Clouds

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Outline of this Lecture

- Overview of clouds
- Warm cloud formation
- Precipitation formation in warm clouds
- Ice cloud formation
- Summary of cloud microphysical processes

Basic 10 Cloud Types in 4 Families

Cumulus : vertical development

Stratus : layered cloud

Cirrus : ice clouds

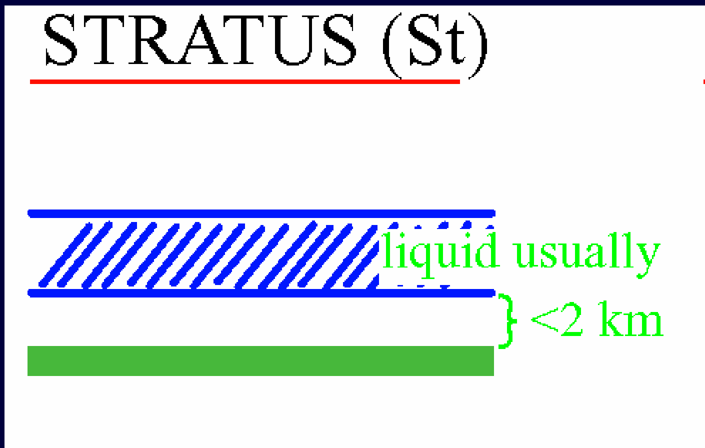
Low Base with vertical extent : Cu, Cb, Ns

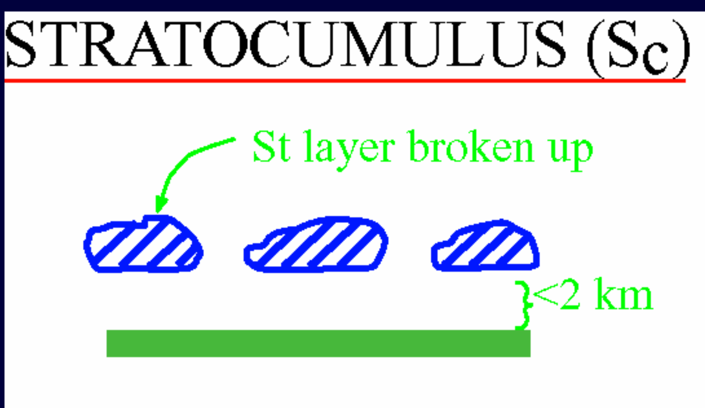
Low Base and layered : (0-2 km) : St, Sc

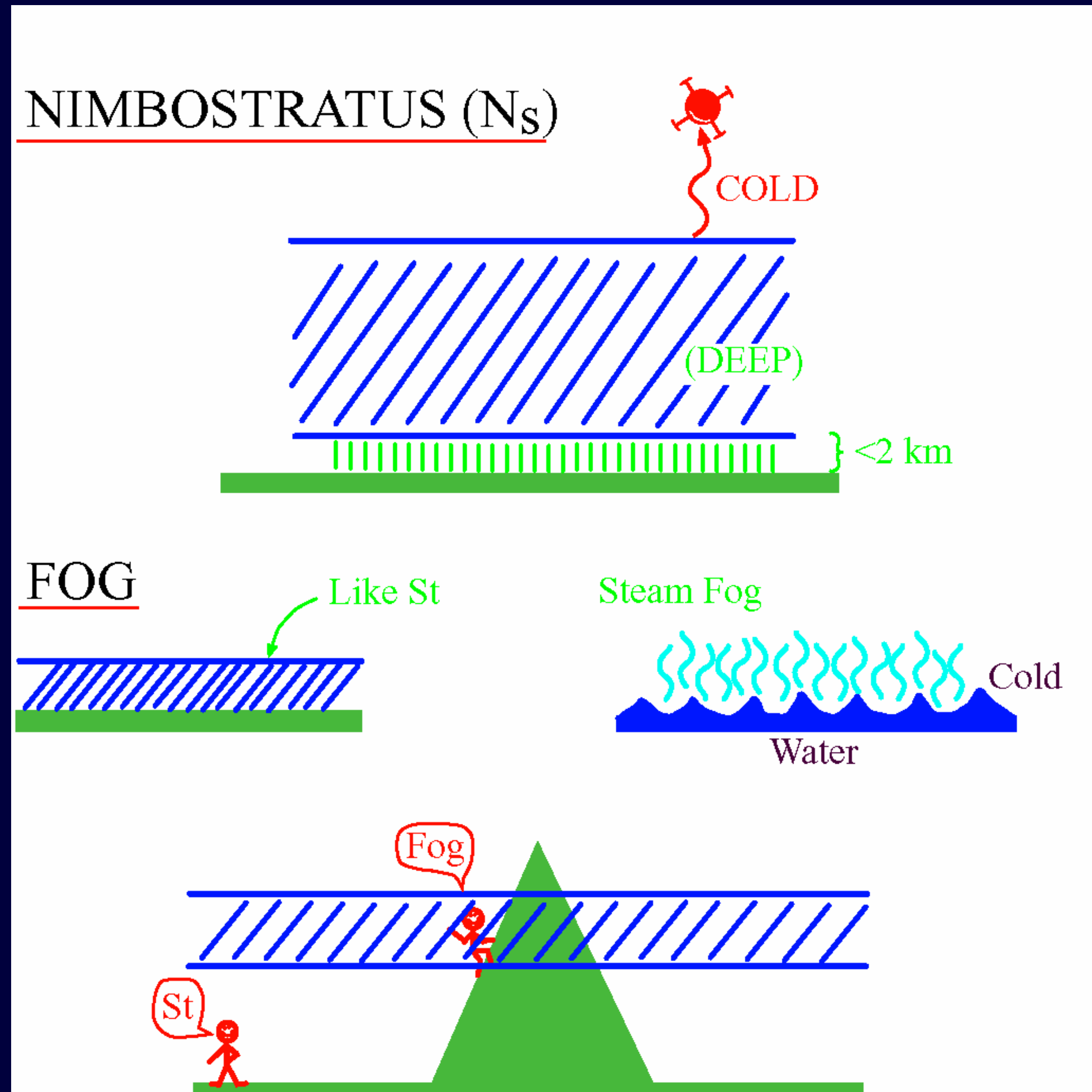
Middle Altitude : (2-7 km) : As, Ac

High Altitude (Ice clouds) (5-13 km) : Ci, Cs, Cc

Fog, Stratus, Stratocumulus, Nimbostratus

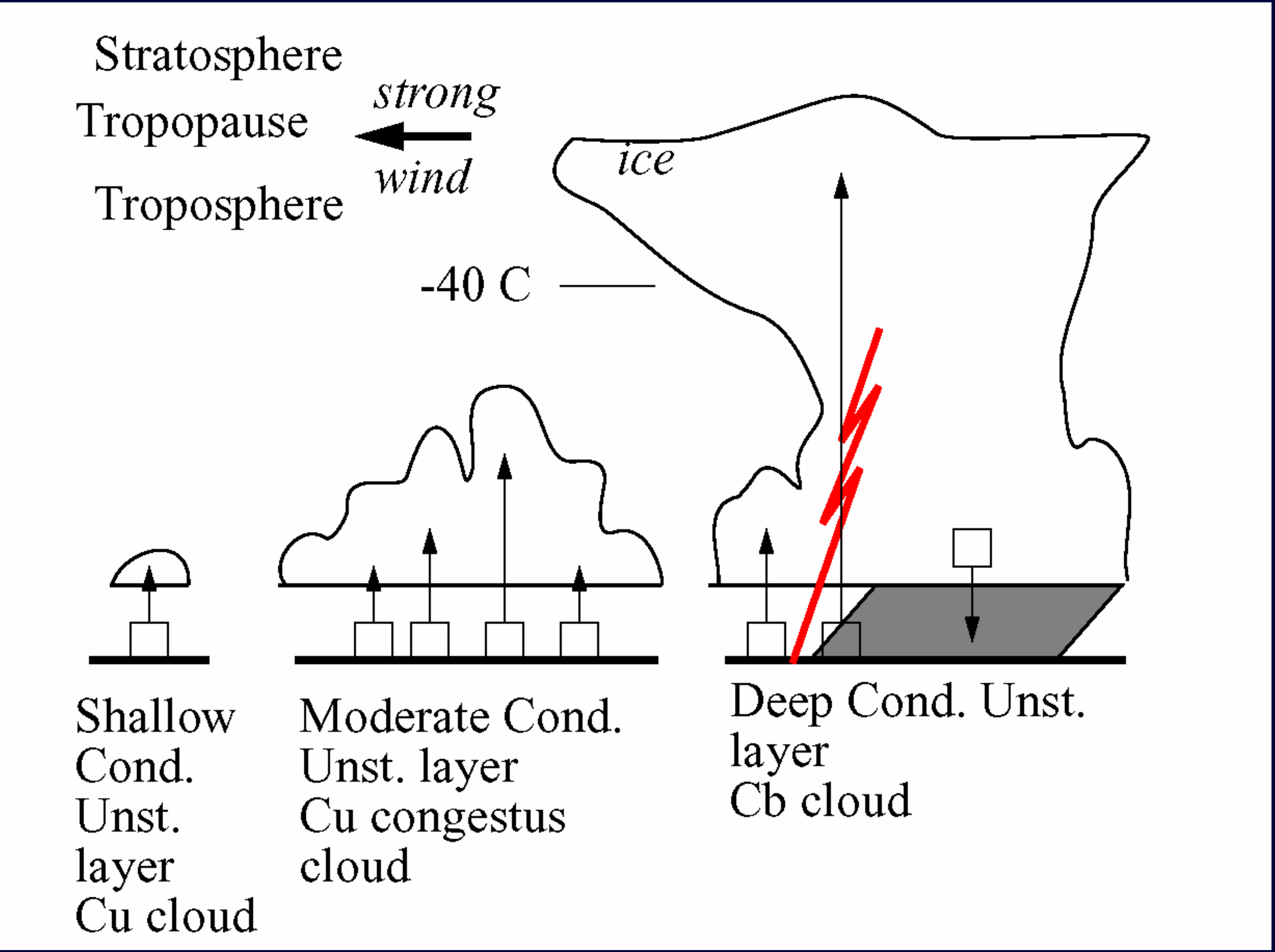






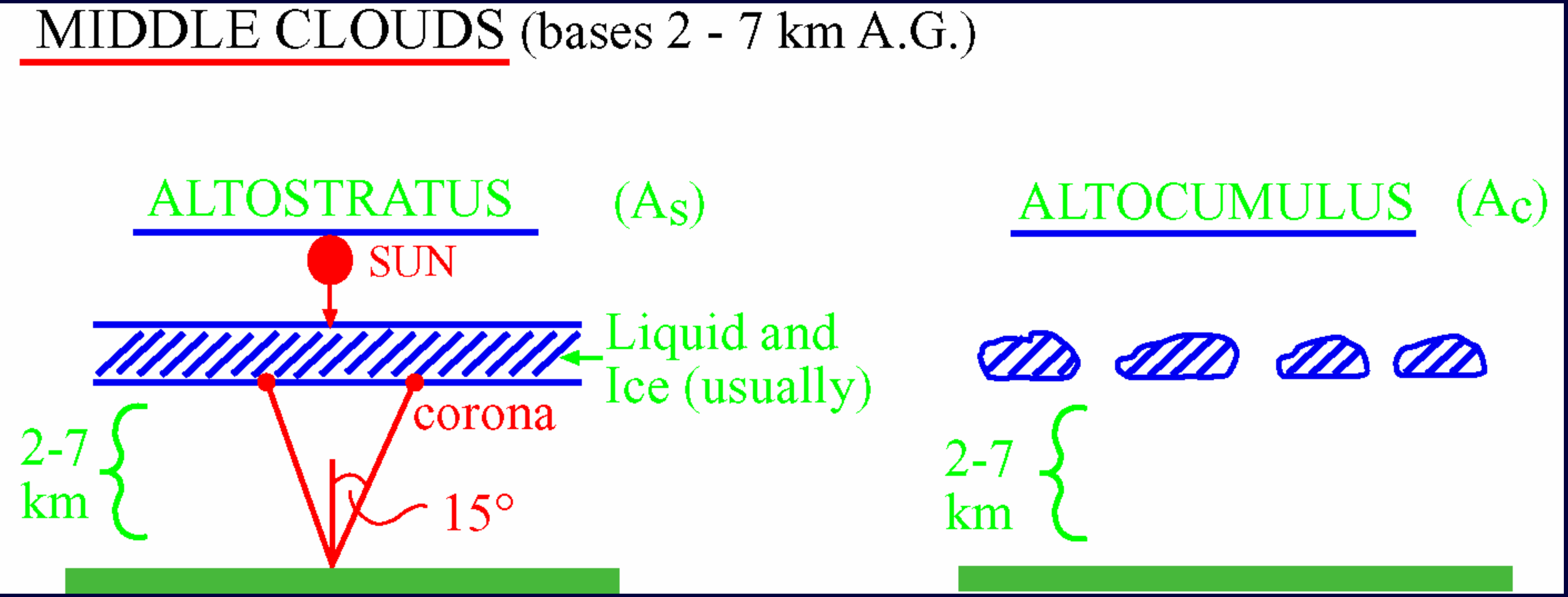
http://www.atmos.washington.edu/gcg/Atlas/

Convective Clouds [http://www.atmos.washington.edu/gcg/Atlas]



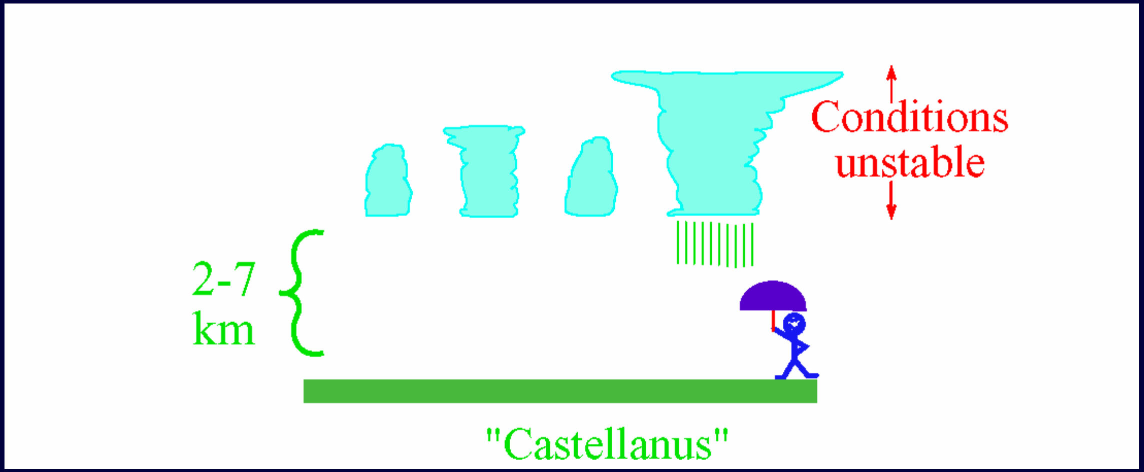
Middle Clouds

[http://www.atmos.washington.edu/gcg/Atlas]

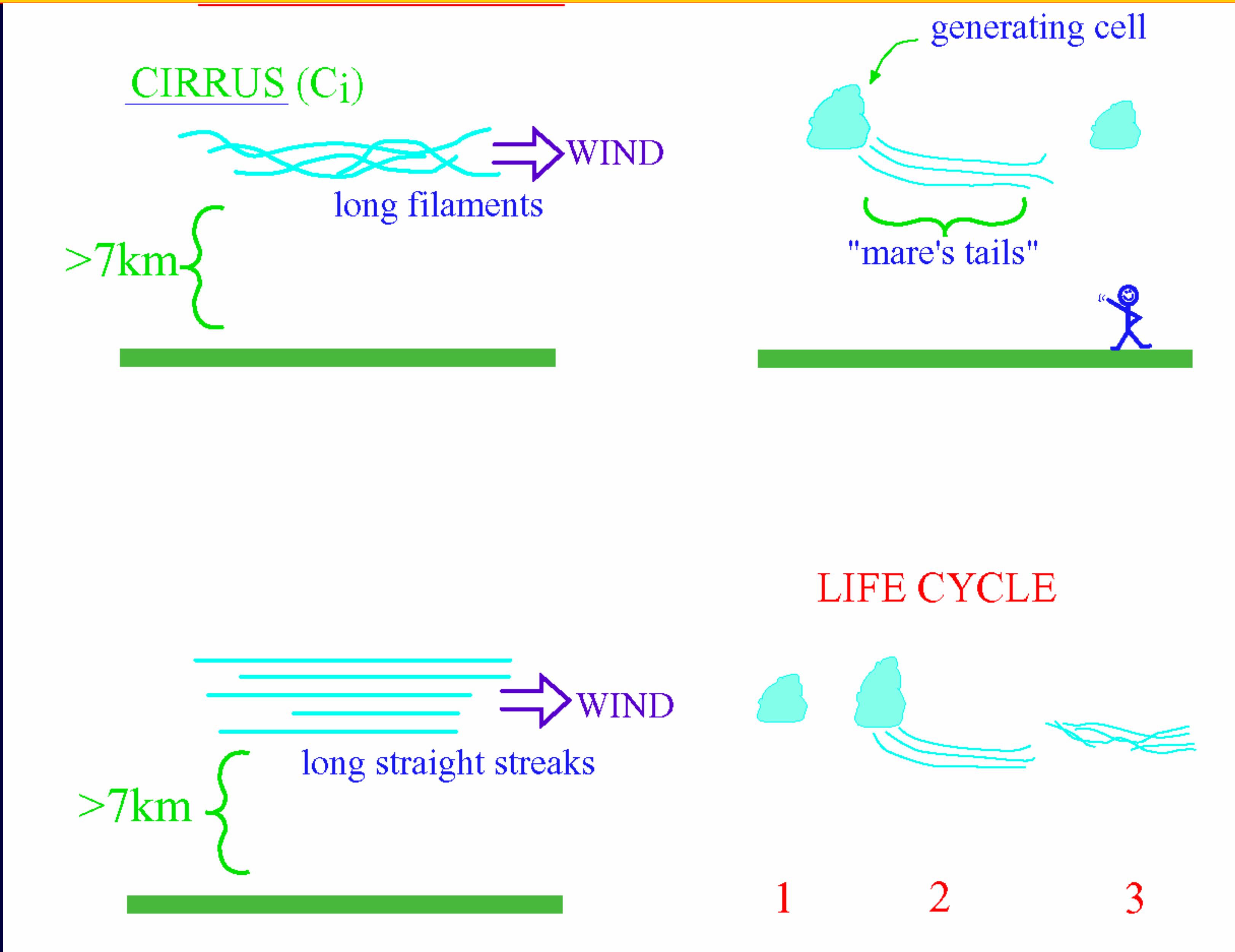


Subtype of Ac:

Castellanus

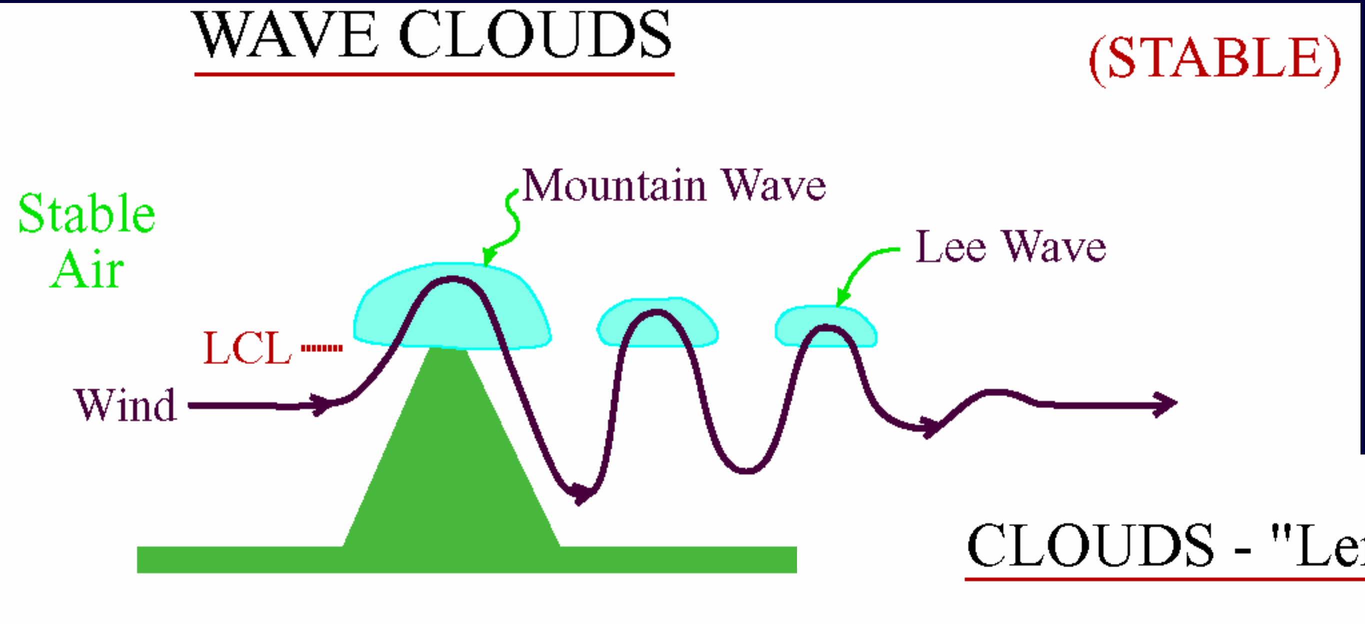


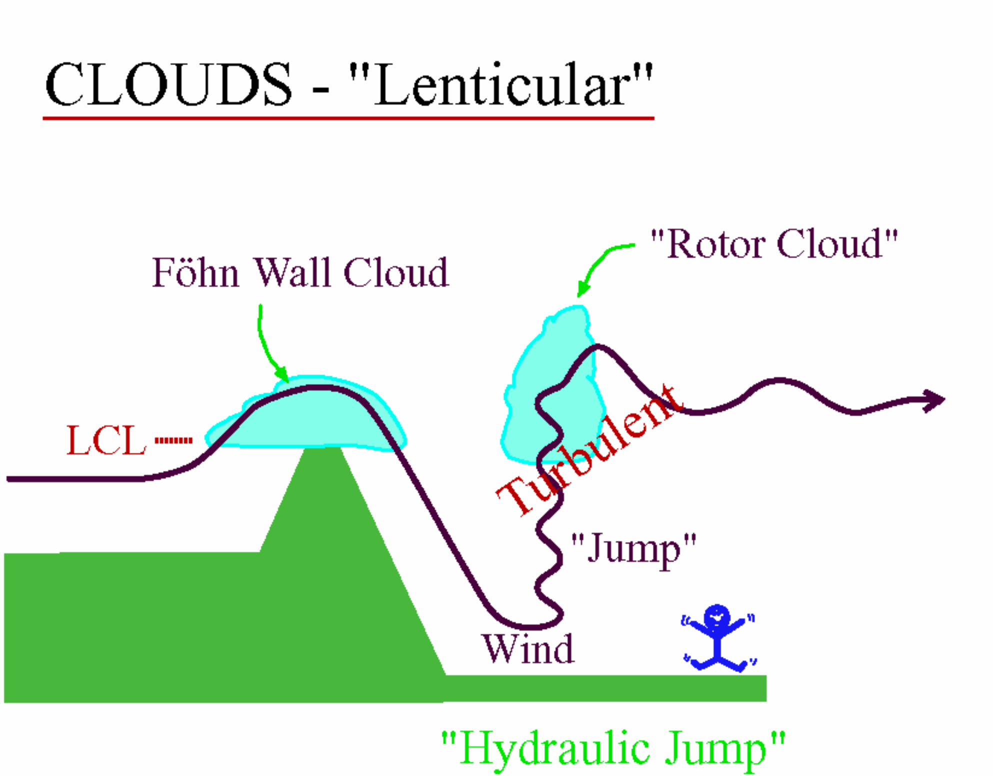
High Clouds (Ice) [http://www.atmos.washington.edu/gcg/Atlas]



Orographic Clouds

[http://www.atmos.washington.edu/gcg/Atlas]





Clausius-Clapeyron Equation

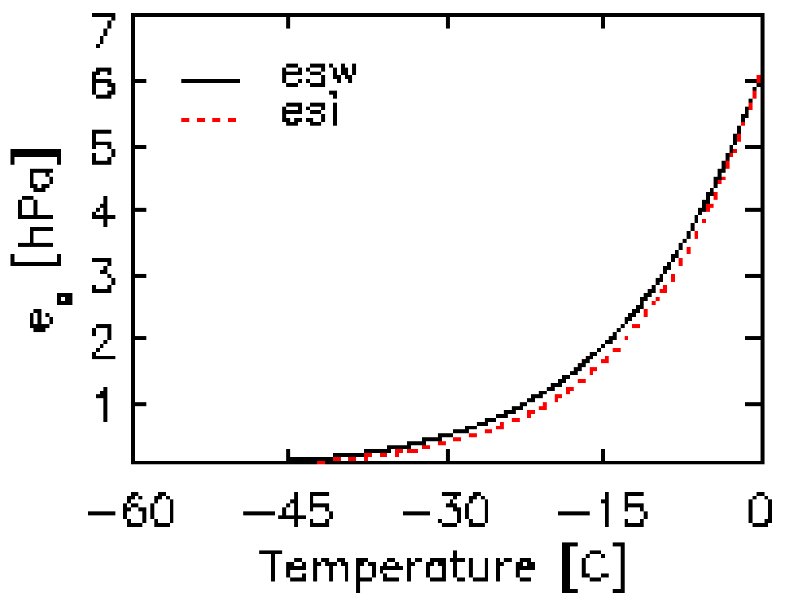
$$de_s/dT = L\, e_s^2/(R_v\, T^2)$$

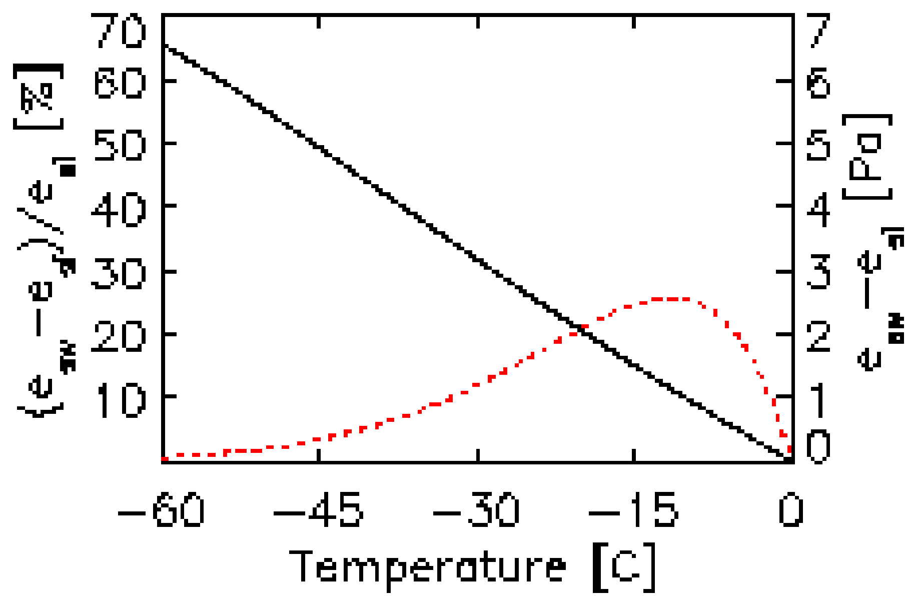
R_v = gas constant of water vapor

e_s = saturation vapor pressure over water/ice

L = latent heat of vaporization/sublimation

T = temperature





Köhler Curve

consists of Raoult's law and Kelvin equation:

$$e_s(r)/e_s(\infty) = \exp(\{2\sigma\}/\{\rho_w R_v T r\}) = \exp(a/r)$$

r = droplet radius

$e_s(r)$ = saturation vapor pressure of droplet of size r

$e_s(\infty)$ = saturation vapor pressure over a bulk surface of water

σ = surface tension

ρ_w = water density

Saturation ratio	Critical radius	Number of molecules
1.01	0.12 μm	2.5×10^8
1.1	0.0126 μm	2.8×10^5
2	1.73 nm	730
10	0.52 nm	20

Köhler Curve (2)

Raoult's law: For a plane water surface the reduction in vapour pressure due to the presence of a non-volatile solute may be expressed:

$$e^*(\infty)/e_s(\infty) = 1 - (3\,\nu\, m\, M_w)/(4\,\pi\, M_s\, \rho_w\, r^3) = 1 - b/r^3$$

$e_s^*(\infty)$ = saturation vapor pressure of bulk solution

M_s = molecular weight of the solute,

m_s = mass of the solute,

ν = degree of dissociation.

Köhler Curve (3)

Combination of Kelvin and Raoults equation (evaluated for $e^*(r)/e_s(r)$) gives the Koehler curve:

$$e^*(r)/e_s(\infty) = (1 - b/r^3) * \exp(a/r) \sim 1 + a/r - b/r^3$$

1. term: surface molecules possess extra energy
2. term: solute molecules displacing surface water molecules

$a \sim 3.3\ 10^{-7}/T$ [m]

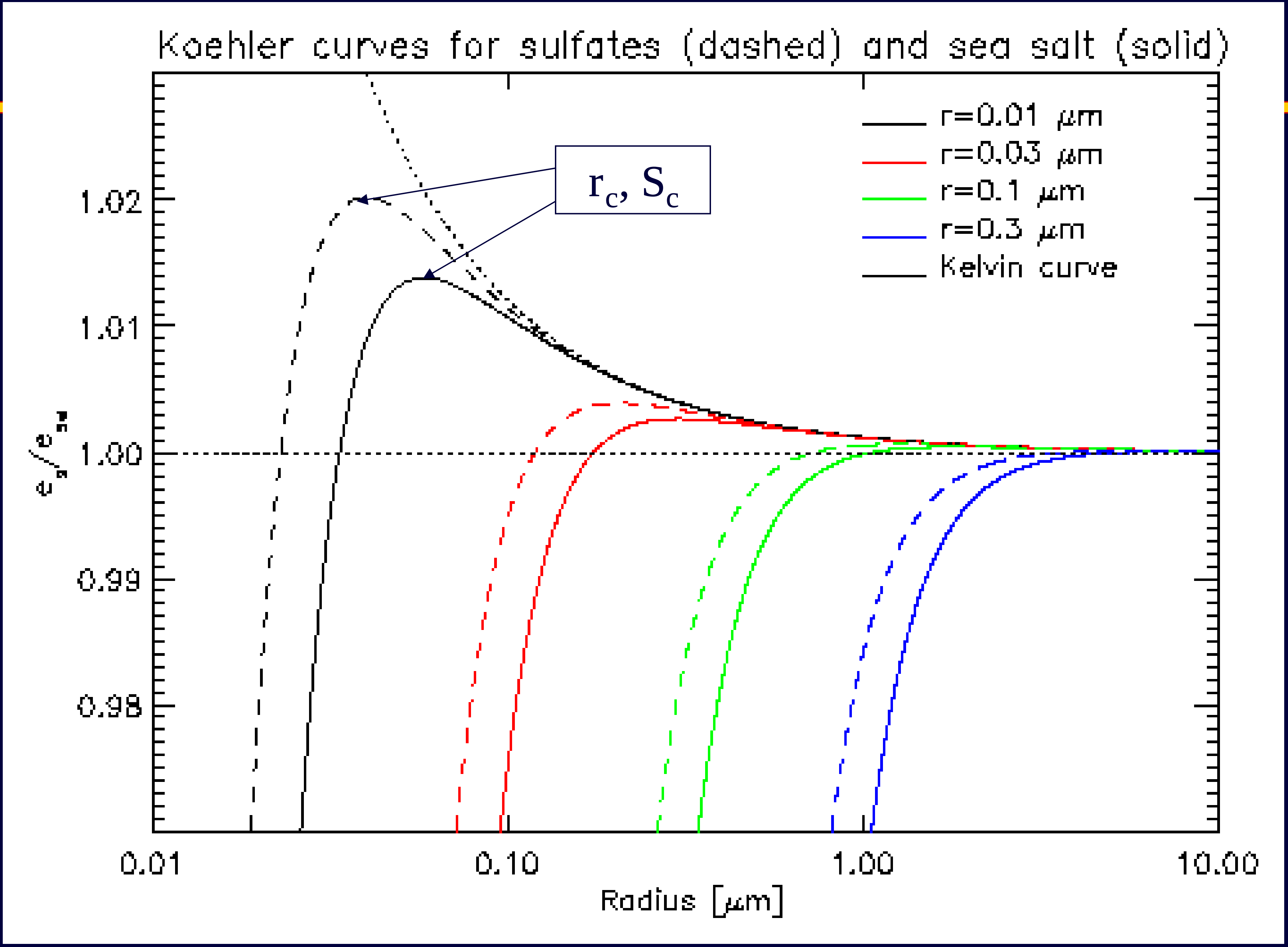
$b \sim 4.3\ 10^{-6}\ i\ M_s/m_s$ [m^3/mol]

M_s = mass of salt [kg]

m_s = molecular mass of salt [kg/mol]

The critical radius r_c and critical supersaturation S_c are given by:

$r_c = (3b/a)^{1/2}$, $S_c = (4\ a^3/[27\ b])^{1/2}$


Koehler curves for sulfates (dashed) and sea salt (solid)
r=0.01 μm
r=0.03 μm
r=0.1 μm
r=0.3 μm
Kelvin curve
r_c, S_c
1.02
1.01
1.00
0.99
0.98
e_s/e_{sw}
0.01
0.10
1.00
10.00
Radius [μm]

Cloud Droplet Formation

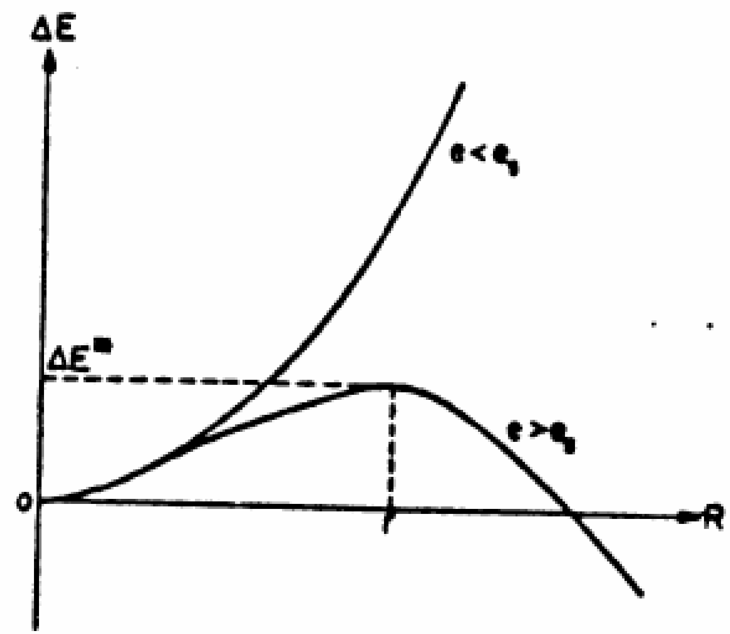


Figure 3.1: The increase ΔG in the energy of a system due to the formation of a water droplet of radius R from water vapor with pressure e; e_s is the saturation vapor pressure with respect to a plane surface of water at the temperature of the system. [From Wallace and Hobbs (1977).]

Observed Cloud Droplet Spectra

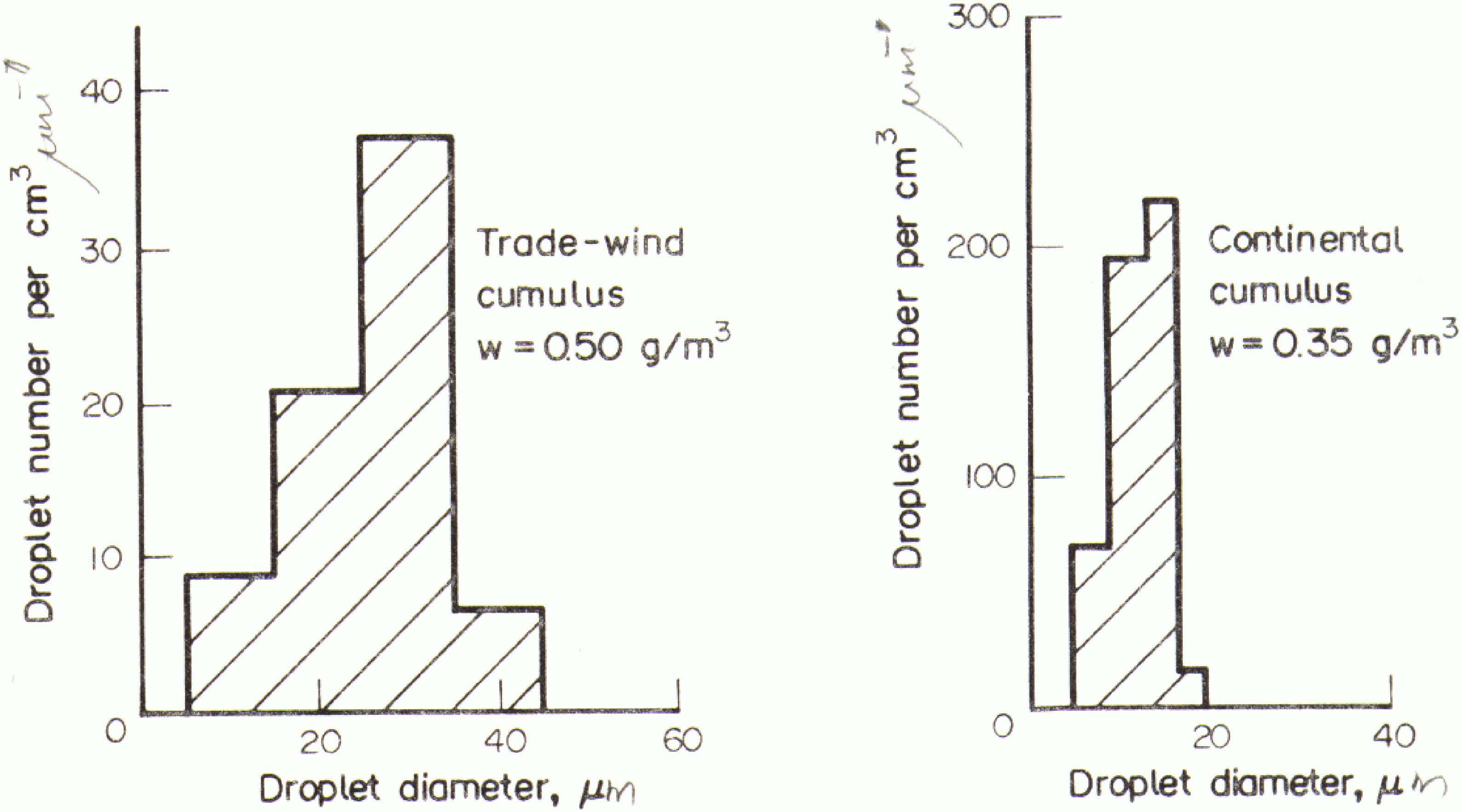
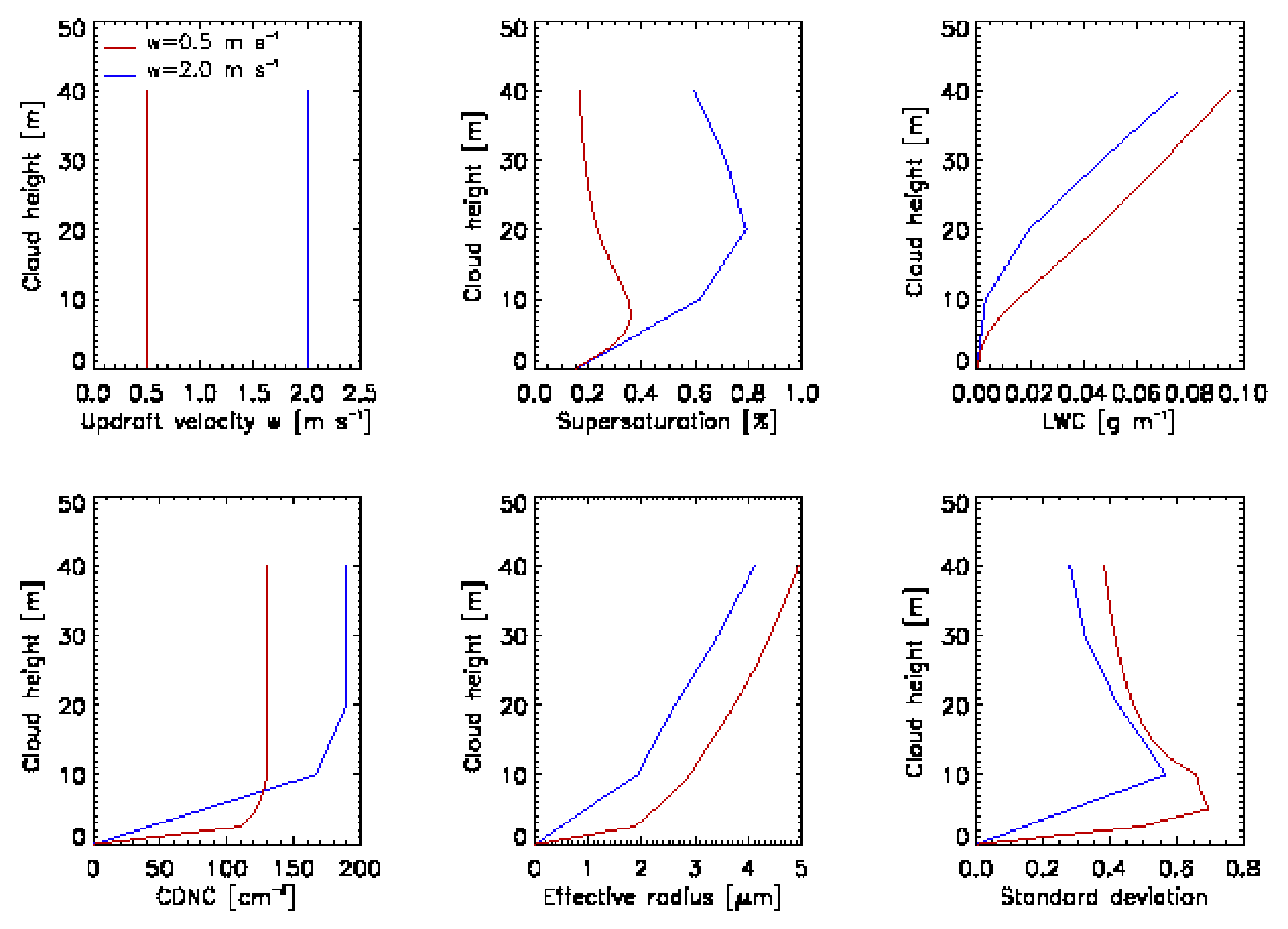


FIG. 5.9. Droplet spectra in trade-wind cumulus off the coast of Hawaii and continental cumulus over Blue Mts. near Sydney, Australia. (From Fletcher, 1962, after Squires, 1958a.)

Cloud Properties in a Developing Cloud



Droplet Sizes *[Rogers and Yau, 1989]*

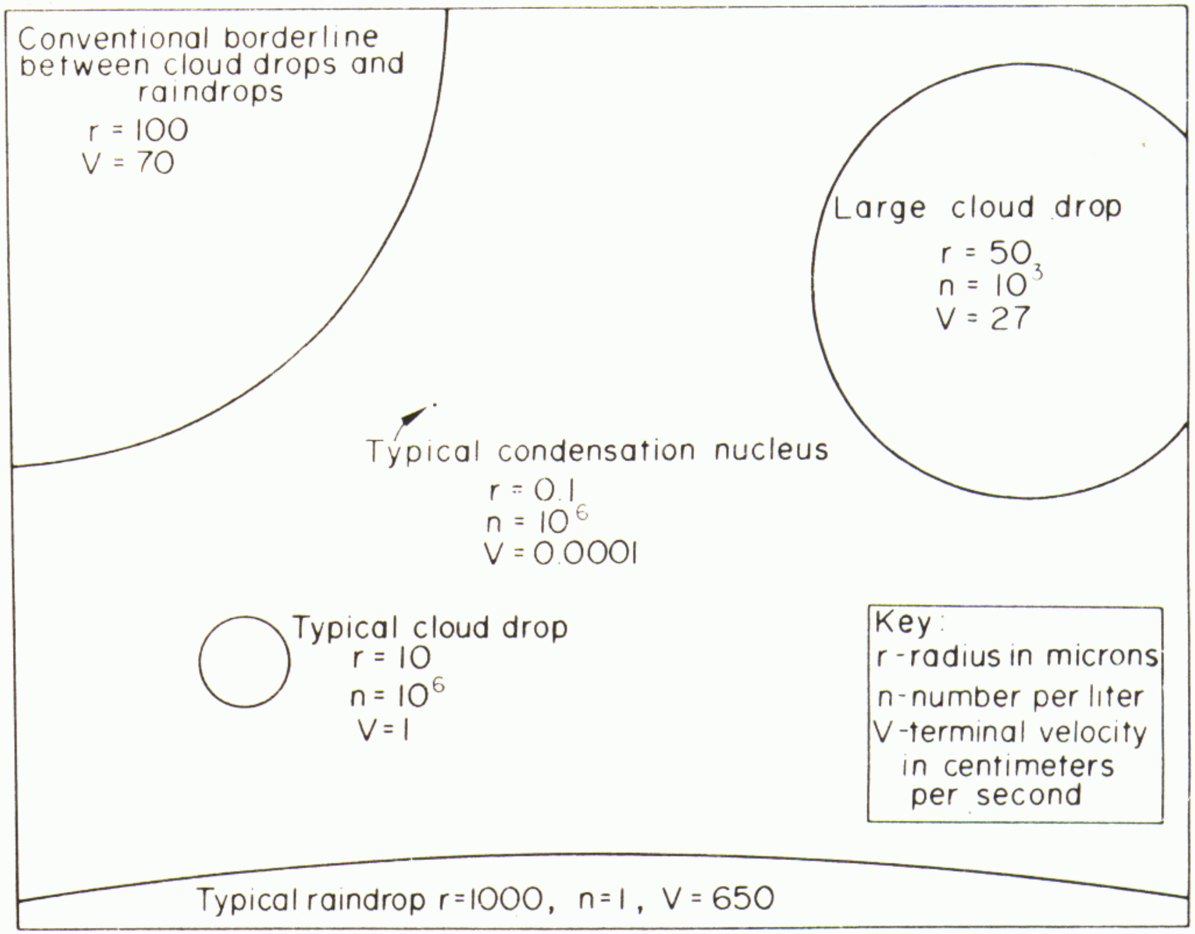


FIG. 6.1. Comparative sizes, concentrations, and terminal fall velocities of some of the particles included in cloud and precipitation processes. (From McDonald, 1958.)

CP—D

Droplet Growth Equation

Before and after the droplet reaches the critical size, it grows by diffusion of water molecules from the vapor onto its surface.

$$r \, dr / dt = (S - 1) / [F_k + F_d]$$

S = ambient saturation ratio

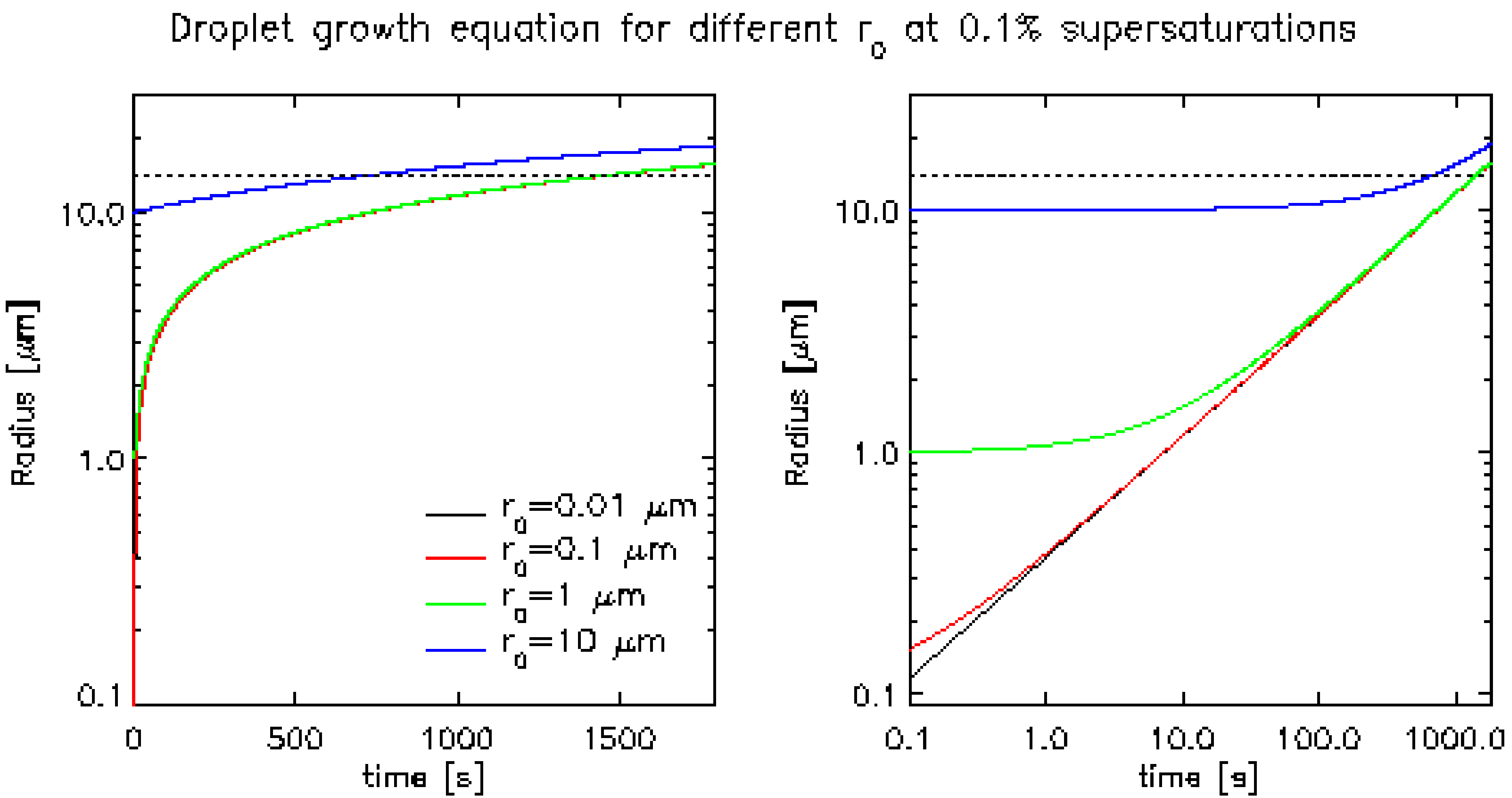
F_k = heat conduction term ~ $L^2 \rho_w / R_v K T^2$

F_d = vapor diffusion term = $\rho_w R_v T / D e_s$

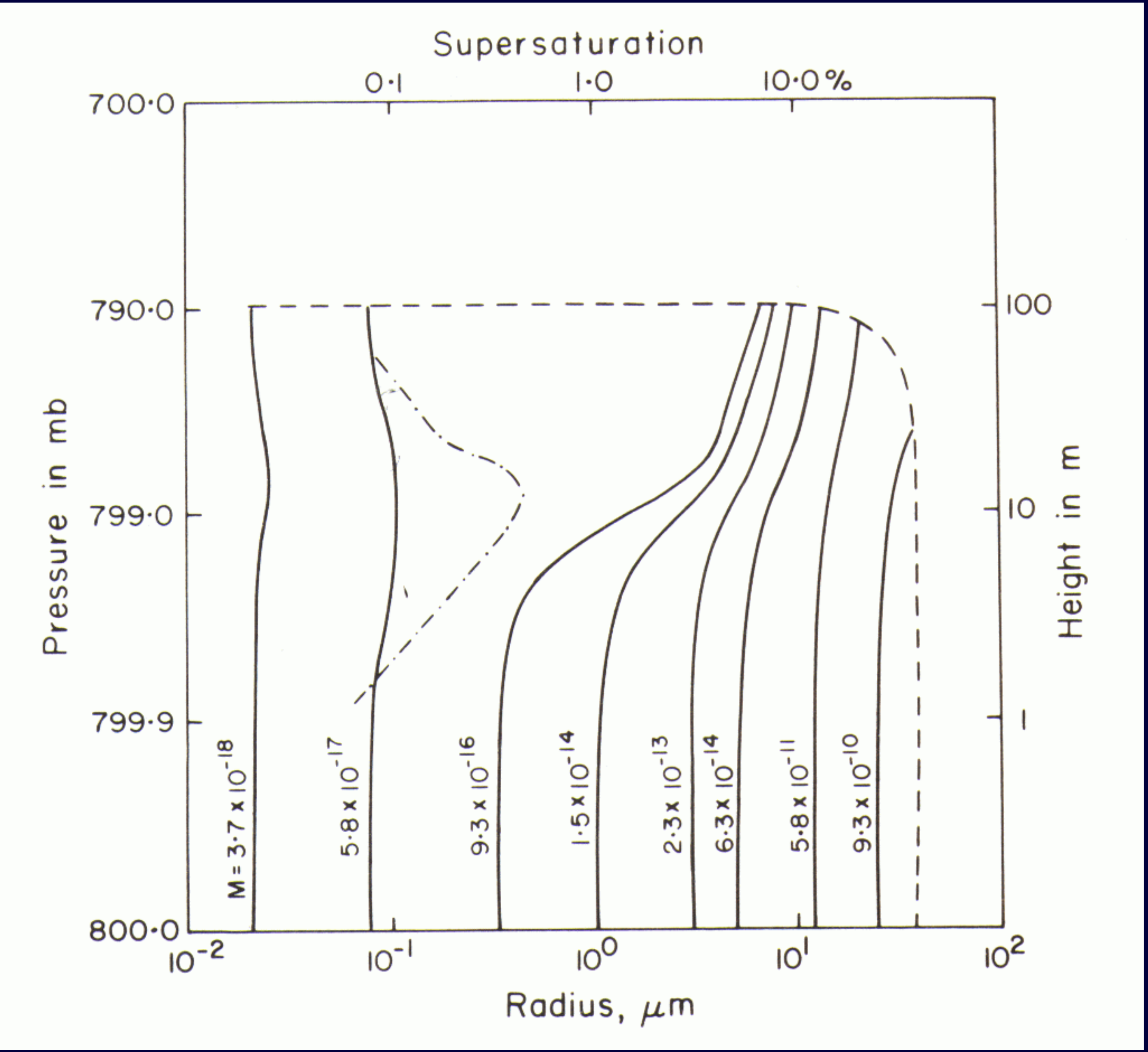
D = diffusion of water vapor in air

K = thermal conductivity of air

Droplet Growth Equation (2)



Evolution of Droplet Population *[Rogers and Yau, 1989]*



How Does Warm Rain Form?

Cloud droplets initially grow by condensation, then through collision-coalescence (sticking together).

Coalescence is not efficient when droplets < 14 μm

Problems in explaining observed droplet growth:

e.g., growth rate to a 14 μm droplet by condensation

~10-20 min

growth by collision-coalescence from 20 μm to 100 μm

~1 hour

i.e., the combined growth time is longer than the lifetime of small, precipitating cumulus clouds

Cloud Spectrum Widening

Need to overcome an effective radius of 14 μm before the collision-coalescence process becomes effective

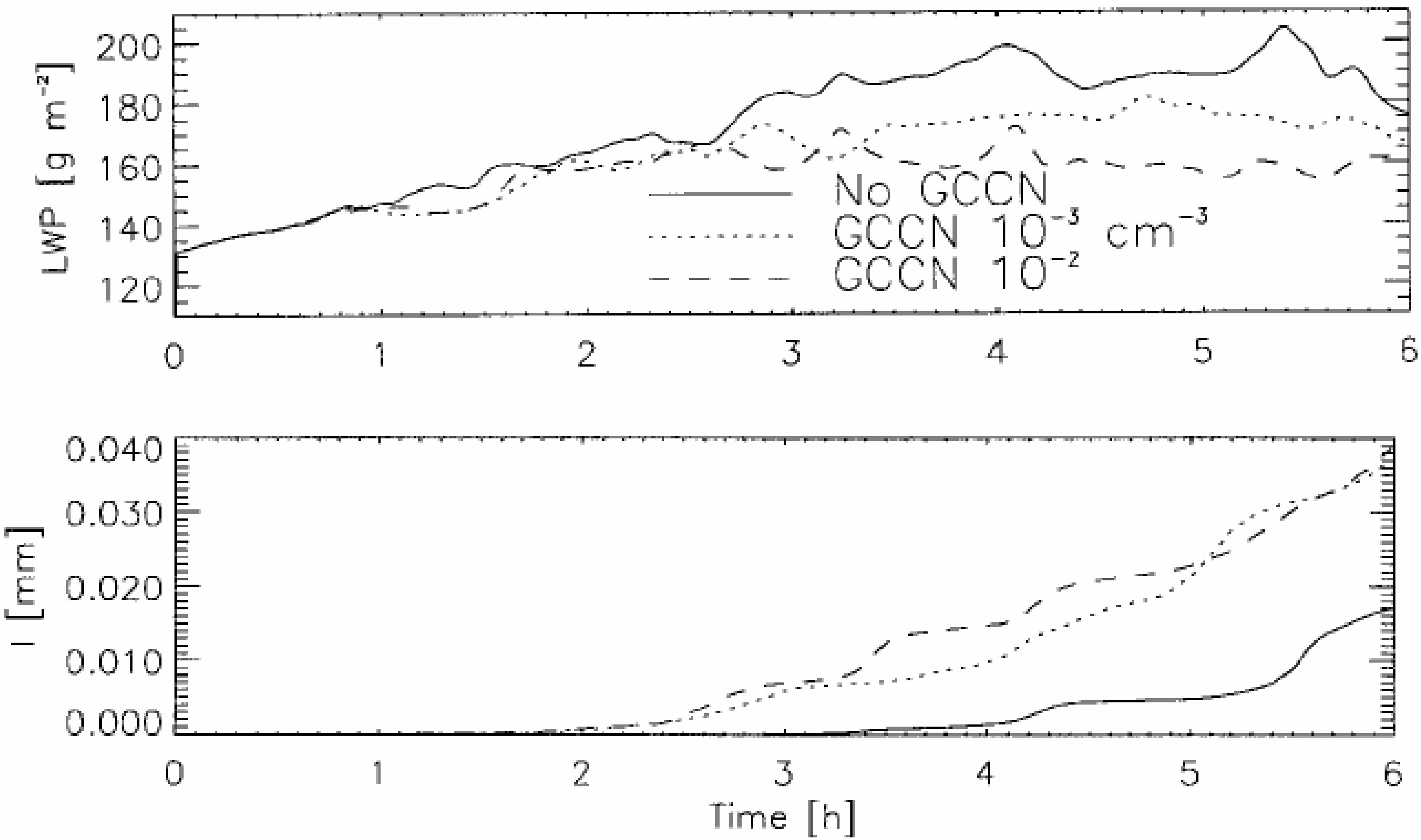
How?

Turbulence or giant CCN

Turbulence may help by providing overlapping eddies, different drop inertias, effects of shear

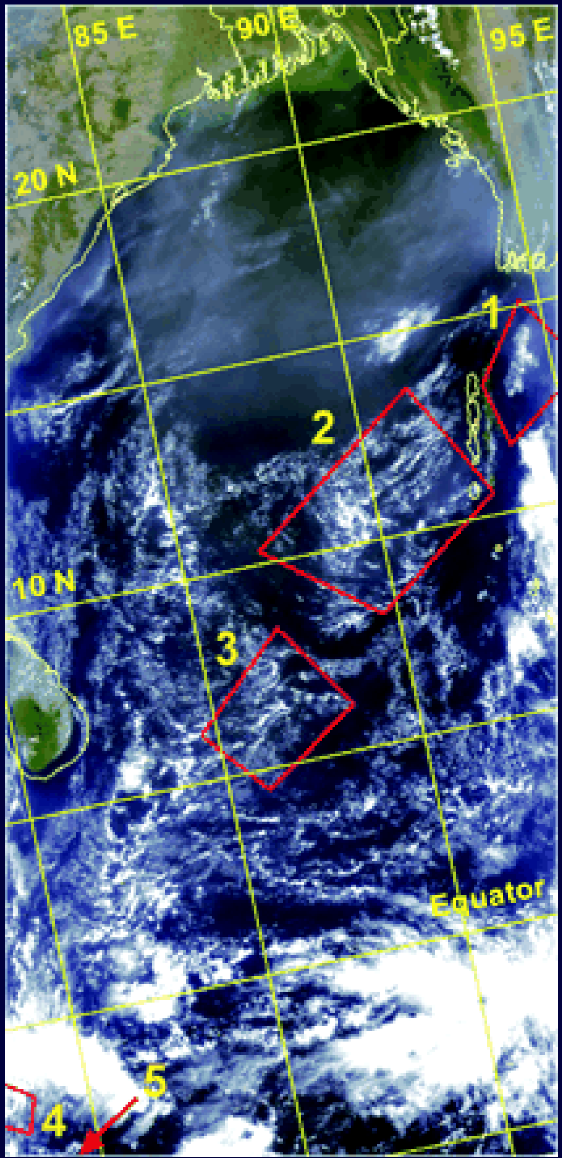
Giant Cloud Condensation Nuclei

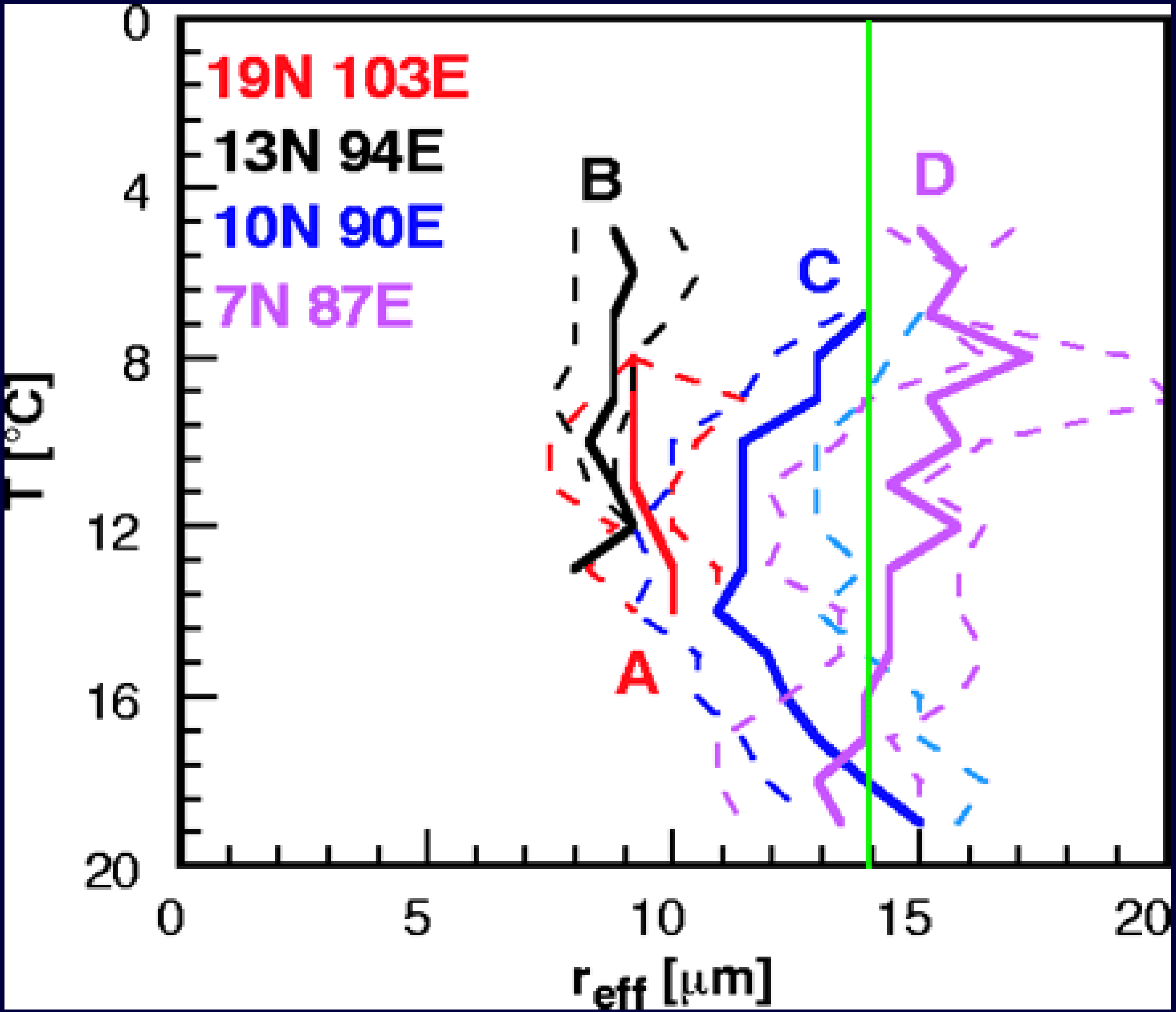
[Feingold et al. 1999]



Can Sea Salt Cleanse Air Pollution over Oceans?

[Rosenfeld et al. 2002]





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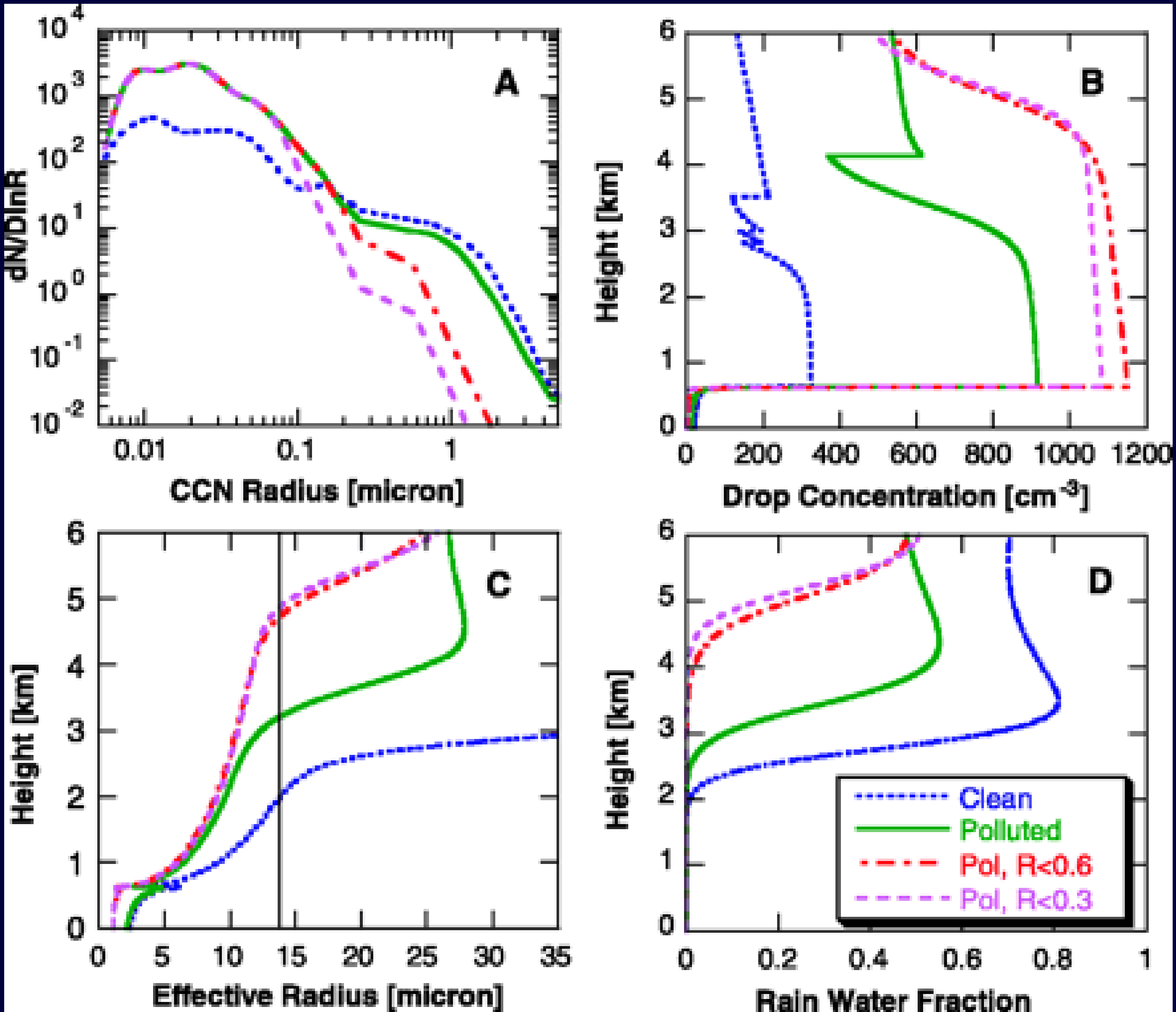
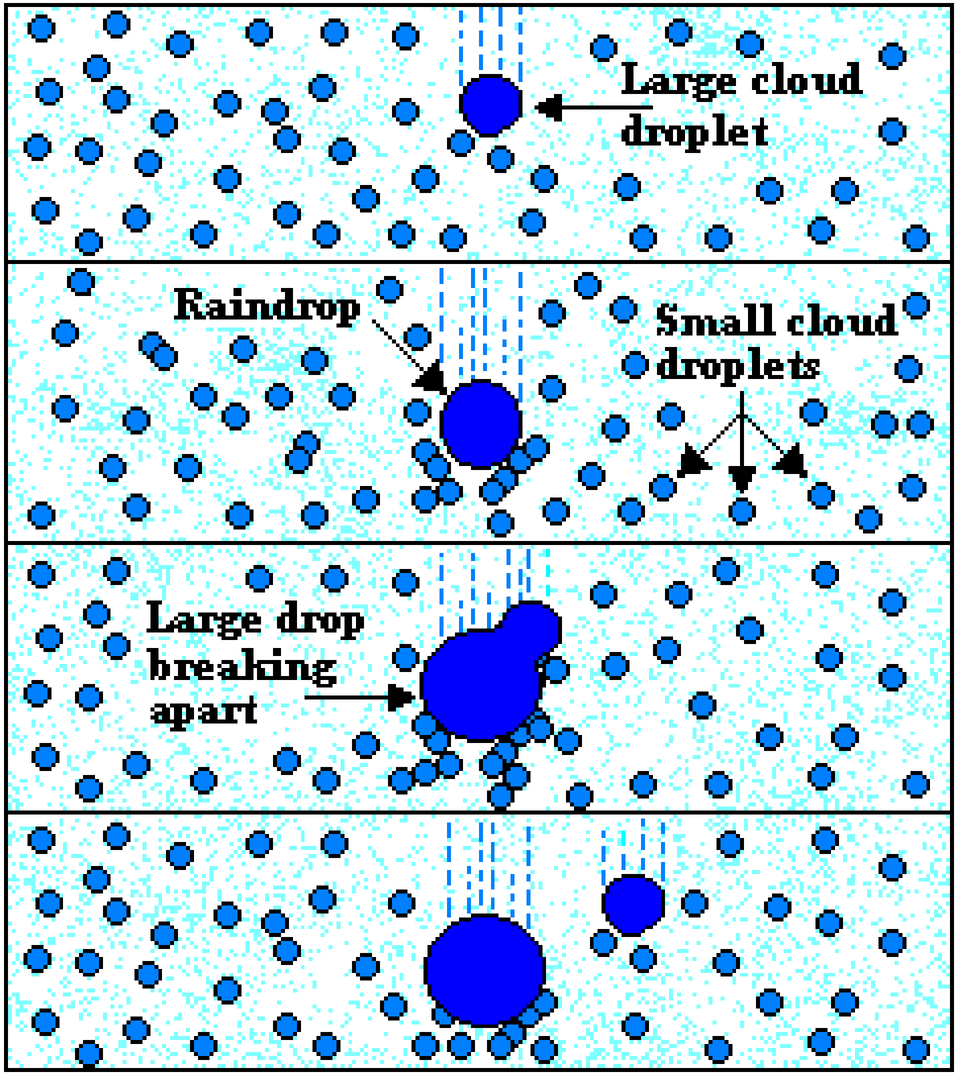


[Rosenfeld et al. 2002]

Collision-Coalescence Process

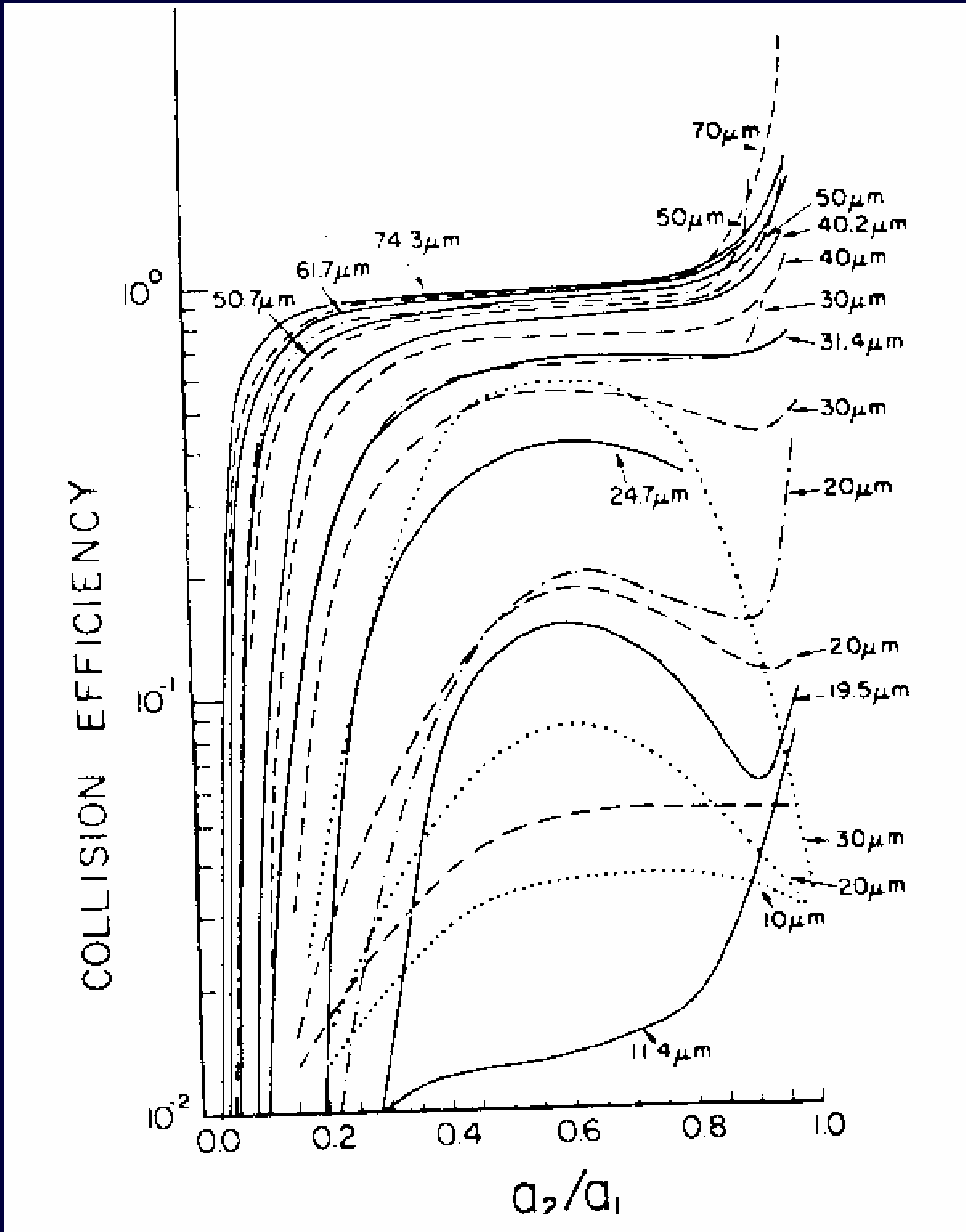
http://physics.uwstout.edu/wx/Notes/ch5notes.htm



Collision-coalescence process

Warm Rain Formation

Collision efficiencies of water droplets of different size by gravitational settling



[Pruppacher and Klett, 1997]

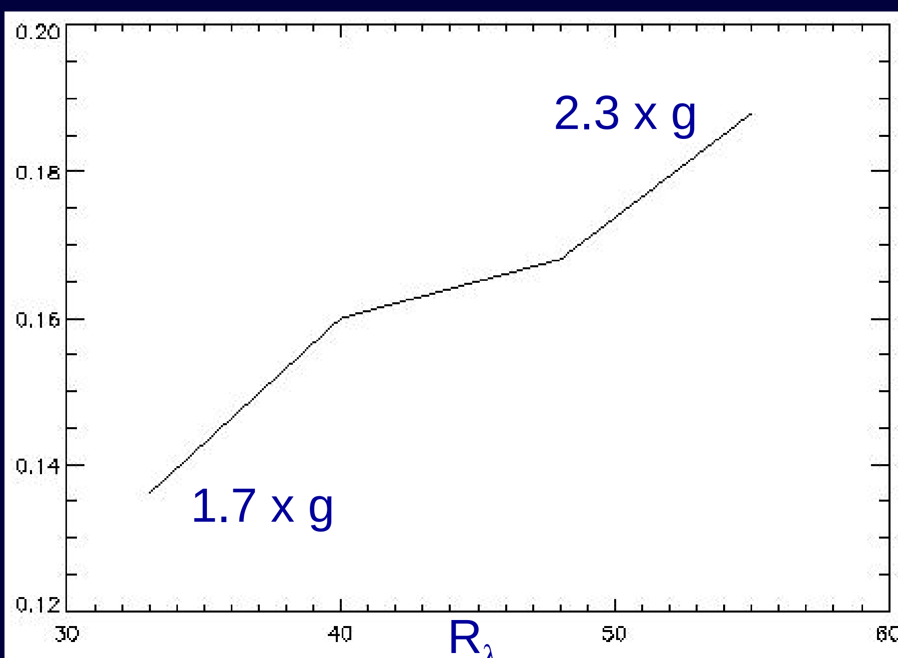
Turbulent Collision Efficiencies

[Charmaine Franklin et al. 2003]

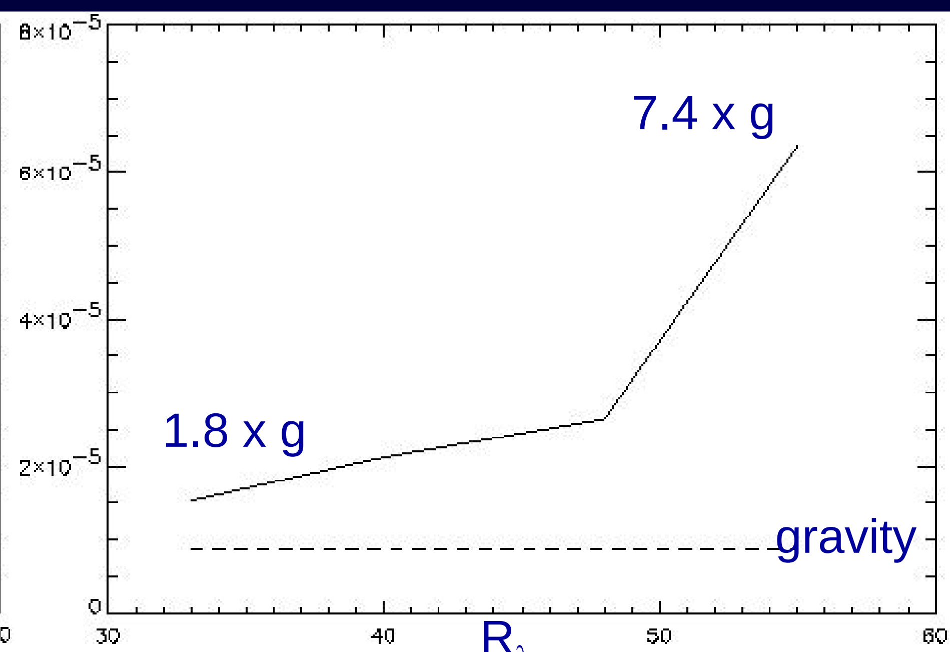
Separation distance = 0.04 cm

E(gravitational) = 0.08 (theoretical values 0.03 – 0.11)

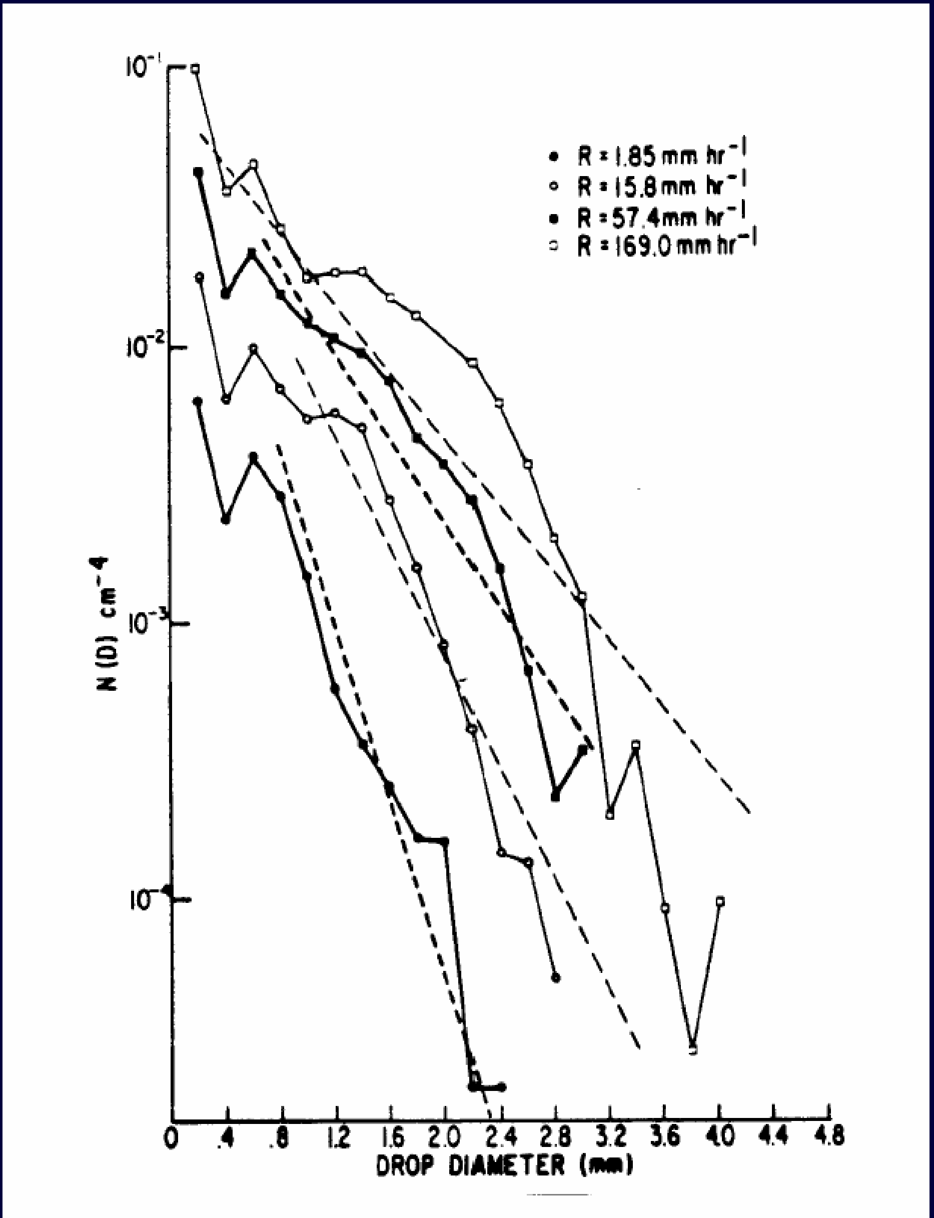
Collision Efficiency



Collision Kernel x Collision Efficiency

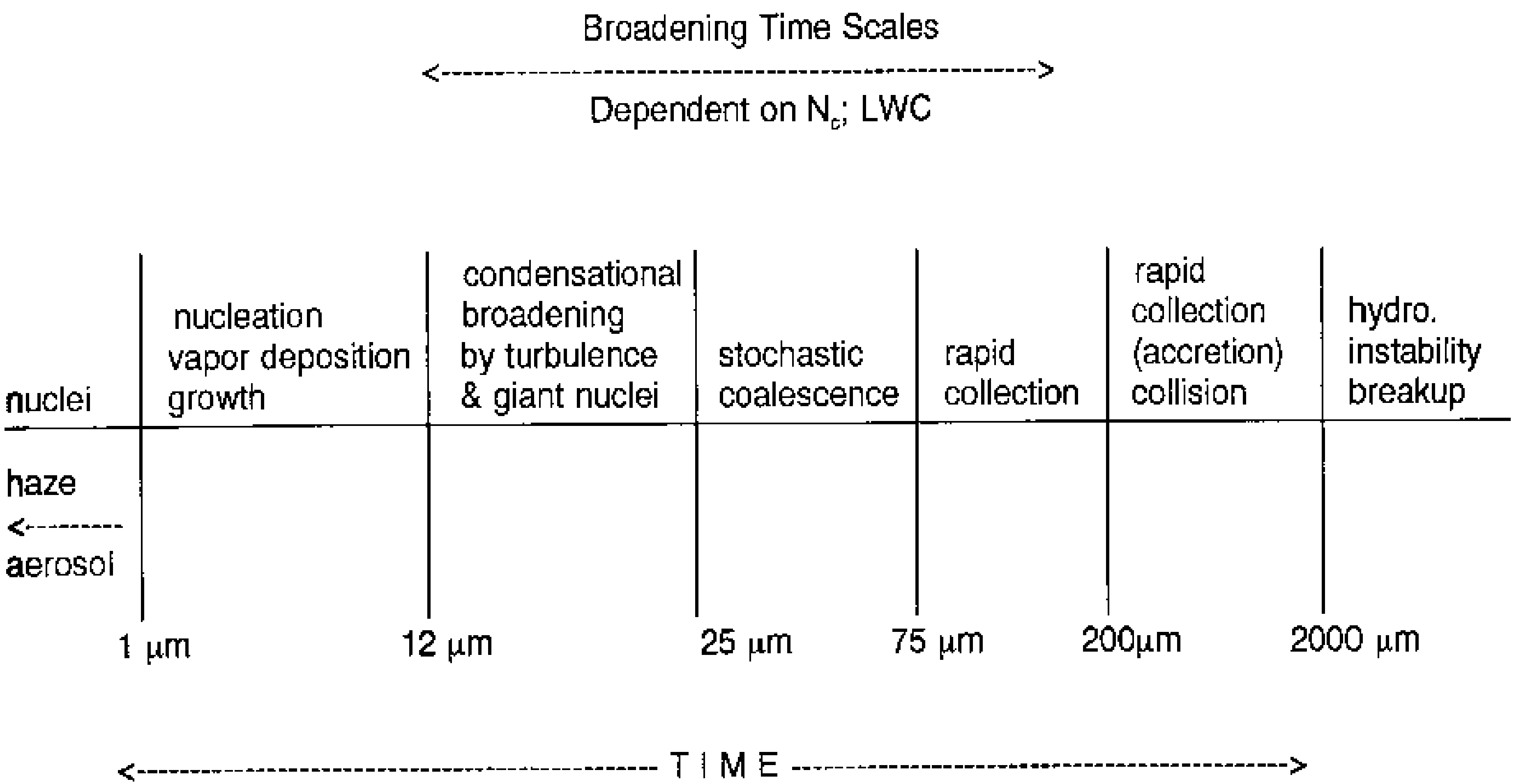


Rain Drop Spectra



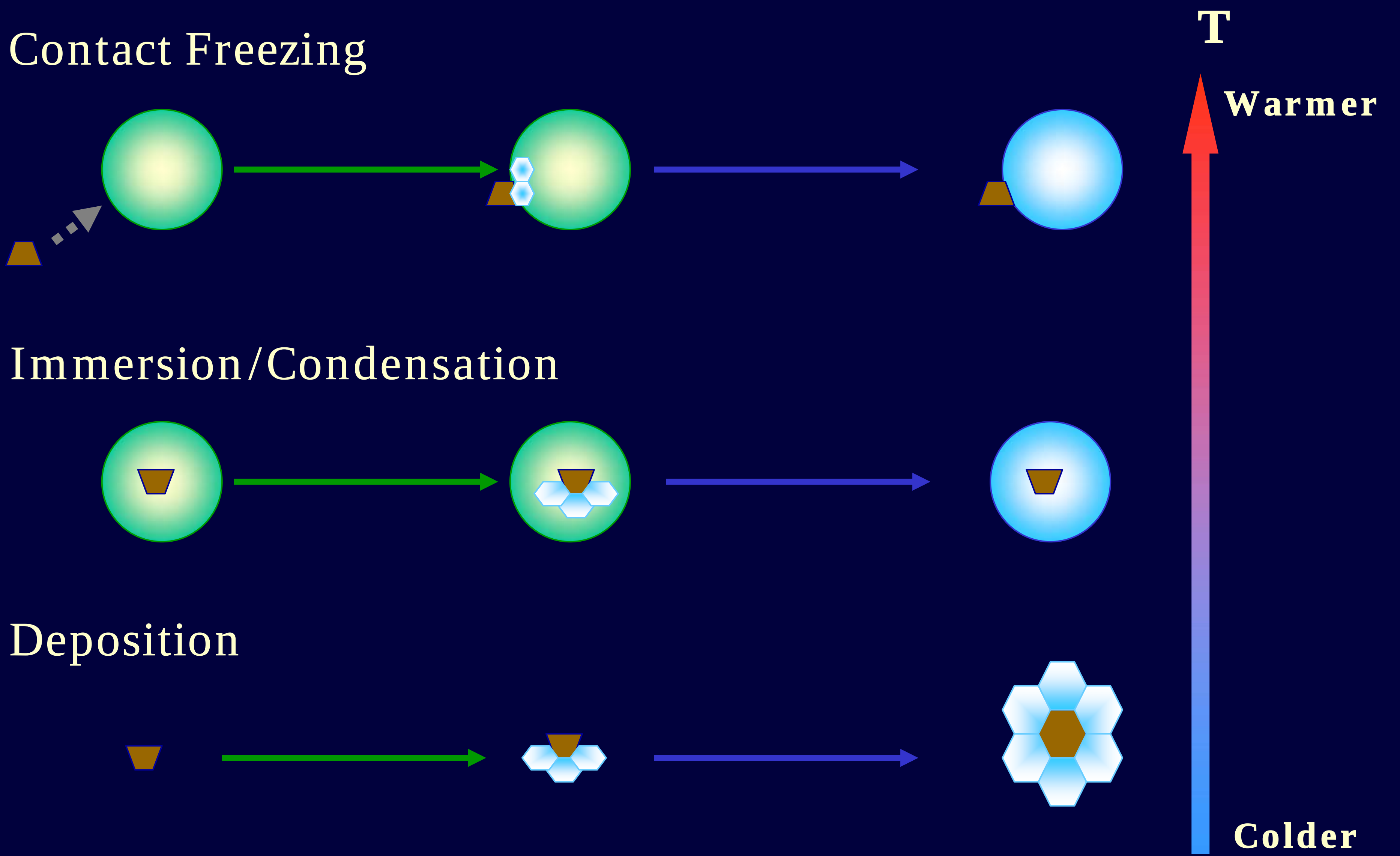
[Willis, 1984]

Warm Cloud Growth Regimes

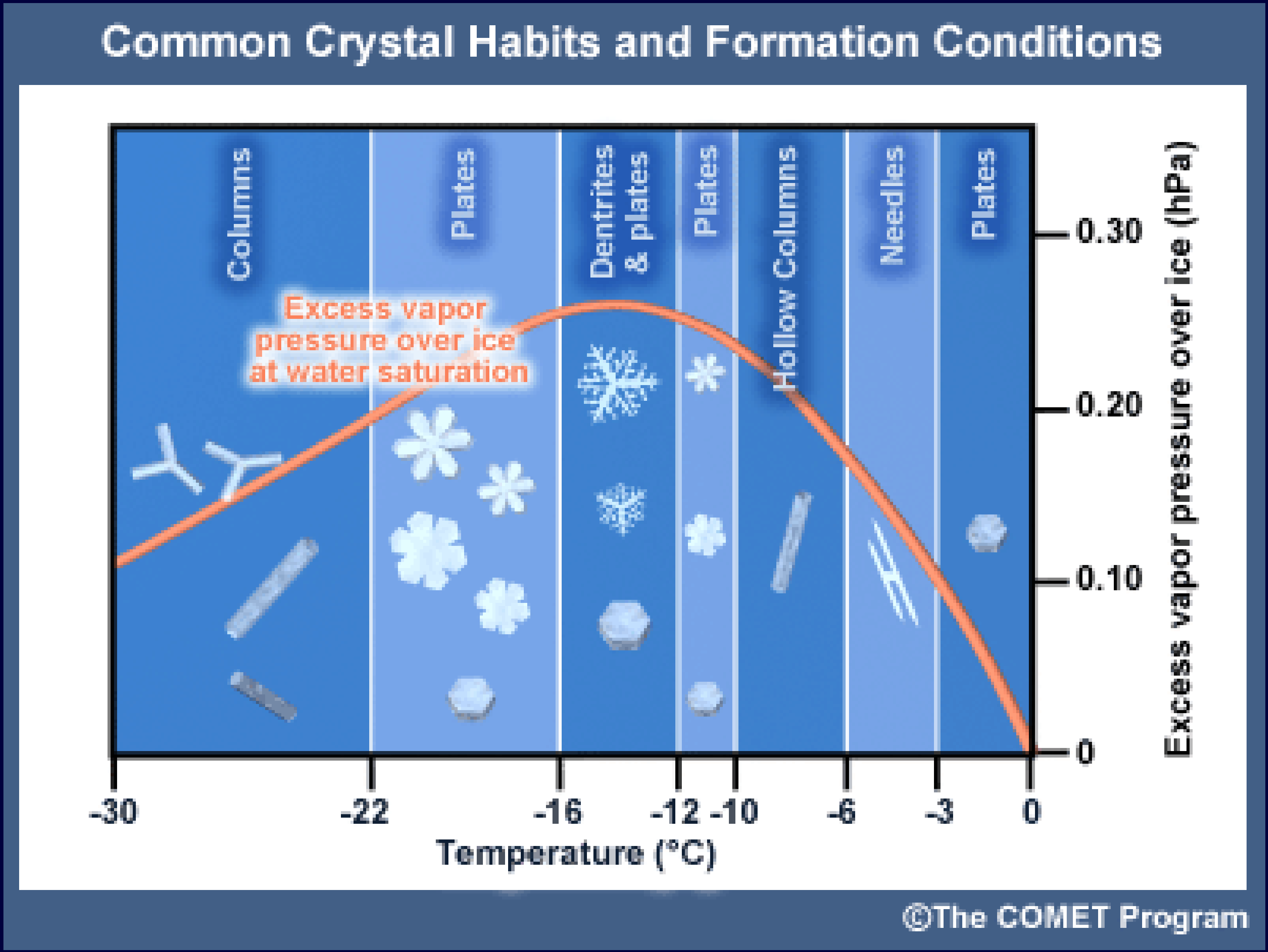


[Cotton, personal notes]

Different Ice Nucleation Mechanisms



Different Ice Nucleation Mechanisms



Requirements for Ice Nuclei (IN)

Insolubility: so that IN do not disintegrate under action of water

(mineral dust, black carbon)

Size: IN must be larger than > 0.1 μm, a critical ice embryo

(mineral dust)

Chemical bonds: complex organic molecules (aerobic bacteria) have hydrogen bonding groups similar to ice

(cholesterol)

Crystallographic resemblance to ice

(silver iodide AgI)

Active Sites: need pits and steps on ice nuclei

(dirty AgI works better for cloud seeding than clean AgI)

Ice Nuclei Concentration vs. Temperature

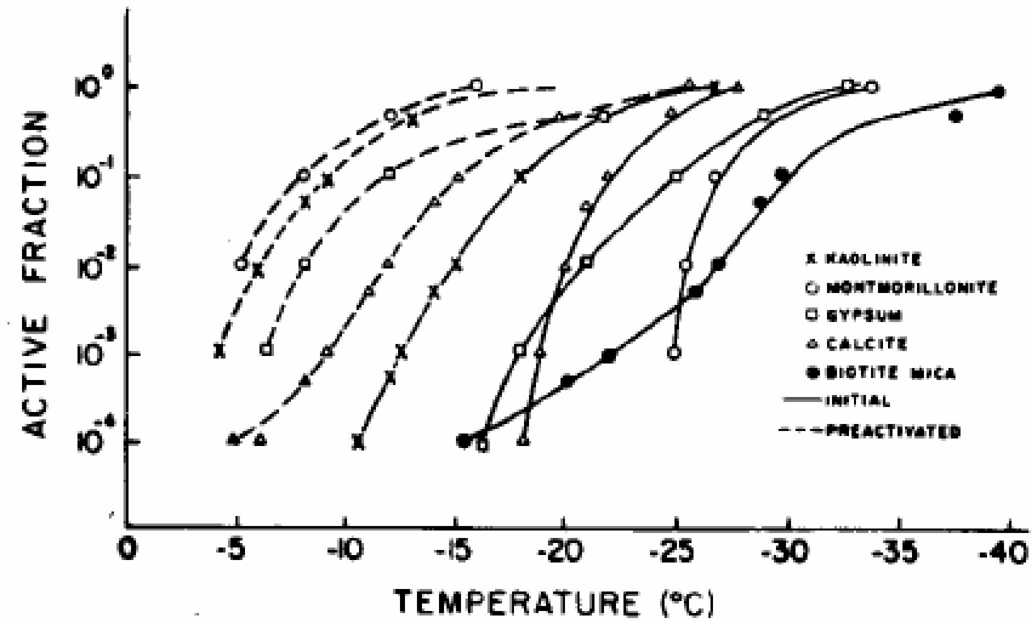


Figure 9.12: Variation of the ice nucleating ability of clay mineral particles with temperature: Initial ice nucleation ability and ice nucleation ability after pre-activation. (From Pruppacher and Klett, 1978)

Ice Nuclei Concentration vs. Size

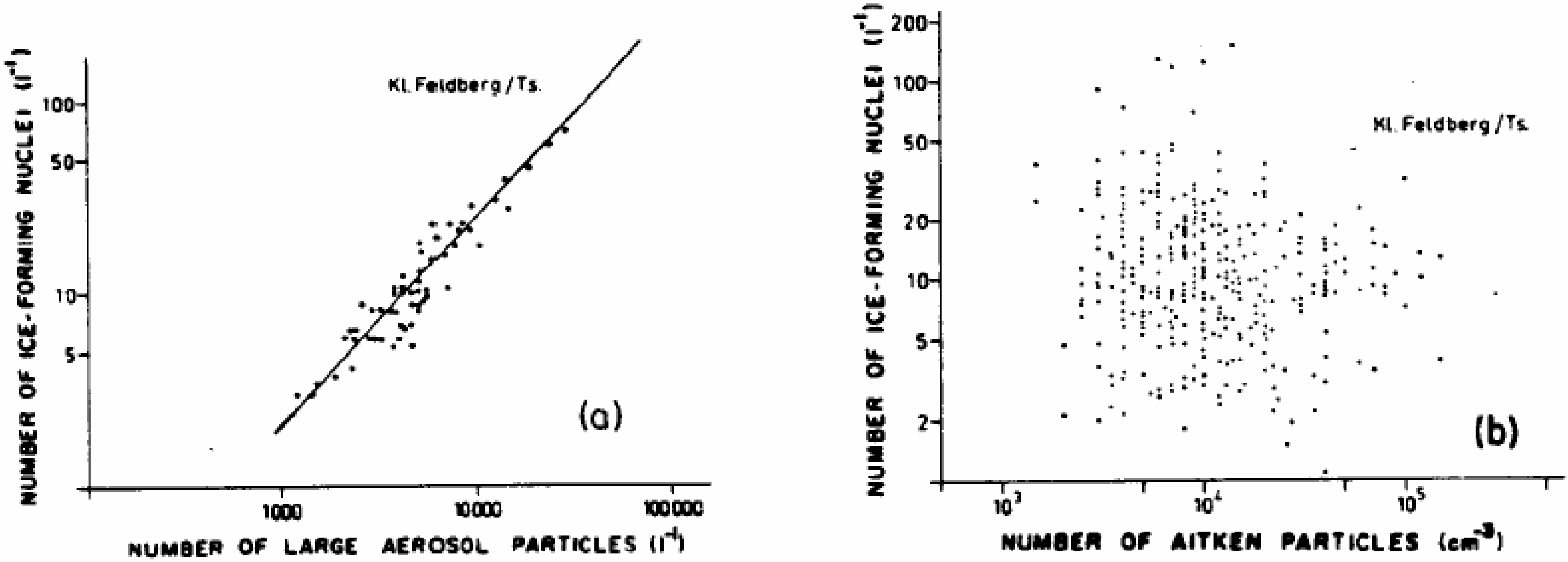


Figure 9.13: Relation between the concentration of IN and aerosol particles on Mt. Kleiner Feldberg/Taunus (Germany): (a) large aerosol particles, (b) Aitken particles. (From Georgii and Kleinjung, 1967; by courtesy of *J. de Rech. Atmos.*, and the authors.)

Clausius-Clapeyron Equation

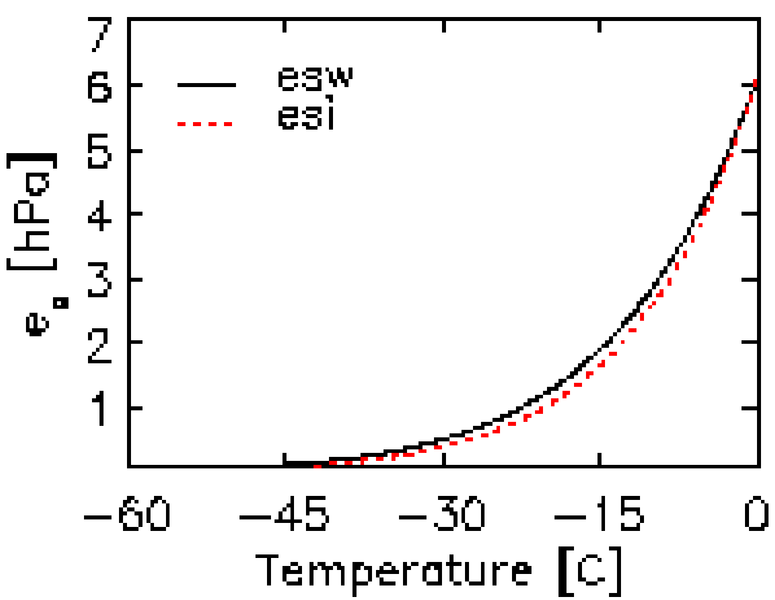
$$de_s/dT = L\,e_s^2/(R_v\,T^2)$$

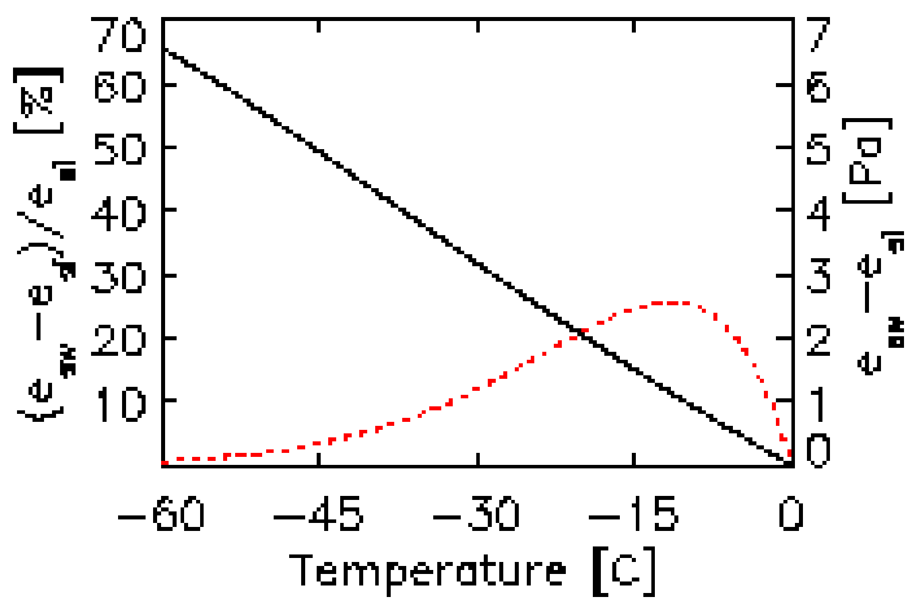
R_v = gas constant of water vapor

e_s = saturation vapor pressure over water/ice

L = latent heat of vaporization/sublimation

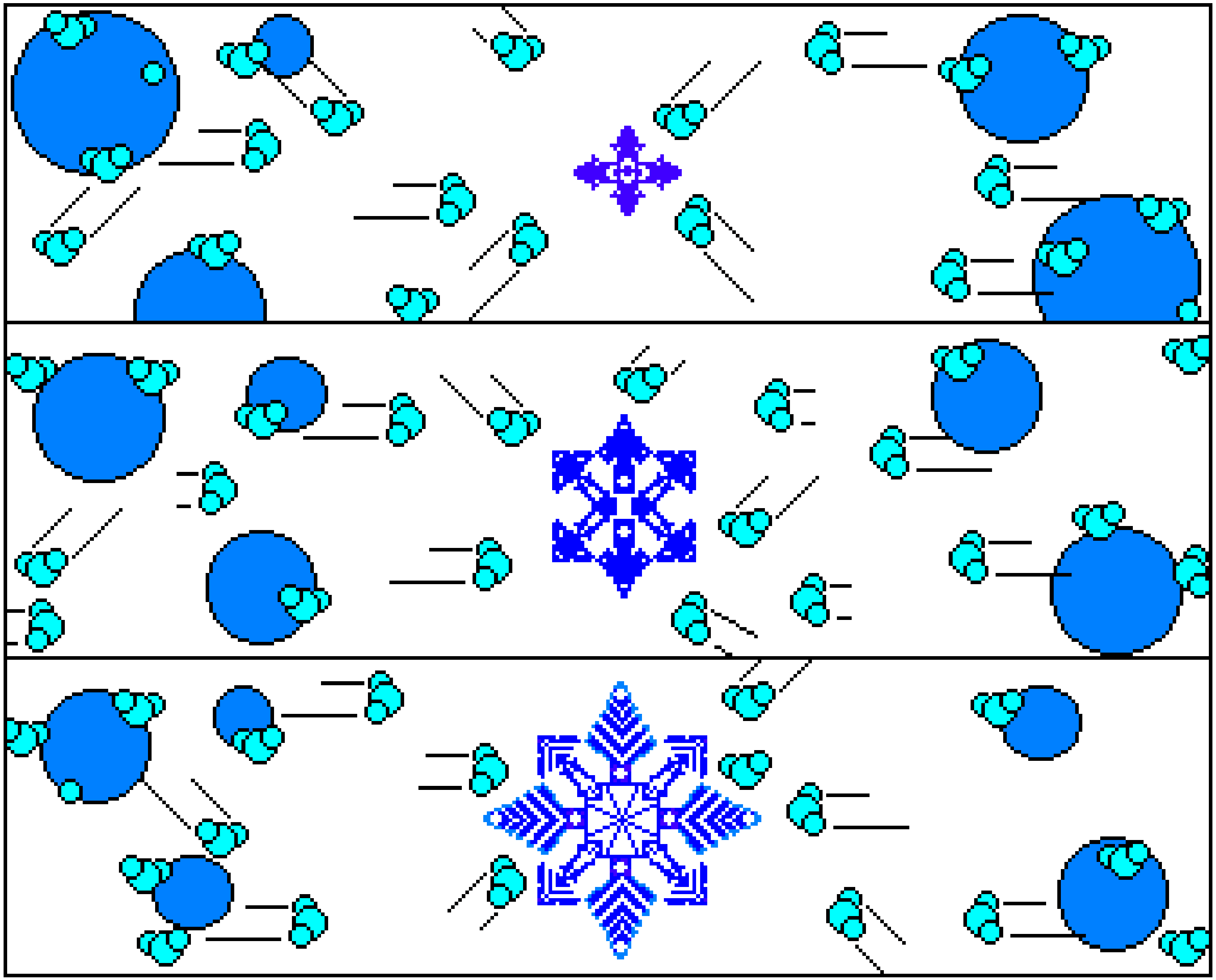
T = temperature





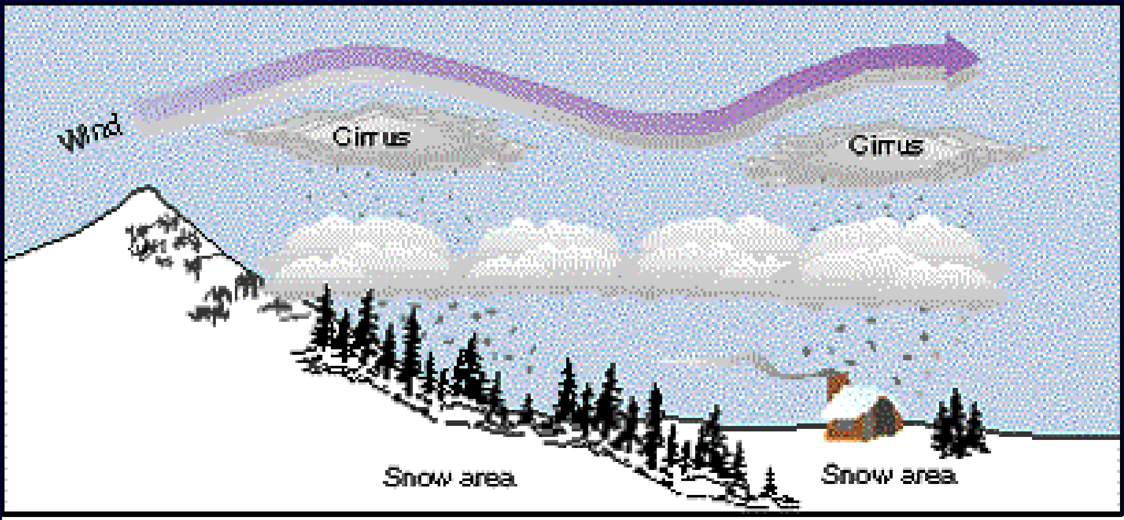
Bergeron-Findeisen Process

http://physics.uwstout.edu/wx/Notes/ch5notes.htm



Bergeron process

Seeder-Feeder Process



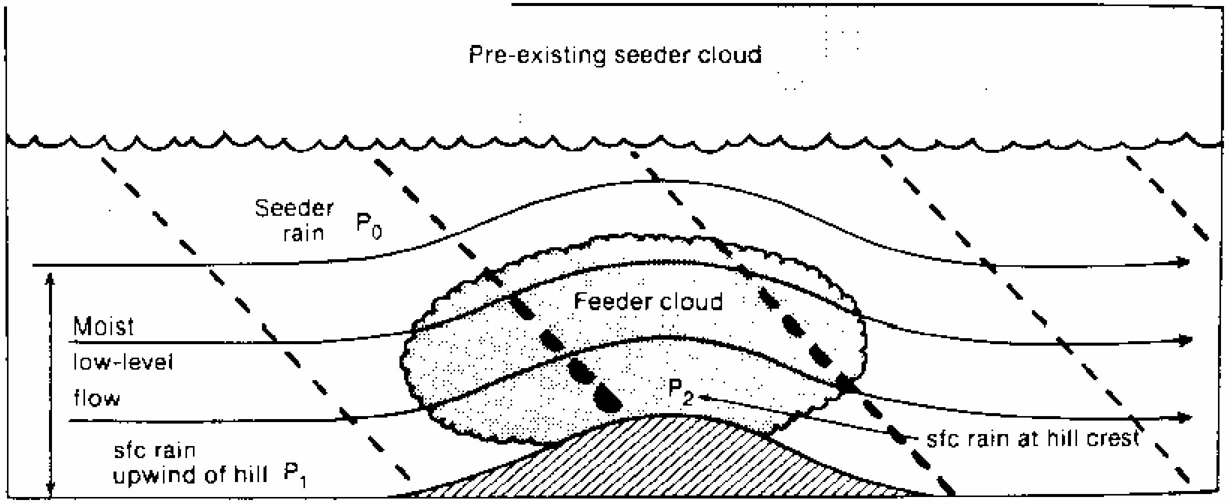
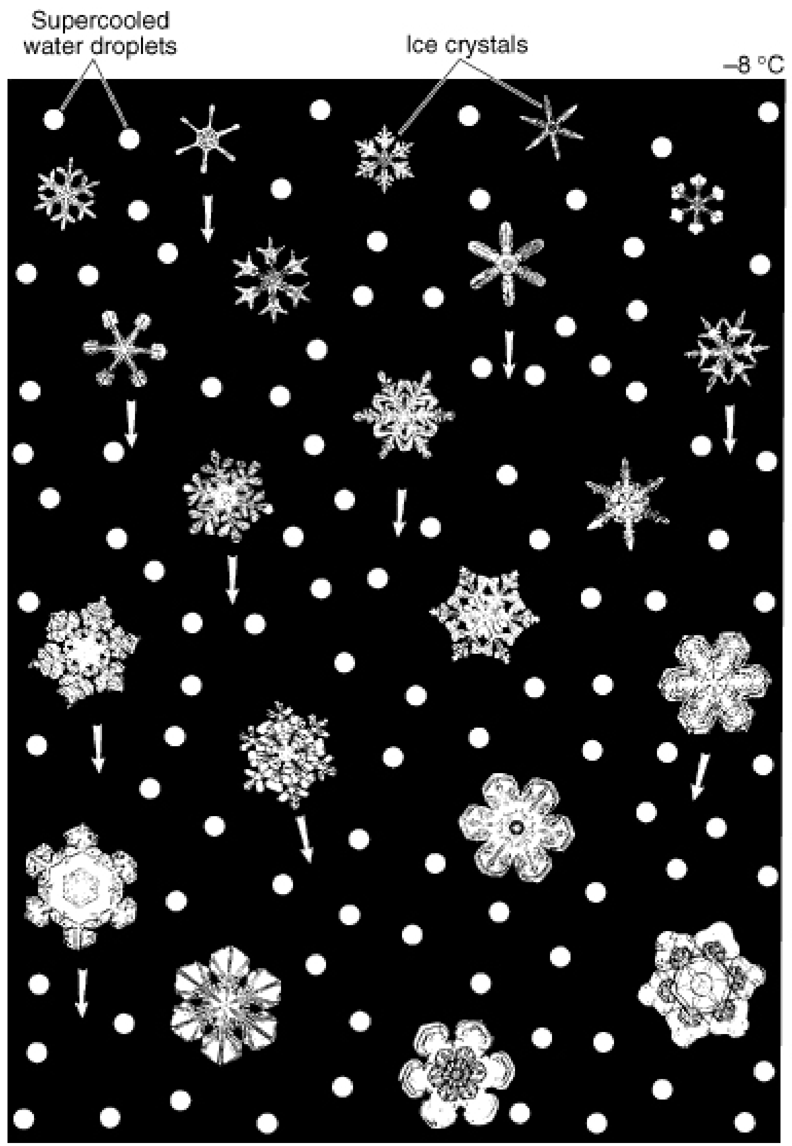


Figure 10.31: Conceptual model illustrating the orographic enhancement of rain. [From Browning's 1979 adaptation of Bergeron's 1965 figure.]

Mixed Phase Cloud

www.usd.edu/esci/figures



Summary of Cloud Microphysical Processes

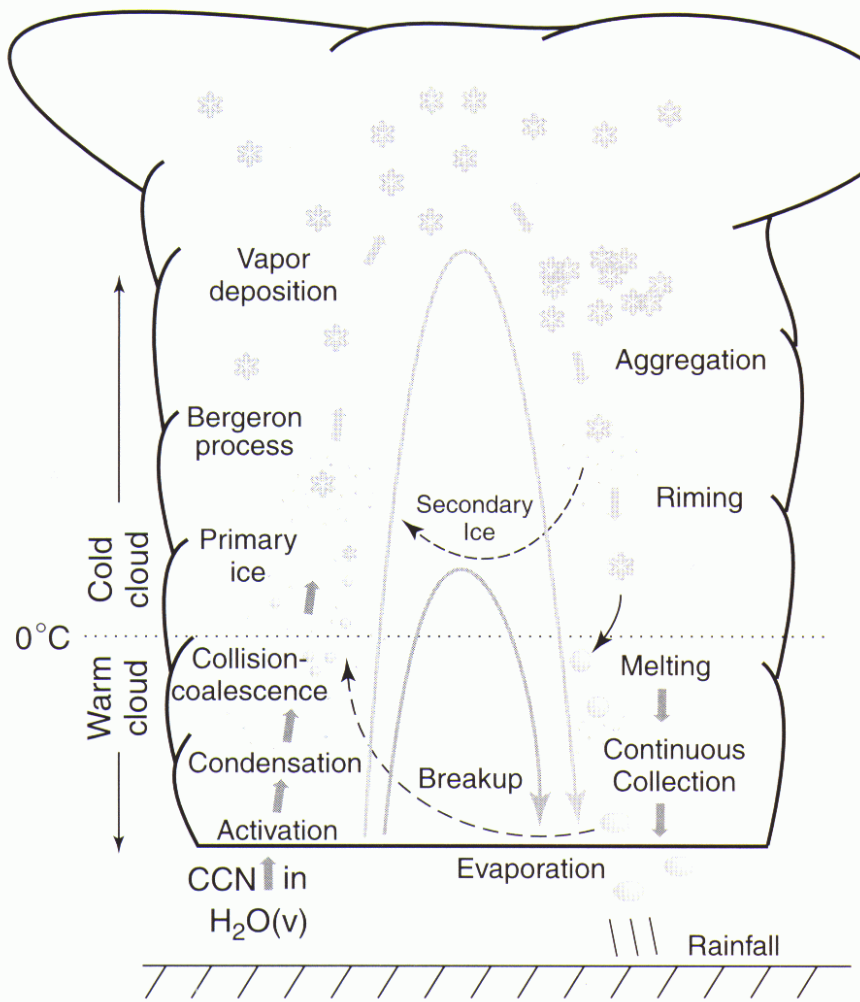


Figure 7 Summary depiction of the microphysical processes operating during the formation of precipitation in a deep convective cloud.

[Encyclopedia of Atmospheric Sciences]