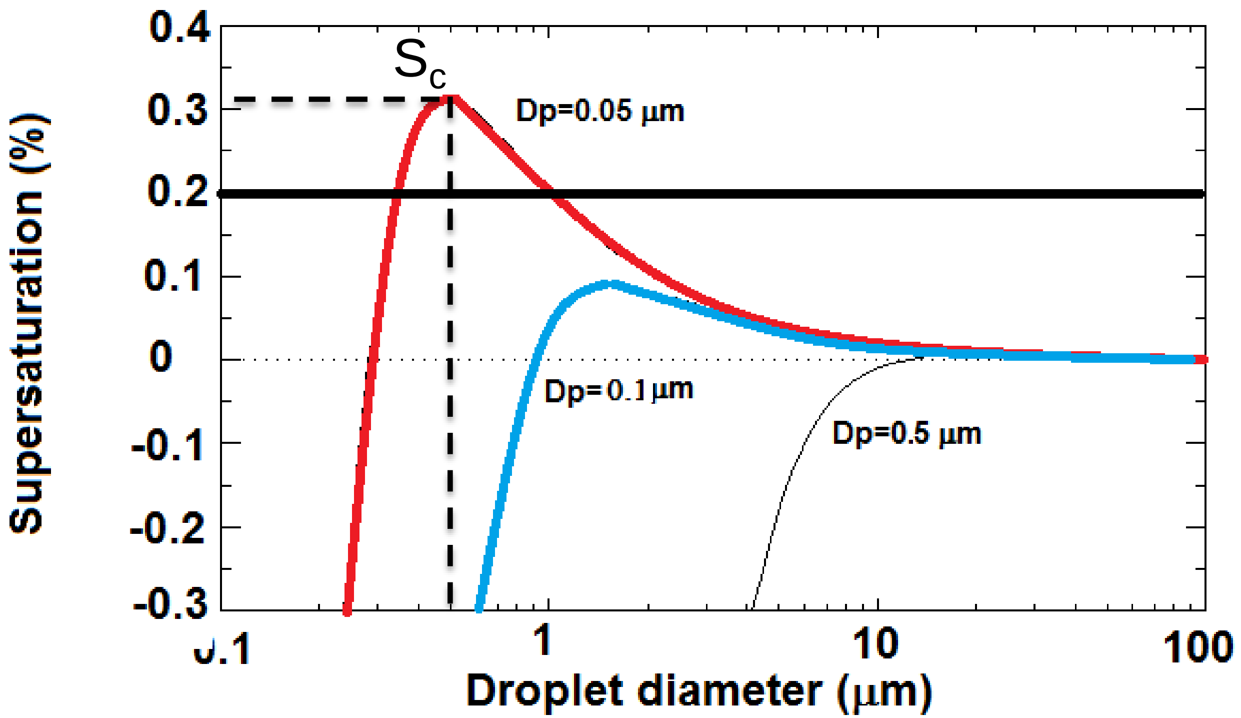


FIG. 3. Measurements made from the C-130 of albedo, cloud droplet radius (μm), and droplet concentrations (cm⁻³), and accumulation-mode aerosol concentrations across the ship track produced by the *Hanjin Barcelona* on 29 Jun 1994. The ship track is between the dashed vertical lines. The measurements were made about 30 min after emission from the ship.

Kohler theory

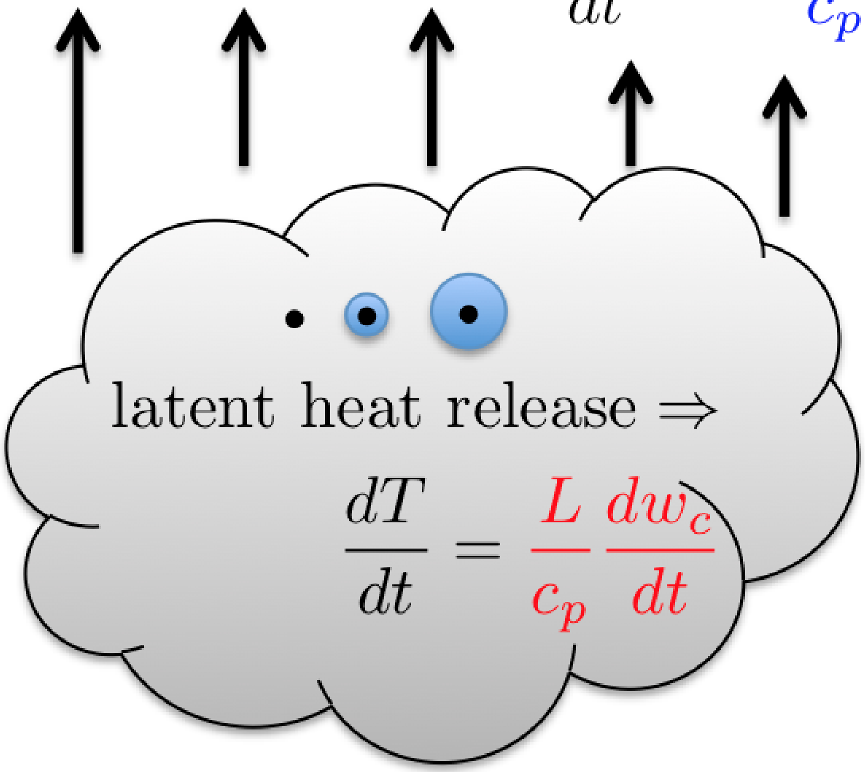
$$S = \frac{A}{r} - \frac{\kappa r_d^3}{r^3}$$

$$S_c \equiv \left(\frac{4A^3}{27 \kappa r_d^3} \right)^{1/2}$$



How cloud droplets are formed?

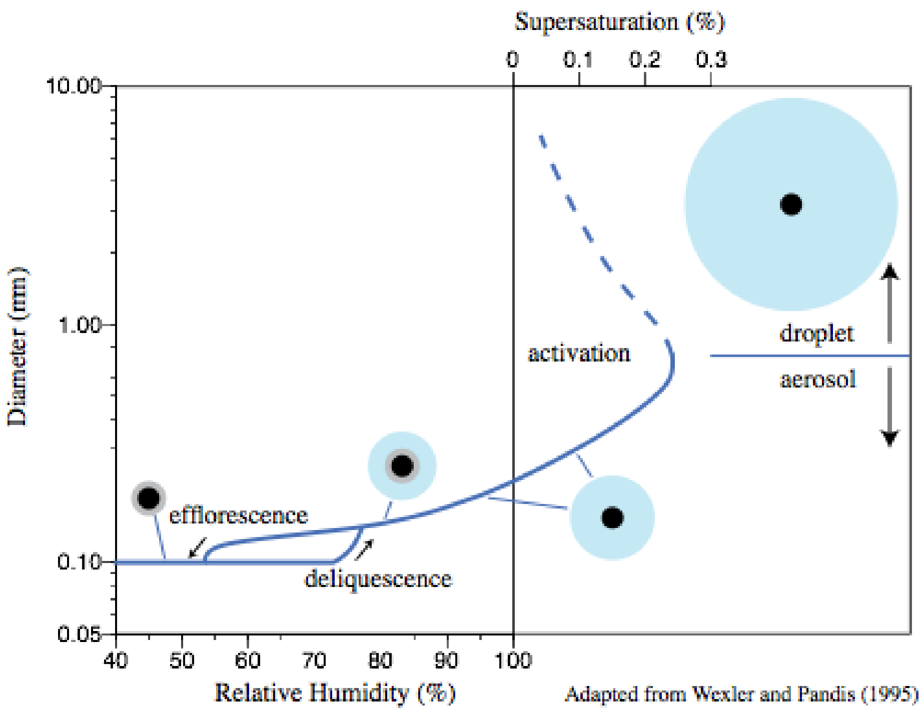
$$\text{adiabatic ascent} \Rightarrow \frac{dT}{dt} = -\frac{gV}{c_p}$$

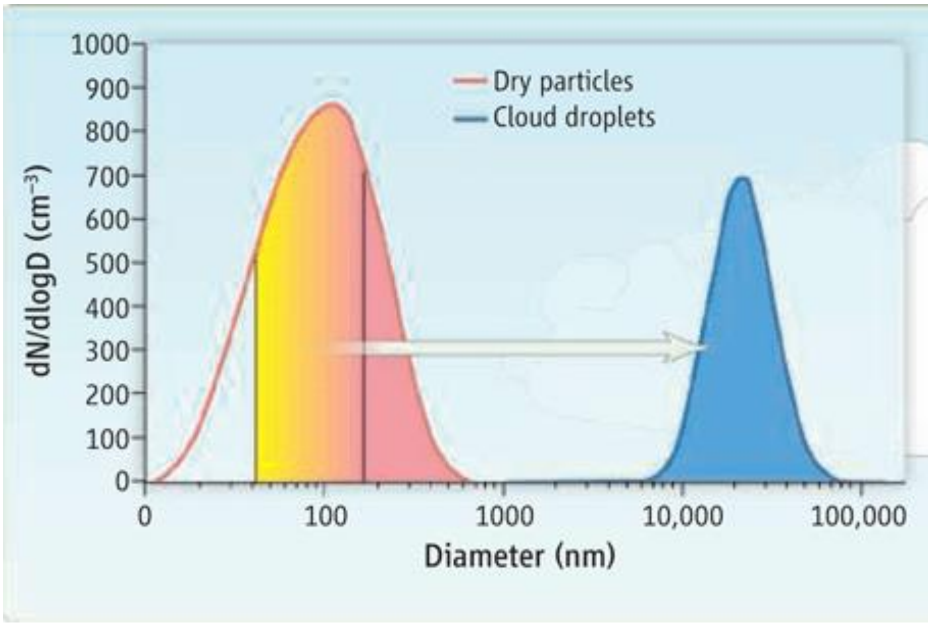


Supersaturation balance :

$$\frac{dS}{dt} = \alpha(T,P)V - \gamma(T,P)\frac{dw_c}{dt}$$

How cloud droplets are formed?

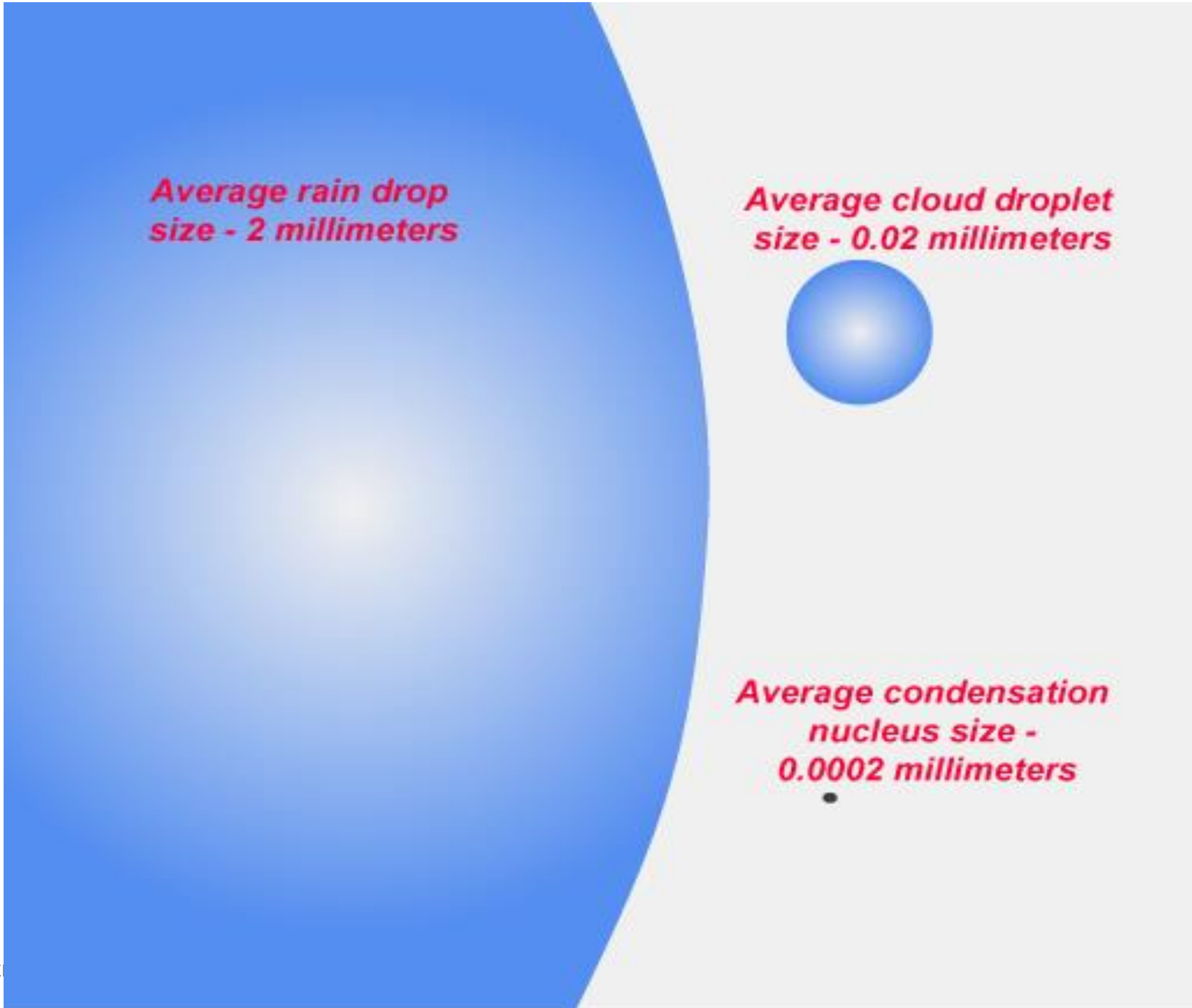




Parameterization of droplet activation in GCMs

- Abdul-Razzak and Ghan (2000)
- Nenes and Seinfeld (2003)

$$S_{\max}^2 = 1 \Big/ \sum_m \frac{1}{S_m^2} \left[f_m \left(\frac{\varsigma}{\eta_m} \right)^{3/2} + g_m \left(\frac{S_m^2}{\eta_m + 3\varsigma} \right)^{3/4} \right]$$


Average rain drop size - 2 millimeters
Average cloud droplet size - 0.02 millimeters
Average condensation nucleus size - 0.0002 millimeters

Parameterization of auto-conversion/accretion in GCMs

- Autoconversion

$$P_{auto}=1350q_c^{2.47}\boldsymbol{N_c}^{-1.79}$$

- Accretion

$$P_{acc}=67(q_cq_r)^{1.15}$$

Khairoutdinov and Kogan (2000)

- Aerosol-cloud interactions dependent on process rate
- Too much autoconversion in GCMs: or too little accretion
- Accretion depends on rain, and diagnostic rain may be the problem
- How to correct it? Prognostic rain (MG2)

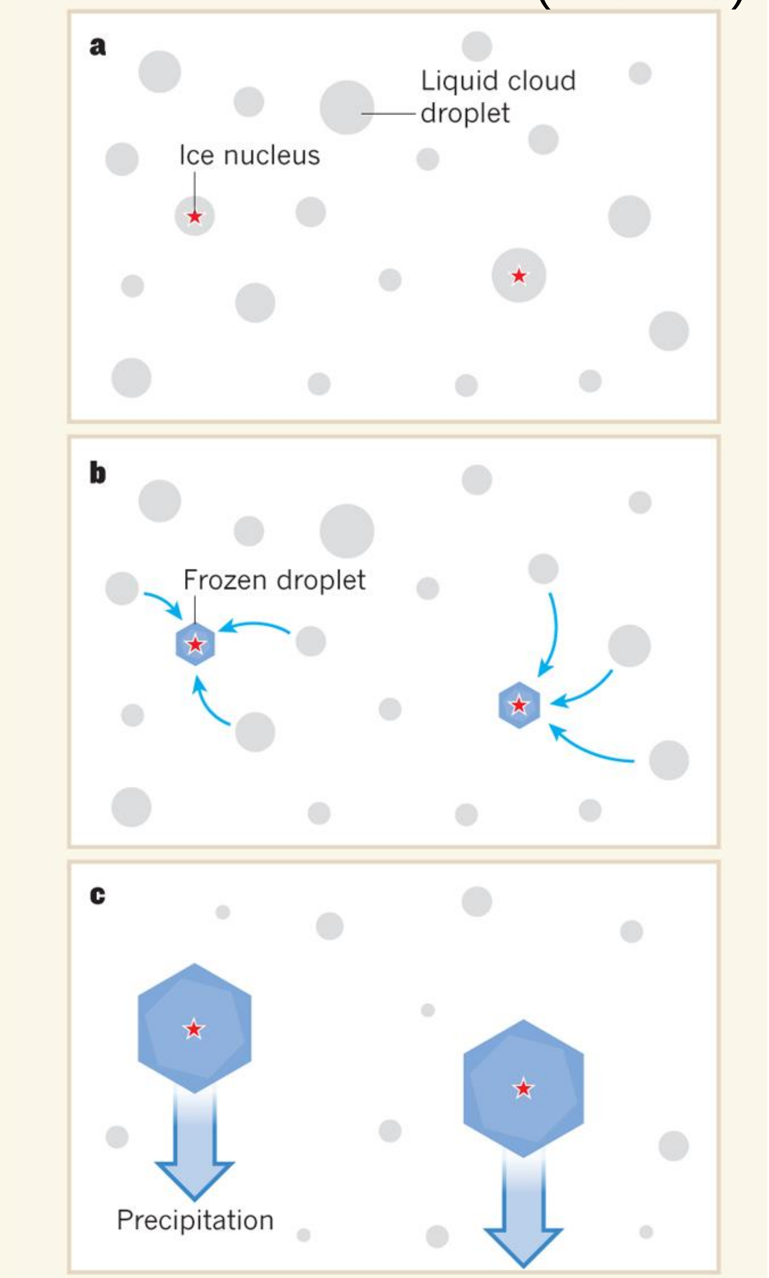
Ice microphysics

(T<0 ° C)

Ice Nucleation

Bergeron-F.
Process

Precipitation
Initiation



Koop, Nature (2013)

Ice Microphysics Process

- Ice formation: ice nucleation and droplet freezing, secondary ice production
- Vapor deposition and Wegener-Bergeron-Findeisen (WBF) process
- Sedimentation
- Autoconversion of cloud ice to snow
- Accretion of cloud ice by snow
- Melting/sublimation
- Convective detrainment

Aerosol effects on ice and mixed-phase clouds

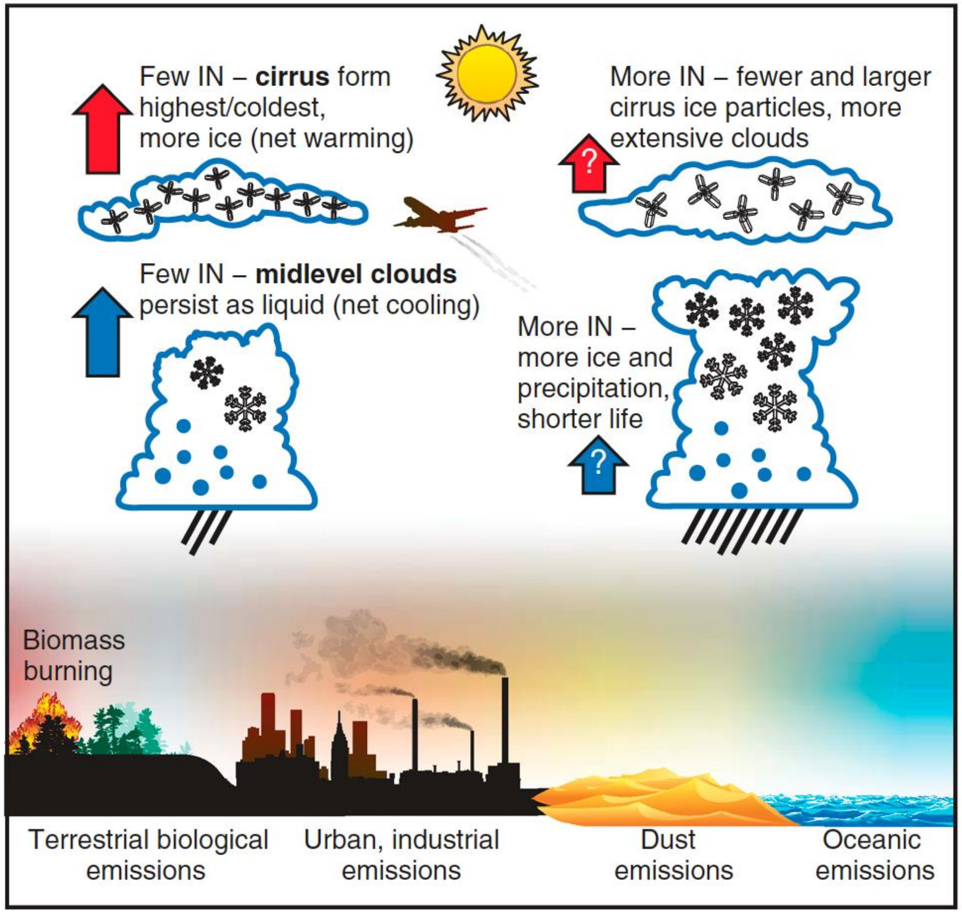
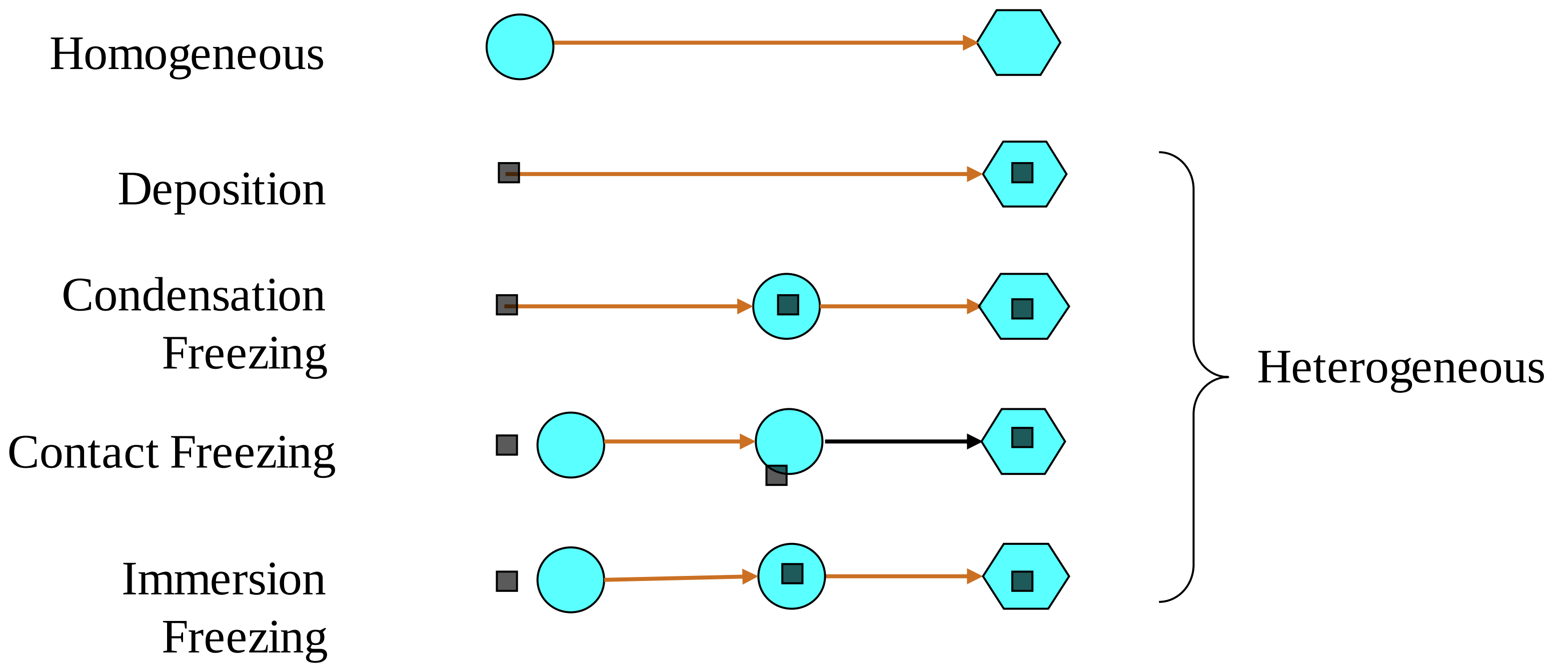


Fig. 1. Schematic diagram of the effect of ice nuclei from various possible aerosol sources on midlevel precipitating clouds and cirrus ice clouds. The likely but uncertain change in the magnitude of the general cooling impact (blue arrows) of midlevel clouds and warming impact (red arrows) of high cirrus clouds in response to increases in the relative number concentrations of IN is indicated (see text for further description).

DeMott et al. (2010)

How ice crystals are formed?

Multiple Ice Nucleation Mechanisms



Soluble/insoluble aerosol particle (substrate) (~10^{-3} – 10^{-5} of aerosol population)

Supercooled solution droplet / cloud droplet

Ice crystal

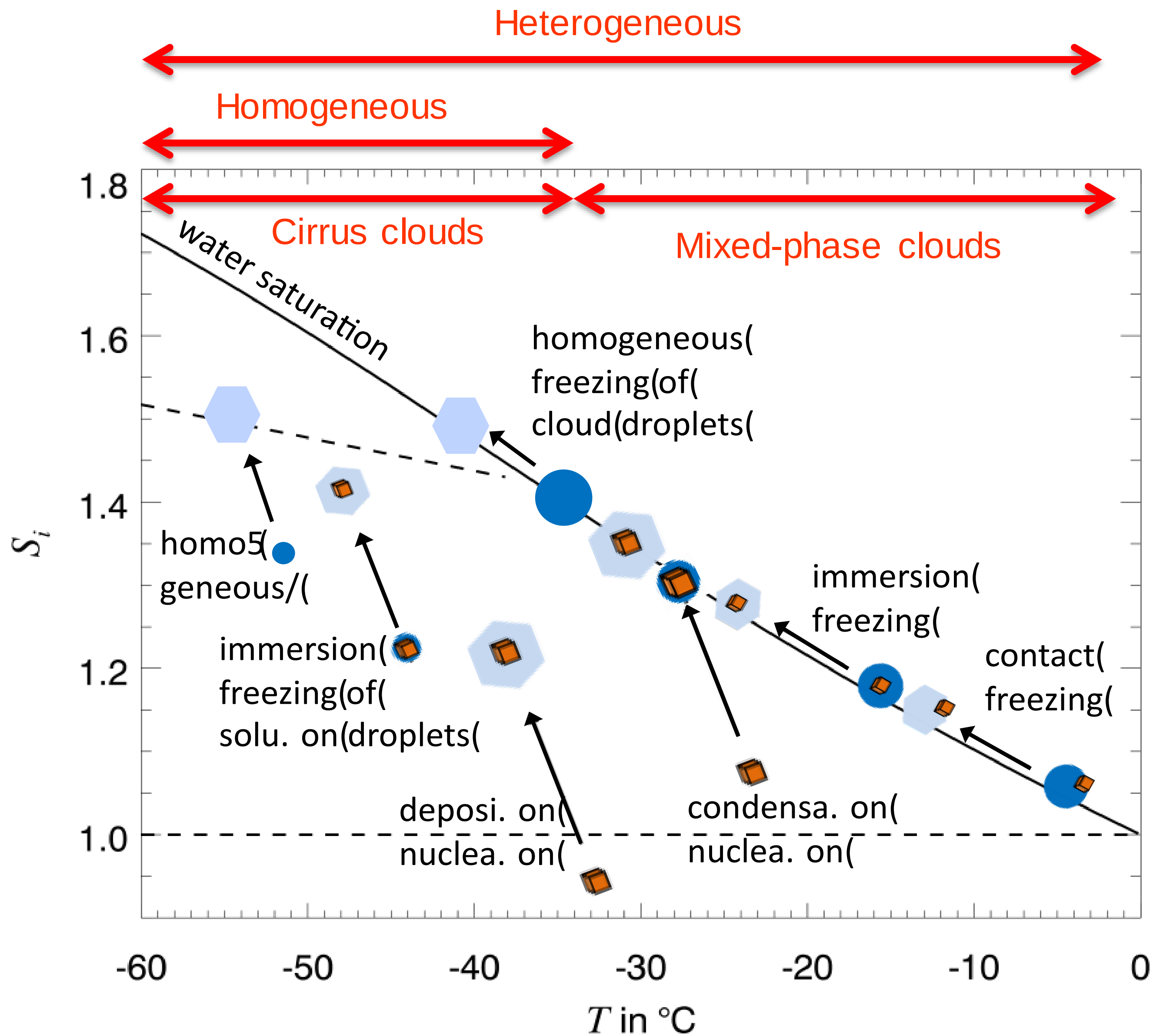
Courtesy of G. Kulkarni

Modes of ice nucleation

No clouds without aerosol particles
➔ CCN

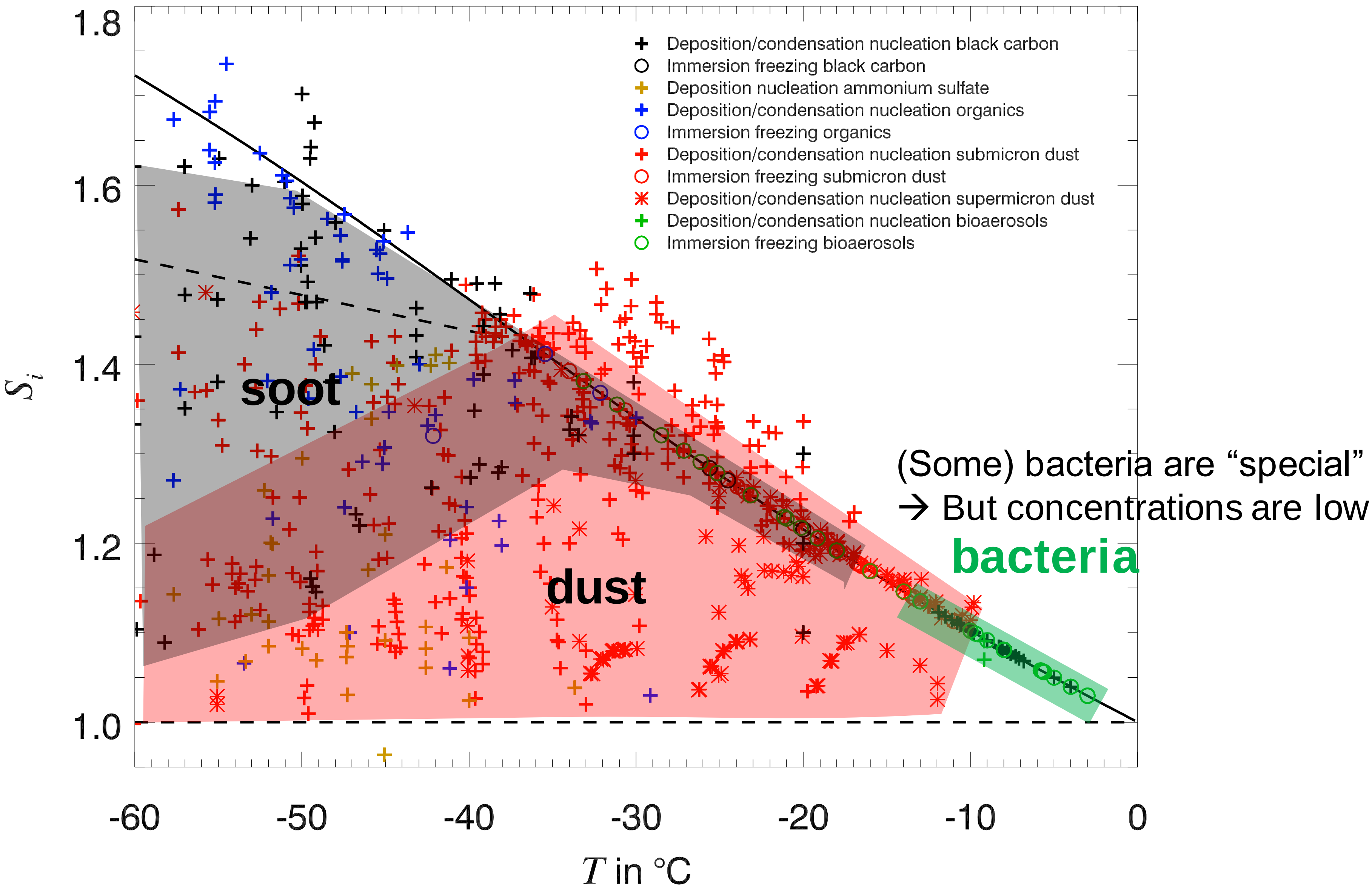
No clouds without aerosol particles
➔IN (ice nuclei)

Except freezing of water droplets at -36 ° C



Hoose and Moeller, ACP (2012)

Onset for heterogeneous ice nucleation

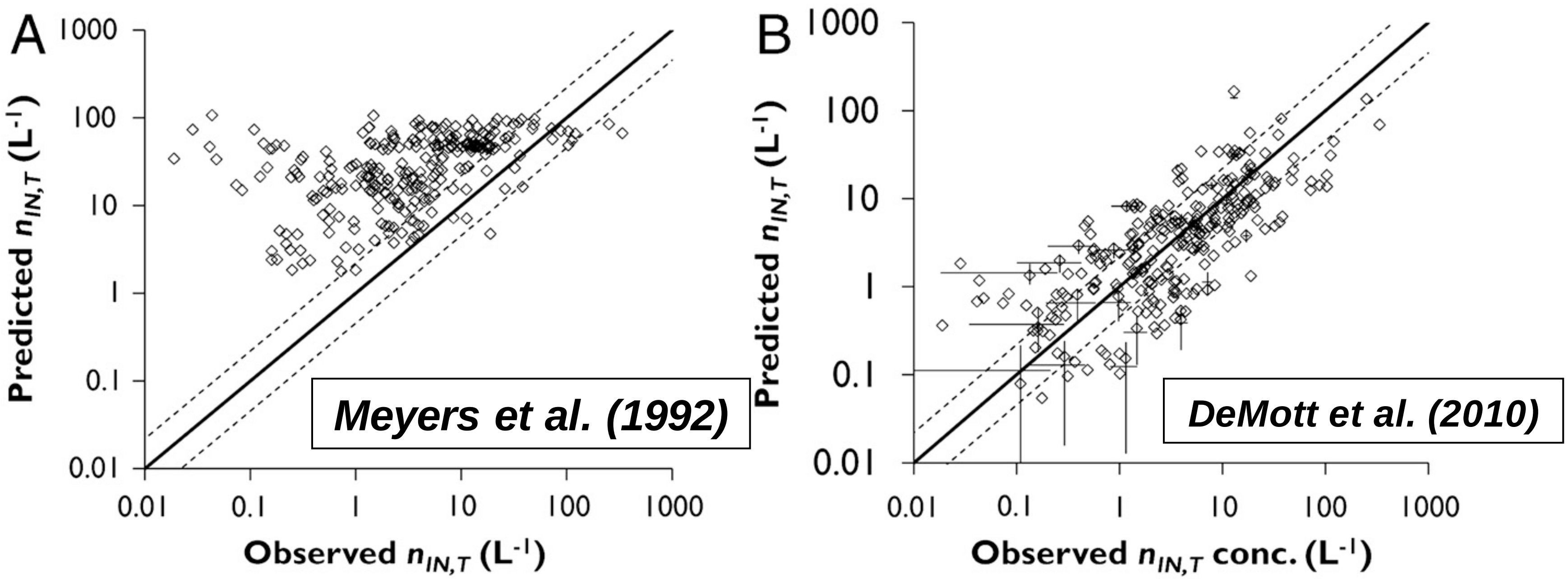


Hoose and Möhler, ACP 2012

Ice nucleation in mixed-phase clouds

DeMott et al. (2010, PNAS) parameterization: T and $n_{aer,0.5}$
Composition matters as well

$$n_{IN,T_k} = a\left(273.16 - \boxed{T_k}\right)^b \left(\boxed{n_{aer,0.5}}\right)^{(c(273.16-T_k)+d)}$$



Classical nucleation theory

Nucleation rate $J = A' r_N^2 \sqrt{\boxed{f}} \exp\left(\frac{-\Delta g^{\#} - f \Delta g_g^{o}}{kT}\right)$

f(α), α is contact angle

Pruppacher and Klett (1997)

Hoose et al. (2010)

Immersion/condensation

$$r_{g,imm} = \frac{2 \upsilon_w \sigma_{i/w}}{kT \ln(a_w e_{sw} / e_{si})}$$

$$\Delta N_{i,imm} = \sum_x Min\{f_{l,x} N_{aer,x} f_{i,\max,x}, \boxed{f_{l,x} N_{aer,x}} [1 - \exp(-J_{imm,x} \Delta t)]\}$$

Activated/cloud-borne aerosol

Deposition

$$r_{g,dep} = \frac{2 \upsilon_w \sigma_{i/v}}{kT \ln(e / e_{si})}$$

Interstitial & uncoated aerosol

$$\Delta N_{i,dep} = \sum_x Min\{\boxed{(1 - f_{l,x})} \boxed{(1 - f_{x,coated})} N_{aer,x} f_{i,\max,x}, (1 - f_{l,x})(1 - f_{x,coated}) N_{aer,x} \times [1 - \exp(-J_{dep,x,RH_W=0.98} \Delta t)]\}$$

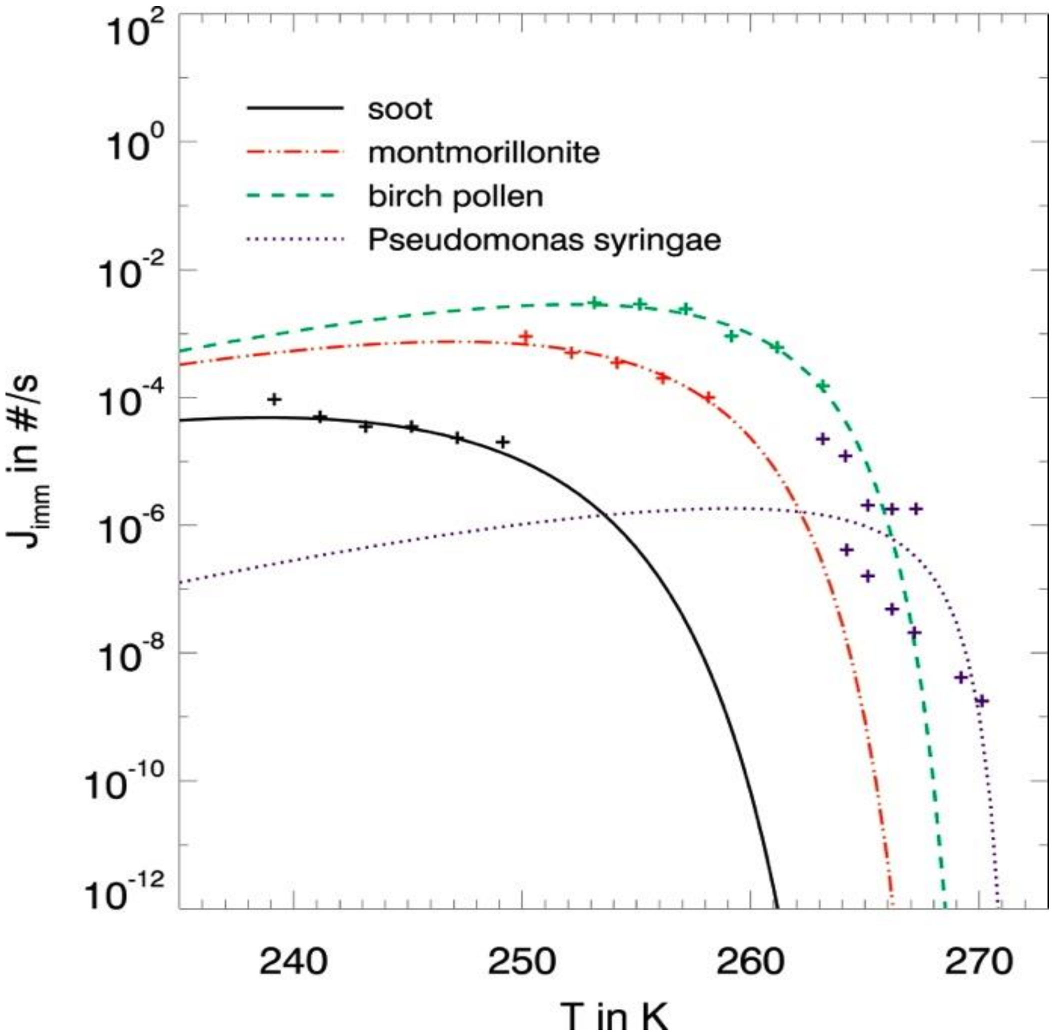
Contact

$$N_{g,contact} \approx 4 \pi r_N^2 \frac{e}{v_s \sqrt{2 \pi m_w kT}} \times \exp[-\frac{\Delta g^{\#}_{dep} + f \Delta g^{o}_{g,dep}(r_{g,imm})}{kT}]$$

$$\Delta N_{i,contact} = \sum_x Min\{(1 - f_{l,x})(1 - f_{x,coated}) N_{aer,x} f_{i,\max,x}, \boxed{(1 - f_{l,x})} \boxed{(1 - f_{x,coated})} N_{aer,x} \times [1 - \exp[-K_{coll}(r_{N,x}, r_l) N_l Max(N_{g.contact,x}, 1) \Delta t]]\}$$

PDF-α model: integrate over the PDF of contact angle α

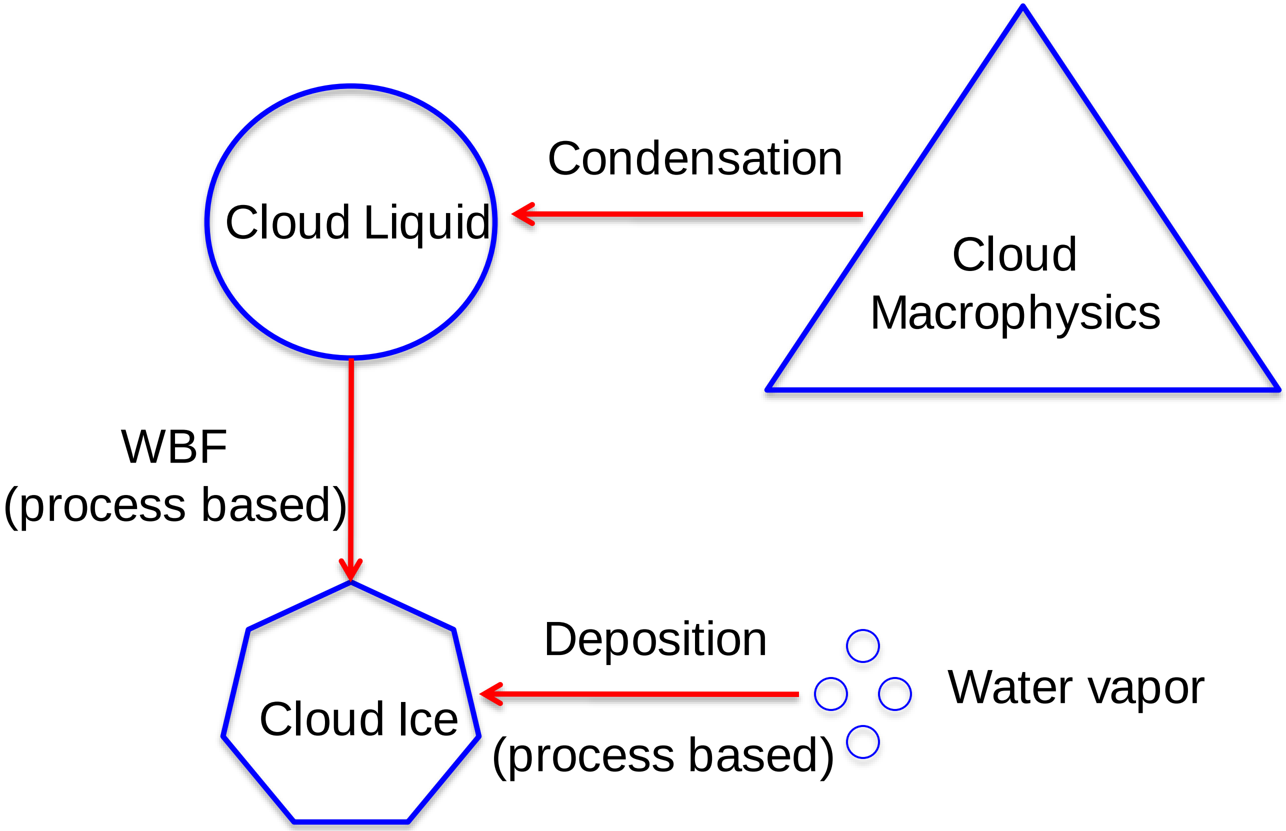
Classical theory links ice nucleation rate to aerosol properties, constrained by experiments



Hoose et al. (2010)

Vapor deposition and WBF process

- Intersection with macrophysics



Subgrid WBF process (Korolev 2007)

In mixed phase clouds, there are three scenarios:

1) $e>e_s>e_i$

   Both droplets and ice crystals grow simultaneously.

2) $e_s>e>e_\mathrm{i}$

   Ice crystals grow at the expense of cloud droplets (WBF process).

3) $e_s>e_i>e$

   Both ice crystals and droplets evaporate simultaneously

Subgrid WBF process (Korolev 2007)

In mixed-phase clouds, there is a link between vertical velocity and vapor pressure.

1) *Uz>Uz**

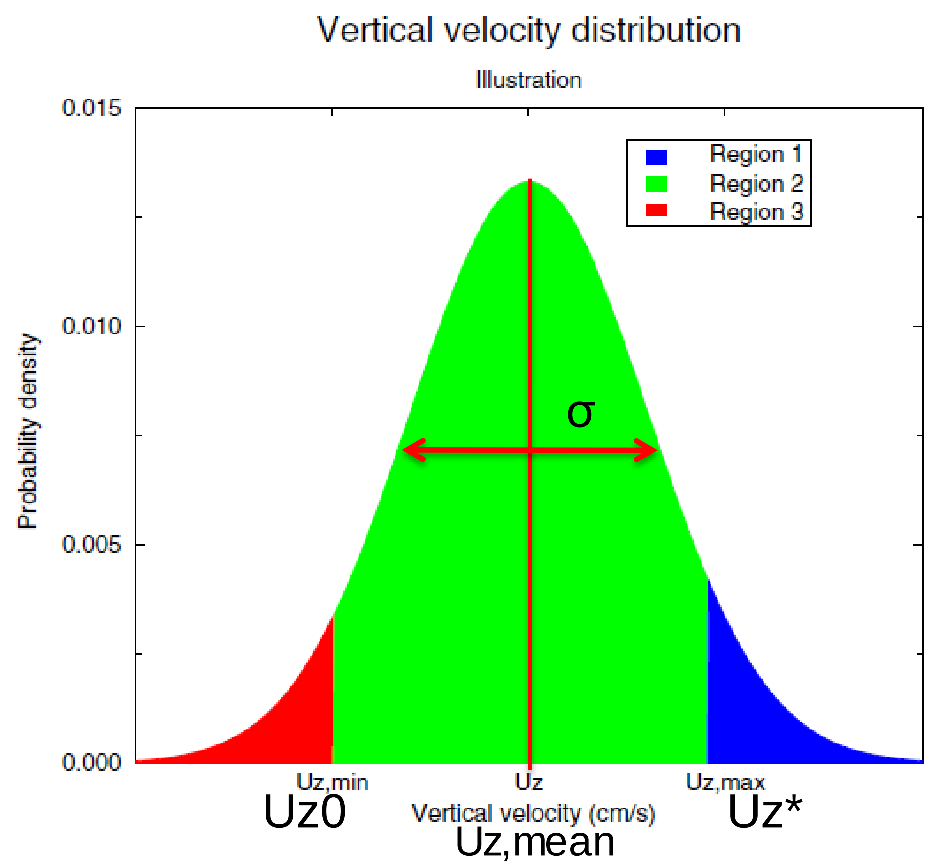
   $e > e_s > e_i$

2) *Uz*>Uz>Uz0*

   $e_s > e > e_i$

3) *Uz<Uz0*

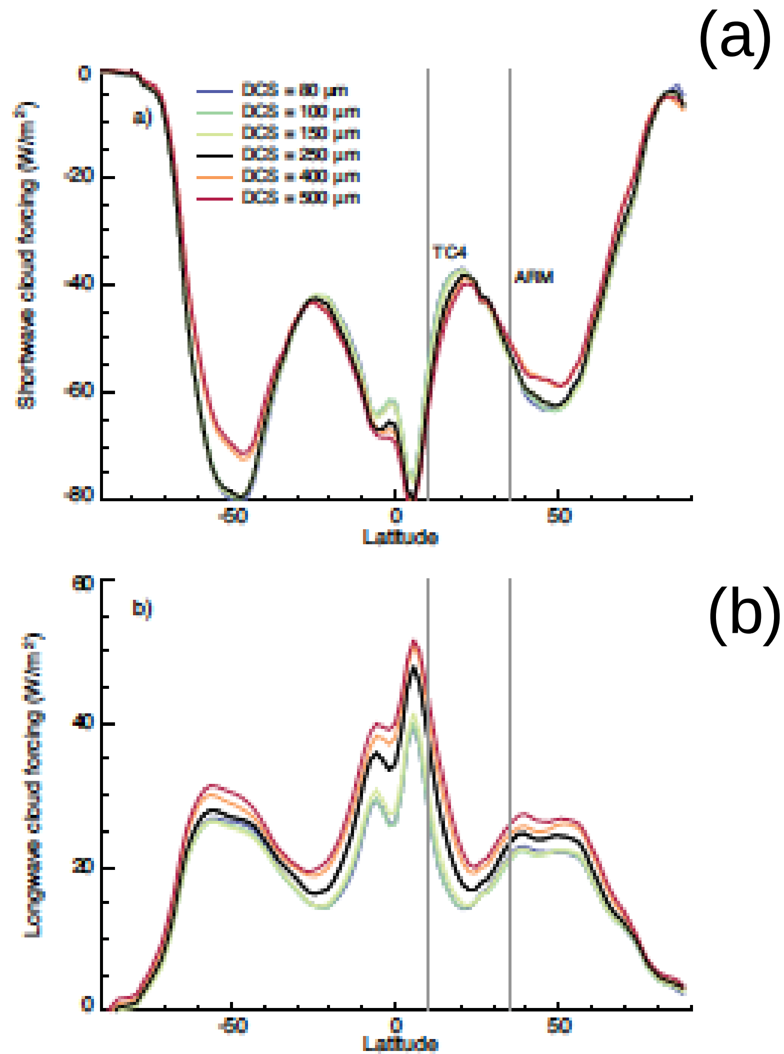
   $e_s > e_i > e$



$$\mathrm{Uz}^* = \frac{e_s - e_i}{e_i}\,\eta N_i \bar{r}_i \qquad \mathrm{Uz0} = \frac{e_i - e_s}{e_s} N_w \overline{r_w} \chi$$

Autoconversion of cloud ice to snow

- **Dcs**, prescribed separating size that distinguishes cloud ice and snow, is one of the most effective knobs in the tuning of CAM5



Zonal averaged (a) shortwave and (b) longwave cloud forcing with varying Dcs

Eidhammer et al. (2014)

Upgrade CAM5 ice microphysics to make it self-consistent (Morrison, Mitchell, Eidhammer)

- Combine cloud ice/snow into a single ice category
- Use observed mass-diameter and area-diameter relationships from observations and apply self-consistently for all processes and parameters for all particle sizes

Convective Cloud Microphysics

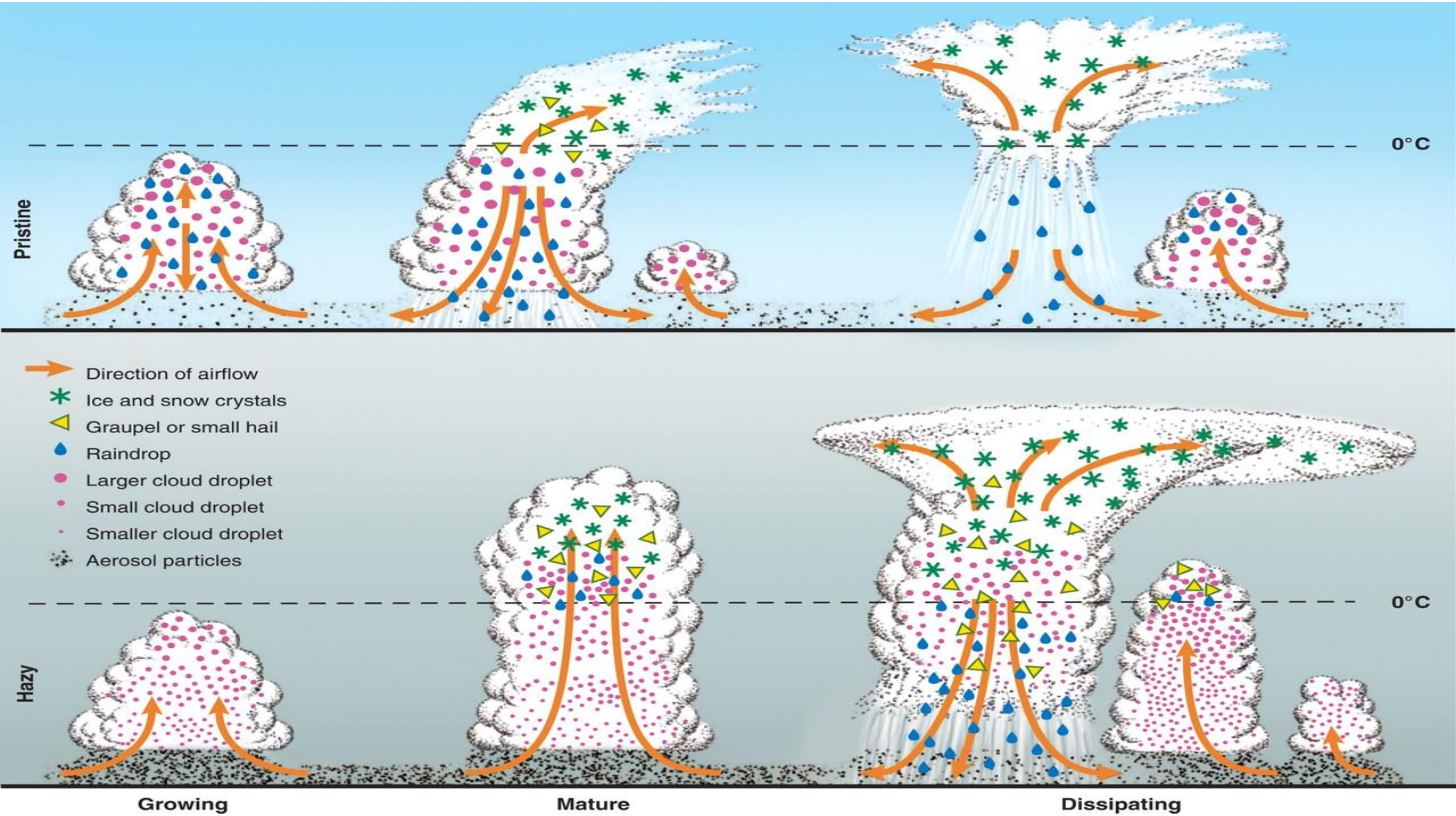
- Simple microphysics in convective clouds
  droplet conversion to rain (c0)
- Convective detrainment
  - Deep convection
    detrainment sizes: 8 μm (cloud droplet);
    25 μm (cloud ice)
  - Shallow convection
    detrainment sizes: 10 μm (cloud droplet);
    50 μm (cloud ice)

- Two-moment convective cloud microphysics
  Song and Zhang (2011), Song et al. (2012)

Some remaining issues in GCMs

- Ice nucleation
  - link to aerosol & environment,
  - prognostic IN, scavenging of IN
- Subgrid processes (e.g., WBF)
- Convective cloud microphysics & aerosol scavenging by convective precipitation

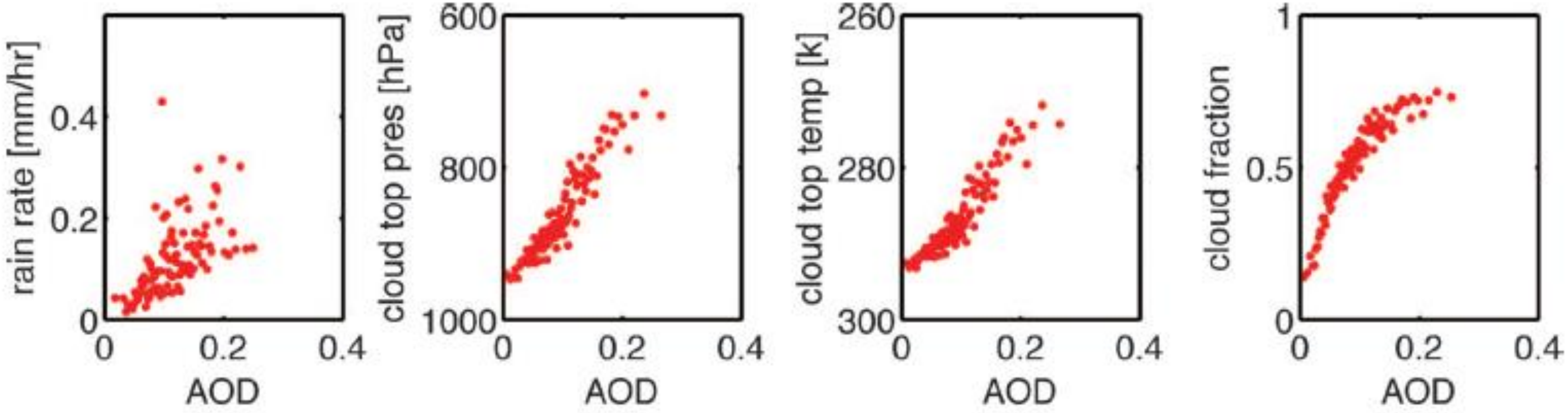
Aerosol invigoration effects on precipitation

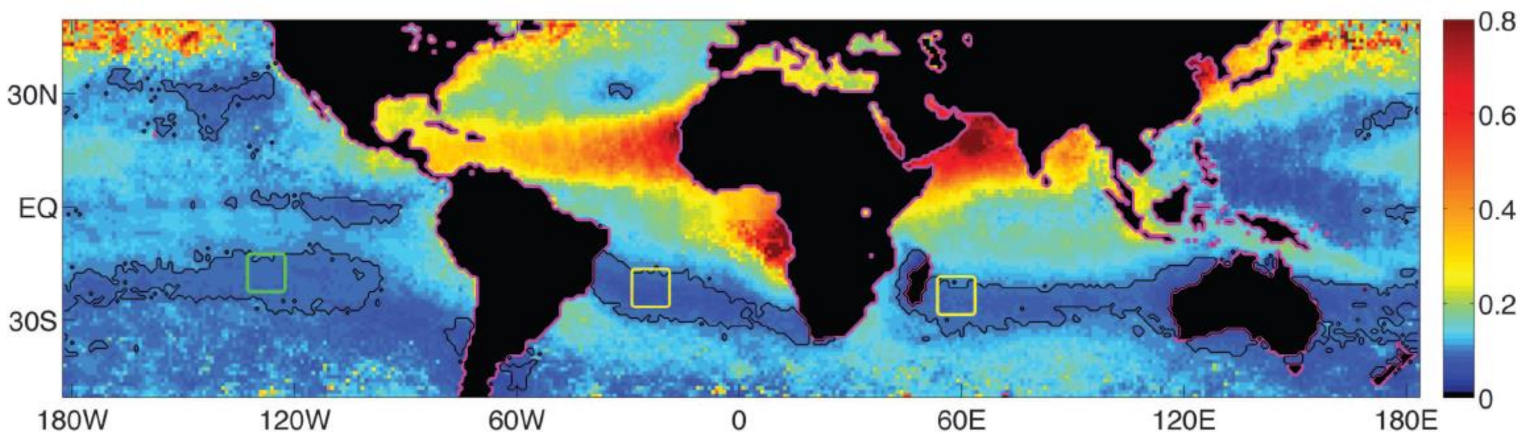


Rosenfeld et al., 2008

Aerosol invigoration effects on warm convective clouds

Koren et al. (2014) Science





Summary

- Strong observational evidences of aerosol effects on clouds
- GCMs have started to implement the two-way aerosol-cloud interactions
  - Important for aerosol lifecycle: wet scavenging of aerosols
  - Aerosol indirect forcing: major uncertainty in total climate forcing, critical for climate sensitivity based on 20th Century temperature change, and for future climate projection

Summary

- Grand challenges of representing aerosol-cloud interactions in GCMs:
  - Multi-scale interactions: starting from micro- to global scale
  - Subgrid processes in GCMs: cloud microphysics (e.g., droplet and ice nucleation), turbulence (updrafts), dynamics (entrainment, convection)
  - Lack fundamental understanding of ice microphysics (e.g., ice nucleation)