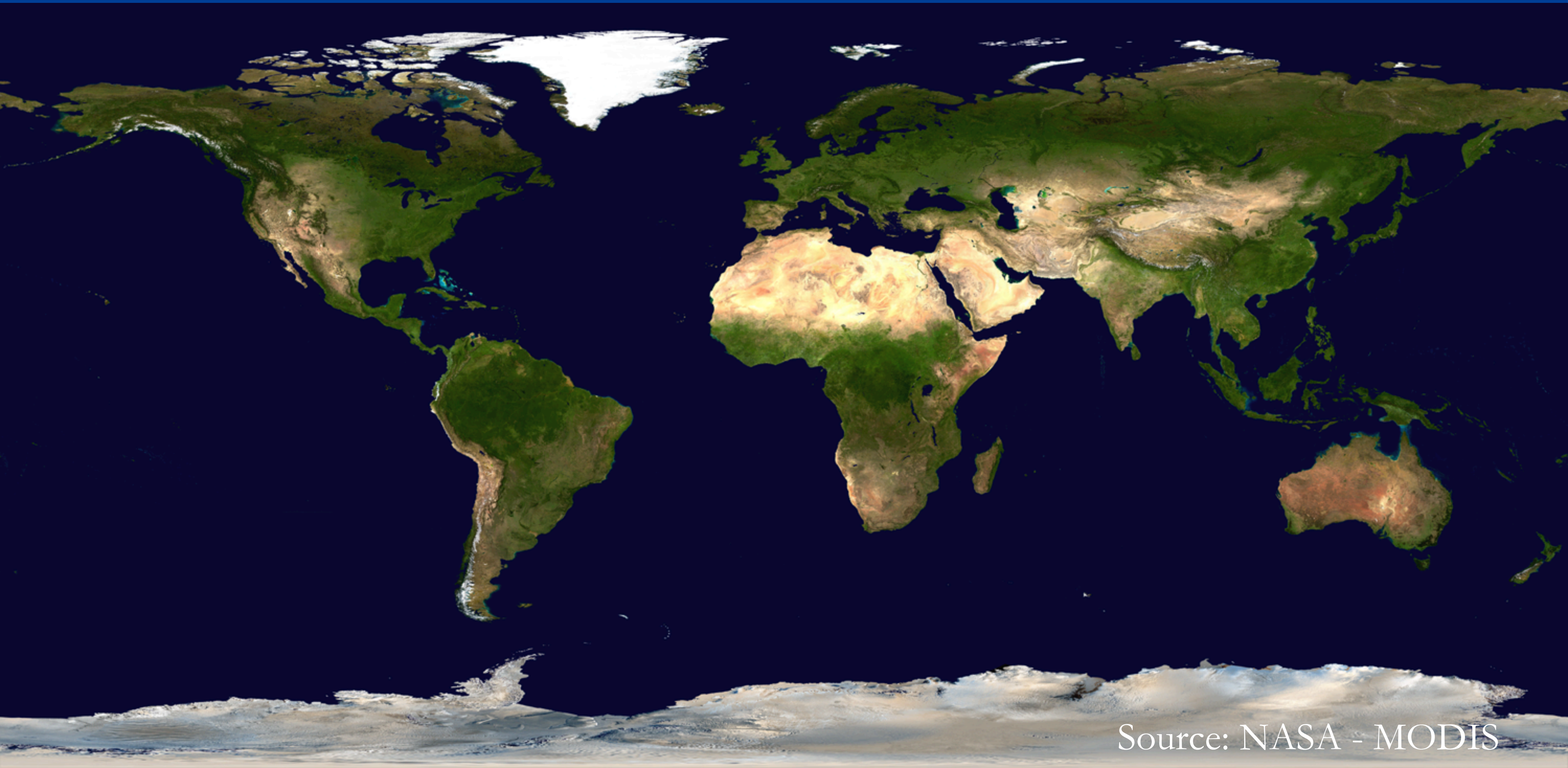
CLOUDS AND PRECIPITATION

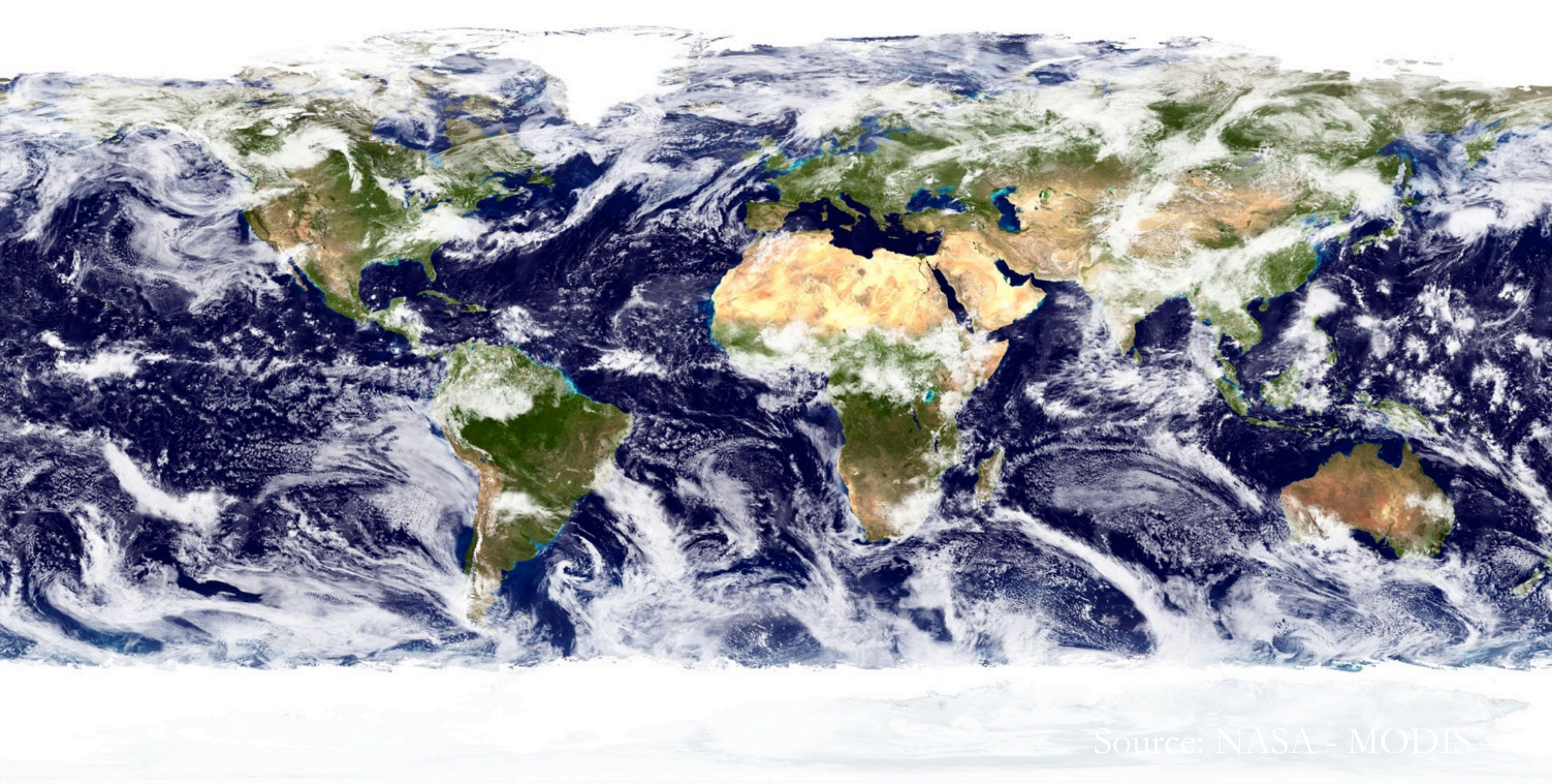
Something wrong with image?

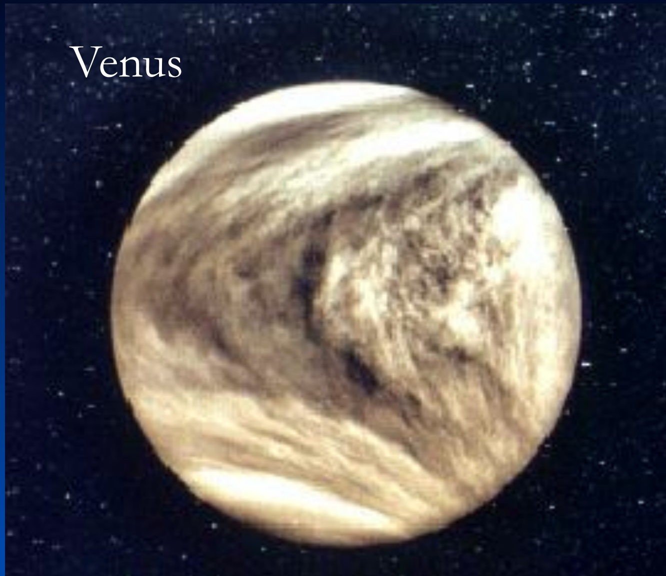


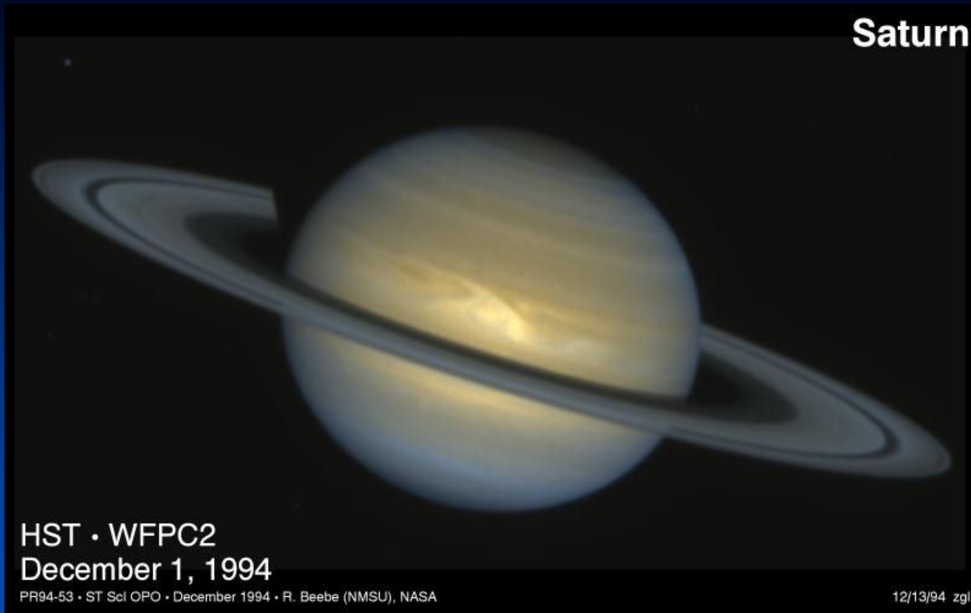
Source: NASA - MODIS

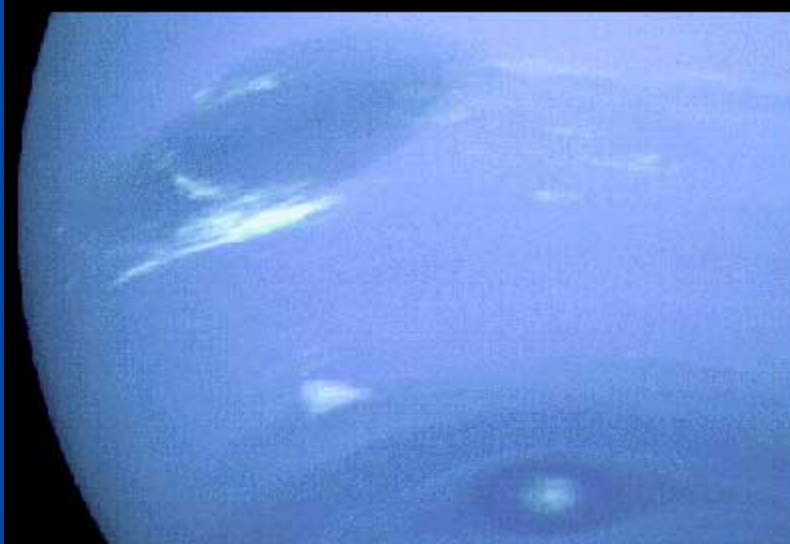
Something wrong with image?

At any time some 40 % of the Earth is covered with clouds









Cirrus clouds on Neptune

Long time ago........

"says…the clouds are formed by the sun's vapor [i.e. vapor caused by the heat from the sun's rays] raising and lifting them to the surrounding air"
Diogenes Laertius (A1.24-5).

"...(says that) things in the heavens occur through the heat of the sun as the initial cause; for when the moisture is drawn up from the sea, the sweet portion, separating because of its fineness and turning into mists, combines into clouds, trickled down in drops of rain due to compression, and vaporizes the winds."
Aëtius (A46)

"The sea is the source of water and of wind,
For without the great sea, there would be no wind
Nor streams of rivers, nor rainwater from on high
But the great sea is the begetter of clouds, winds, and rivers."
Xenophanes B30

The Pythagorean philosopher Hippon (5th century BC) recognizes that all waters originate from the sea.

Anaxagoras, who lived in Athens (500-428 BC) and together with Empedocles, is recognized as the father of experimental research, clarified the concept of hydrological cycle: the sun raises water from the sea into the atmosphere, from where it falls as rain; then it is collected underground and feeds the flow of rivers. He also studied several meteorological phenomena, generally supporting and completing

Anaximenes's theories; his theory about thunders, which fought the belief that they are thrown by Zeus, probably cost him imprisonment (430 BC). In particular, he correctly assumed that winds are caused from differences in the air density: the air, heated by the sun, moves towards the north pole and leaves gaps that cause air currents. He also studied Nile's floods attributing them to the snow melt in Ethiopia. The "enigma" of Nile's floods (which, contrary to the regime of Mediterranean rivers, occur in summer) was also thoroughly studied by Herodotus (480-430 BC), who seems to have clear knowledge of hydrological cycle and its mechanisms.

Aristotle (384-323 BC) in his treatise Mereorologica clearly states the principles of hydrological cycle, clarifying that water evaporates by the action of sun and forms vapor, whose condensation forms clouds; also, he recognizes indirectly the principle of mass conservation within hydrological cycle.
Theophrastus (372-287 BC) adopts and completes the theories of Anaximenes and Aristotle for the forming of precipitation from vapor condensation and freezing; his contribution to the understanding of the relation between wind and evaporation was significant.
Epicurus (341-270 BC) contributed to physical explanations of meteorological phenomena, contravening the superstitions of his era.

Archimedes (287-212 BC), among other significant contributions, founded hydrostatics introducing the principle named after him.
Hero of Alexandria (after 150 BC) is recognized (U.S. Committee on Opportunities in the Hydrological Sciences, 1992) as the first who formulated the discharge concept and made flow measurements.

Cloud classification

Luke Howard (1803)

Cumulus – vertical clouds
Stratus – layer clouds
Cirrus – fiber like cloud
Nimbus – rain clouds

→

Cumulonimbus
Cirrostratus
Stratocumulus

That which no hand can reach, no hand can clasp,
He first has gain'd, first held with mental grasp;
Defin'd the doubtful, fix'd its limit-line,
And nam'd it fitly -- Be the honor thine!
As clouds ascend, are folded, scatter, fall,
Let the world think of thee who taught it all.
(J.W.Goethe)

Observed Cloud Properties

We can learn a lot about clouds and the processes that make them by just using

our eyes!

Observed Cloud Properties

Cirrus uncius

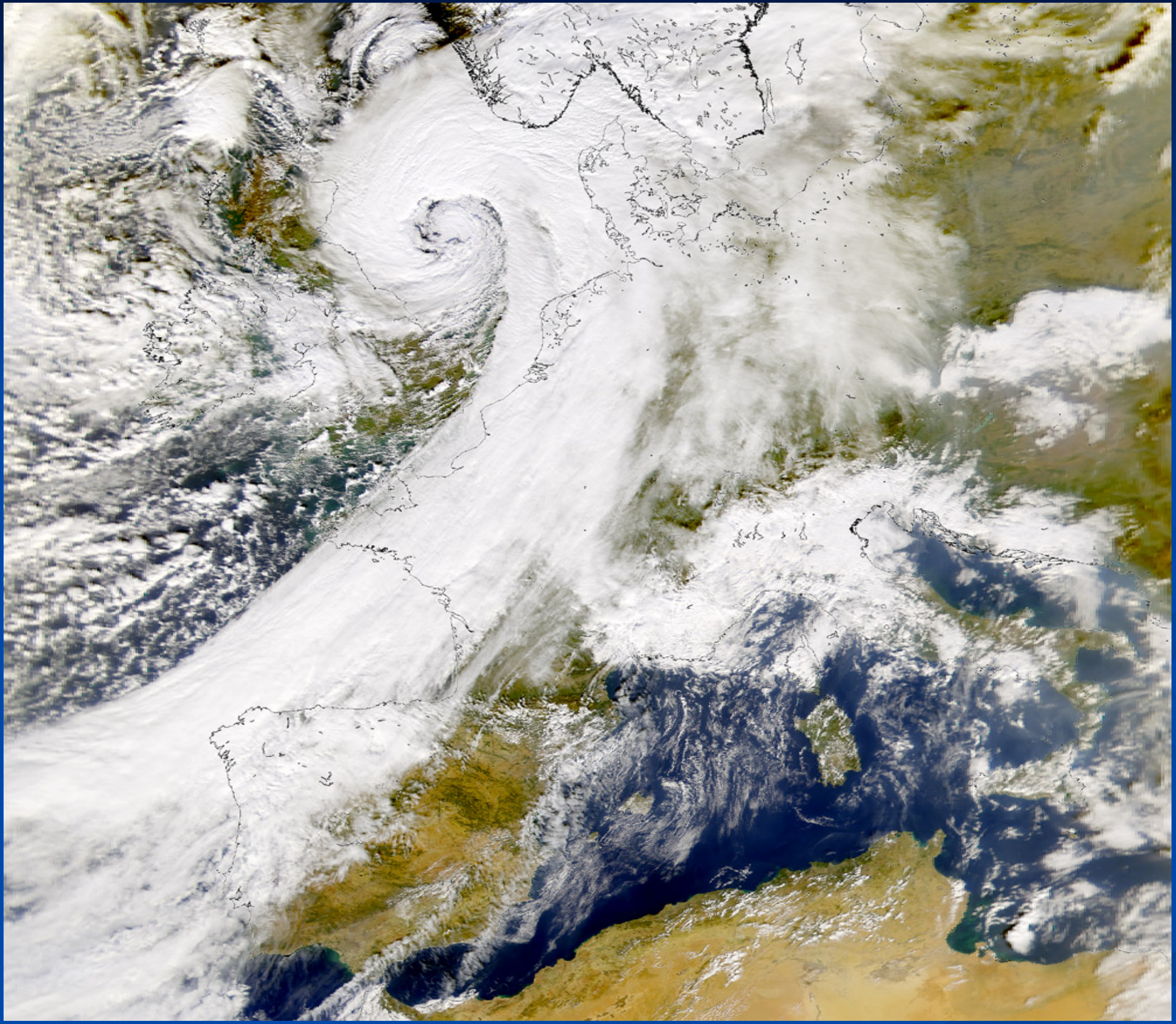
Observed Cloud Properties

Cumulonimbus

Observed Cloud Properties

NASA - EOS

Scale and size of cloud systems



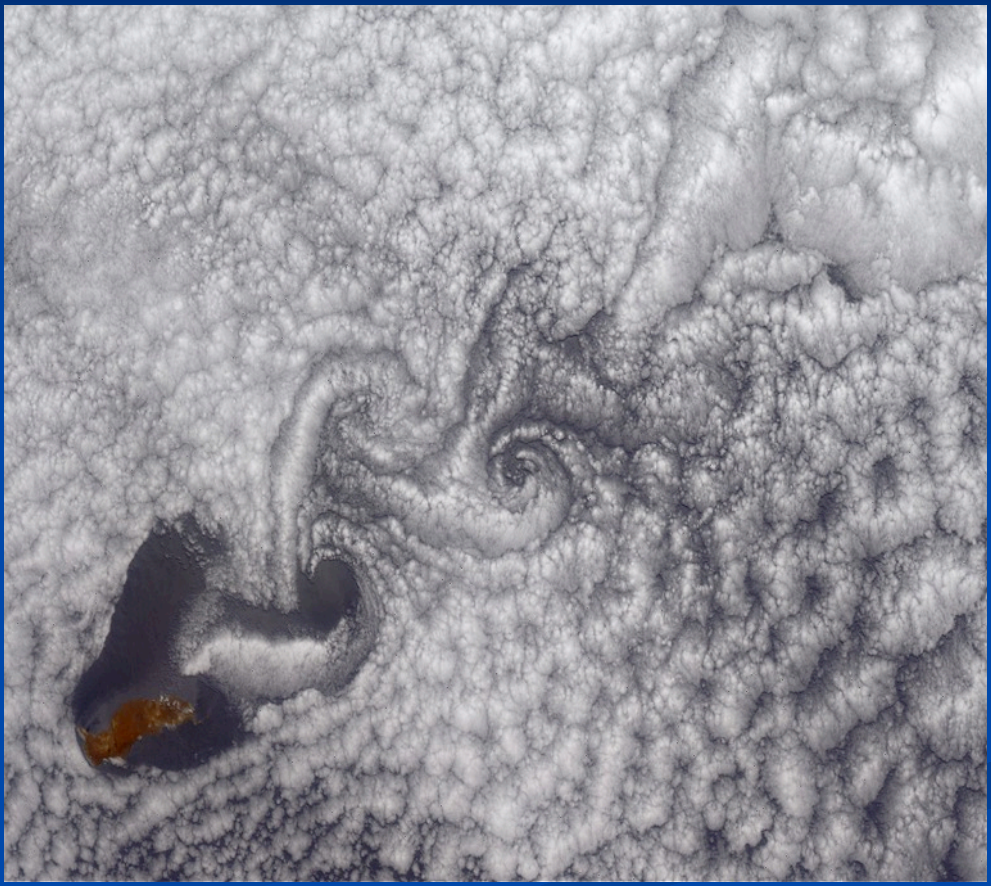
Superstorm over Great Britain – November 2000 (NASA-MODIS)

Why do we actually study clouds?

Clouds appearance is dominated by dynamics...........

Cloud formation is caused by dynamical processes:

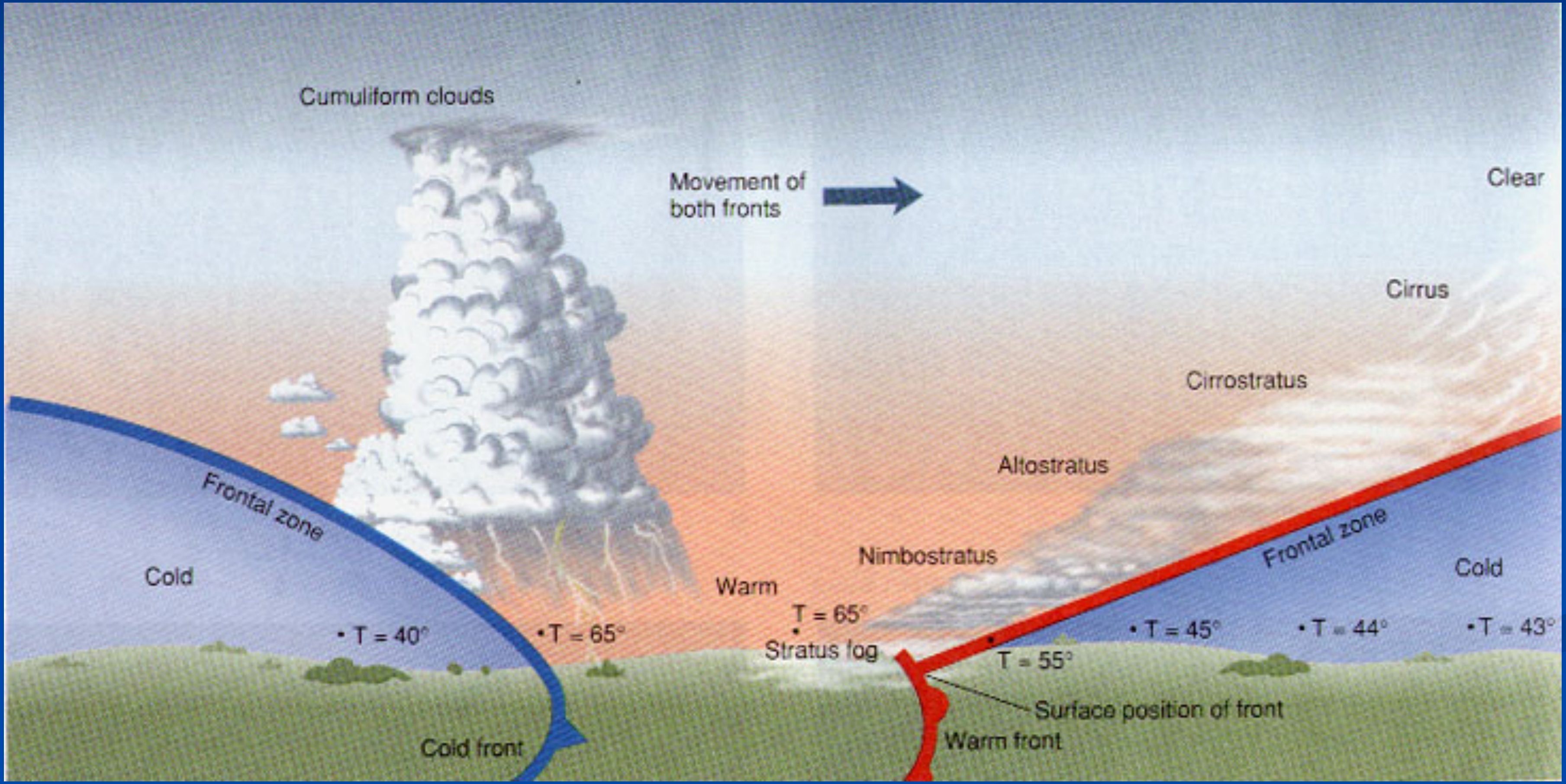
- Verical motions
- Convection
- Mixing of air masses
- stabilty of the atmosphere
- convergence
- fronts and cyclones



Von Kaarman vorticies behind Guadeloupe – ISS/NASA

Why do we actually study clouds?

Clouds appearance is dominated by dynamics...........



Why do we actually study clouds?

<u>but dynamics is influenced by clouds</u>

Redistribution of water and energy in the atmosphere (latent heat)

Modulating the Earth radiative balance

And by the way........

it will be pretty cold here without clouds

No rain and people will have big troubles to start unformal conversation with a stranger

Formation of Cloud Droplets

Small droplets are not formed at equlibrium saturation of bulk water.............

......due to free energy barrier it happens when relative humidity (RH) is several hundreds %. This process is called homogeneous nucleation and it is not important for atmopheric applications.

Hard to observe in our world......check wine bottle

Question: Why cloud droplets are formed in real atmosphere when just fraction of percent over equilibrium?

Answer: Because of aerosol particles present in the atmosphere. They are called Condensational Nuclei (CN) and formation process is heterogeneous nucleation

Nucleation process: Free energy barrier must be overcome
(vapor to liquid)
(liquid to ice)

Formation of Cloud Droplets

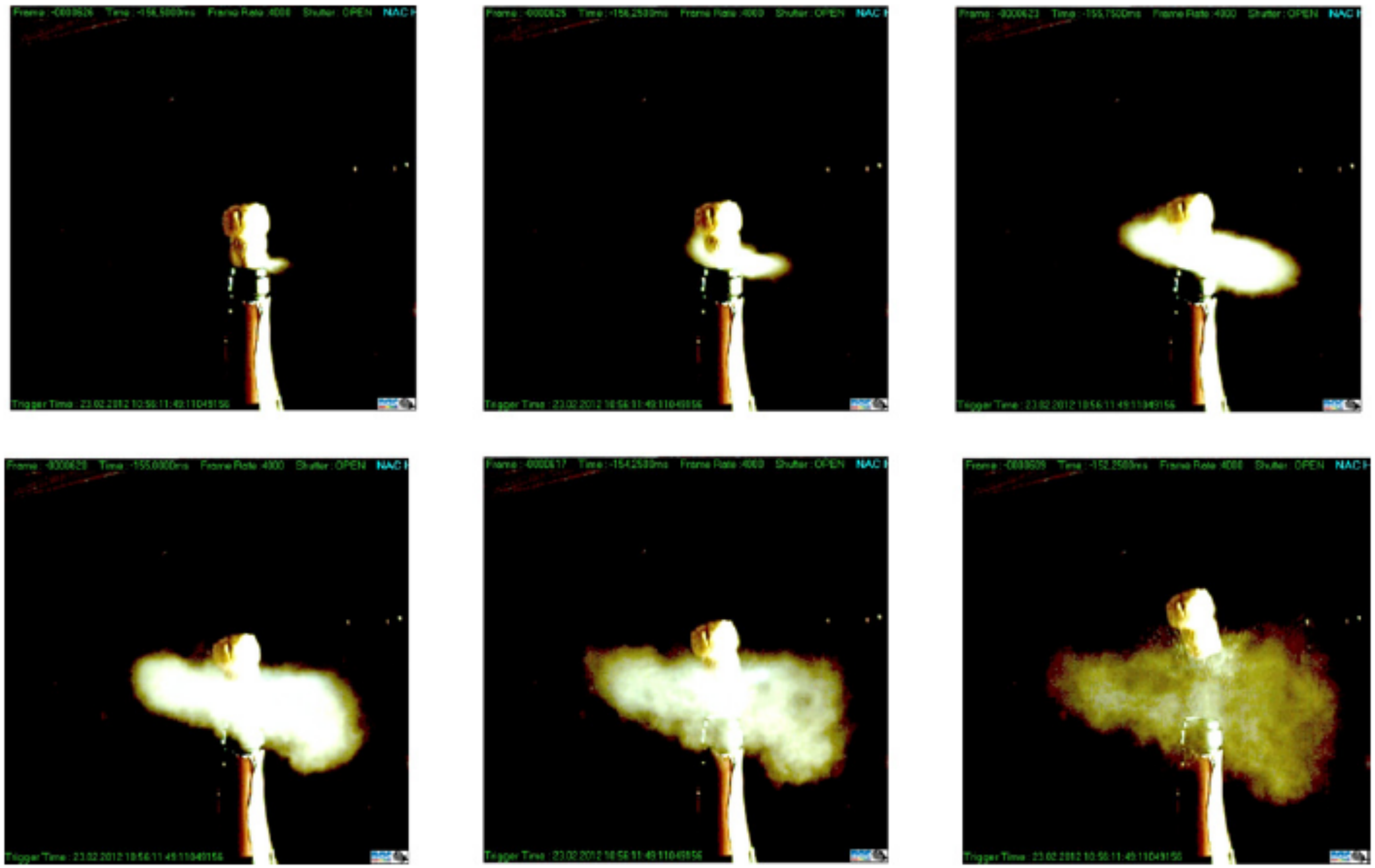


Figure 6. The condensation cloud observed for a few ms during adiabatic expansion of CO_2 upon opening of a bottle of champagne in air with relative humidity of around 70% (for details, see the text).

Vollmer and Mollmann, Phys. Edu. 2012

Formation of Cloud Droplets

Prior cloud formation, moist air is cooled in adiabatic ascent to saturation (RH=100%)

If adiabatic ascent continues, supersaturation is produced, but at the same time it is depleted by condensation on nuclei present in the atmosphere
(if RH = 101.5 %........supersaturation is 1.5%)

Usually there is enough nuclei in the atmosphere to keep supersaturation below 1 %)

Formation of Ice crystals

If the ascent continues and ambiet temperature below 0oC is reached, cloud droplets become supercooled. (In case of pure water they can stay supercooled down to -40 C when spontaneous homogeneous freezing take place)

However, in case of ice nuclei presence, the formation of ice crystals can start already at few degrees below zero (heterogenous freezing).

Supercooled droplets are usually observed down to -15 C

When ice crystals are present, they will grow on expense of water droplets as the equilibrium supersaturation over the ice is lower compared to liquid water.

Qualitative description of condensation in a rising air

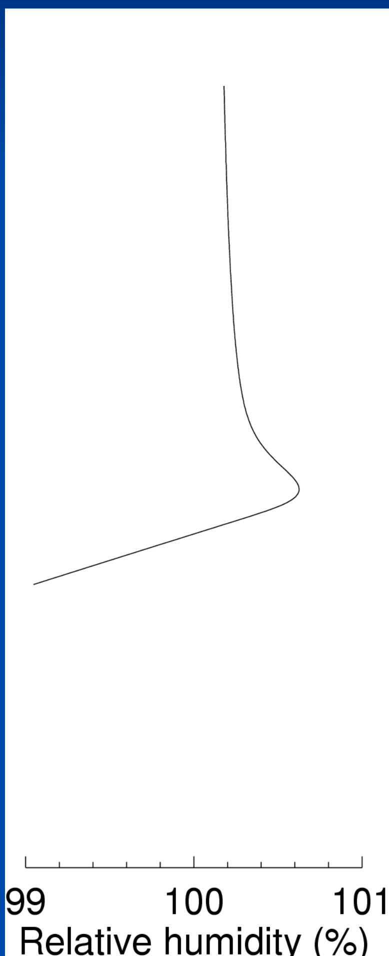
- As an initially unsaturated air parcel rises and expands approximately adiabatically, and the saturation ratio
  $S = (e_\infty / e_{s\infty})$ increases and nuclei swell.

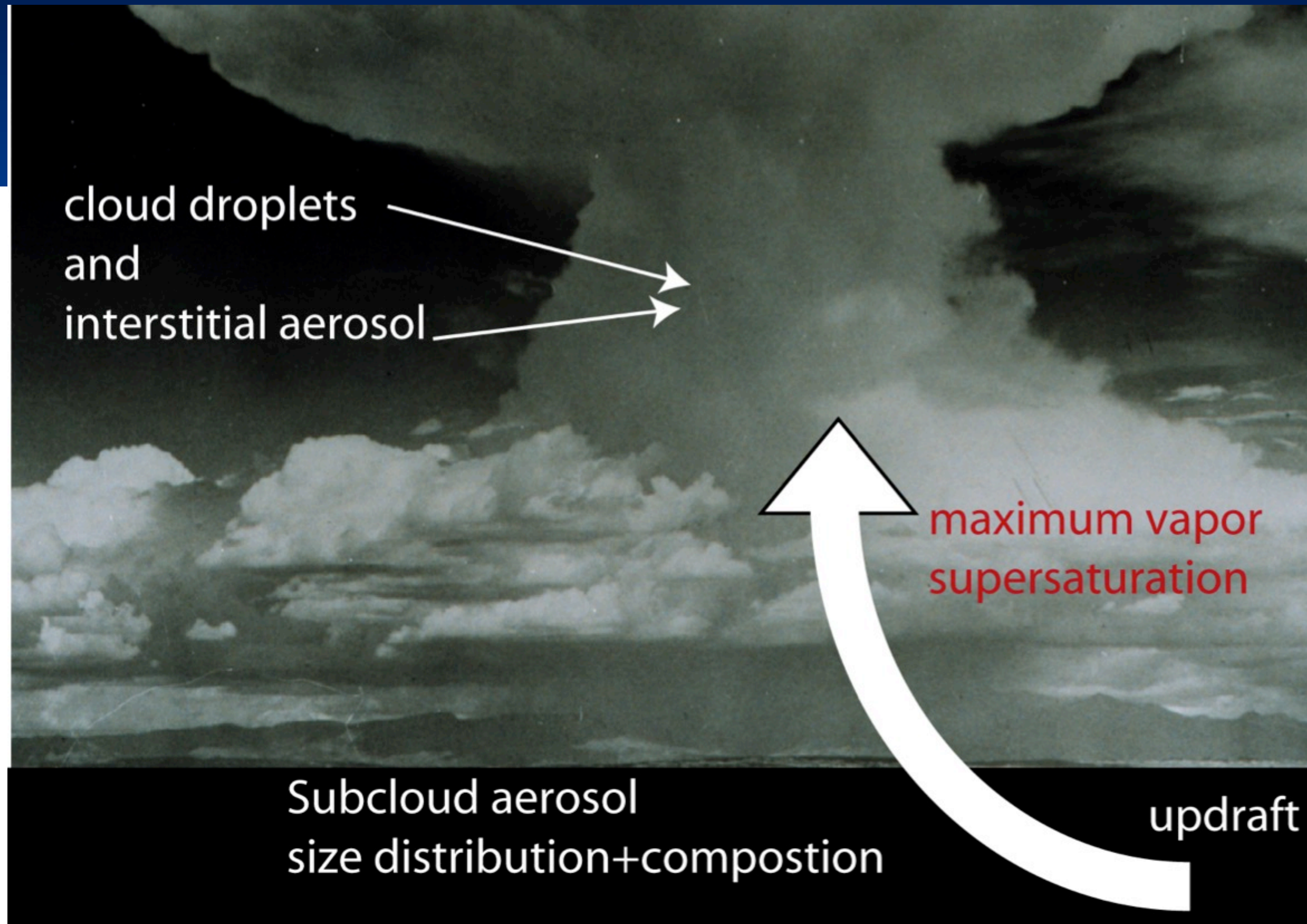
- After the saturation level (LCL) is reached, condensation begins to occur on the largest most active nuclei. Supersaturation results.

- S continues to increase and more and more nuclei are activated and begin to grow as droplets. However, the rate of increase in S is slower than above because the growing droplets are rapidly removing the excess water vapor from the parcel.

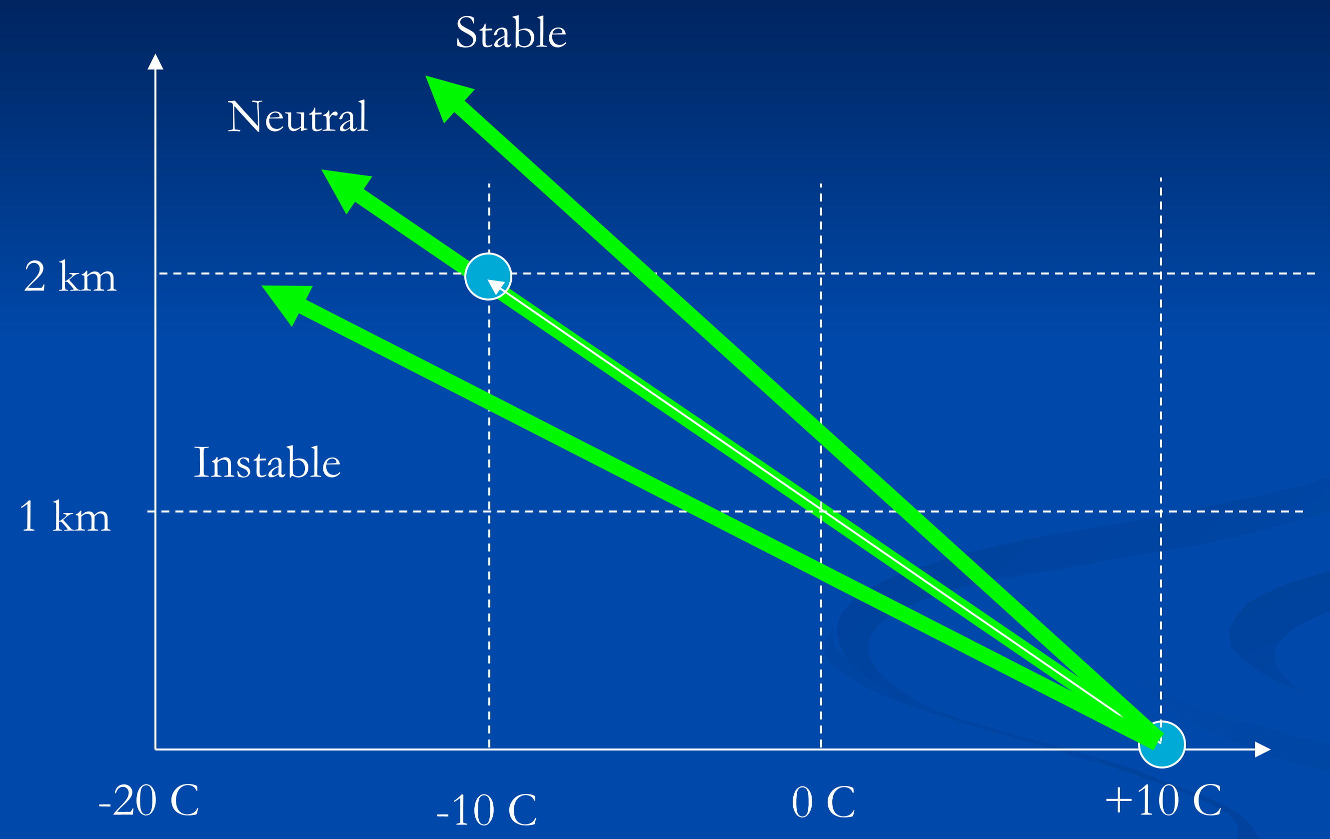
- Since the large droplets remove the water vapor more quickly than the smallest ones, the excess vapor is soon being removed from the air as fast as it is supplied from expansion. Then S decreases toward 1.

The formation of cloud droplets in updrafts





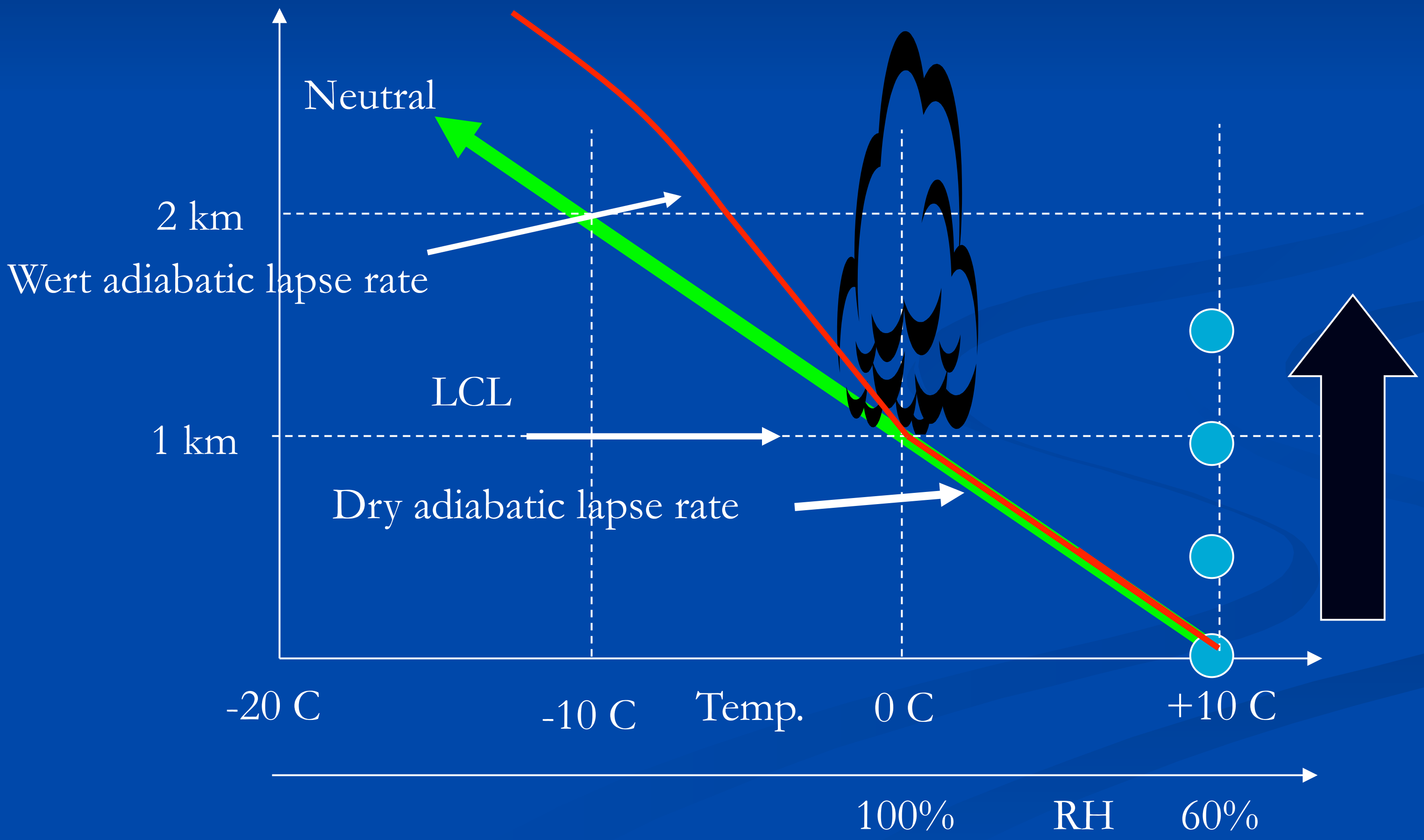
Dry adiabatic lapse rate (1°C/100m)



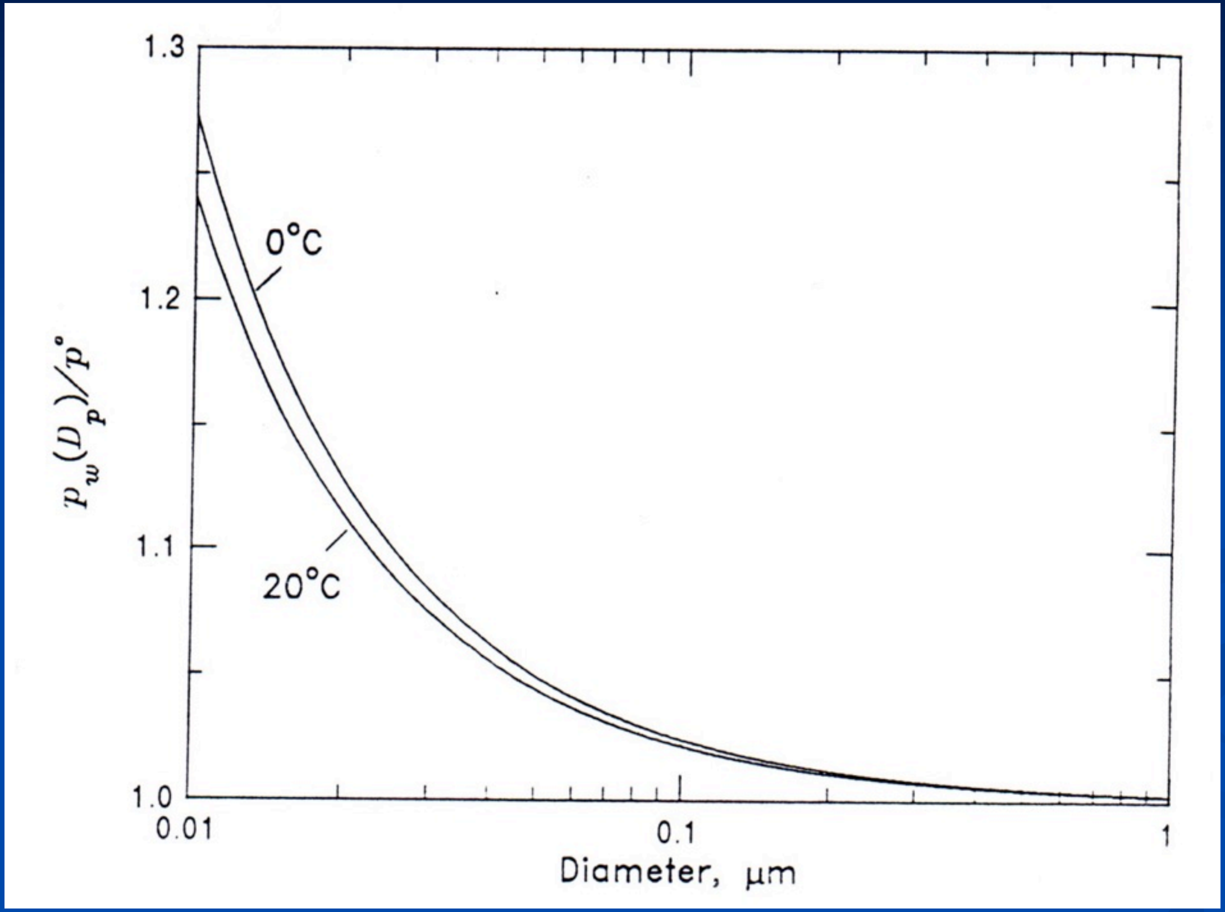
Temperature is decreasing with altitude approx. 1 K/100m when clouds are not formed

In average, the mean lapse rate in the troposphere is 0.65 K/100m

Liquid Condensation Level (LCL)



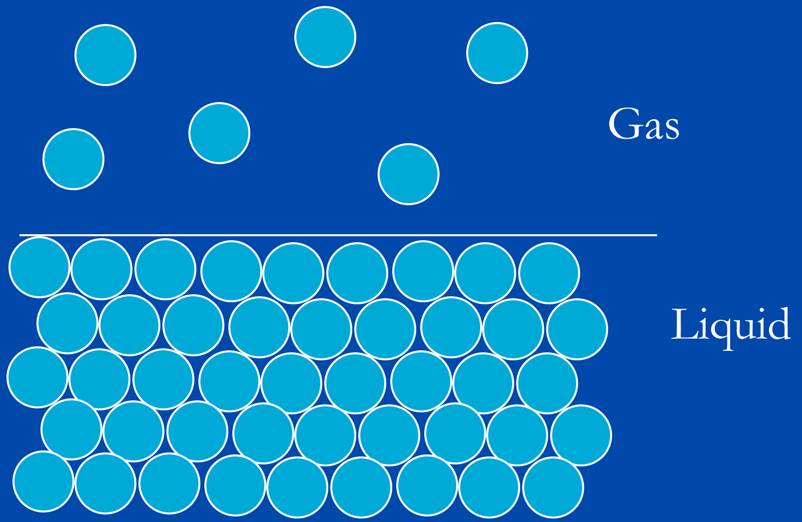
The *Kelvin* (curvature) effect 2

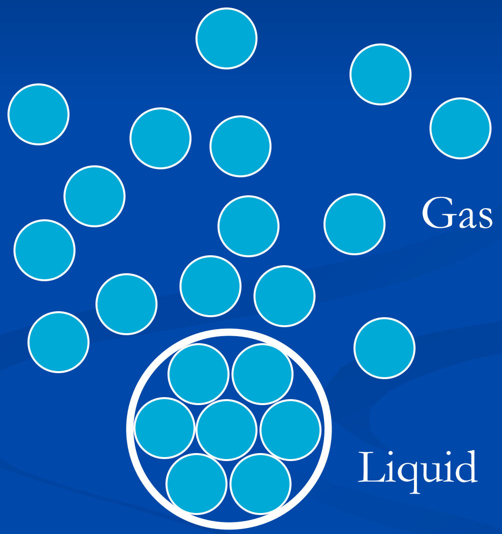


$$p(r) = p(\infty)\exp\left(\frac{2\sigma M_w}{rR\rho_w T}\right)$$

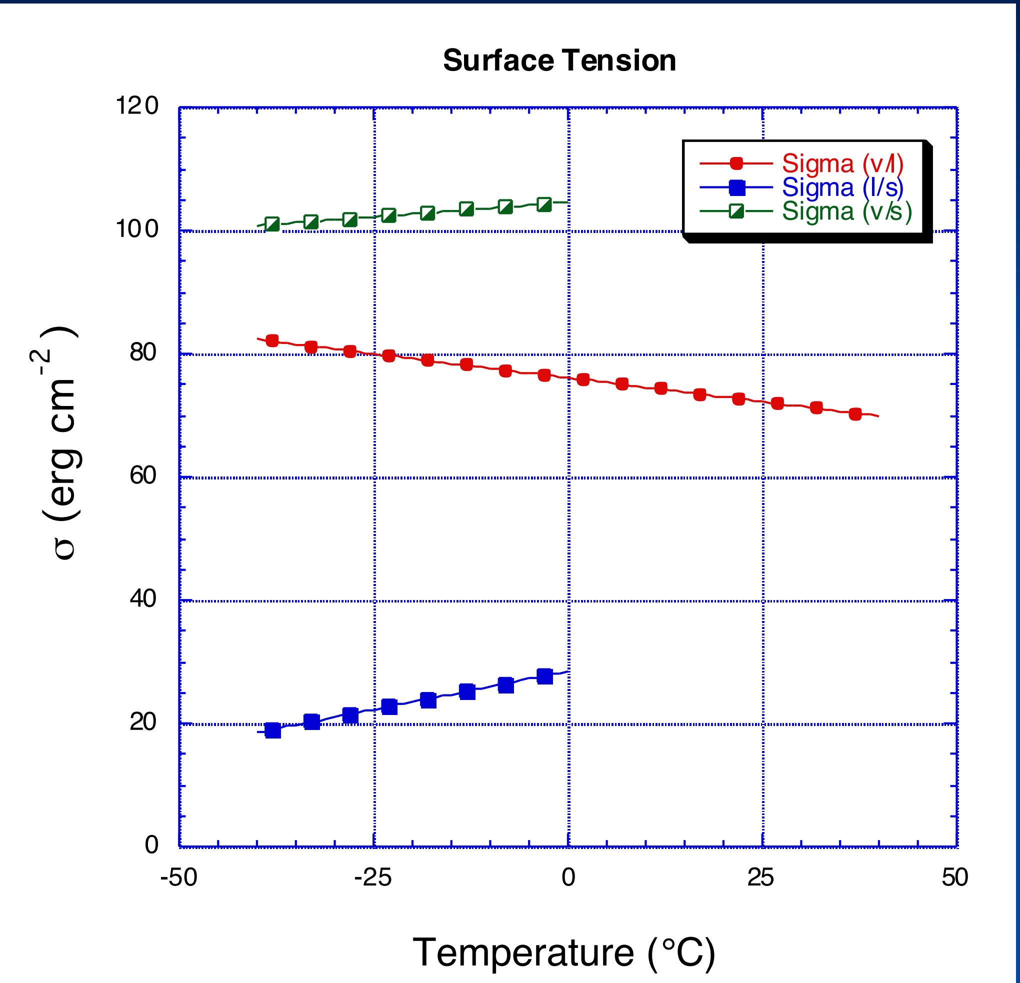
Seinfeld & Pandis Fig. 15.2

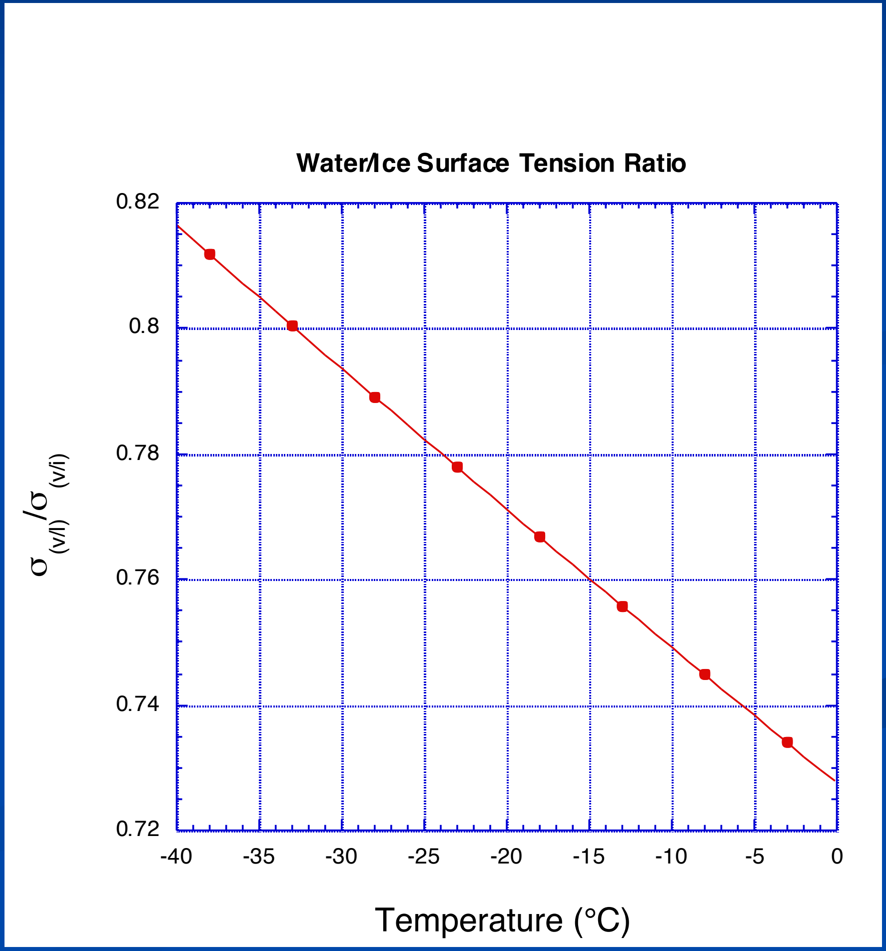
Water vapor saturation





Kelvin effect - Surface Tension vs. Temperature





The Raoult (Solute) Effect - I

We've seen that a curved surface raises the equilibrium vapor pressure of water over a droplet compared with a planar surface of pure water.

We know though, that droplets start their lives as aerosol particles, so that droplets in the atmosphere are not pure water, but are solution droplets.

What effect can this dissolved material have on the equilibrium vapor pressure over a solution droplet?

The Raoult (Solute) Effect - II

Water equilibrium between the gas and aqueous phases requires that the chemical potentials in the two phases are equal:

$$\mu_w(g) = \mu_w(aq)$$

Water vapor behaves like an ideal gas:

$$\mu_w(g) = \mu_w^{\circ}(T) + RT\ln p_s$$

The chemical potential of liquid water is:

$$\mu_w(aq) = \mu_w^{*} + RT\ln \gamma_w x_w$$

The chemical potentials with the superscripts ° and * denote *standard state* chemical potentials for the vapor and aqueous phases, respectively. The standard state for vapor is 1atm pressure, and the standard state for a condensed phase refers to the pure species.

The Raoult (Solute) Effect - III

Combining, we arrive at:

$$\frac{p_s}{\gamma_w x_w} = \exp\left(\frac{\mu_w^{\circ} - \mu_w^{*}}{RT}\right) = K(T)$$

The mole fraction of water (x_w) is:

$$x_w = \frac{n_w}{n_w + n_s}$$

And the vapor pressure of water over a solution is:

$$p_s = \frac{n_w}{n_w + n_s}\gamma_w p$$

For an ideal solution, $g_w = 1$, and

$$p_s = x_w p$$

The terms n are the number of moles of water (w) and solute (s).

The Raoult (Solute) Effect - IV

The number of moles of solute is

$$n_s = {iN_0 m_s}\big/{M_s}$$

The number of moles of water is

$$n_w = {N_0 m_w}\big/{M_w}$$

Since the mass of water is (4/3)pr^{3}r$_w$, and for a dilute solution we can ignore the volume of the solution occupied by the solute, the result becomes

$$\frac{p_s}{p} = 1 - \frac{3iM_w m_s}{4\pi\rho_s M_s r^3} = 1 - \frac{B}{r^3}$$

The terms n are the number of moles of water (w) and solute (s).

The Köhler Equation

Combining the Kelvin and Raoult expressions leads us to an expression for the equilibrium of water vapor over a solution droplet:

$$\frac{p_s(r)}{p} = 1 + \frac{2\sigma M_w}{R\rho_w T r} - \frac{3 i M_w m_s}{4\pi\rho_w M_s r^3}$$

Raoult effect

Kelvin effect

$$\frac{p_s(r)}{p} = 1 + \frac{A}{r} - \frac{B}{r^3}$$

"Traditional" Köhler Curves - II

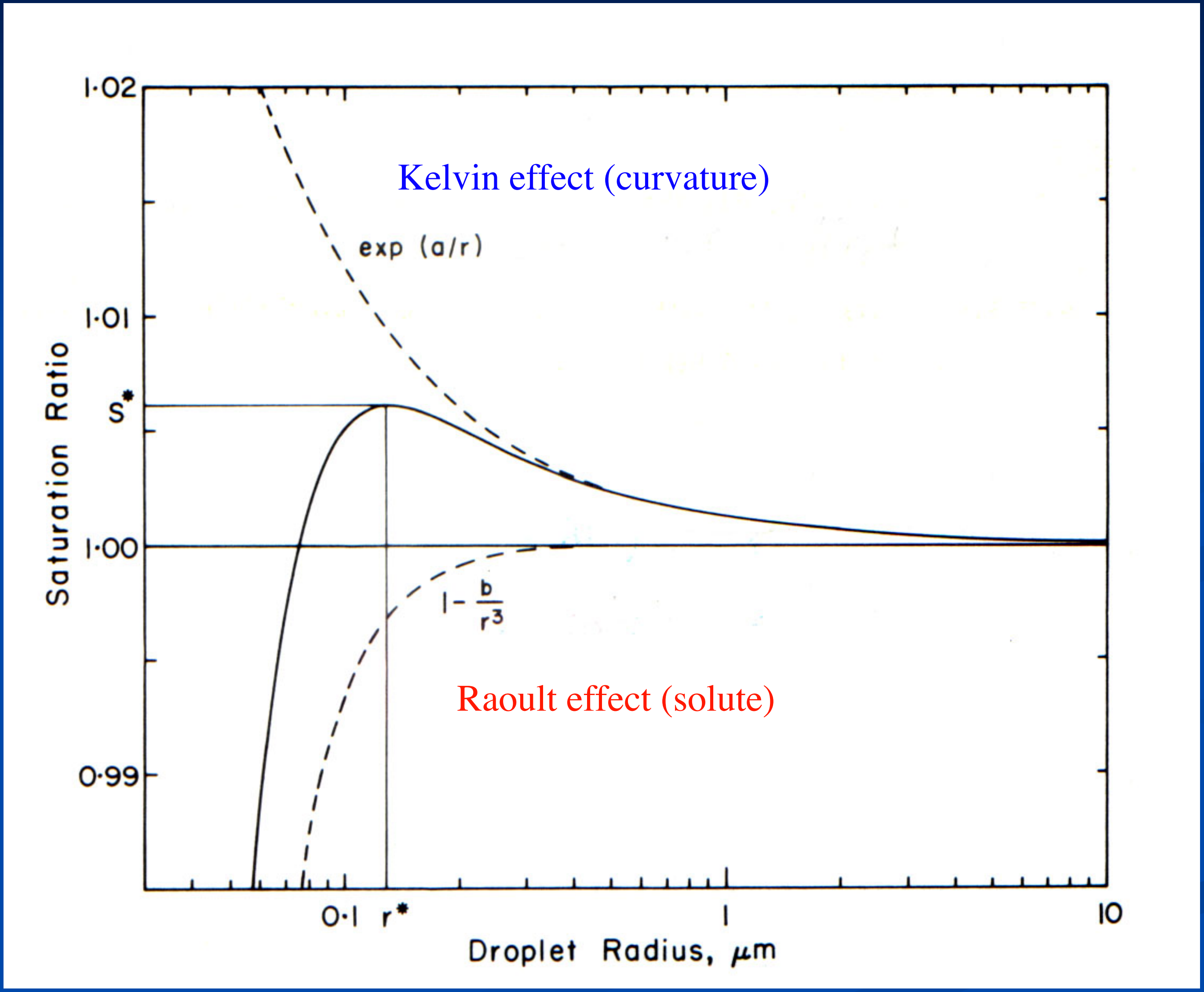
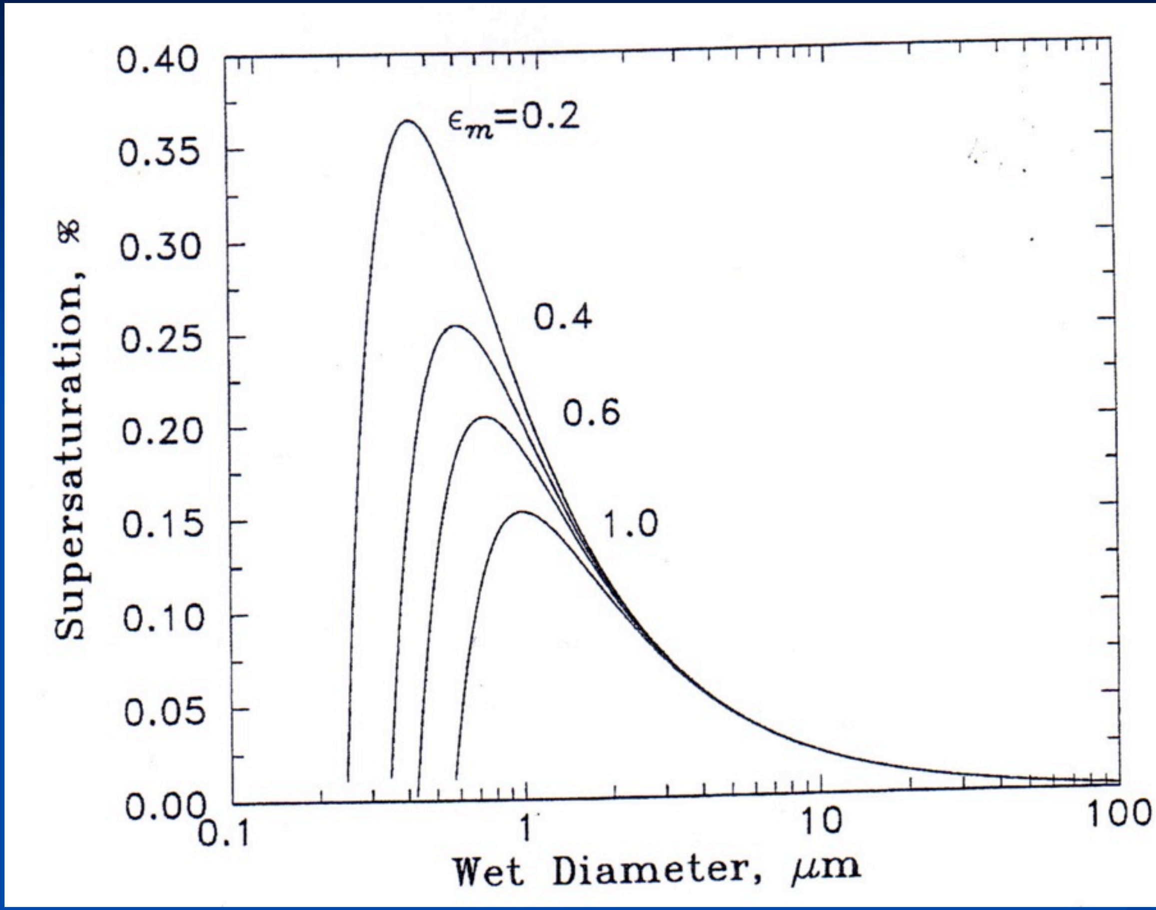


Fig. 6.2

Effects of insoluble inclusions - I



$$\frac{p_s(r)}{p} = 1 + \frac{A}{r} - \frac{B}{(r^3 - r_i^3)}$$

Sainfeld & Pandis Fig. 15.8

The Modified Köhler Equation - I

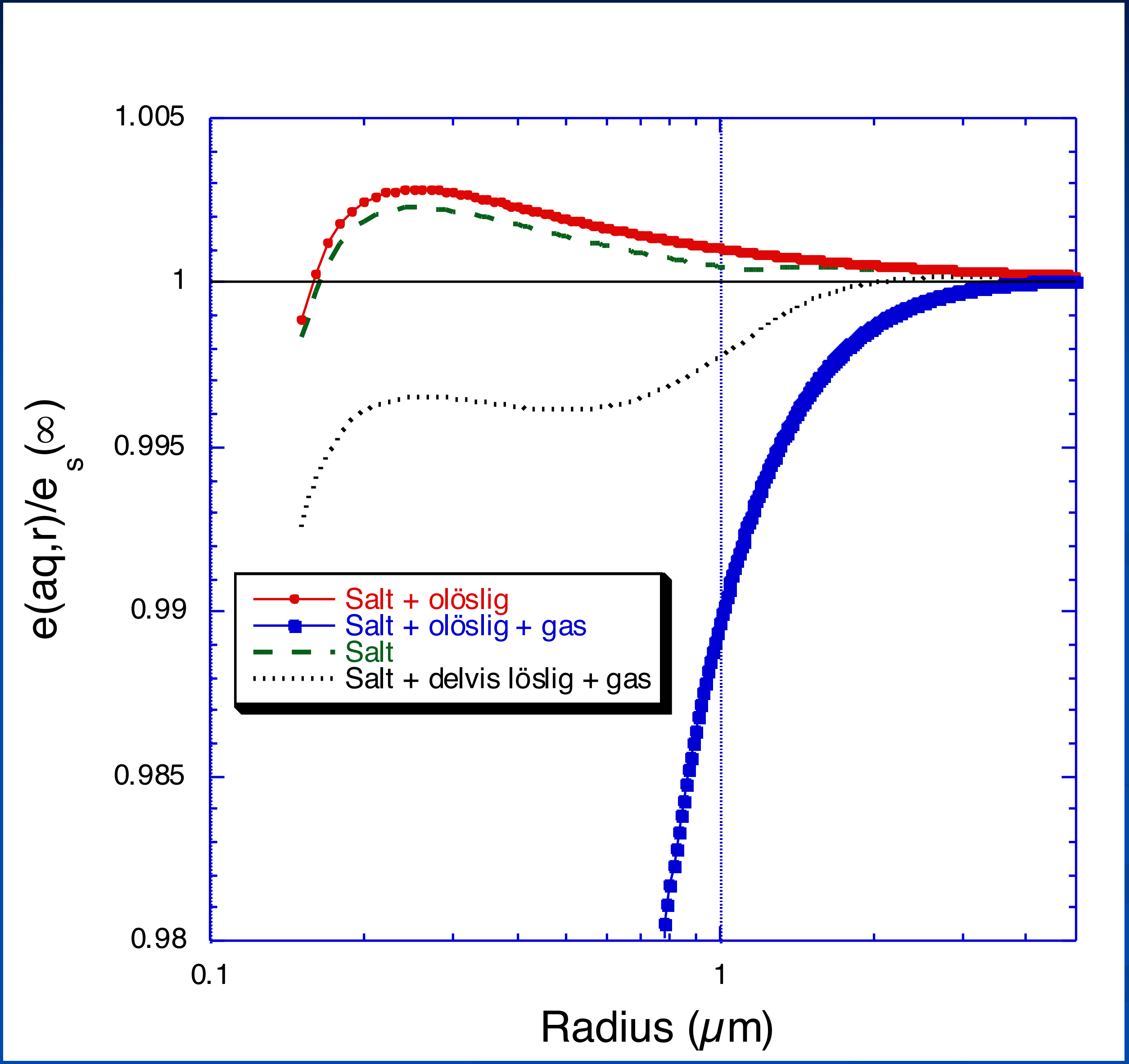
The Köhler equation has been extended to include slightly soluble species and co-condensing gases:

$$\frac{p_s(r)}{p} = 1 + \frac{2\sigma_w M_w}{R\rho_w T r} - \left(\frac{3M_w}{4\pi\rho_w r^3}\right)\sum \frac{i m_i X_i}{M_i} - i_g\left(p_g H_g\right)^{1/2}$$

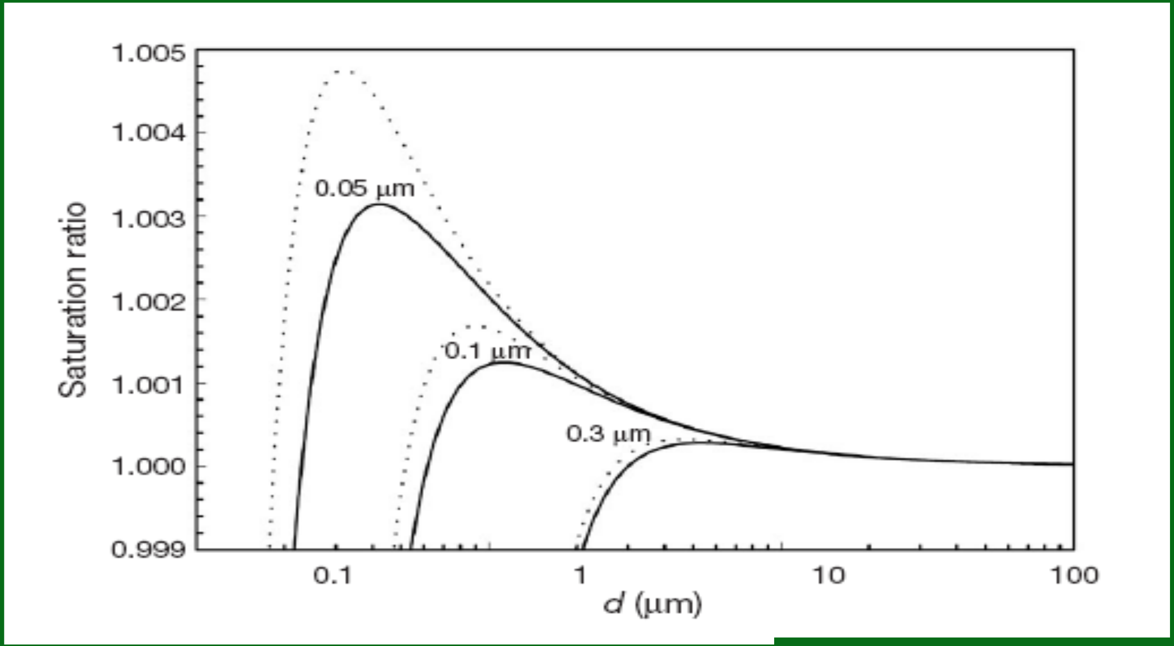
where X_i is the dissolved fraction of solute i
p_g is the partial pressure of co-condensing gas g
H_g is the Henry's law constant for gas g

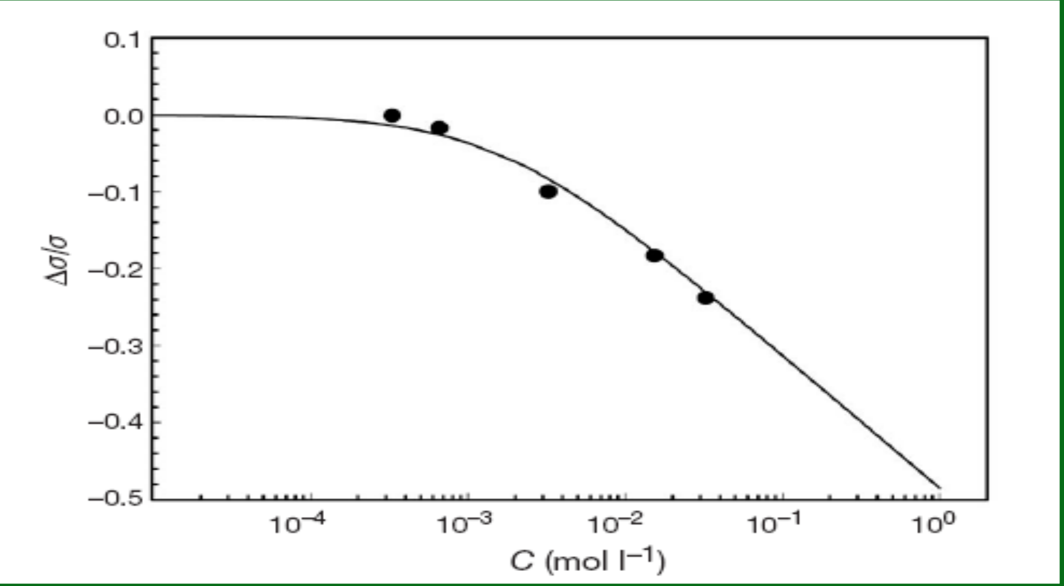
See Laaksonen, A., P. Korhonen, M. Kulmala, and R.J. Charlson, Modification of the Köhler Equation to Include Soluble Trace Gases and Slightly Soluble Substances, *J. Atmos. Sci.*, *55* (1 March), 853-862, 1998.

Modified Köhler Equation - II



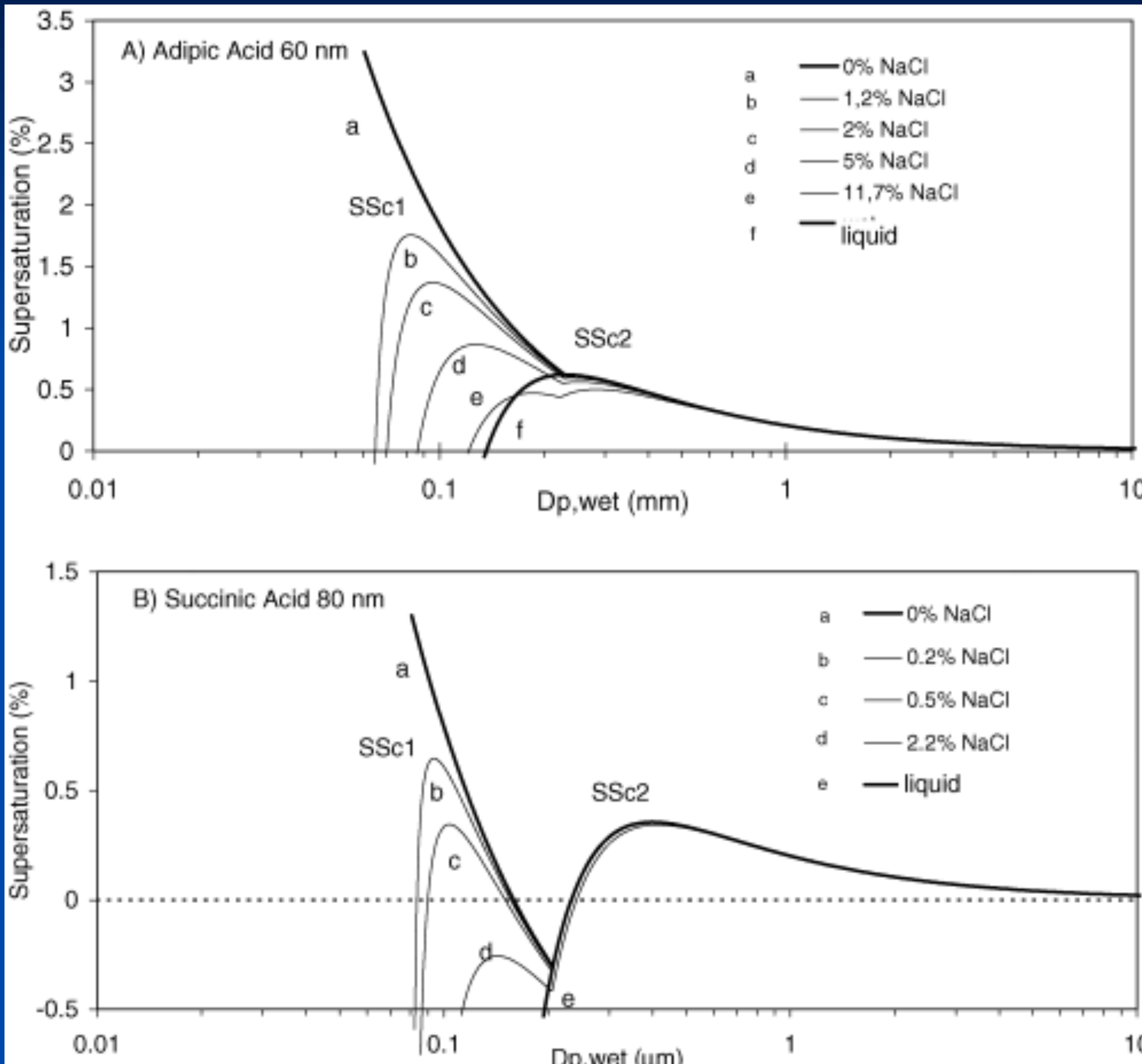
Köhler curves – role of soluble organics





Mircea, M., M.C. Facchini, S. Decesari, S. Fuzzi and R.J. Charlson The influence of the organic aerosol component on CCN supersaturation spectra for different aerosol types. Tellus, 2002

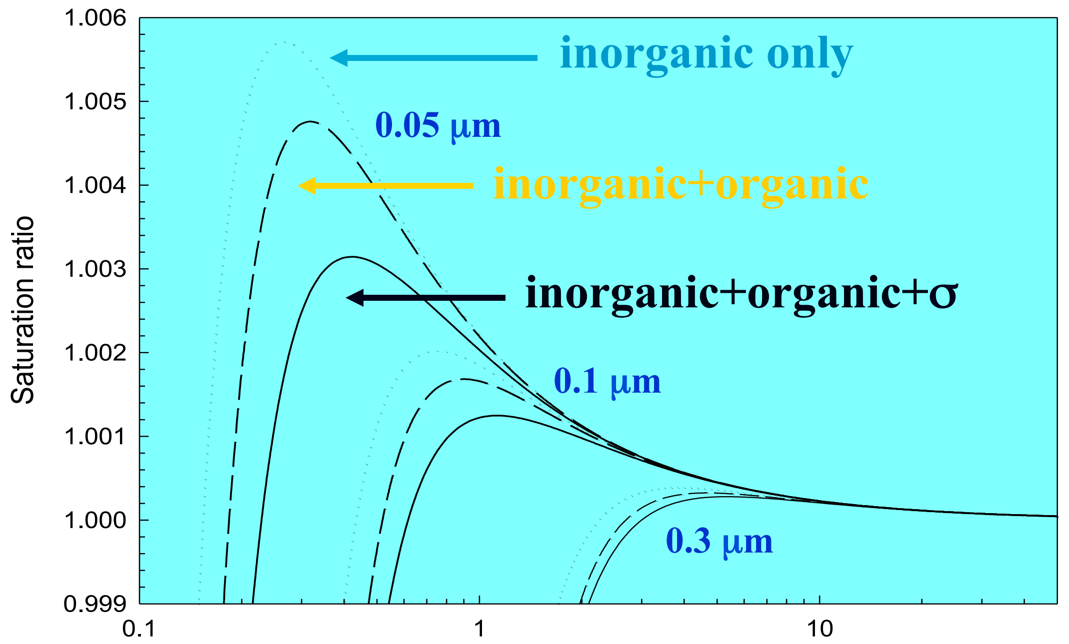
Köhler curves – role of slightly soluble organics and inorganic salts



Köhler curves modified to take account of limited solubility for (a) adipic acid particles (60-nm dry diameter) and (b) succinic acid particles (80-nm dry diameter) with varying amounts of NaCl at 298 K.

BILDE, MERETE & SVENNINGSSON, BIRGITTA
CCN activation of slightly soluble organics: the importance of small amounts of inorganic salt and particle phase.
Tellus B **56** (2), 128-134.
doi: 10.1111/j.1600-0889.2004.00090.x

Köhler curves - Effect of organics on S_c



Courtessy of Sandro Fuzzi, Uviv. Bologna, Italy

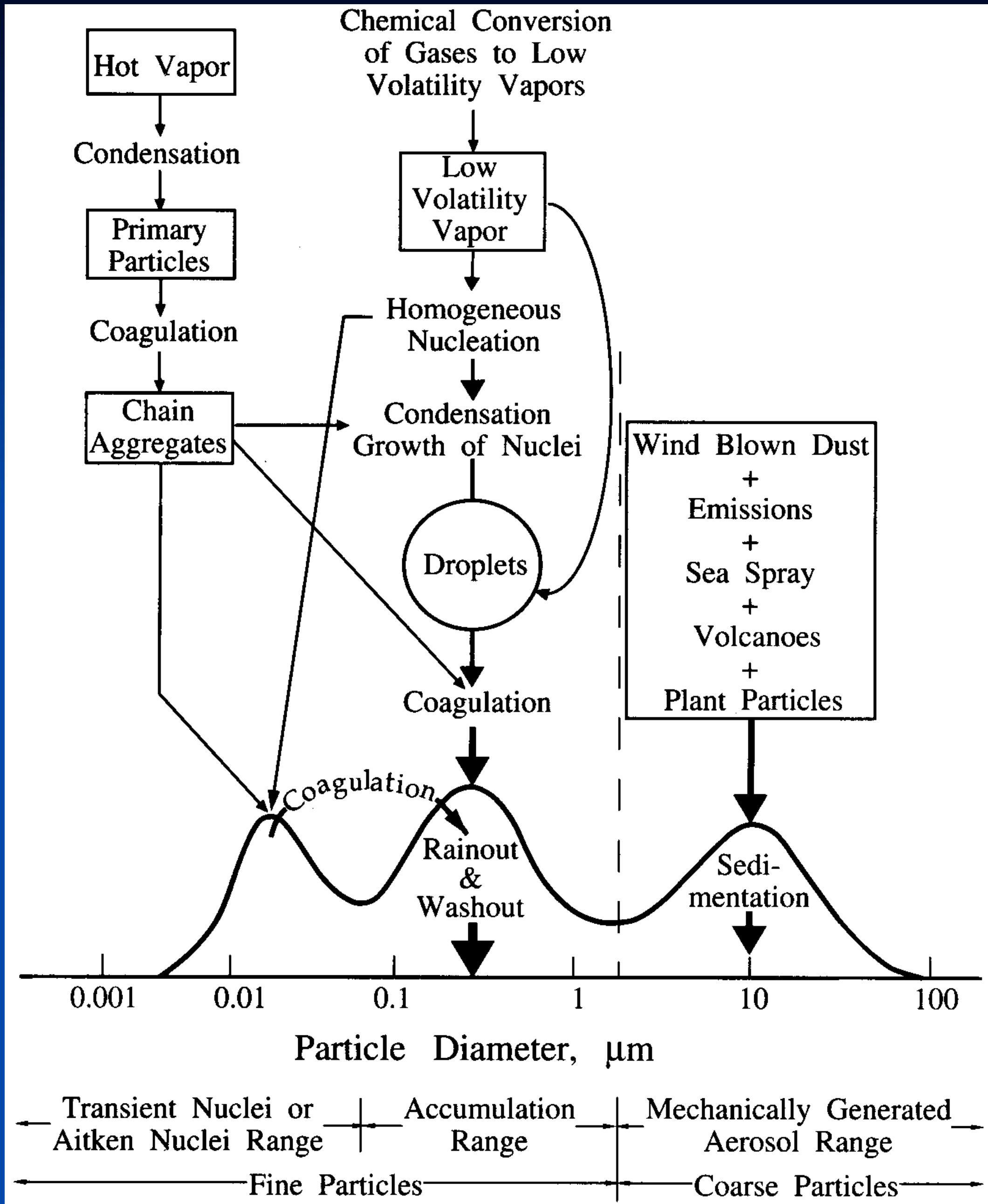
Cloud Condensation Nuclei (CCN)

Empirical relationships have been derived to come up with *cloud condensation nucleus* concentrations - the number of particles that could become cloud droplets at a given supersaturation

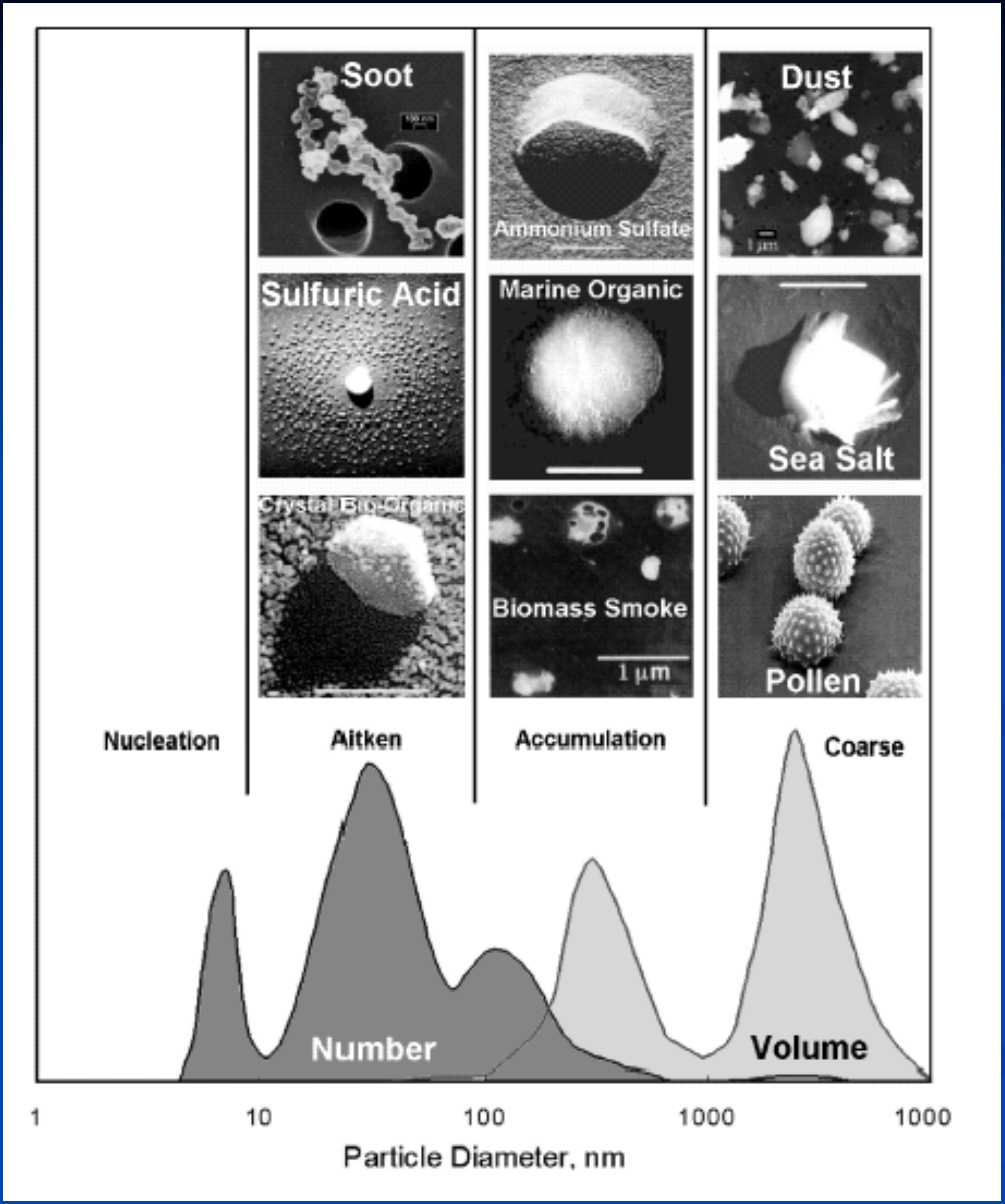
$$CCN = Cs^{k}$$

$$CCN \approx 0.88C^{2/(k+2)}\left[7 \times 10^{-2} U^{3/2}\right]^{k/(k+2)}$$

where s is the % supersaturation [(S-1)*100] and U is the vertical velocity (in cm s^{-1}). C and k are “constants” that depend on the airmass type.

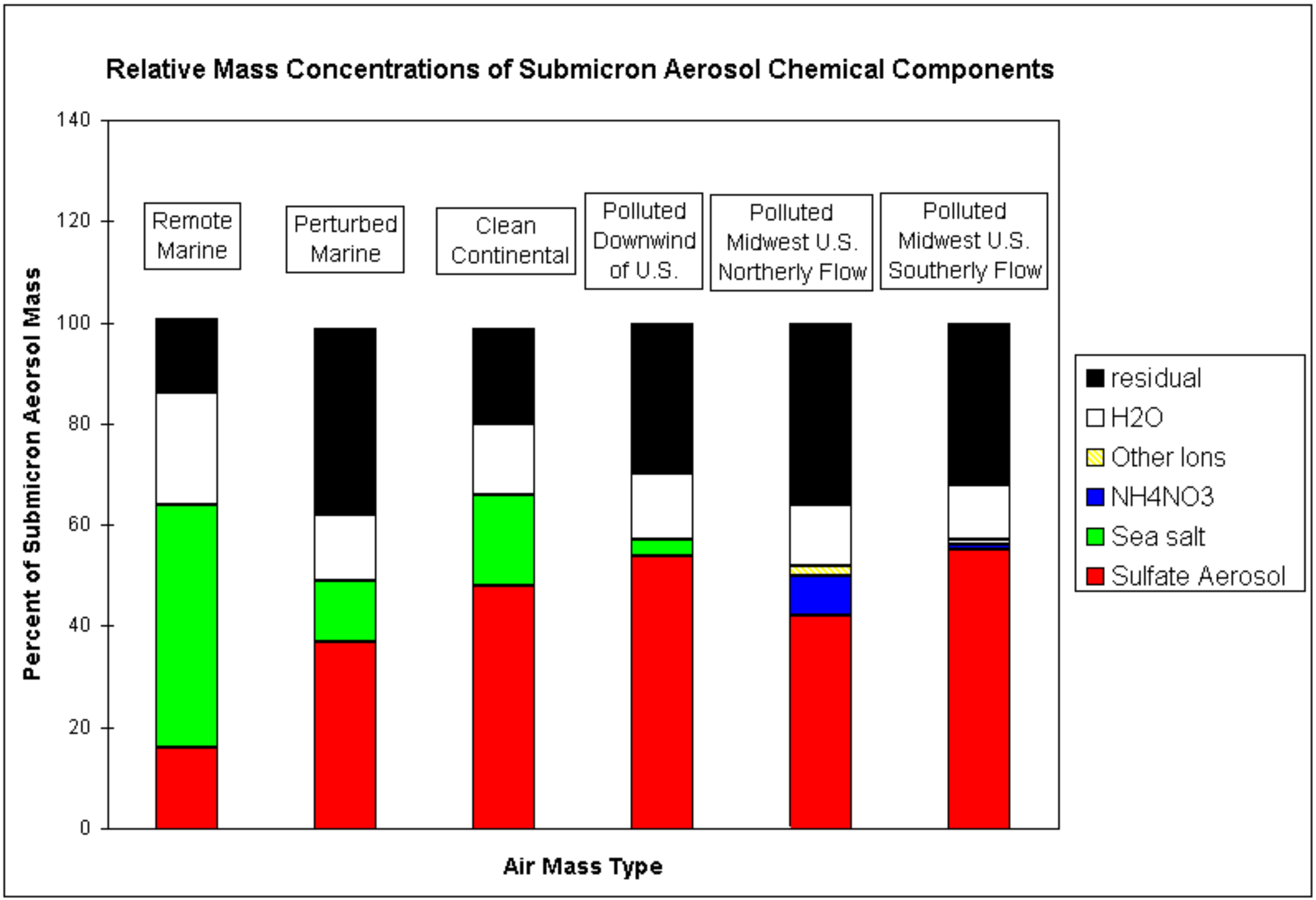


Whitby et al, 1978

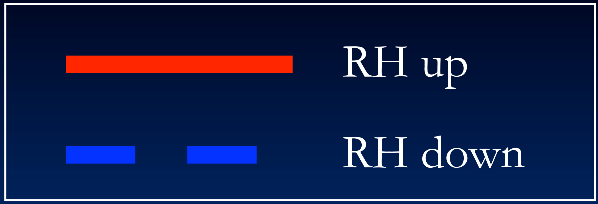


Different types of aerosol particles and typical size modes where they can be found

Source:IGACP


Relative Mass Concentrations of Submicron Aerosol Chemical Components
Percent of Submicron Aeorsol Mass
140
120
100
80
60
40
20
0
Remote Marine
Perturbed Marine
Clean Continental
Polluted Downwind of U.S.
Polluted Midwest U.S. Northerly Flow
Polluted Midwest U.S. Southerly Flow
residual
H2O
Other Ions
NH4NO3
Sea salt
Sulfate Aerosol
Air Mass Type

Hygroscopic growth



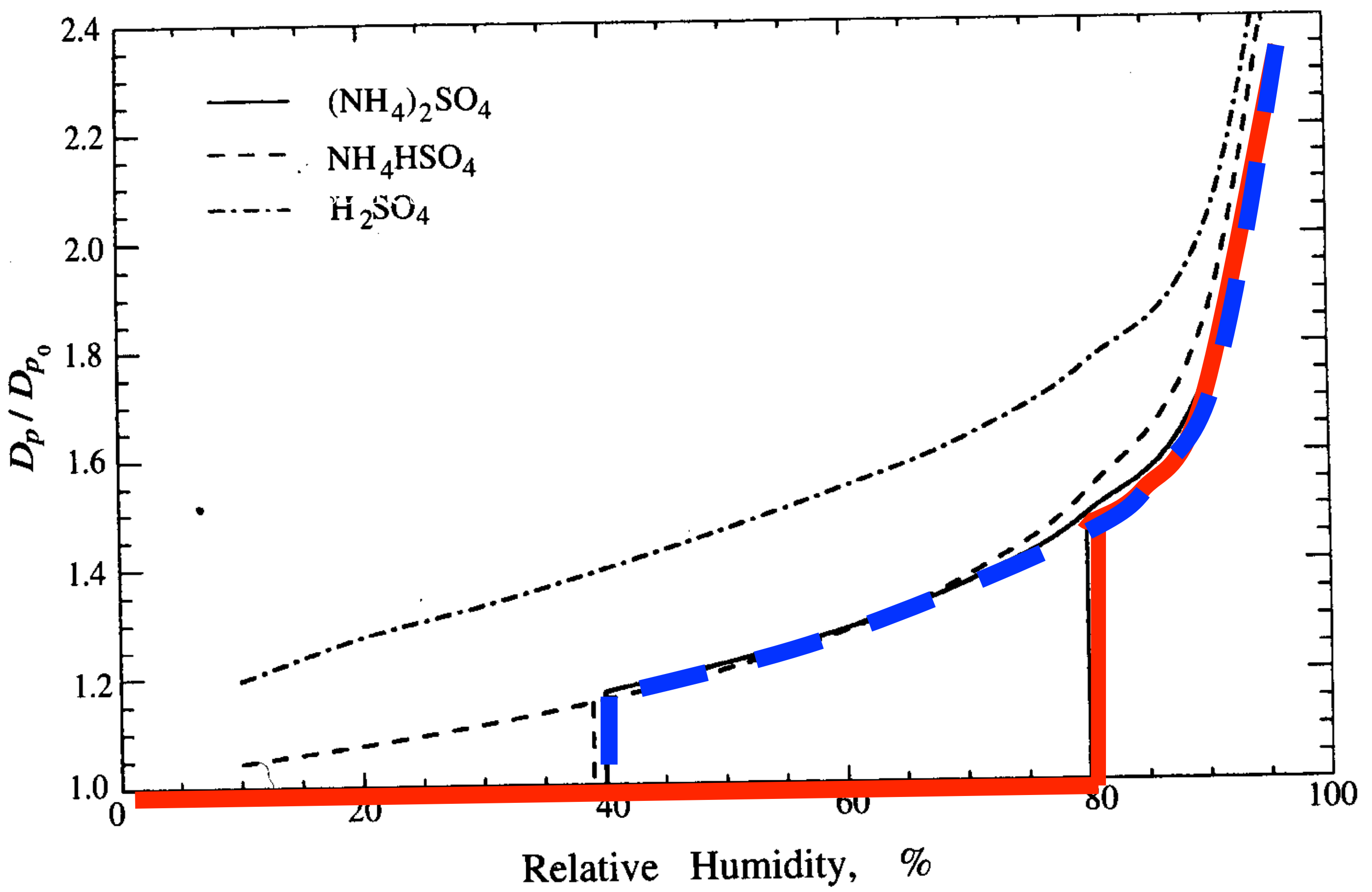
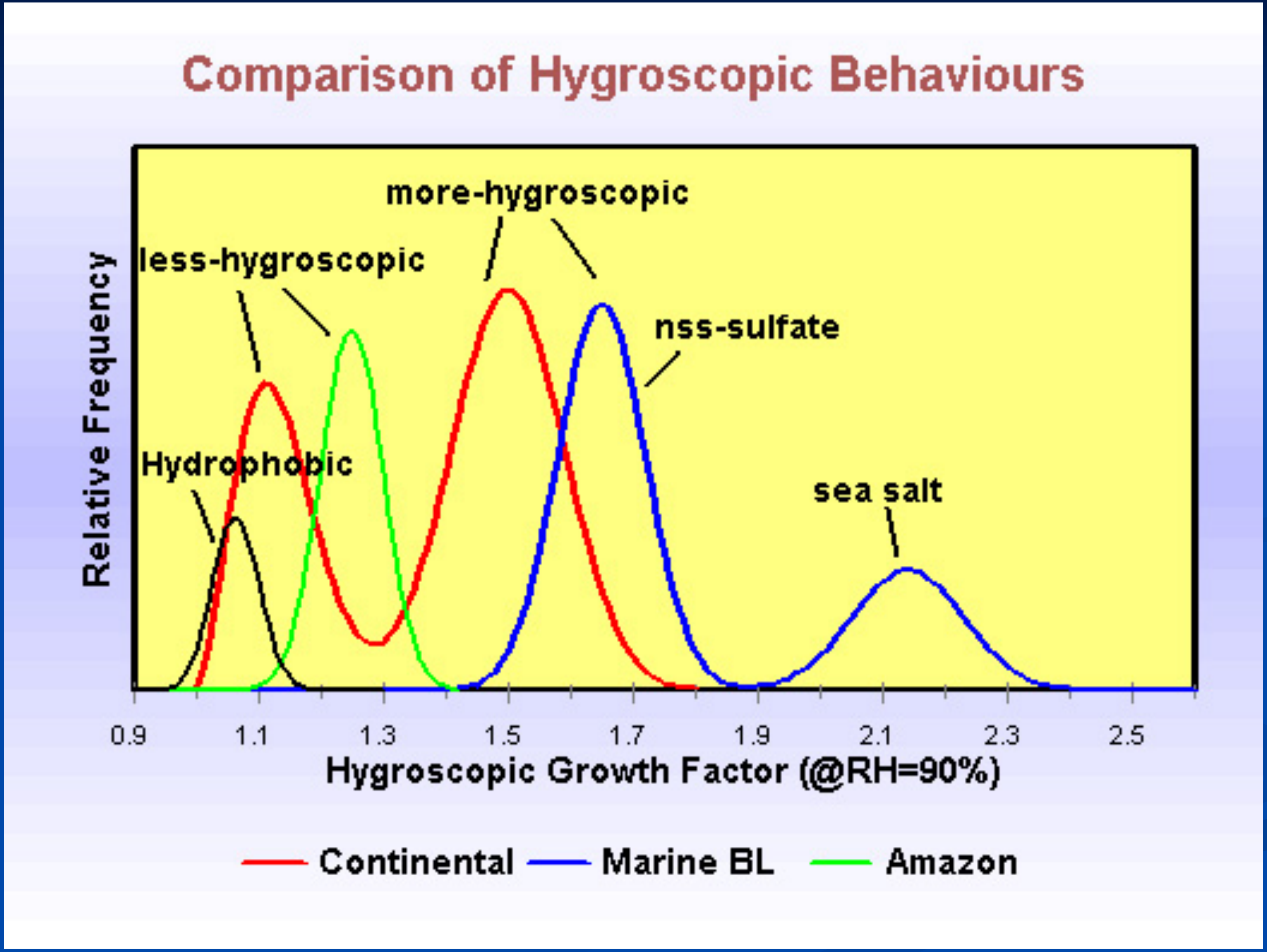


FIGURE 9.4 Diameter change of $(NH_4)_2SO_4$, NH_4HSO_4, and H_2SO_4 particles as a function of relative humidity. D_{p0} is the diameter of the particle at 0% RH.



Courtessy of E. Swietlicki, Lund University

Hygroscopic behavior of different compounds often found in atmospheric aerosol

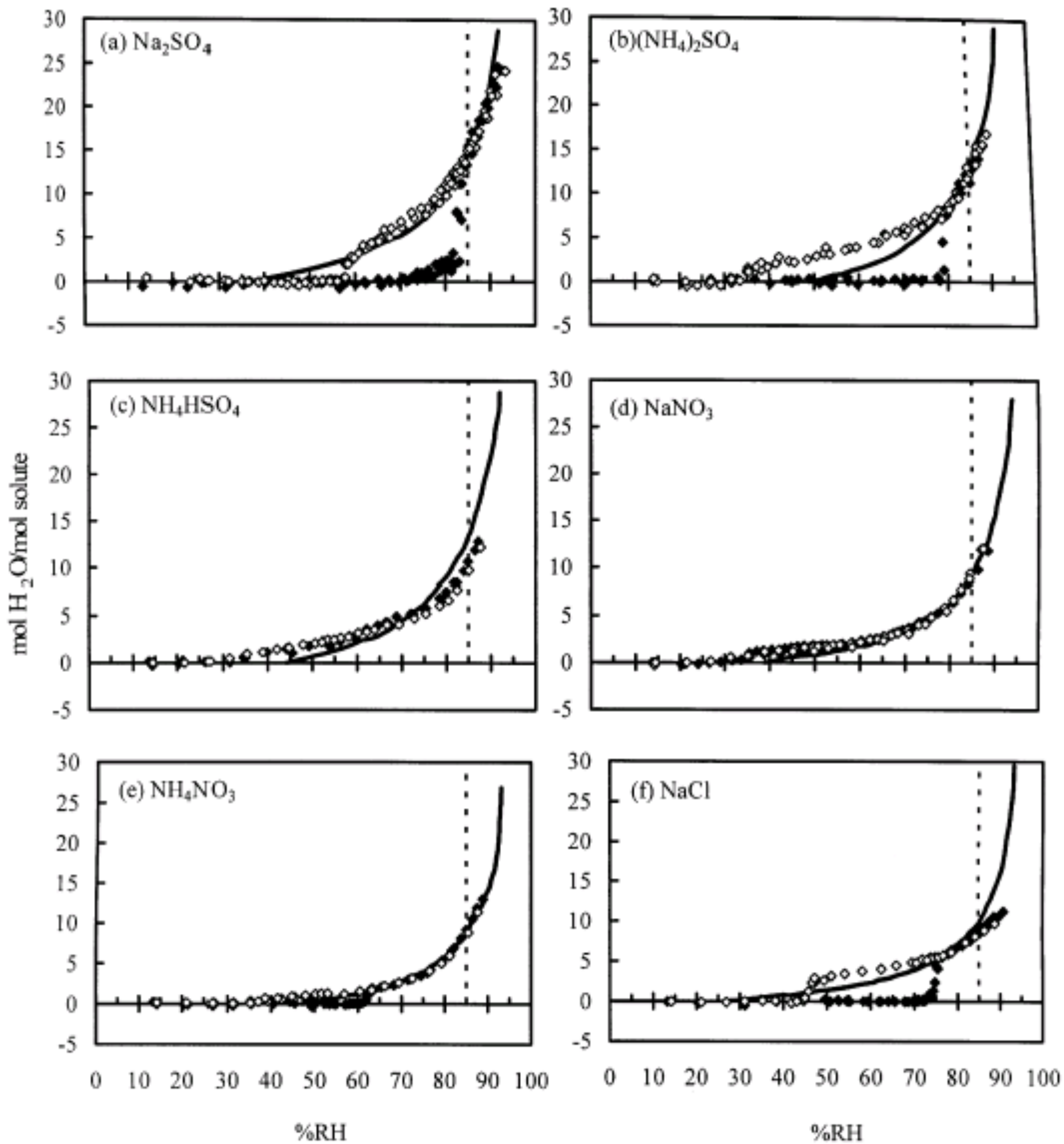


Fig. 6. Comparison between (—) model and measurements in (◆) the ascending mode and (◇) the descending mode. The vertical dashed line specified the point of 85% RH for the comparison of water uptake capacity.

Lee & Hsu, J. Aerosol Sci., 31(2) 2000

At minimum 12 input parameters are needed to calculate cloud droplet number concentration

$$T \quad p \quad \alpha$$

$$w$$

The
mas

What are the aerosol chemical properties in the atmosphere?

Size distribution parameters (number concentration, mode diameter, standard deviation)

$$N_t \, D_g \, \sigma_g$$

Aerosol chemical properties, e.g. $(NH_4)_2SO_4$

$$\nu \, \Phi \, \rho_s \, M_s \, \sigma_{s/a}$$

Courtessy of M. Petters

The hygroscopicity parameter

H_2O + solute

saturation ratio over droplet

$$S = a_w \exp\left(\frac{A}{D}\right)$$

Kelvin term

water activity

Parameterize water activity

$$a_w^{-1} = 1 + \kappa \frac{\text{solute volume}}{\text{water volume}}$$

hygroscopicity parameter

Petters and Kreidenweis, 2007

Courtessy of M. Petters

kappa can represent chemical composition in models

Aerosol chemical properties, e.g. $(NH_4)_2SO_4$

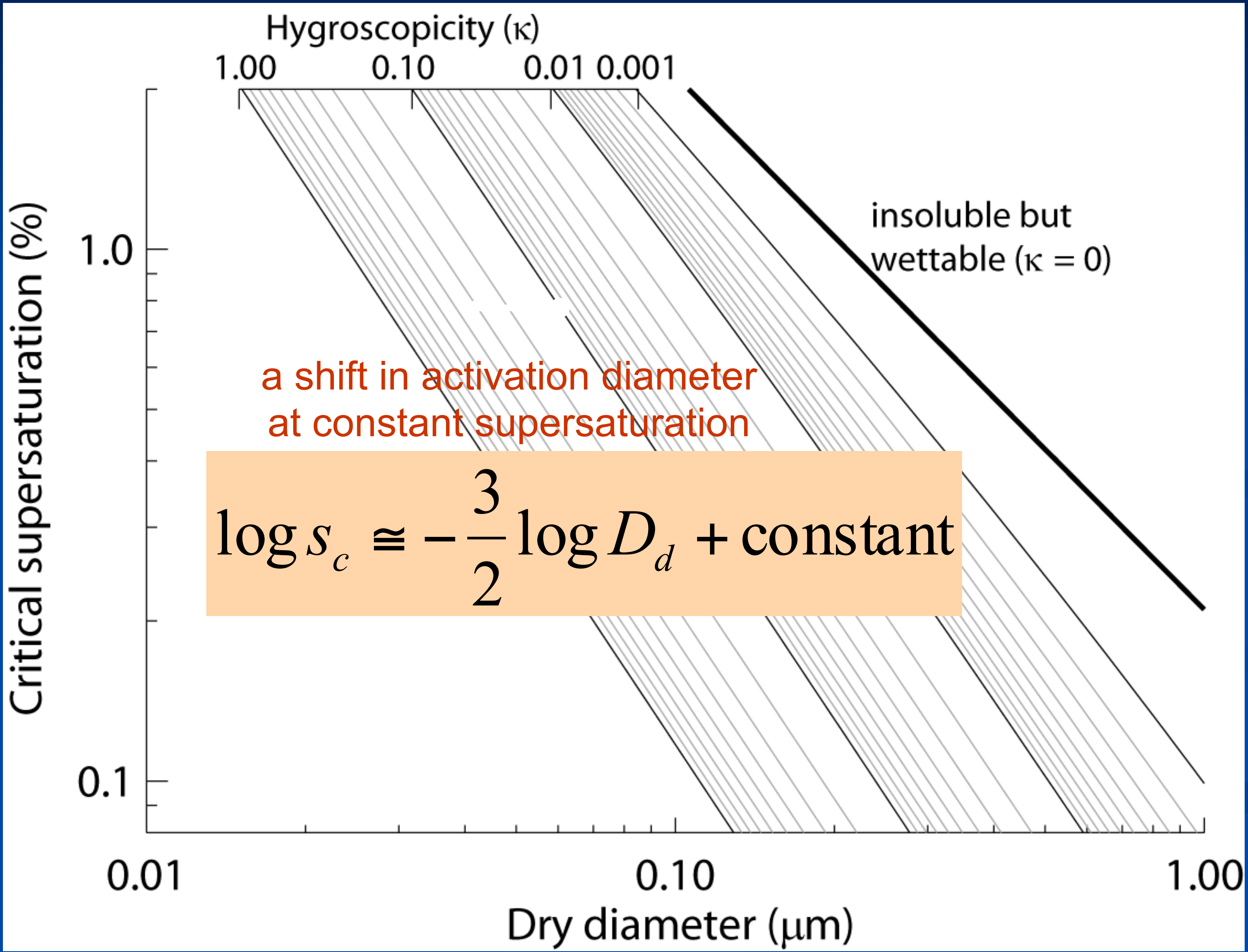
$$\kappa \nu \Phi \rho_s M_s$$

$$\sigma_{s/a} = 0.072\ \mathrm{J\,m^{-2}}$$

Note that kappa and surface tension cannot be measured independently inside a CCN instrument if the aerosol obey the -3/2 relationship.

Courtessy of M. Petters

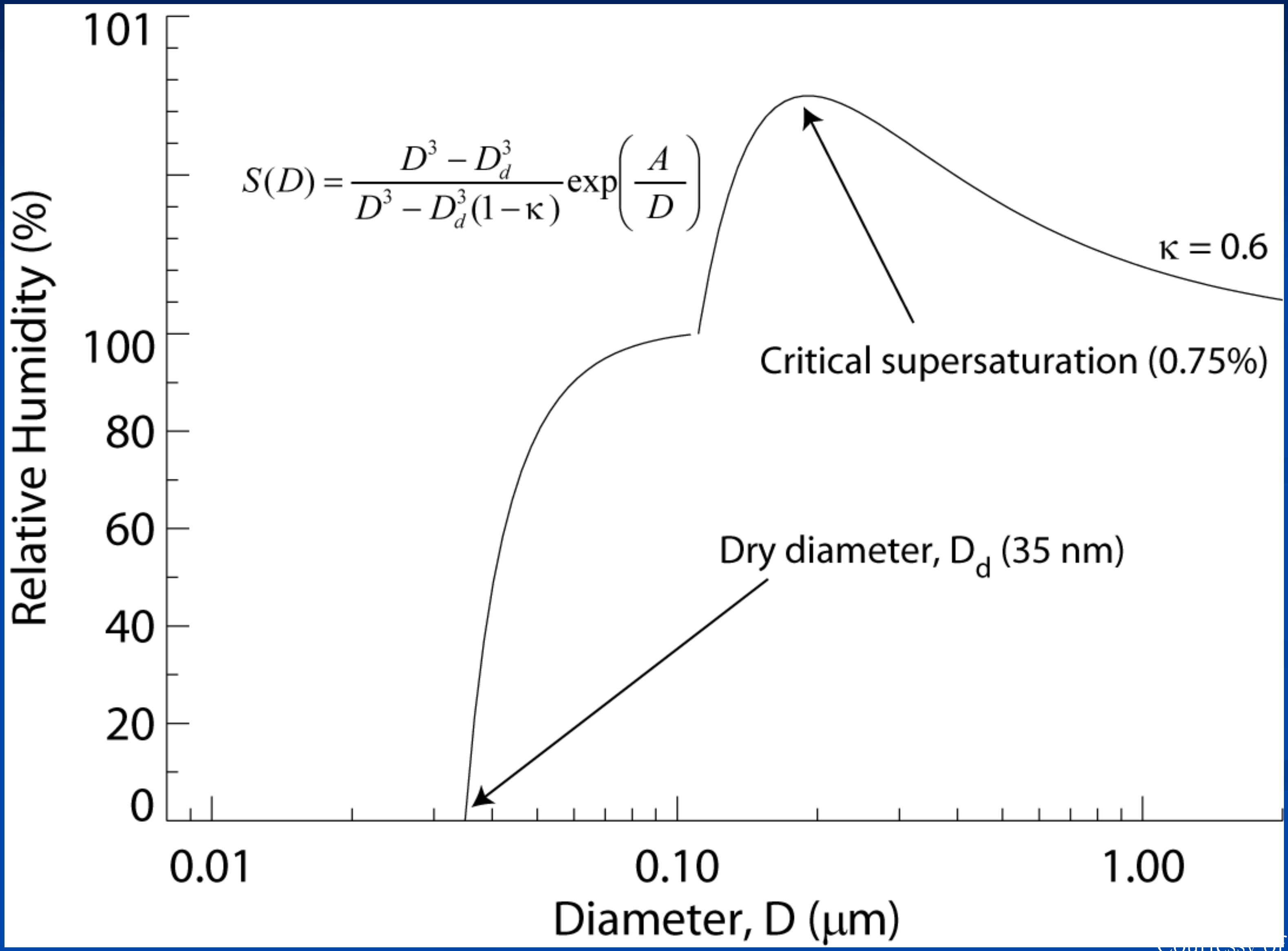
The hygroscopicity parameter, κ, relates critical supersaturation and dry particle diameter



$$\log s_c \cong -\frac{3}{2}\log D_d + \text{constant}$$

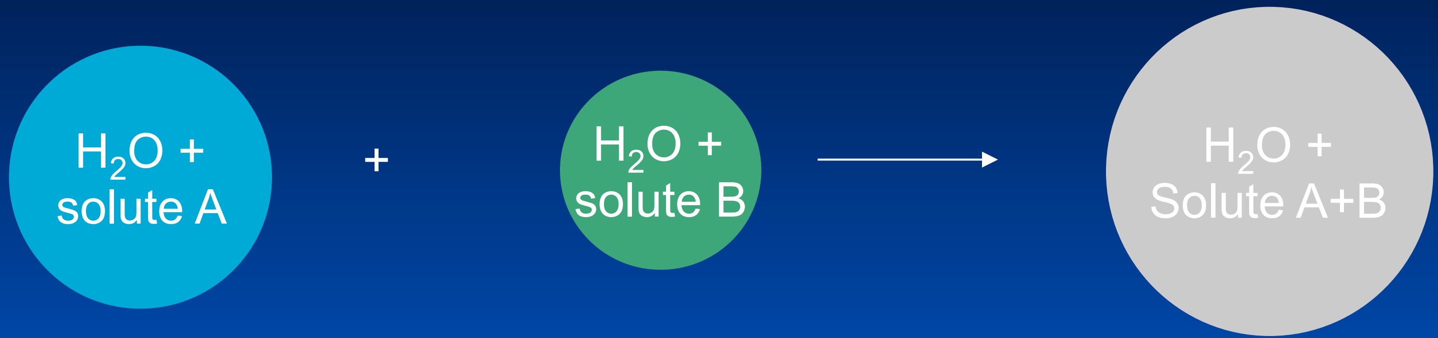
Courtessy of M. Petters

The hygroscopicity parameter, κ, relates critical supersaturation and dry particle diameter



Courtessy of M. Petters

The hygroscopicity parameter mixes linearly with aerosol volume fraction



Assumption 1: Volume Additivity

Volume I + Volume II = Volume Mixture

Assumption 2: ZSR Relationship

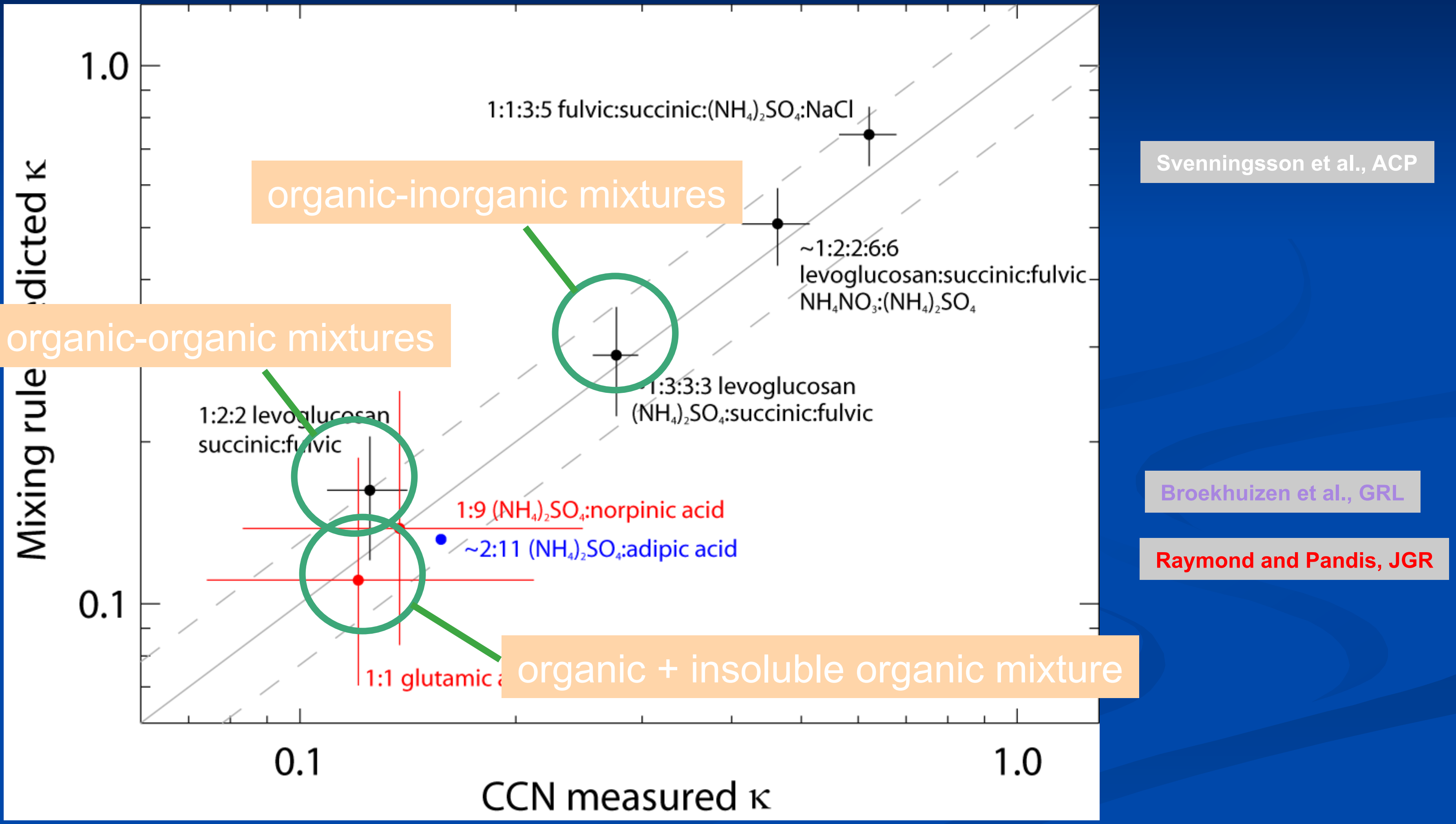
water volume contributed by solute A + water volume contributed by solute B = Total water volume of the mixture

κ mixes linearly with solute volume fraction ε

$$\kappa = \varepsilon_1 \kappa_1 + \varepsilon_2 \kappa_2 + \cdots + \varepsilon_n \kappa_n$$

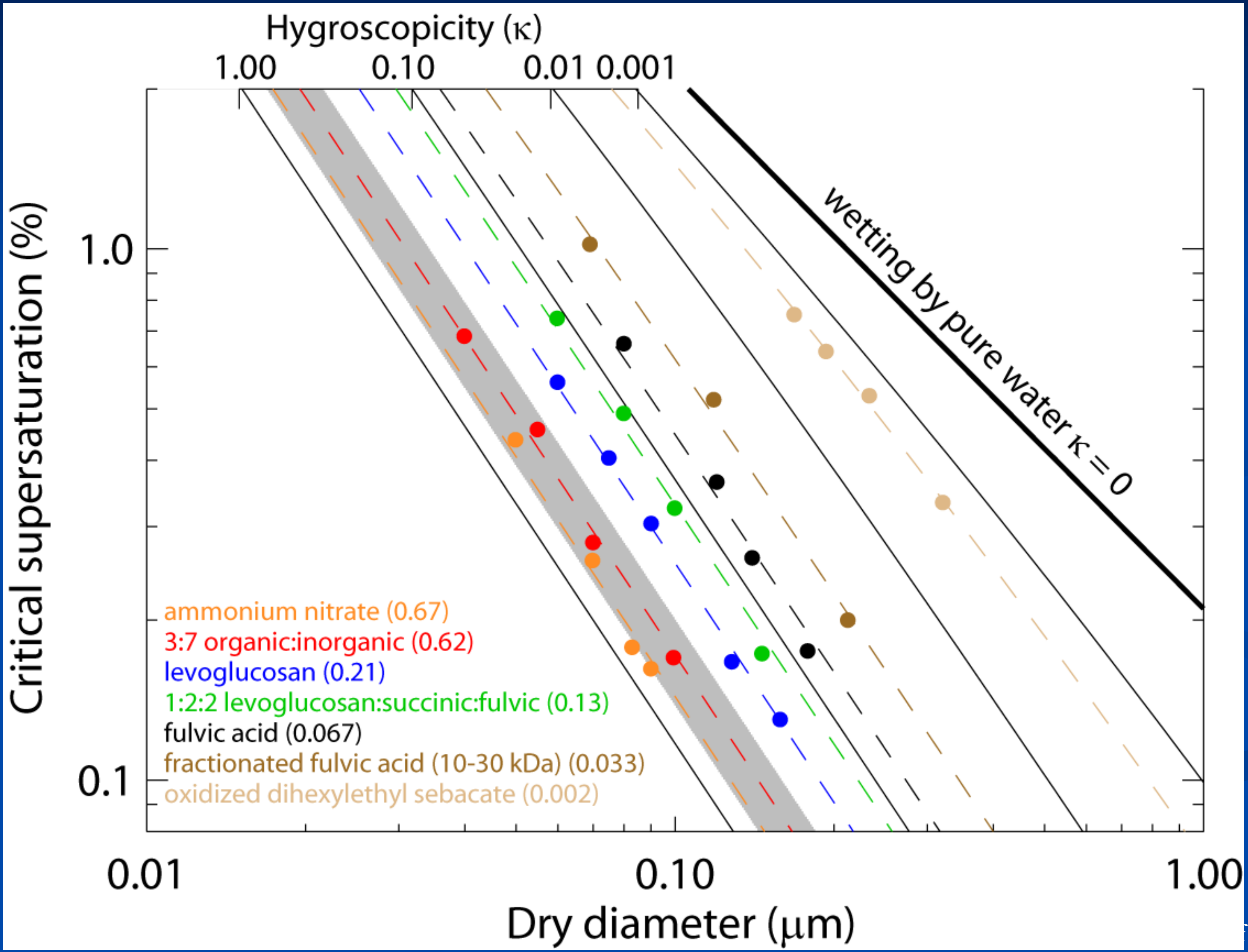
Courtessy of M. Petters

Mixing rule predicted hygroscopicity vs. CCN measured hygroscopicity from published data



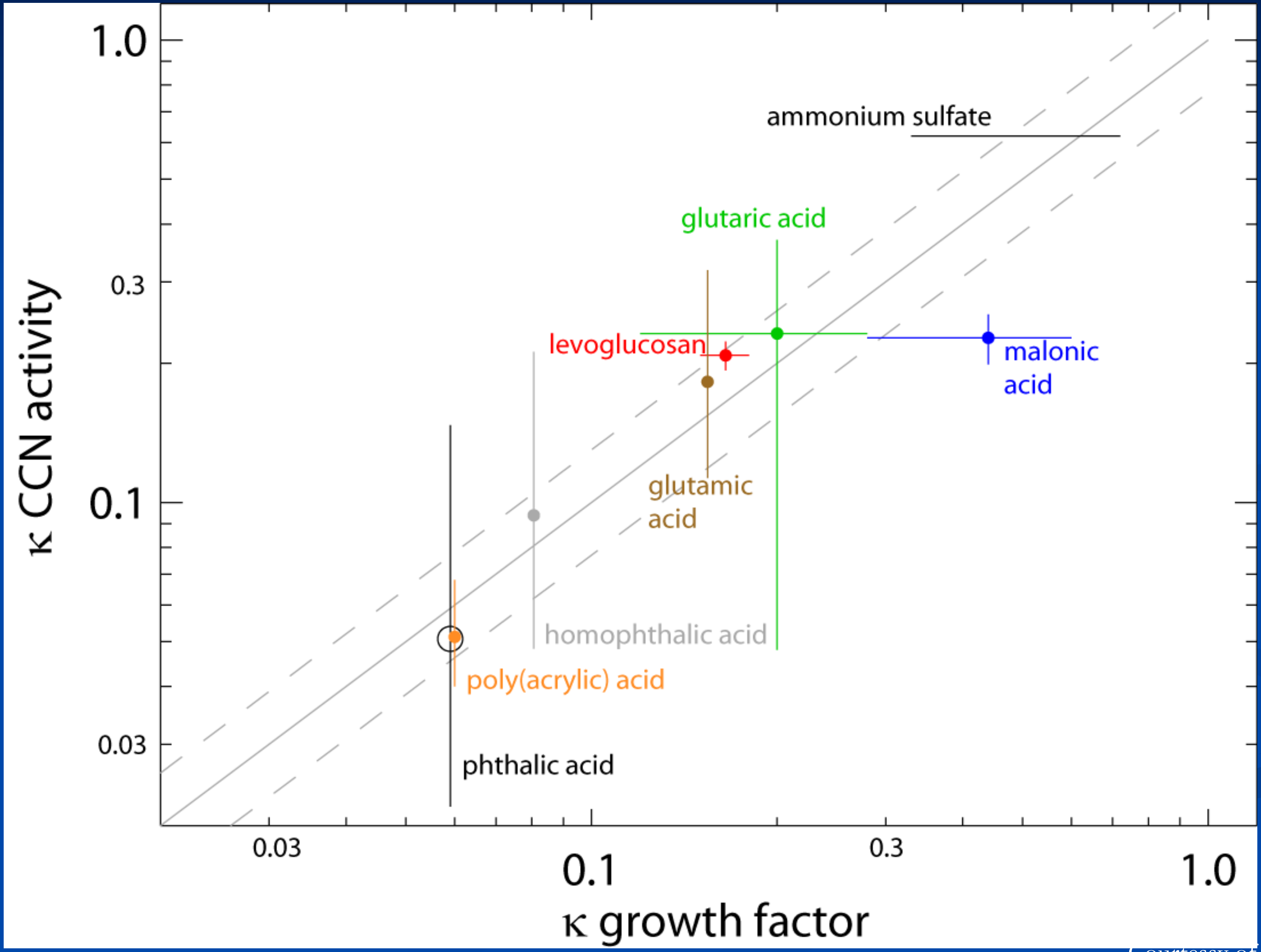
Courtessy of M. Petters

From measured CCN data we can infer the hygroscopicity of the aerosol



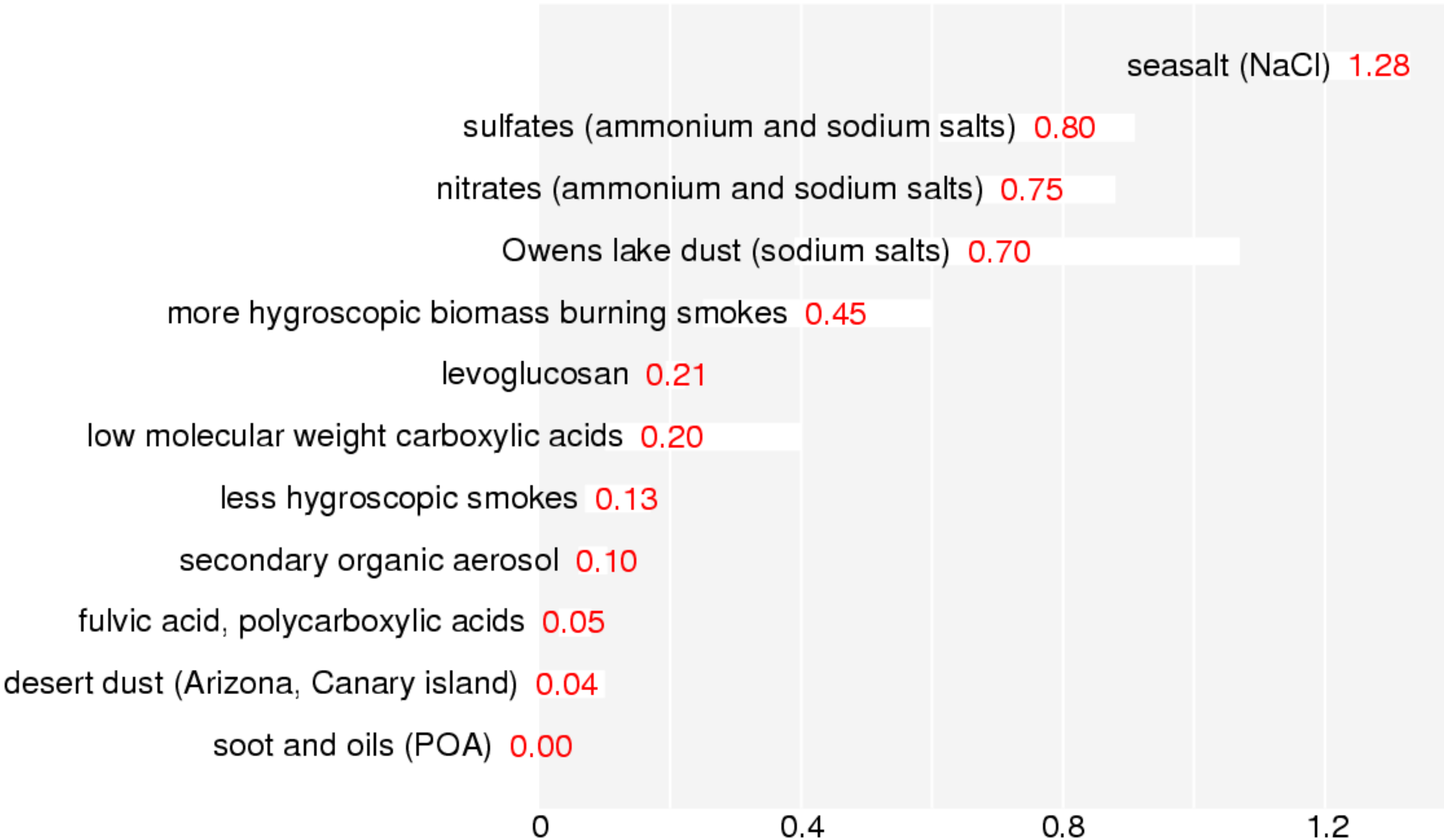
f M. Petters

Usually the κ values from HTDMA and CCN measurements are in reasonable agreement



Courtessy of M. Petters

Ranked hygroscopicity based on CCN measurements for atmospheric aerosols



Courtessy of M. Petters

Still 9 input parameters are needed to calculate cloud droplet number concentration

$$T \quad p \quad \alpha$$

Thermodynamics and mass accommodation

$$w$$

Cloud dynamics (updraft velocity)

Size distribution parameters (number concentration, mode diameter, standard deviation)

$$N_t \; D_g \; \sigma_g$$

Aerosol chemical properties, e.g. $(NH_4)_2SO_4$

$$\kappa \quad \sigma_{s/a}$$

Courtessy of M. Petters

- **The hygroscopicity parameter (κ) organizes CCN data in critical supersaturation vs. dry diameter space and in groups of similar hygroscopicity**
- **The activation parameter (Ψ) and hygroscopicity parameter (κ) reduce the number of dimensions that need be considered in aerosol-cloud interaction simulations**
- **Monte-Carlo type analysis ranks the sensitivity of warm cloud formation to size distribution (70%), dynamical effects (20%), and chemical effects (10%).**

Courtessy of M. Petters

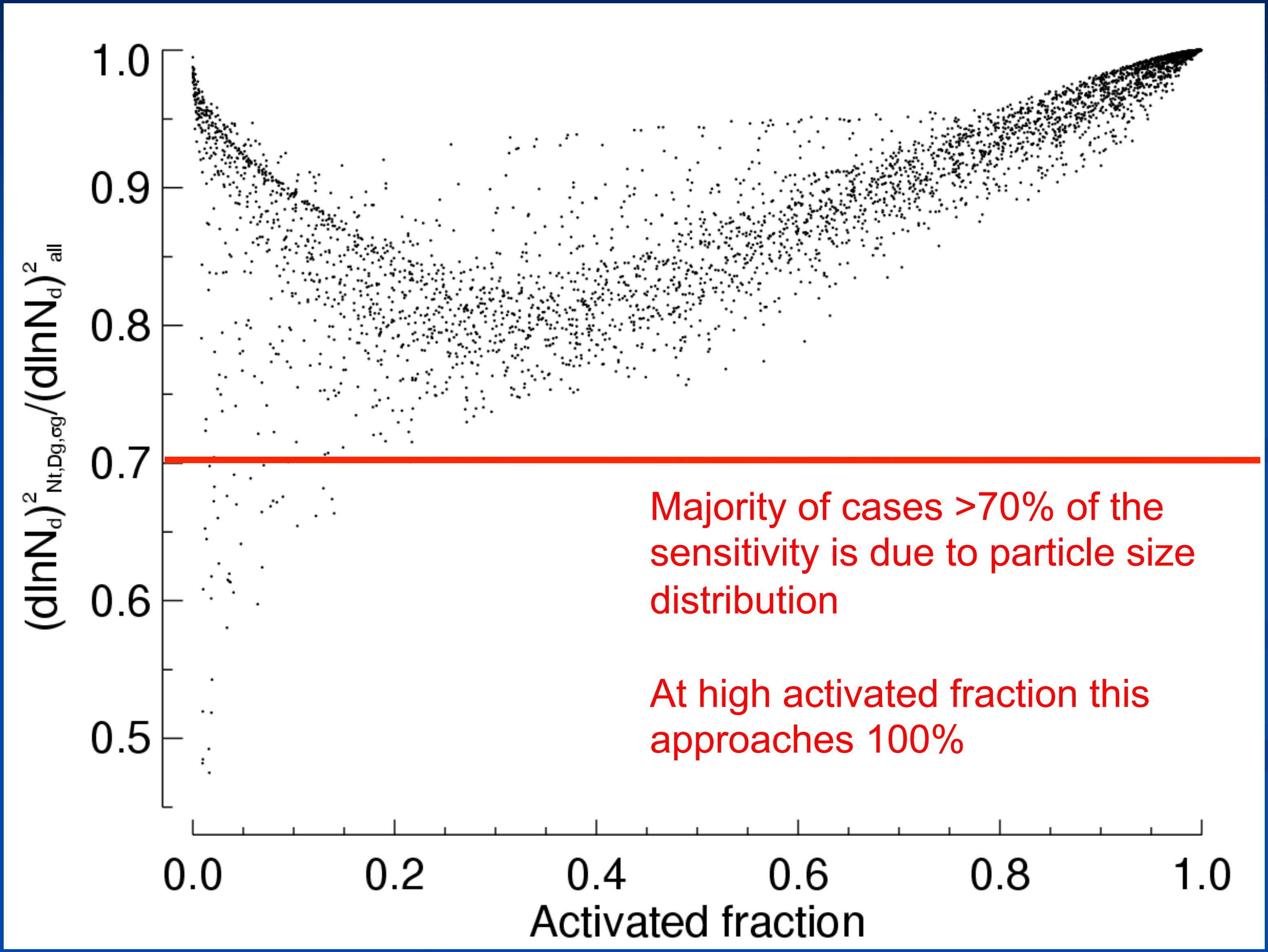
Sensitivity analysis only valid for

- **Lognormally-distributed, single mode aerosol**
  - giant CCN are omitted
- **Chemically homogenous size distribution**
  - κ invariant with size
- **Adiabatic updrafts**
  - no turbulent mixing/entrainment, etc.
- **Some parameters are better constraint**
  - hygroscopicity vs. accommodation coefficient

But: It is difficult to imagine that these effects significantly reduce the dominant effect of size distribution.

Courtessy of M. Petters

Microphysical effects vs. total sensitivity



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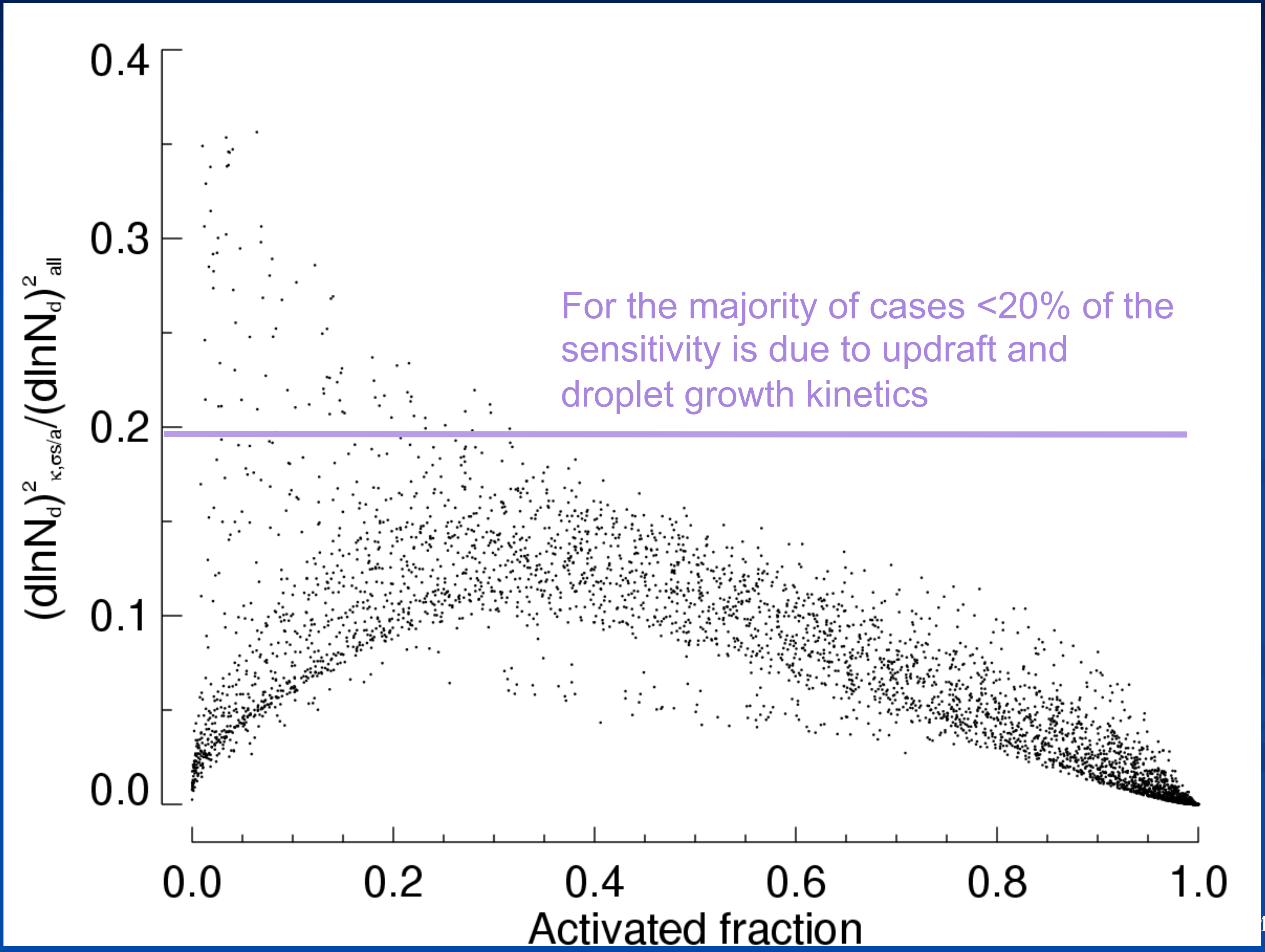
Dynamical effects vs. total sensitivity



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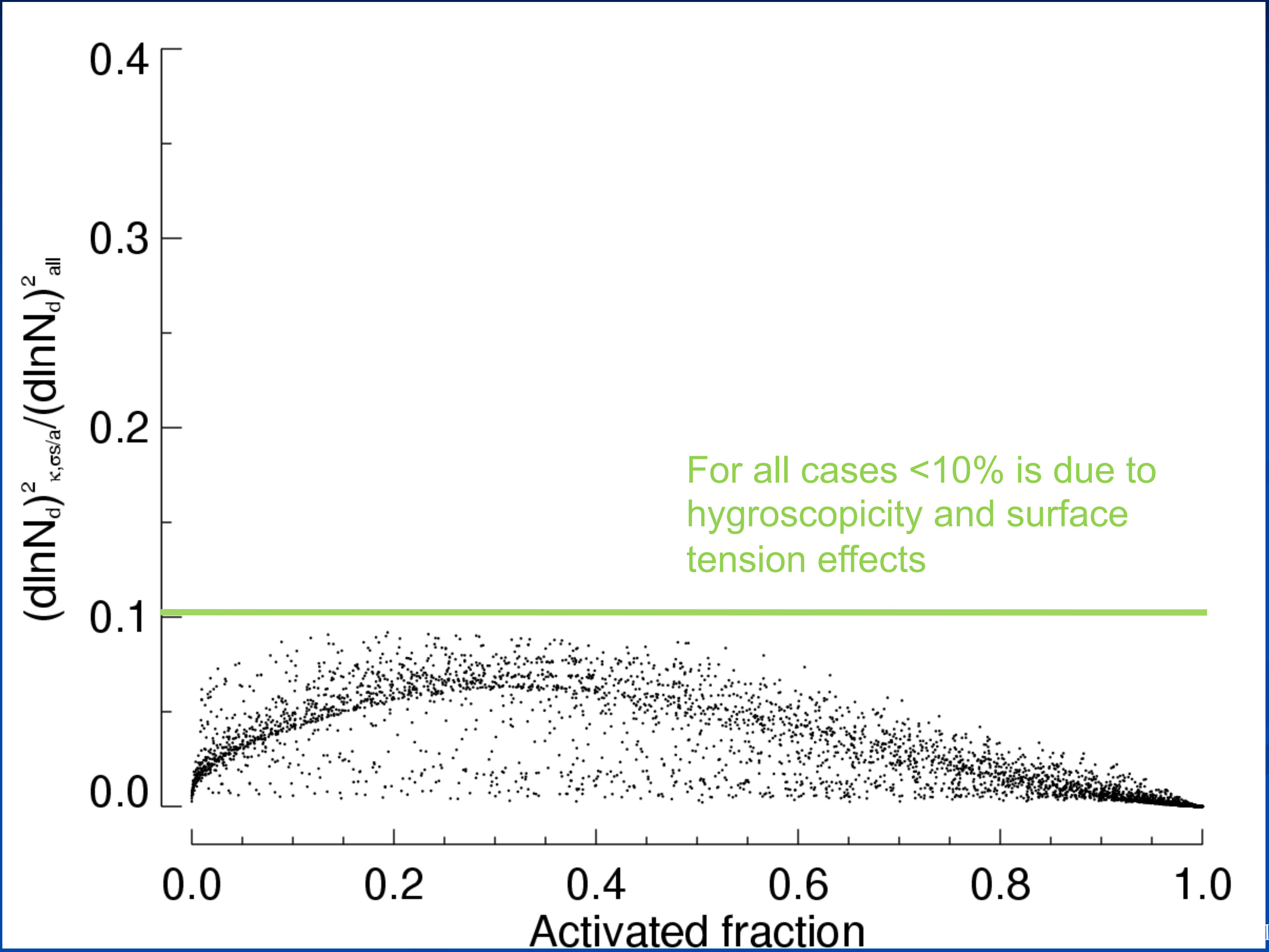
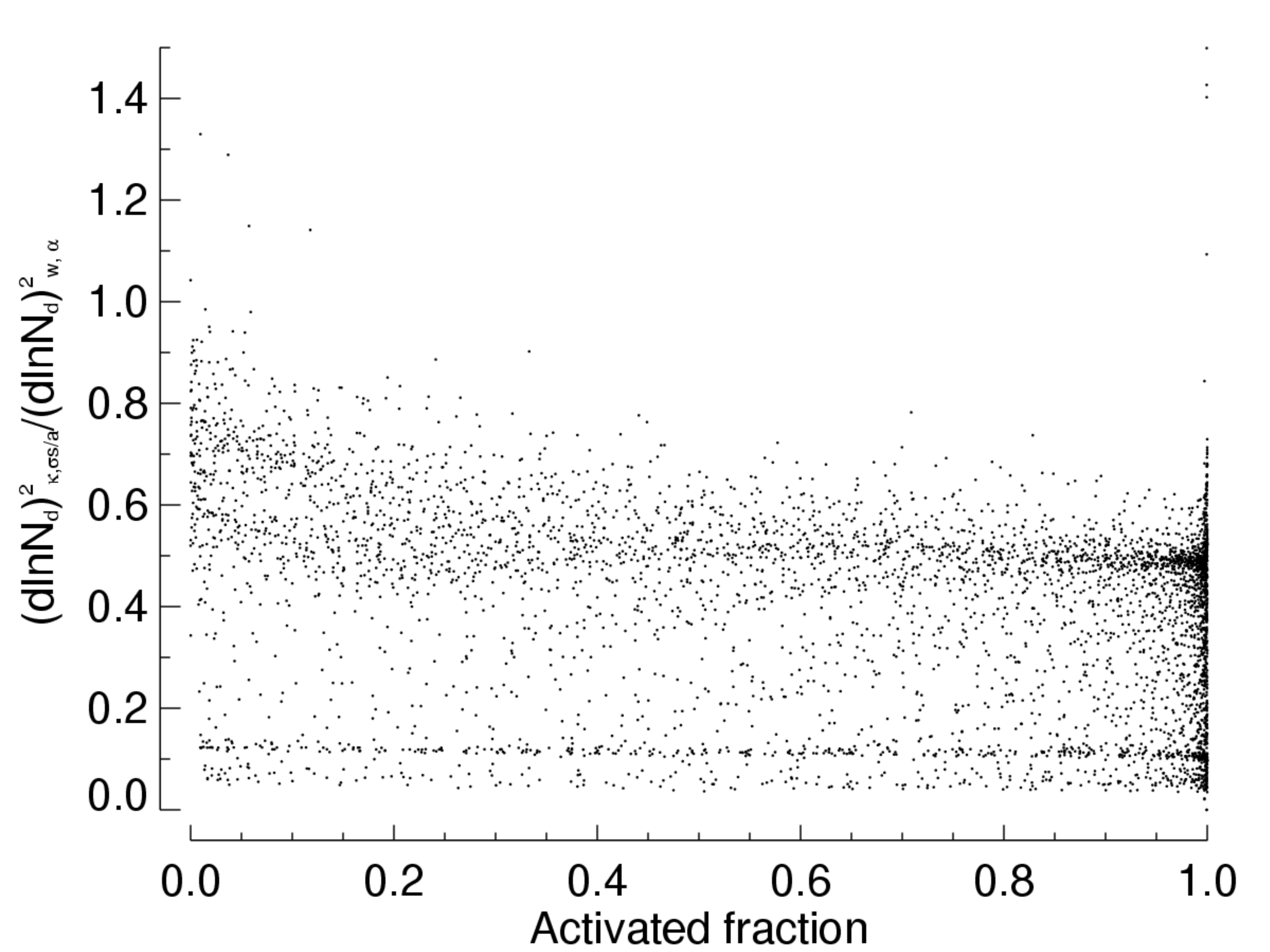
Chemical effects vs. total sensitivity



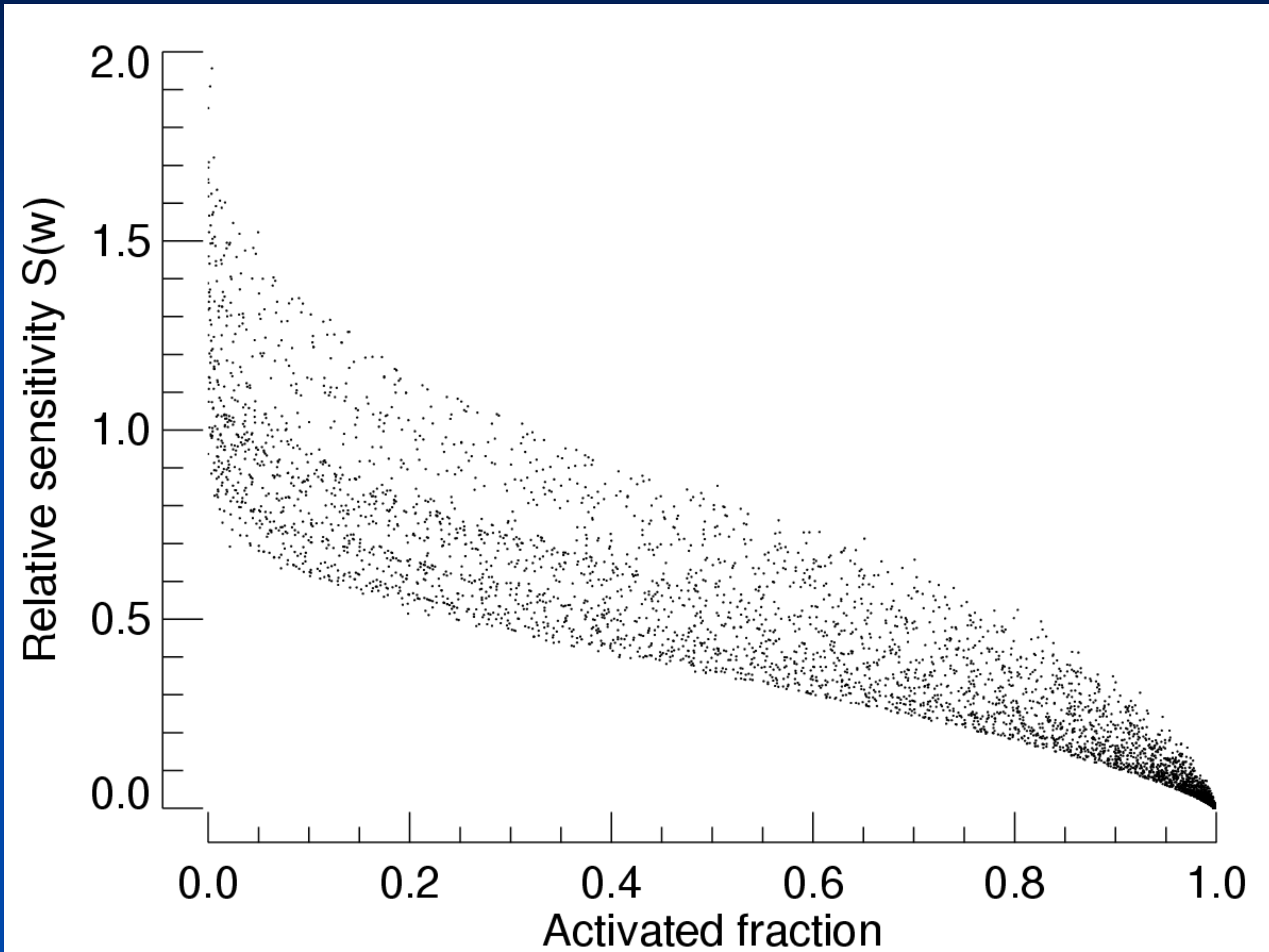
Petters

Chemical effects vs. dynamic effects



Courtesy of M. Petters

Dynamical effect: Change in droplet concentration due changes in updraft (w)



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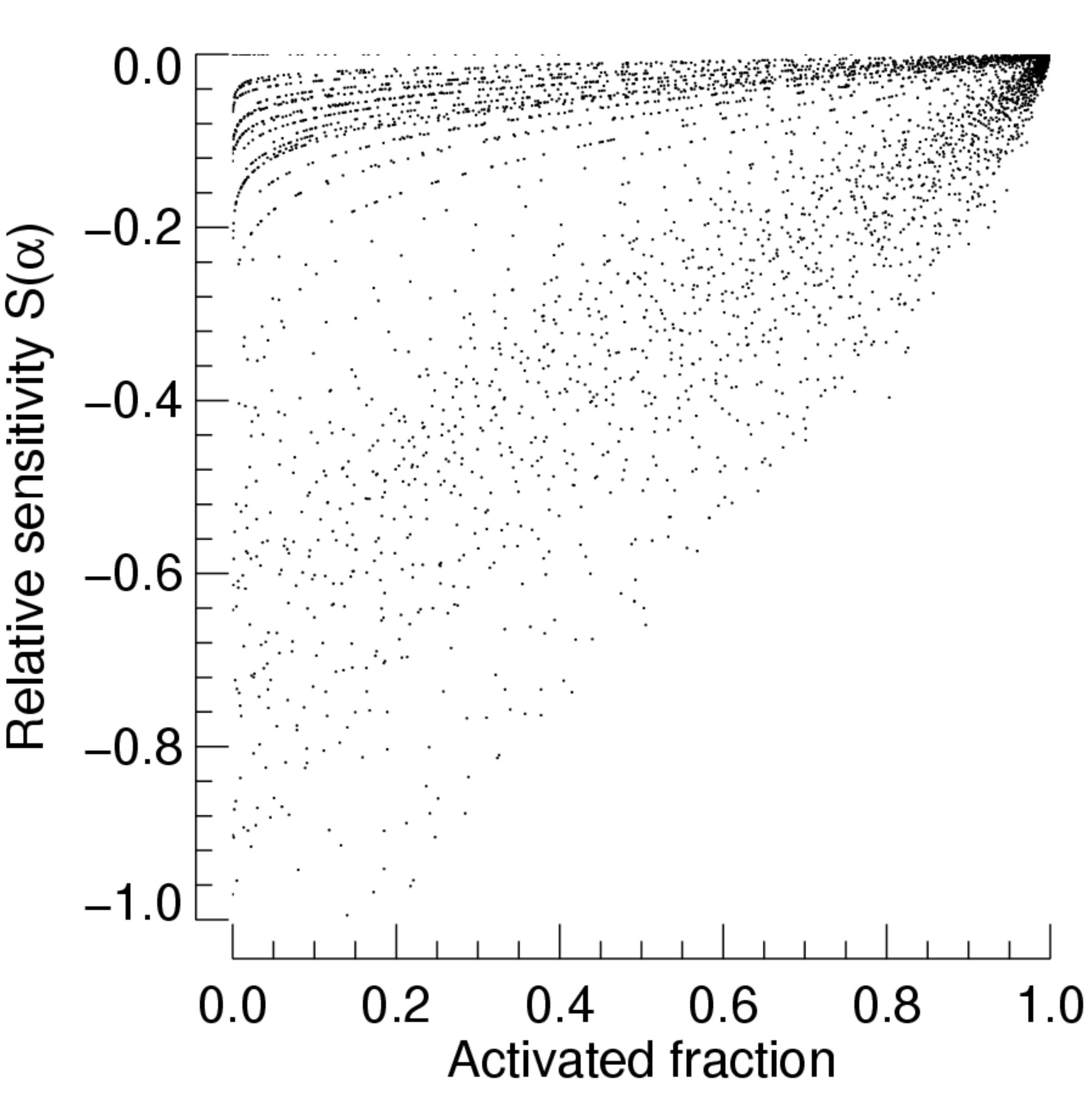
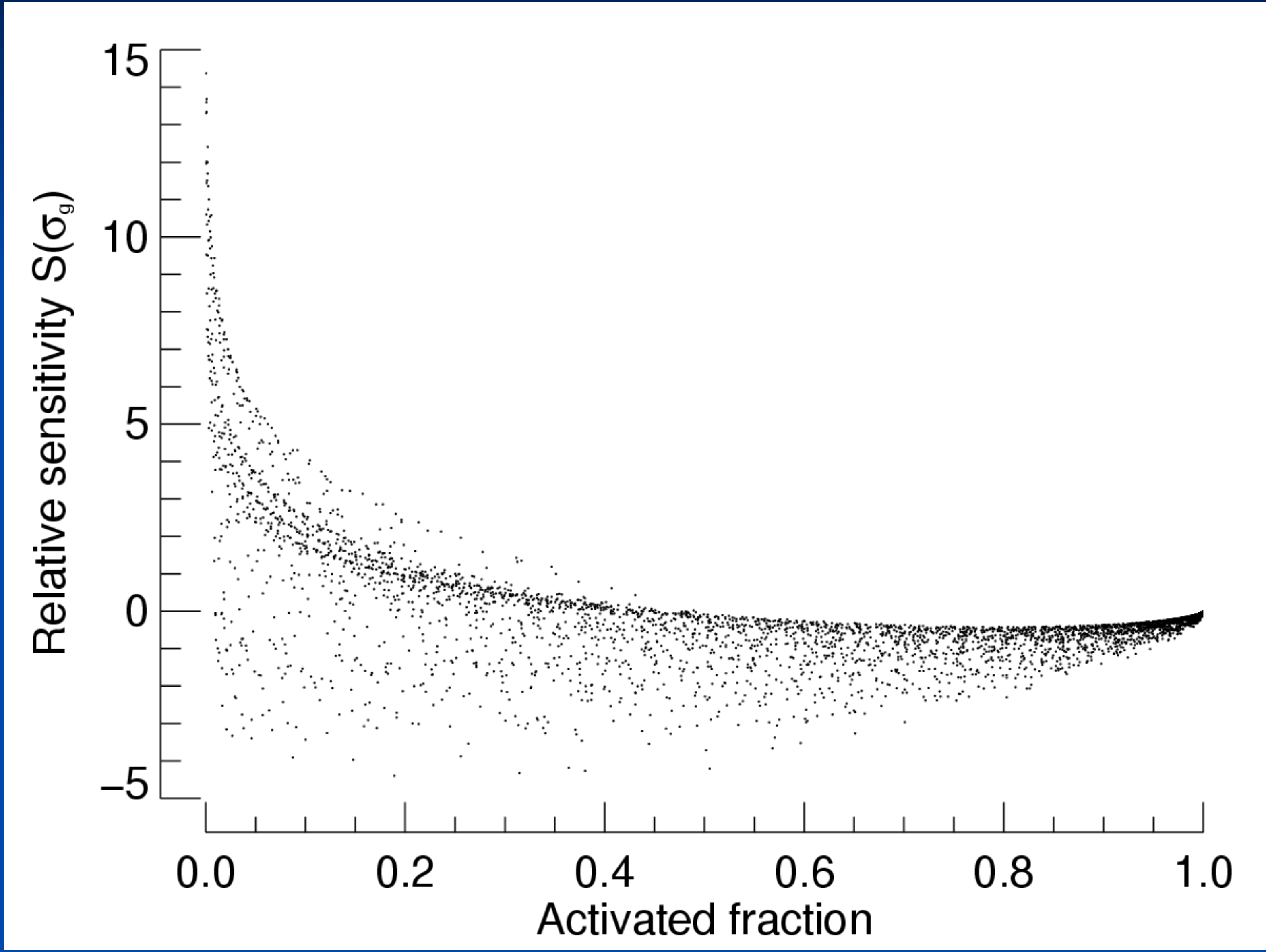
Dynamical effect: Change in droplet concentration due changes in condensation coefficient (α)



Negative sensitivity: Alpha increases, droplets take up water faster, max supersaturation decreases.

Courtessy of M. Petters

Size distribution: Change in droplet concentration due changes in geometric standard deviation



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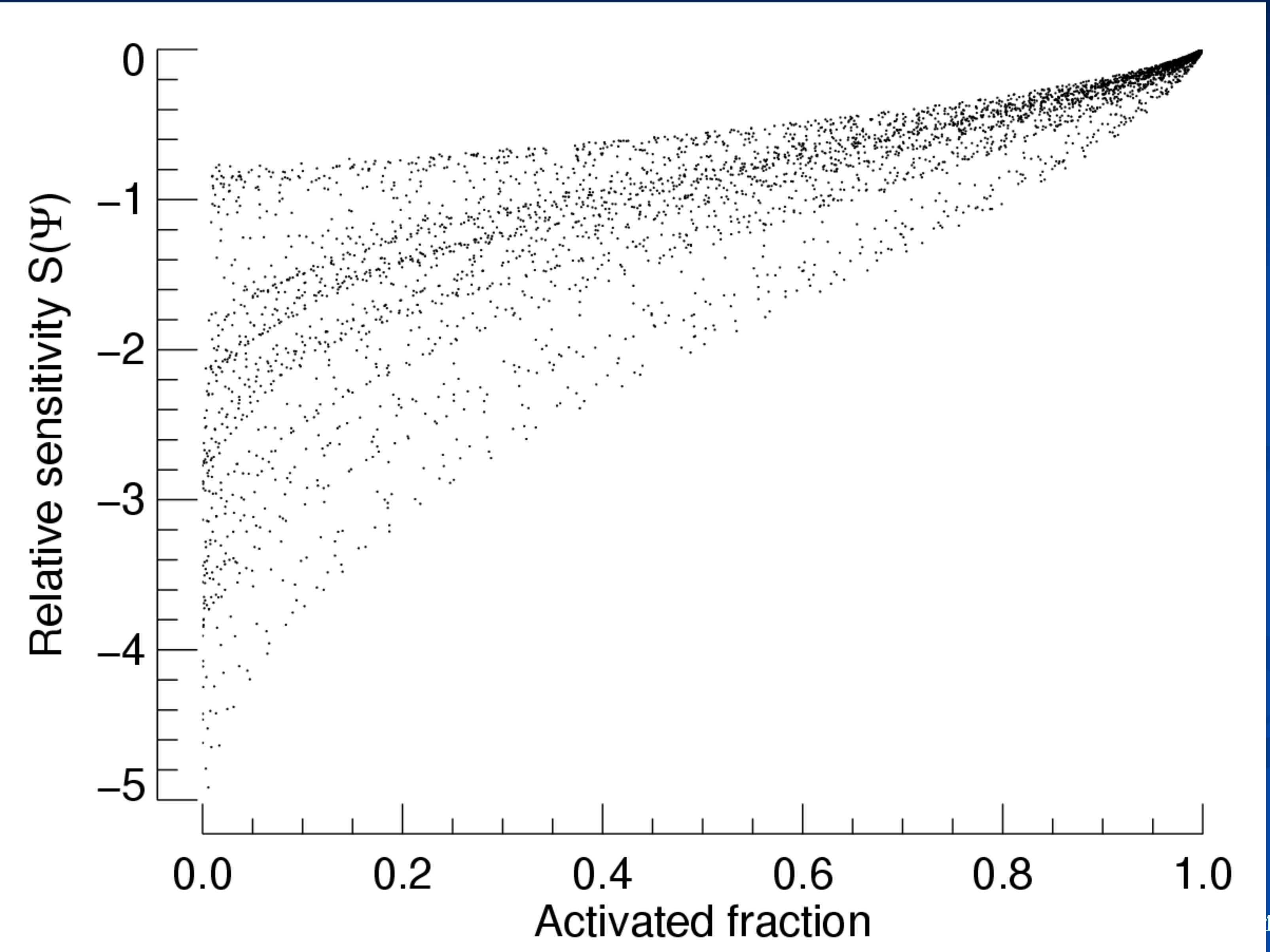
Size distribution: Change in droplet concentration due changes in activation parameter (Ψ)



M. Petters

How does a percent change in input X_i transmute into a percent change in droplet concentration

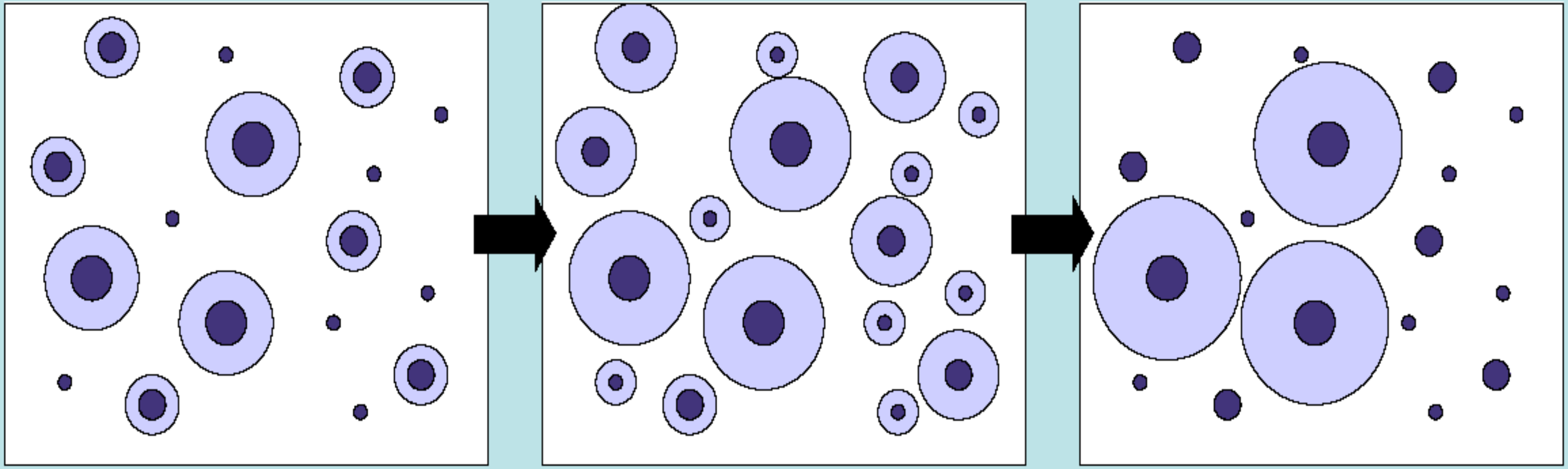
Relative sensitivity of CDNC to X_i

$$S(X_i) \equiv \frac{\frac{\Delta N_d}{N_d}}{\frac{\Delta X_i}{X_i}} = \frac{\partial \ln N_d}{\partial \ln X_i}$$

$$X_i \in \{\Psi, N_t, D_g, \sigma_g, \alpha\}$$

"Traditional" Köhler Curves - I

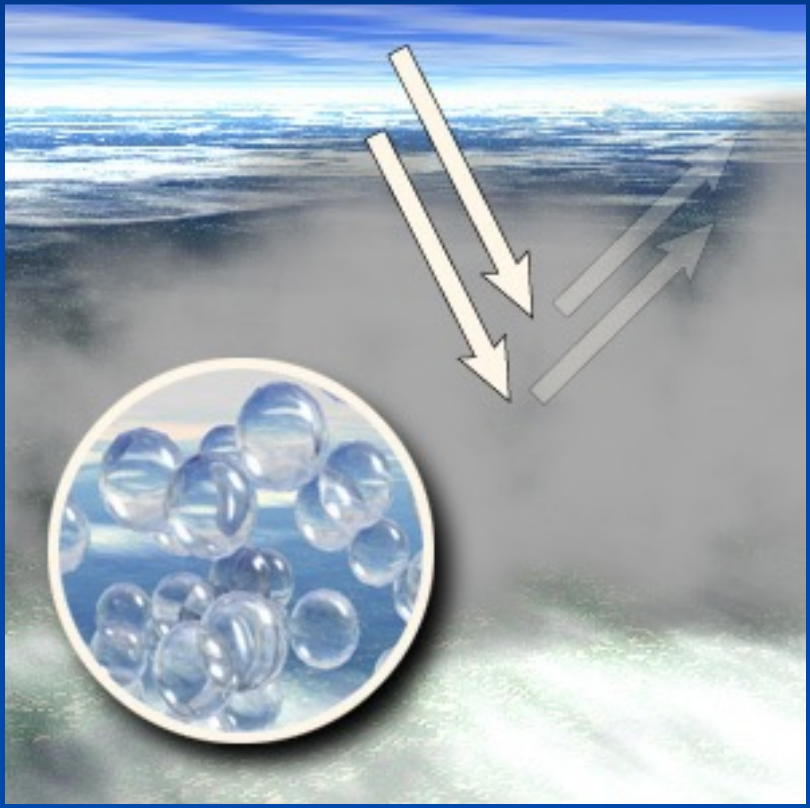
- As air becomes saturated, large drops deliquesce first (curvature effects)
- As pass through saturation some drops pass barrier some do not…
- As vapor continues to condense to reach equilibrium vapor pressure, drops that did not pass the radius ("concentration") barrier will shrink (evaporate) to a smaller size allowing larger particles to continue to grow…

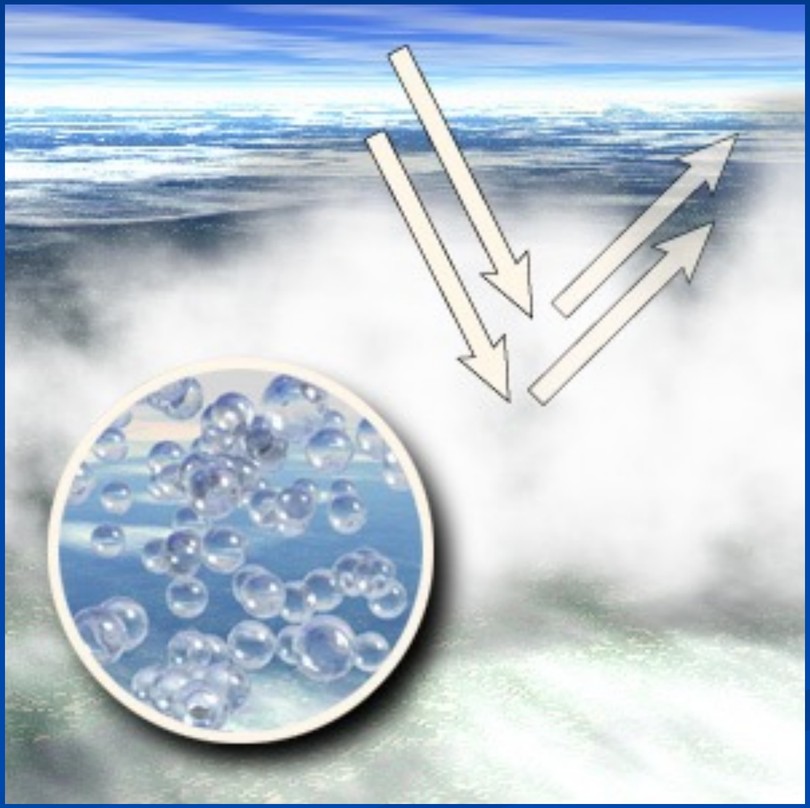


Courtesy of Hilding Köhler, Aerosol group, SCRIPTS Institute USA

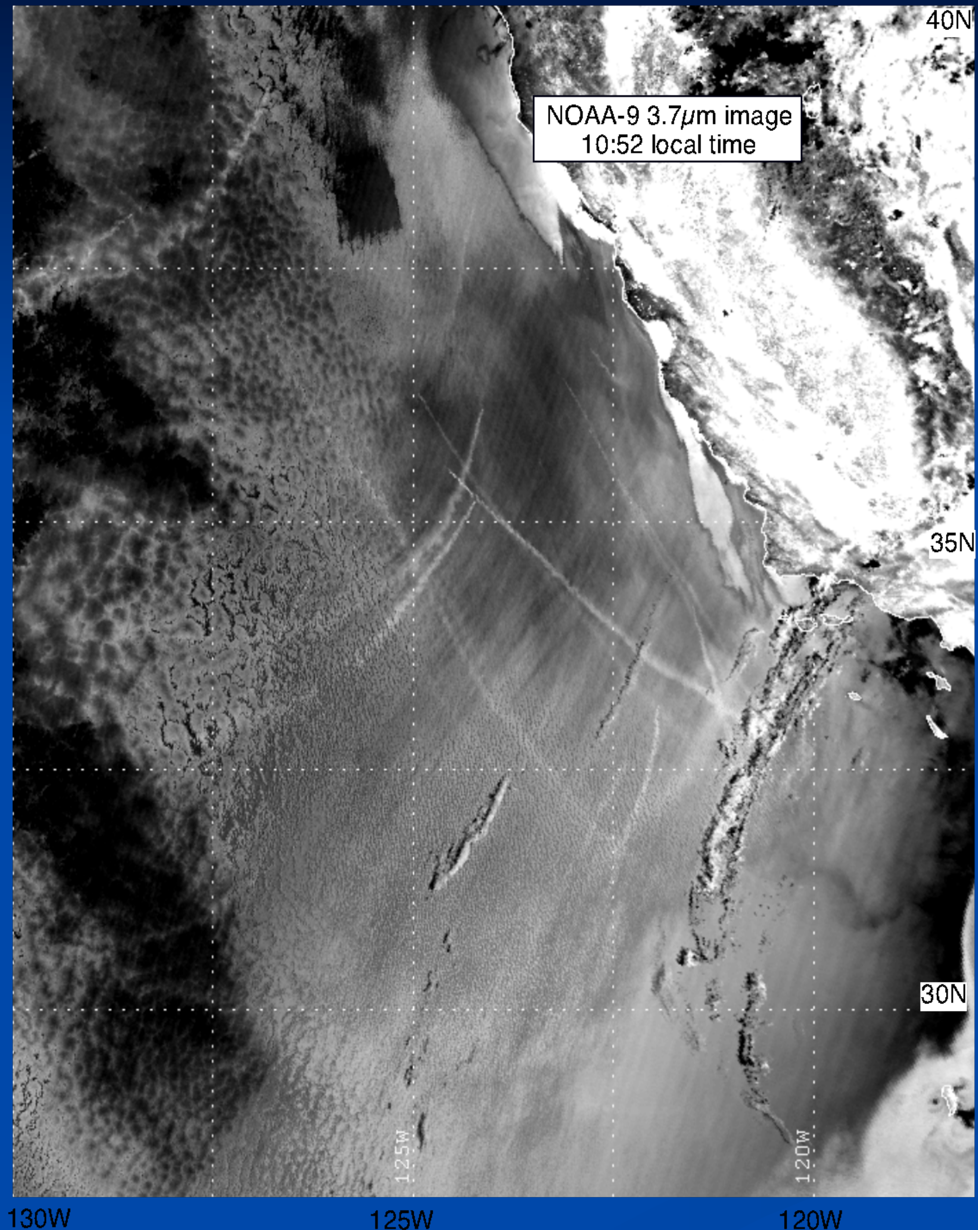
Twomey effect

For a given LWC and geometric height,
clouds with more droplets are more reflective



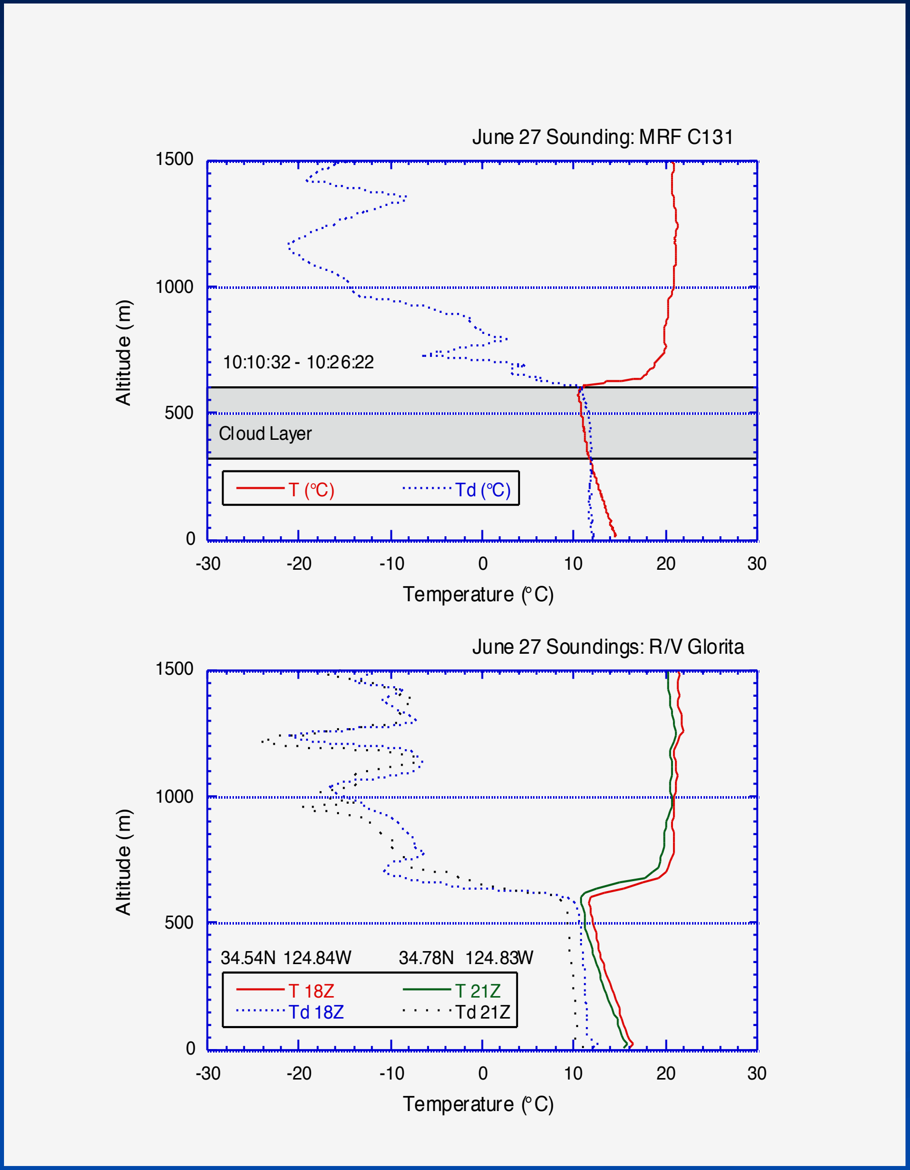


Some "Real" Cloud Physics: Ship Tracks



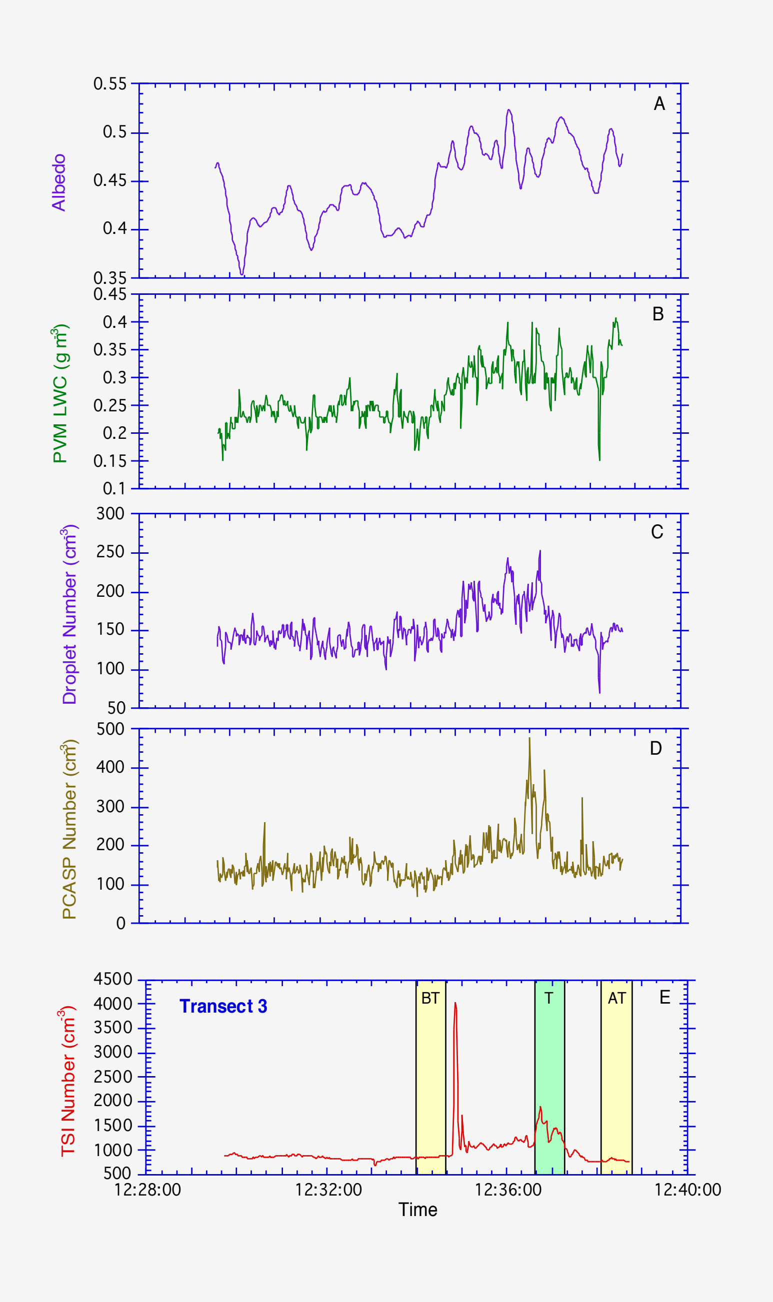
Noone, et al., JAS (2000)

Boundary Layer Properties



Noone, et al., JAS (2000)

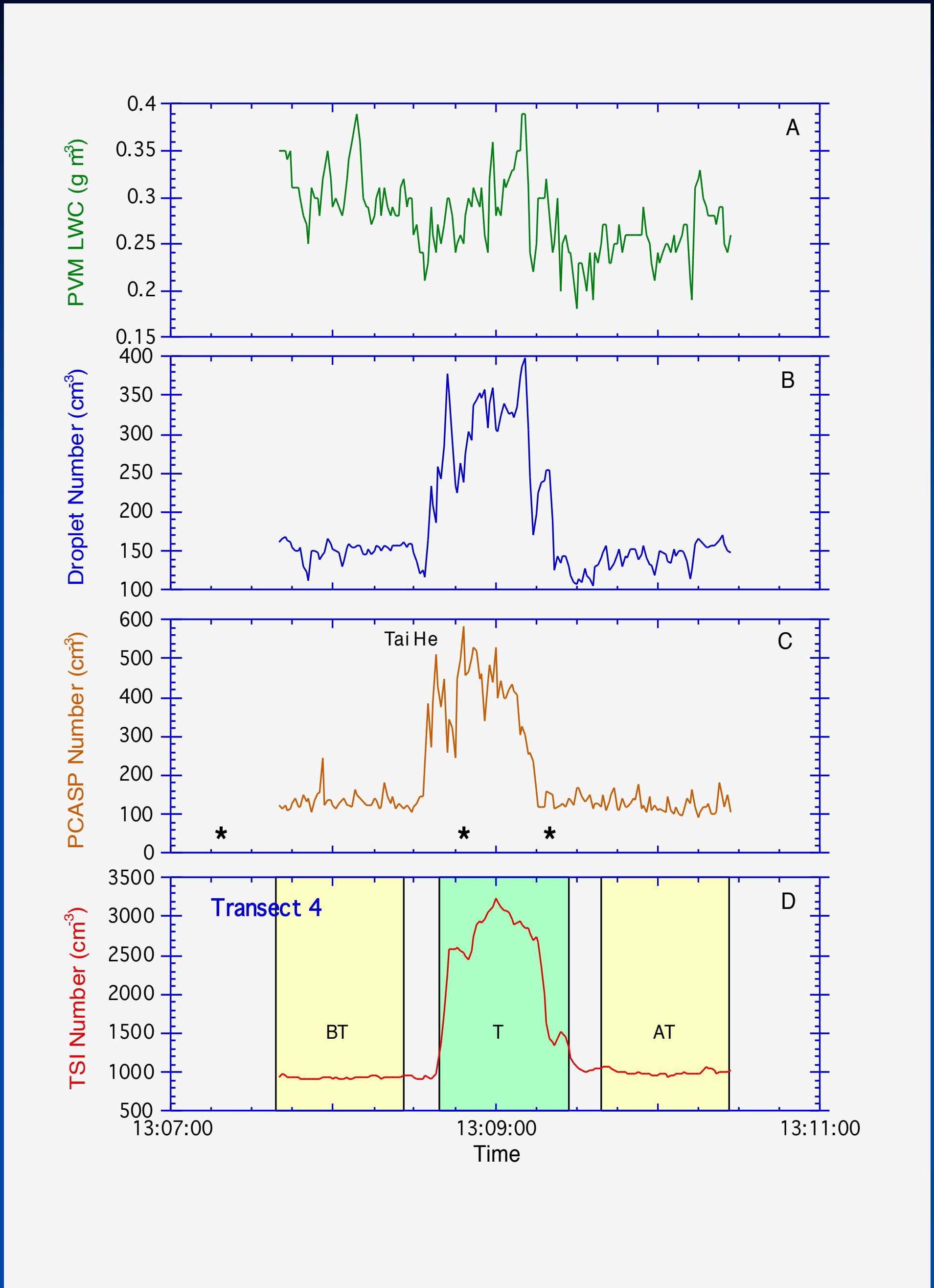
Ship Track Transect



"Typical" marine stratocumulus clouds

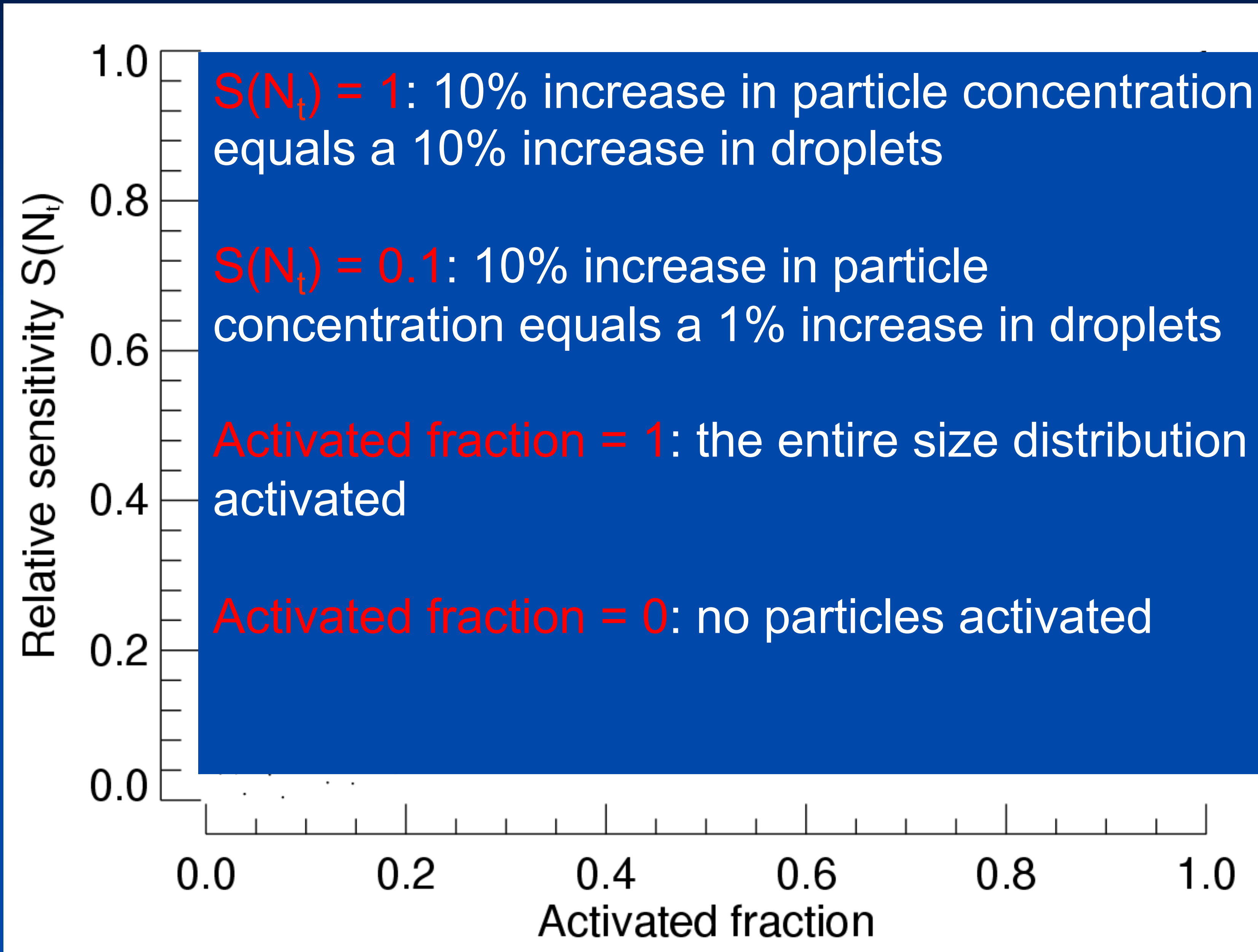
Noone, et al., JAS (2000)

Another Ship Track Example



Noone, et al., JAS (2000)

The Twomey effect: Change in droplet concentration due to the addition of CCN number



$S(N_t) = 1$: 10% increase in particle concentration equals a 10% increase in droplets

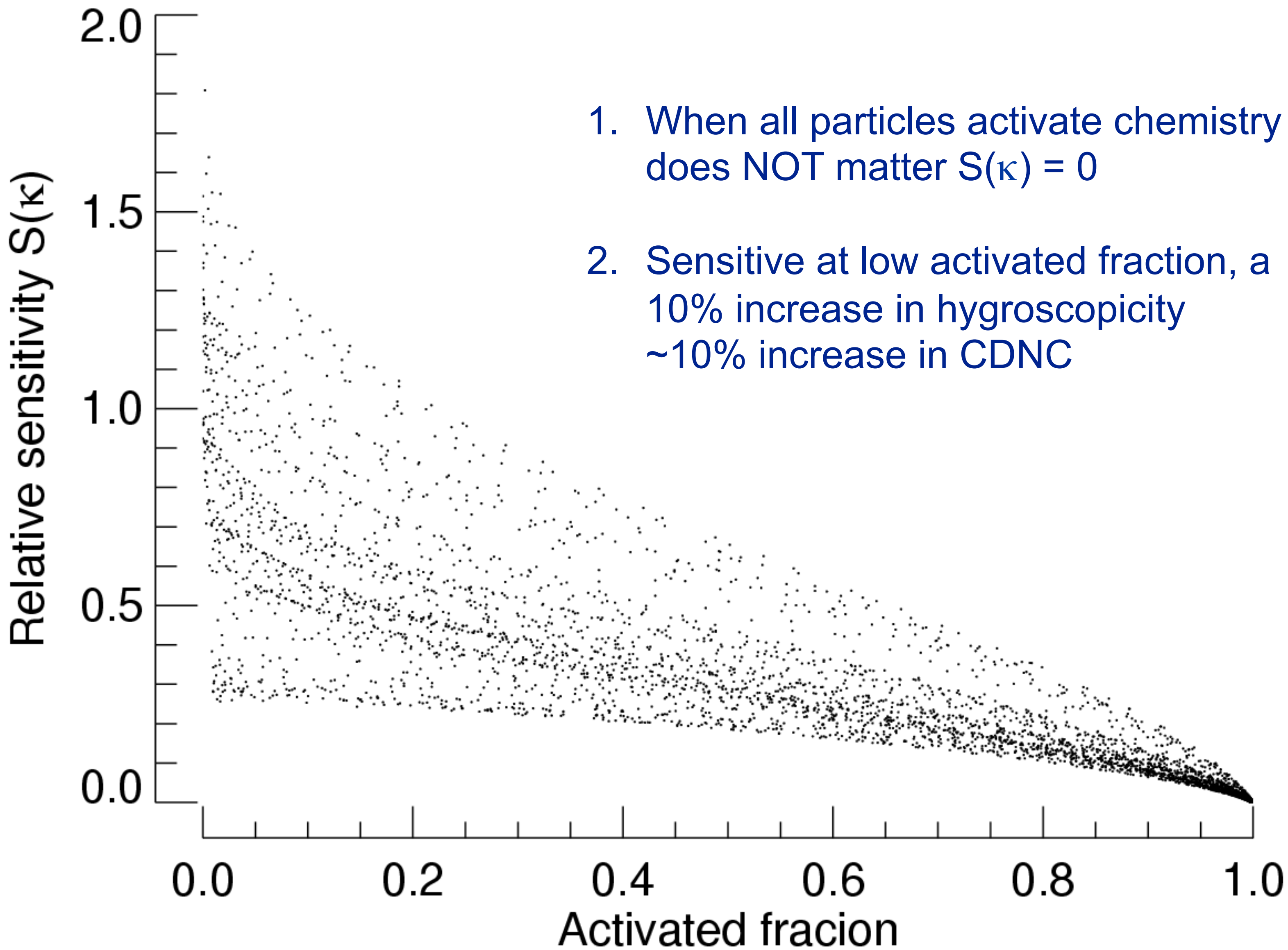
$S(N_t) = 0.1$: 10% increase in particle concentration equals a 1% increase in droplets

Activated fraction = 1: the entire size distribution activated

Activated fraction = 0: no particles activated

Petters

Chemical effect: Change in droplet concentration due changes in particle hygroscopicity (κ)



1. When all particles activate chemistry does NOT matter S(κ) = 0

2. Sensitive at low activated fraction, a 10% increase in hygroscopicity ~10% increase in CDNC

essy of M. Petters

How to make sense of all the information?

$$\text{Total sensitivity}^2 =$$

$$S(N_t)^2 + S(D_g)^2 + S(\sigma_g)^2$$

$$+ S(w)^2 + S(\alpha)^2$$

$$+ S(\kappa)^2 + S(\sigma_{s/a})^2$$

Microphysical effects
(size distribution)

Dynamical effects
(updraft + growth kinetics)

Chemical effects
(hygroscopicity + surface tension)

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Sensitivity scaling

$$\frac{\text{Microphysical effects}}{\text{Total sensitivity}}$$

70% (size distribution)

$$\frac{\text{Dynamical effects}}{\text{Total sensitivity}}$$

20% (updraft + growth)

$$\frac{\text{Chemical effects}}{\text{Total sensitivity}}$$

10% (hygroscopicity + surface tension)

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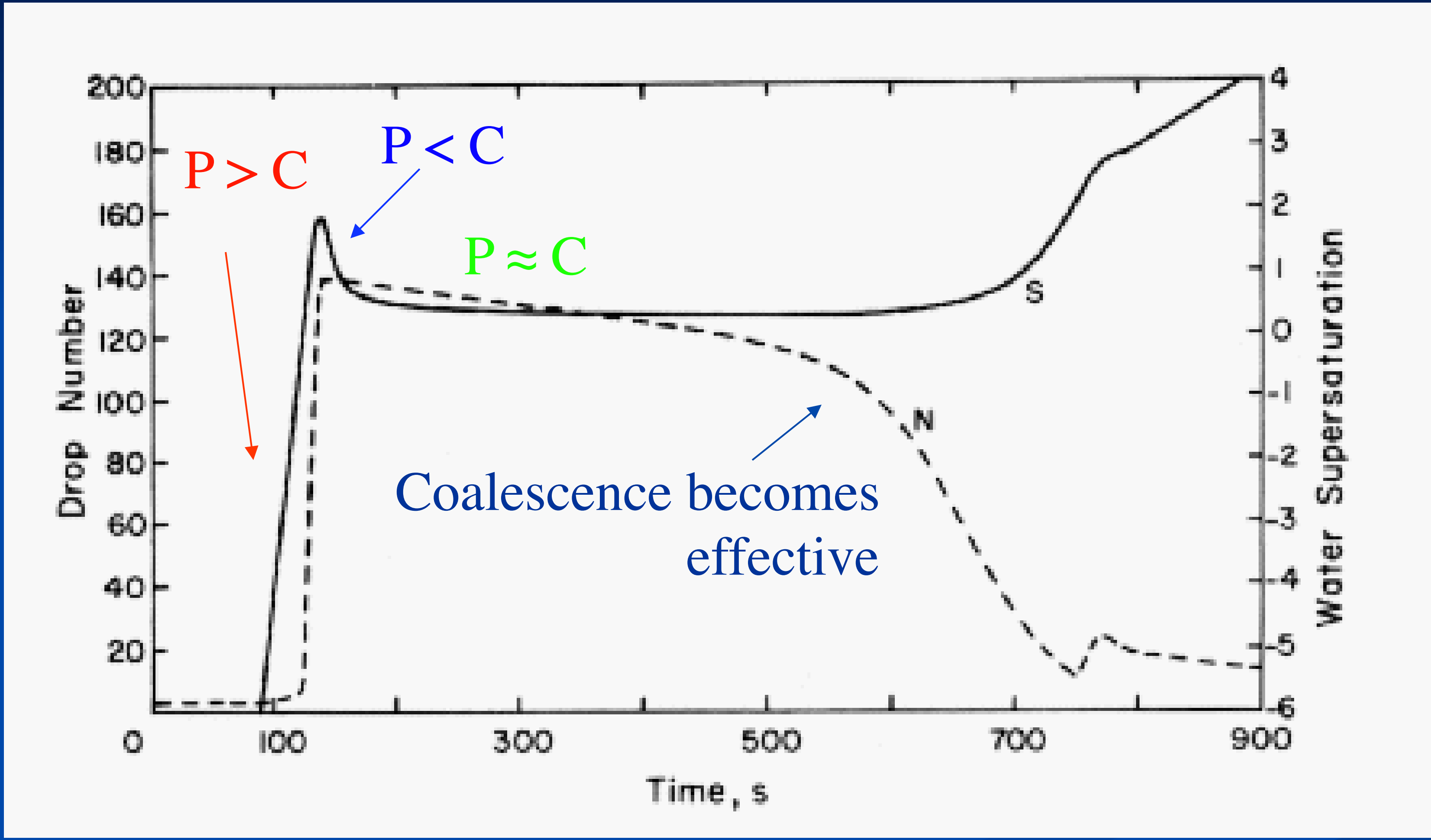
N & S Variations 1

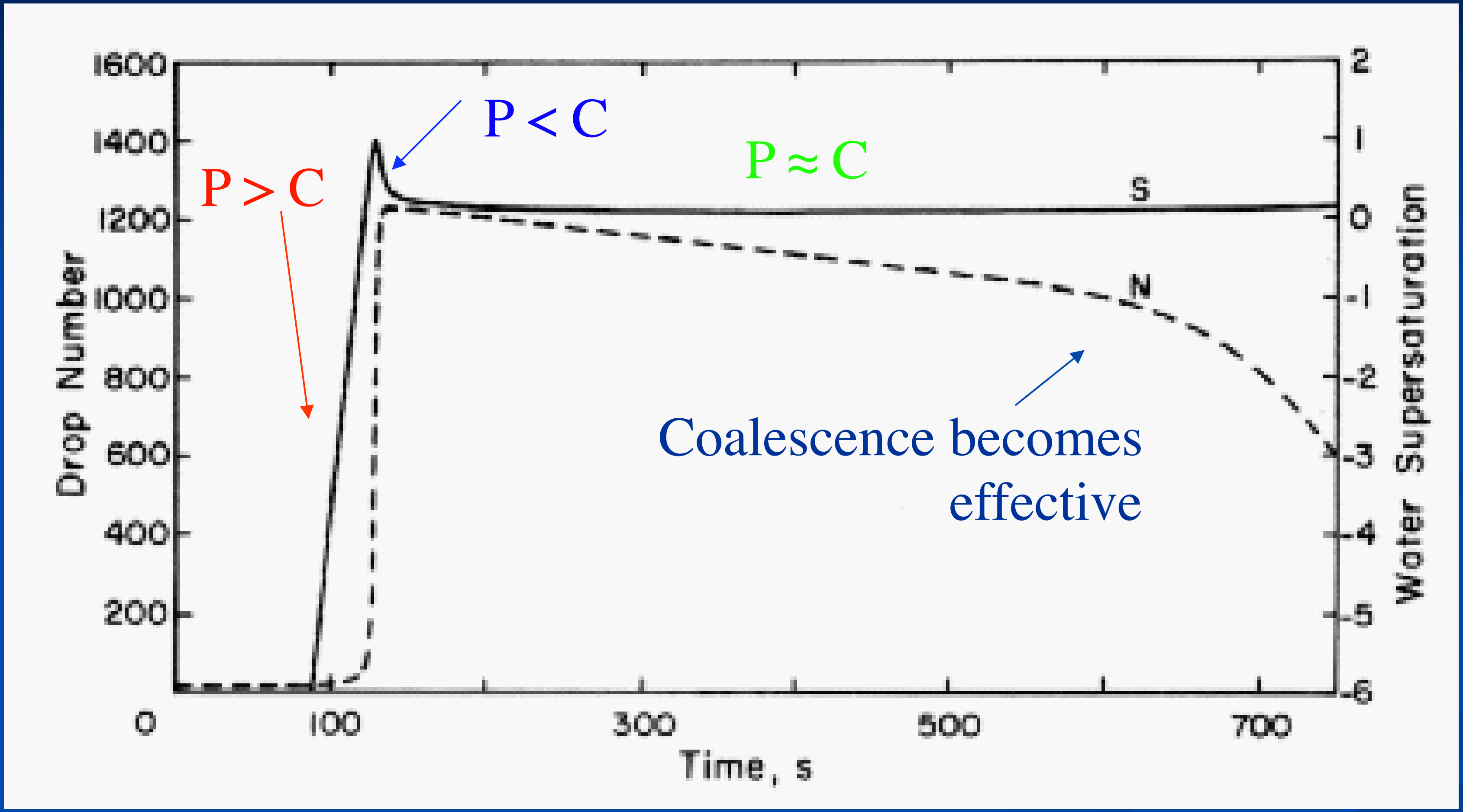


$$\frac{dS}{dt} = P - C$$

Maritime case: $N_{CCN} = 105\ s^{0.63}$

Fig. 8.13

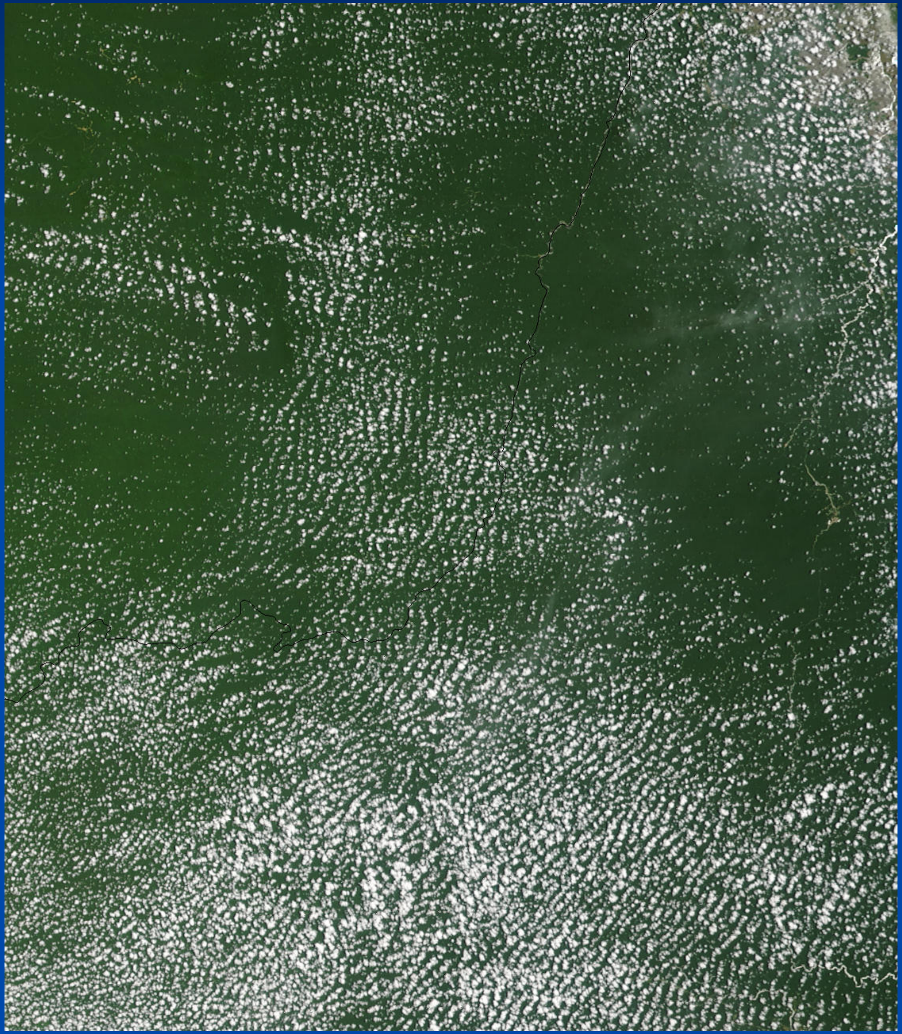
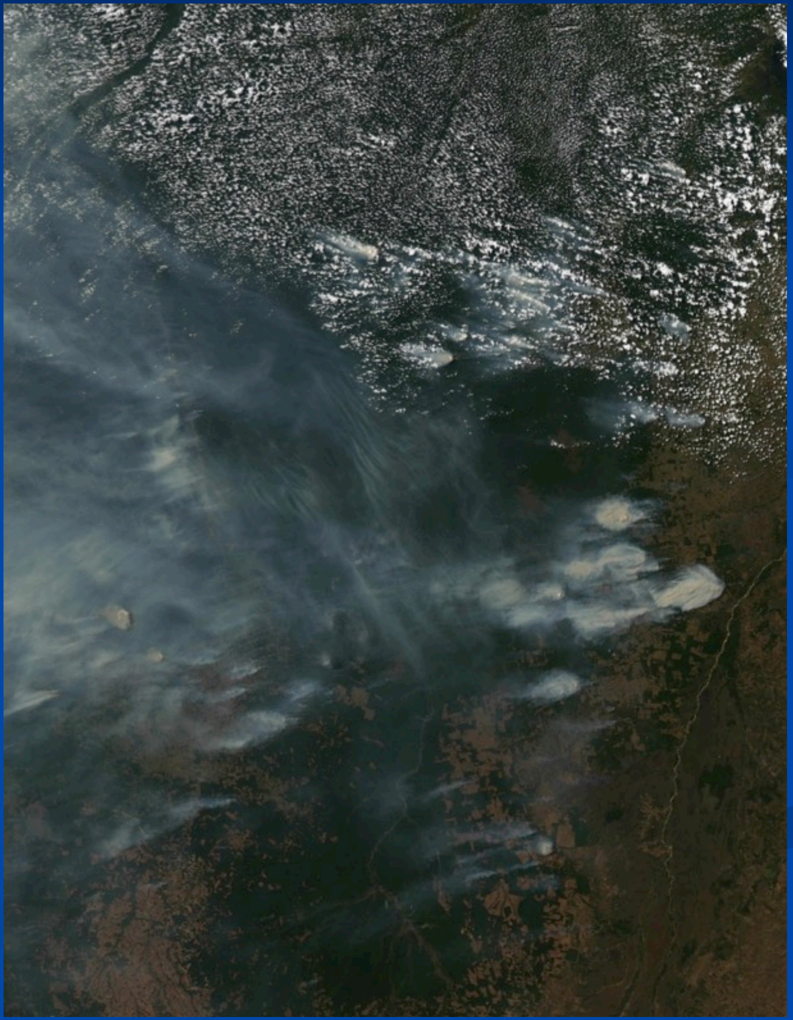
N & S Variations 2



$$\frac{dS}{dt} = P - C$$

Continental case: $N_{CCN} = 1450\ s^{0.84}$

Fig. 8.14

Droplet Growth by Condensation

Once critical size r* and saturation ratio S* is exceeded solution droplet become a cloud droplet

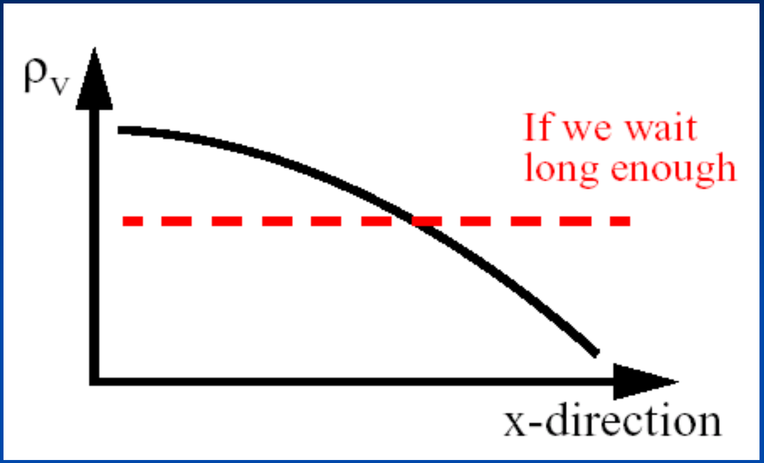
The growth of droplet continues is due to diffusion of water molecules onto its surface

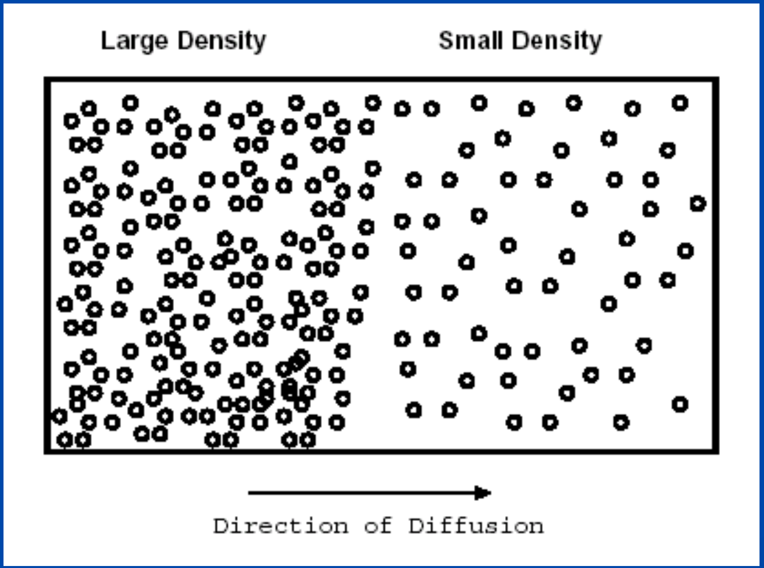
First we will have a look on a single droplet

Later on we will examine more realistic situation of droplet population where single droplets compete for available water vapor

Diffusional growth – summary 1

Diffusion theory is essentially what vapor growth is based on.





1.) Density is large to the left.

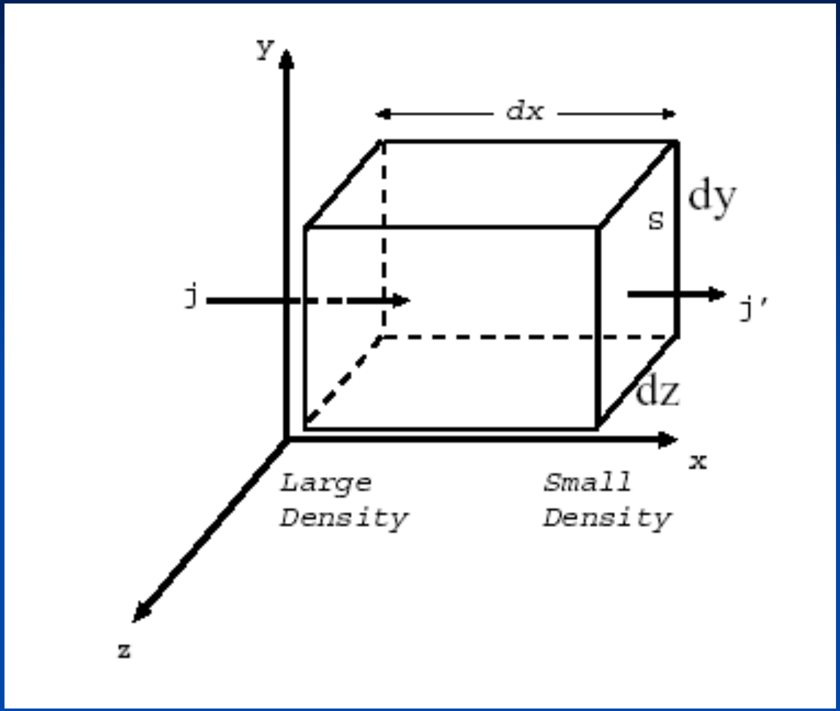
2.) Molecules are continually moving around in the gas. Since there are more molecules to the left in the figure, more molecules will be moving to the right than to the left.

3.) There will be a net transfer of vapor molecules to the right with time ("diffusion").

4.) If we wait long enough, diffusion will smooth-out the original gradient. So, diffusion acts to remove gradients.

5.) Diffusion is slow over large distances. Hence it is of little direct importance in large-scale dynamics. However, vapor growth occurs on small scales and diffusion is very important here.

Diffusional growth – summary 2



6.) **Fick's law** tells us that the *flux* of vapor along the x direction due to diffusion is dependent on the gradient and a diffusion coefficient:

$$j_v = -D_v \frac{\partial \rho_v}{\partial x}$$

This is a mass flux: $kg\ m^{-2}\ s^{-1}$

7.) *Dv* depends on *T, P* and is called the vapor diffusivity - it tells us how quickly vapor will diffuse. For example, as temperature rises molecules in the gas move faster. Diffusion should increase. This dependence is taken into account in *Dv*.

This flux is important because it is what will determine the mass growth rate of a drop.

Growth of droplet population

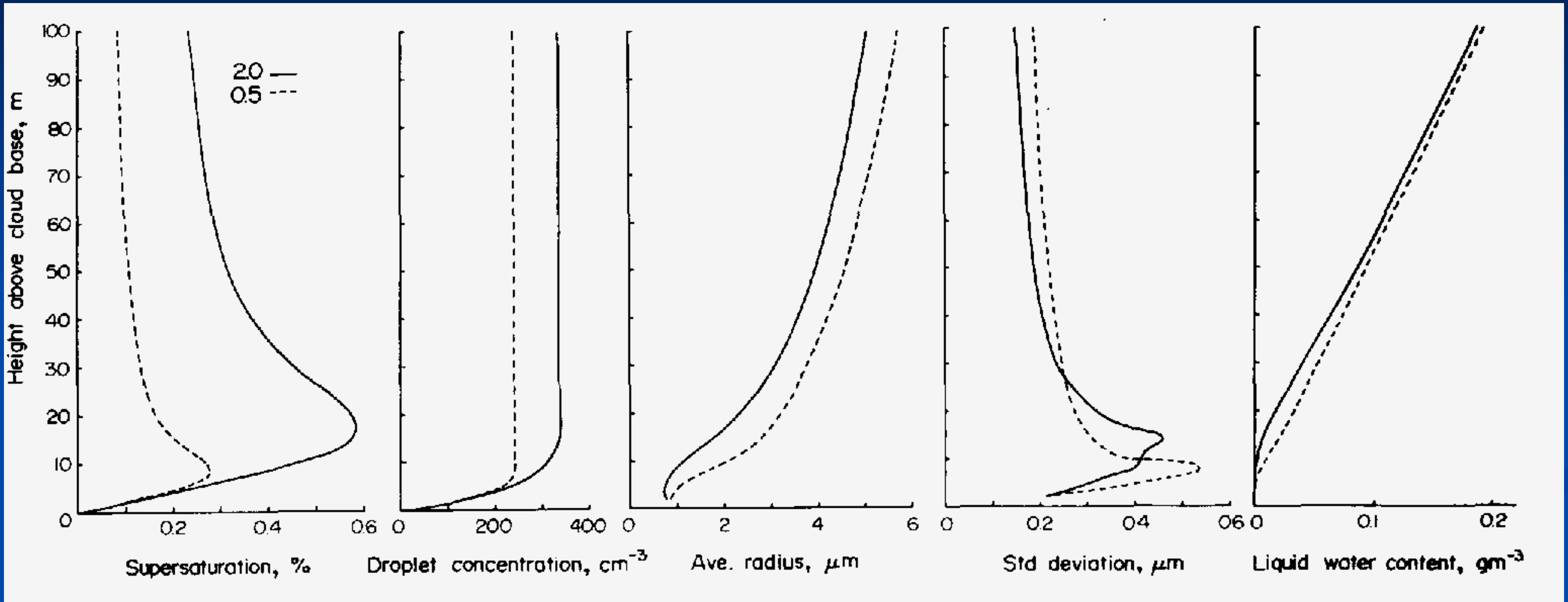


FIG. 7.4. Early development of cloud properties in air ascending at constant velocity of 0.5 m/s or 2 m/s.

<u>Initial conditions</u>

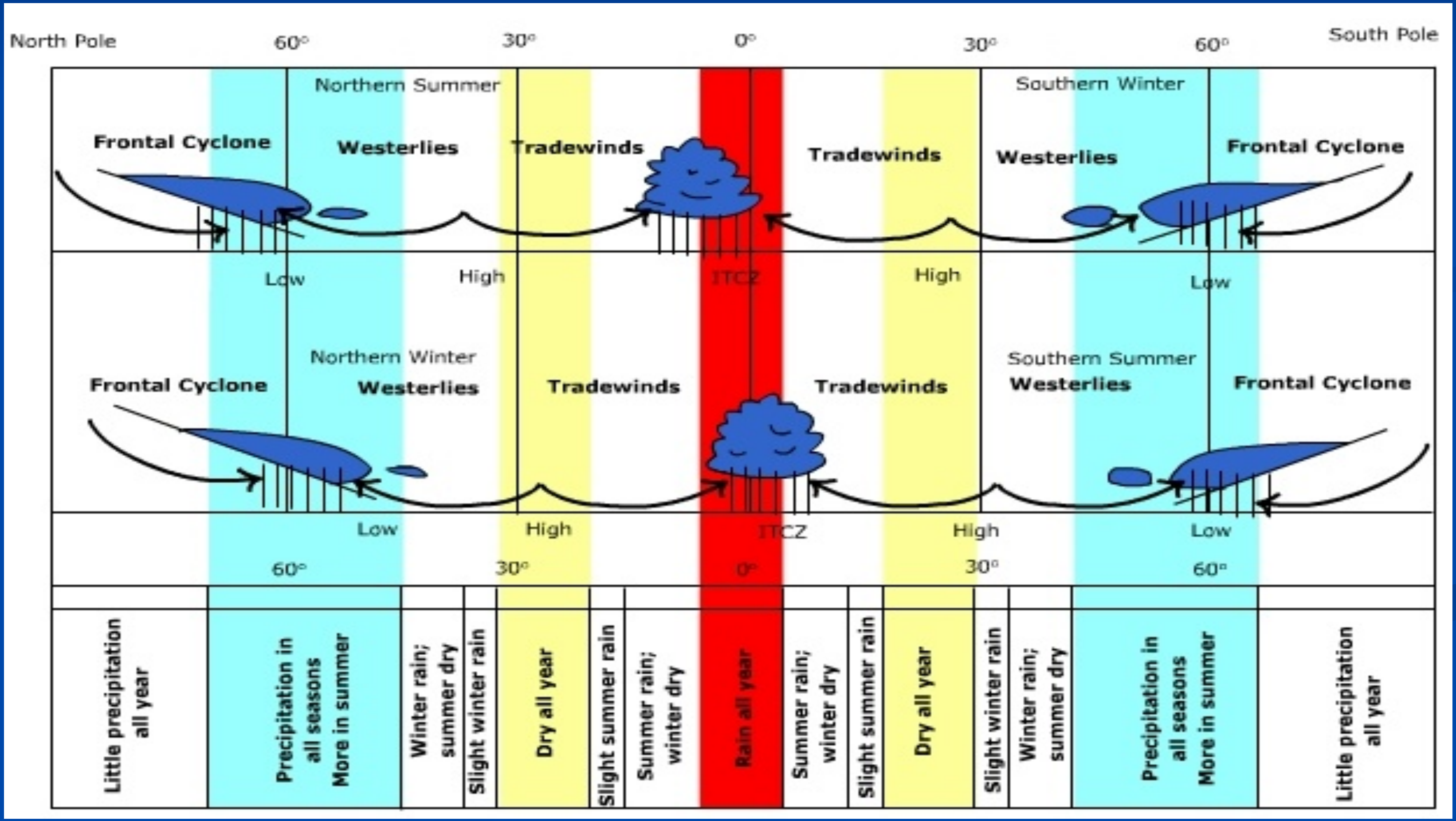
Population of NaCl nuclei with $N_c = 650 \cdot S^{*0.7}$ cm^{-3}

U = 2 m s^{-1} (solid) and 0.5 m s^{-1} (dashed)

Setting the stage 1

Rain removes from cloud mass and energy

Most of the precipitation on Earth is associated with clouds where temperatures do not extend below 0 C (warm clouds). Due to a regional distribution of precipitation.



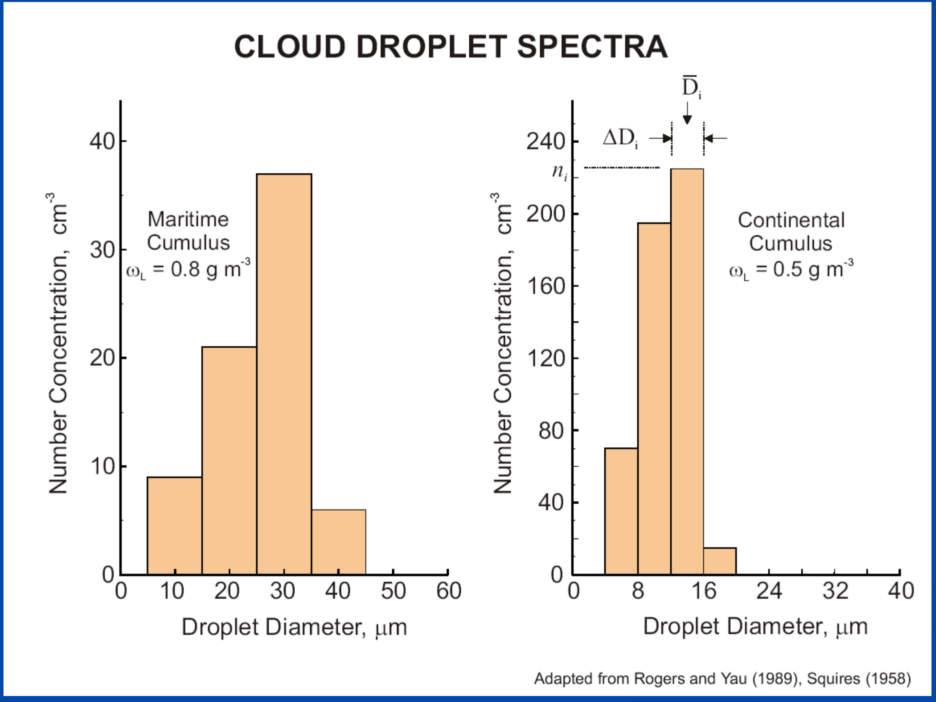
Setting the stage 2

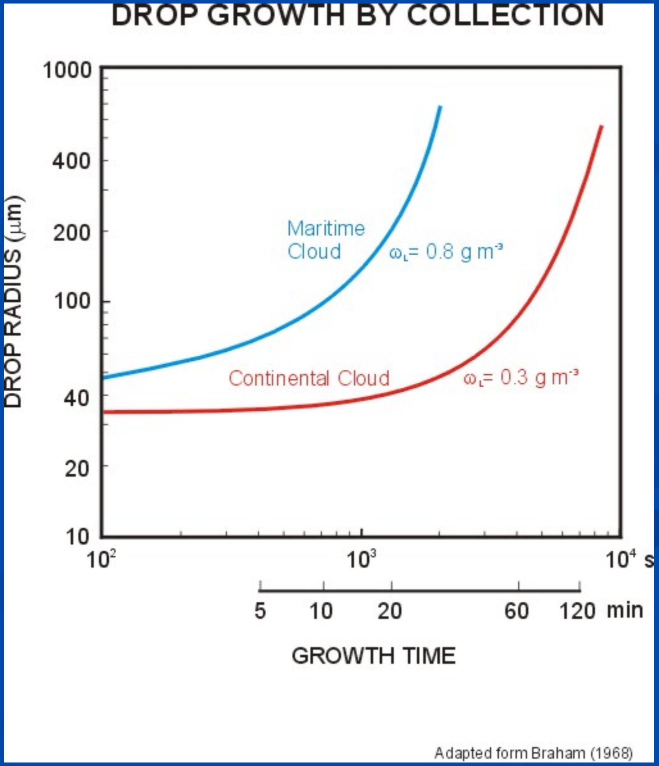
How we can form precipitation in a warm cloud in 20 minutes? Why 20 minutes?

General opinion: collision and coalescence are major rain forming mechanisms

They are effective > 20 μm drop size?

What is a size of ususal cloud drop when cloud is formed?





Setting the stage 3

$$r(t) = \left[r_0^2 + 2\xi t \right]^{1/2}$$

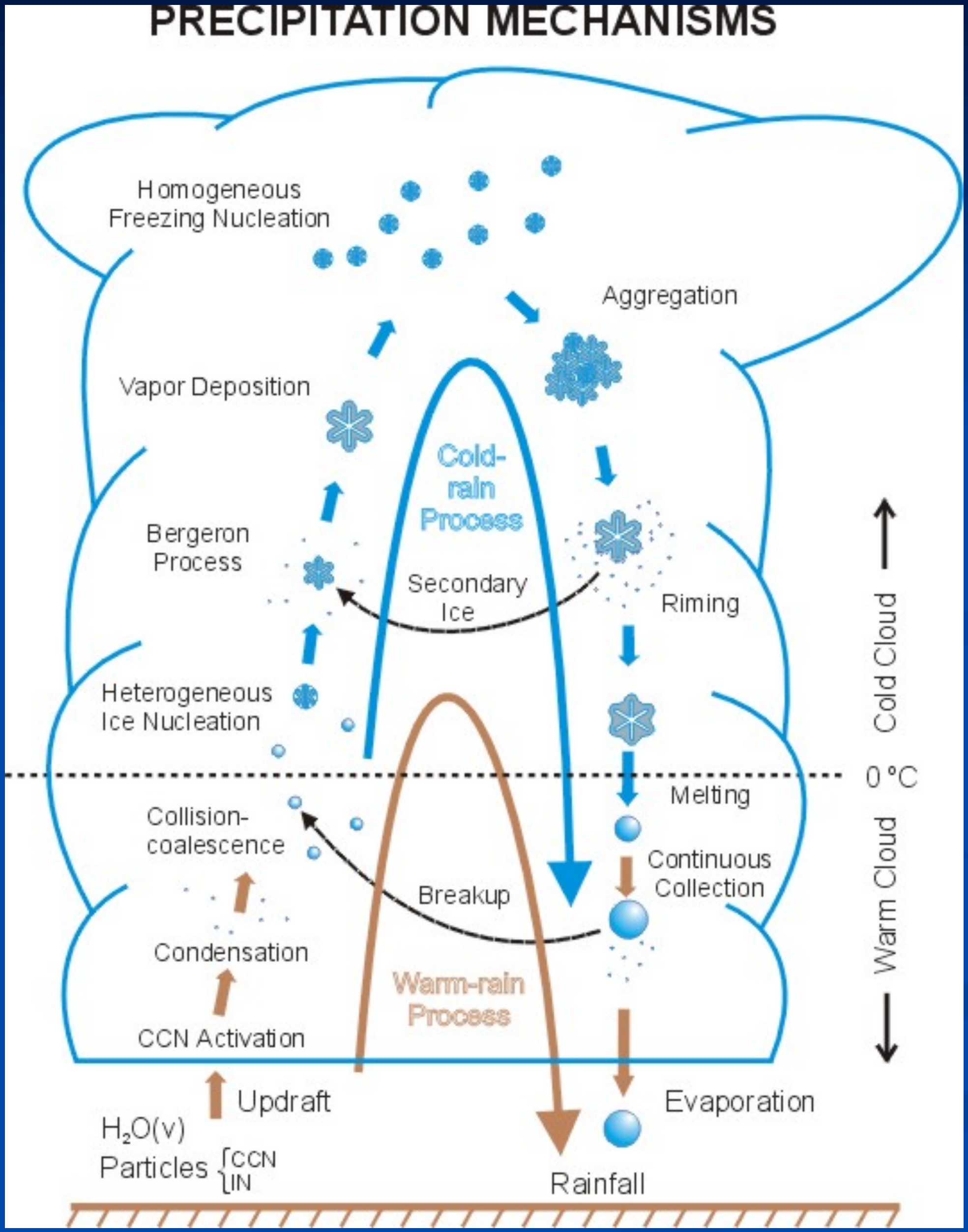
To reach 20 μm
S = 0.5%
Updraft 5 m/s

Is it realistic or not?

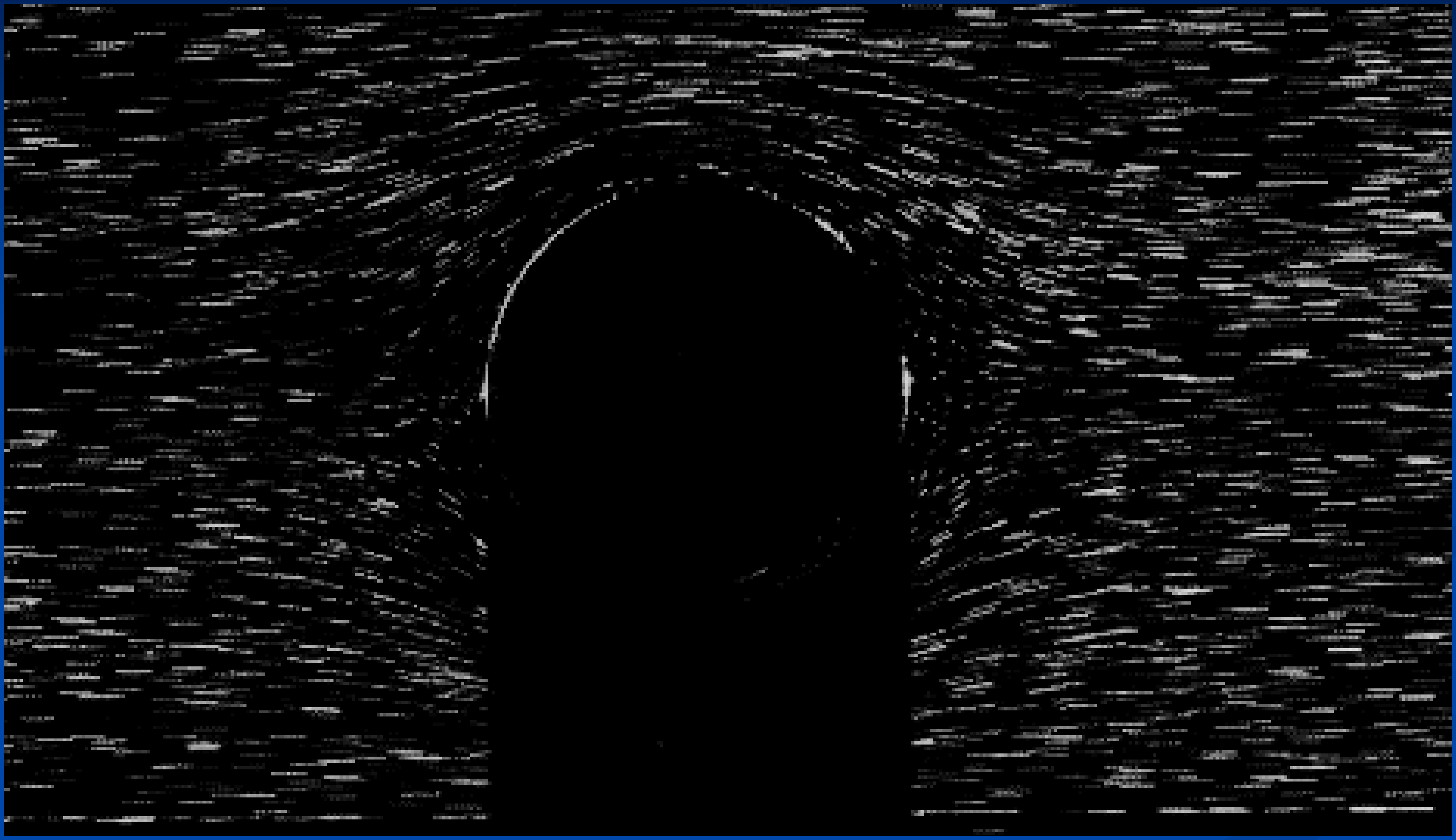
So, how can make drops large enough in a short time so that coalescnece can be effective?:

Broadening of cloud rop spectra due to a mixing, entrainment and turbulence

Setting the stage 4



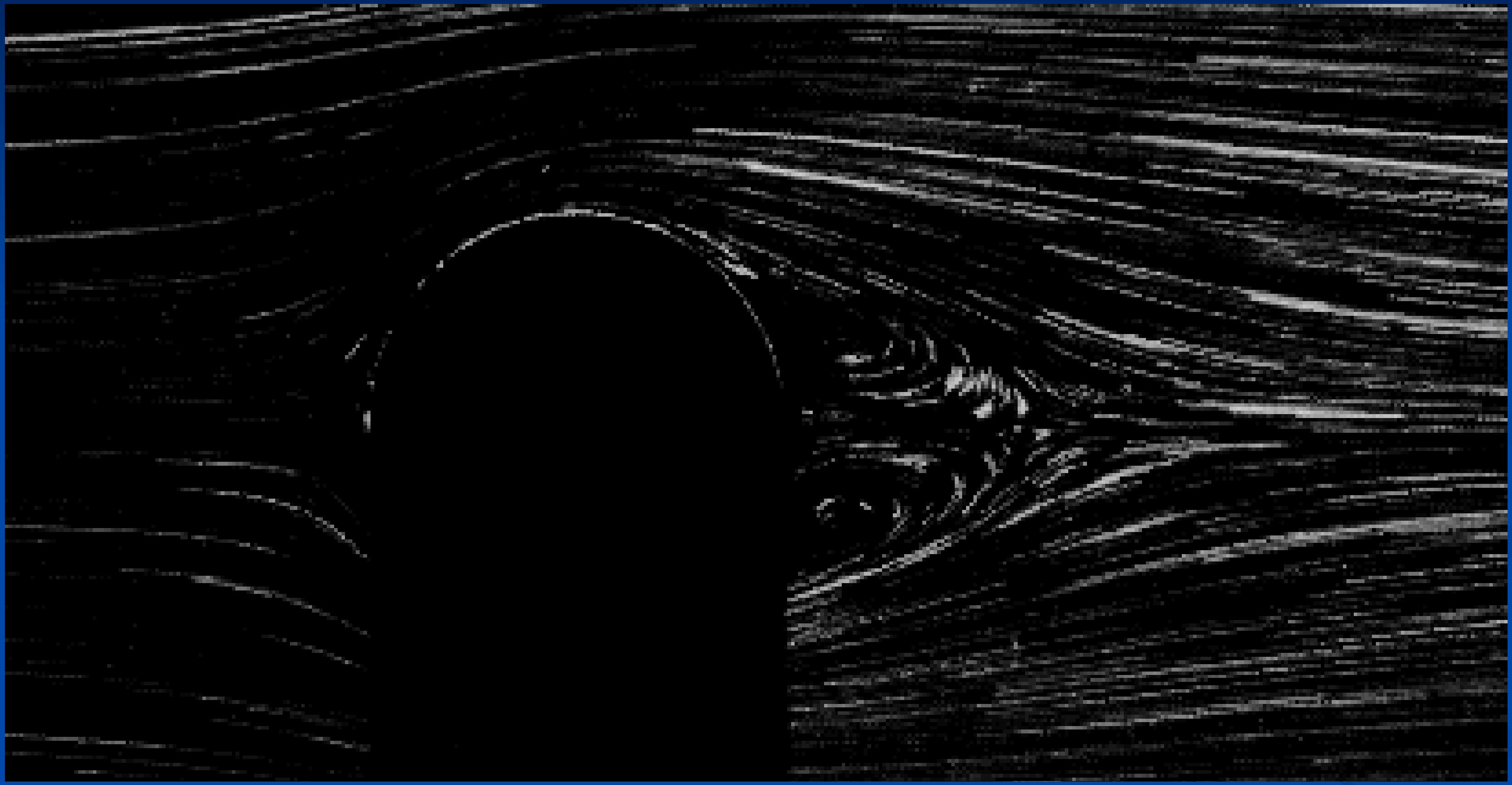
Flow Patterns around droplet 1



Sphere, Re=0.1

An Album of Fluid Motion
M. Van Dyke

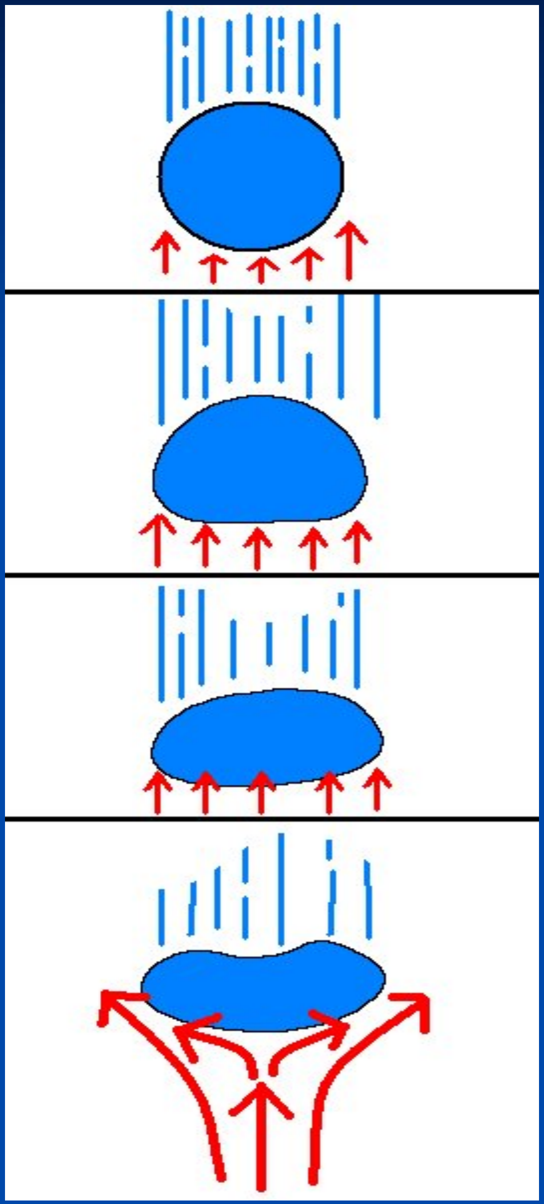
Flow Patterns around droplet 2

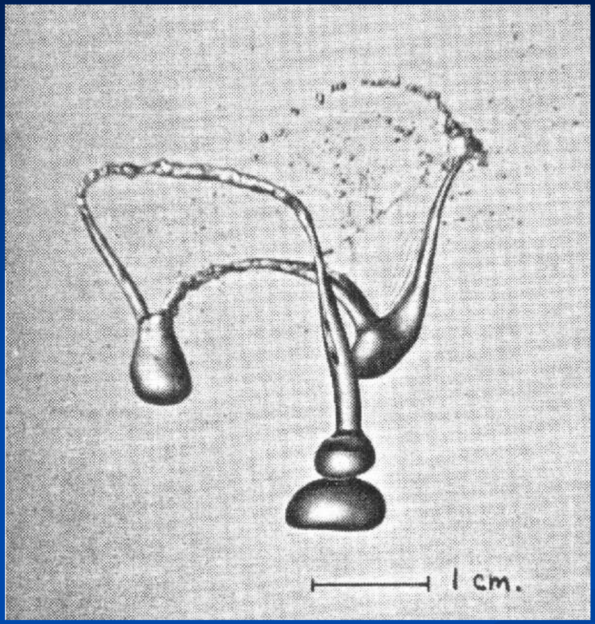


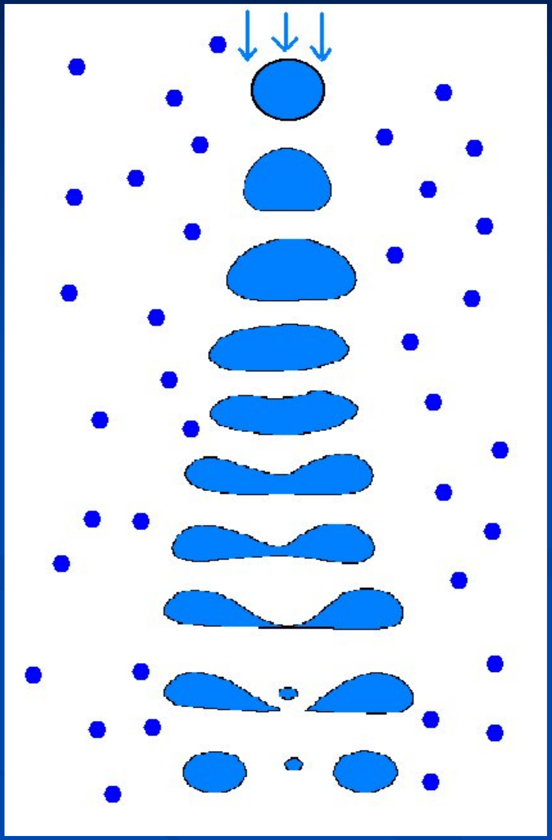
Sphere, Re=56.5

An Album of Fluid Motion
M. Van Dyke

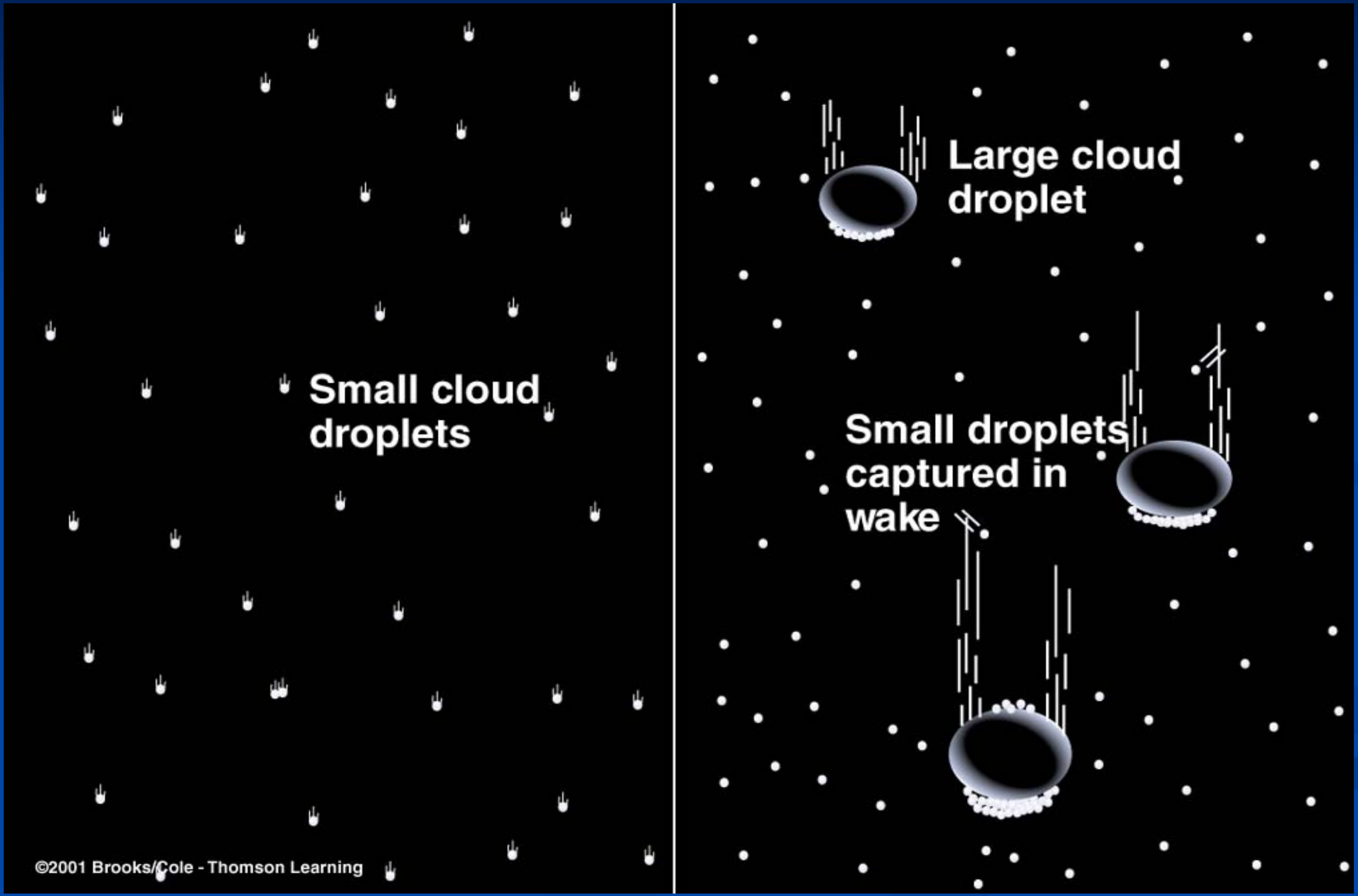
Fall Speeds 2



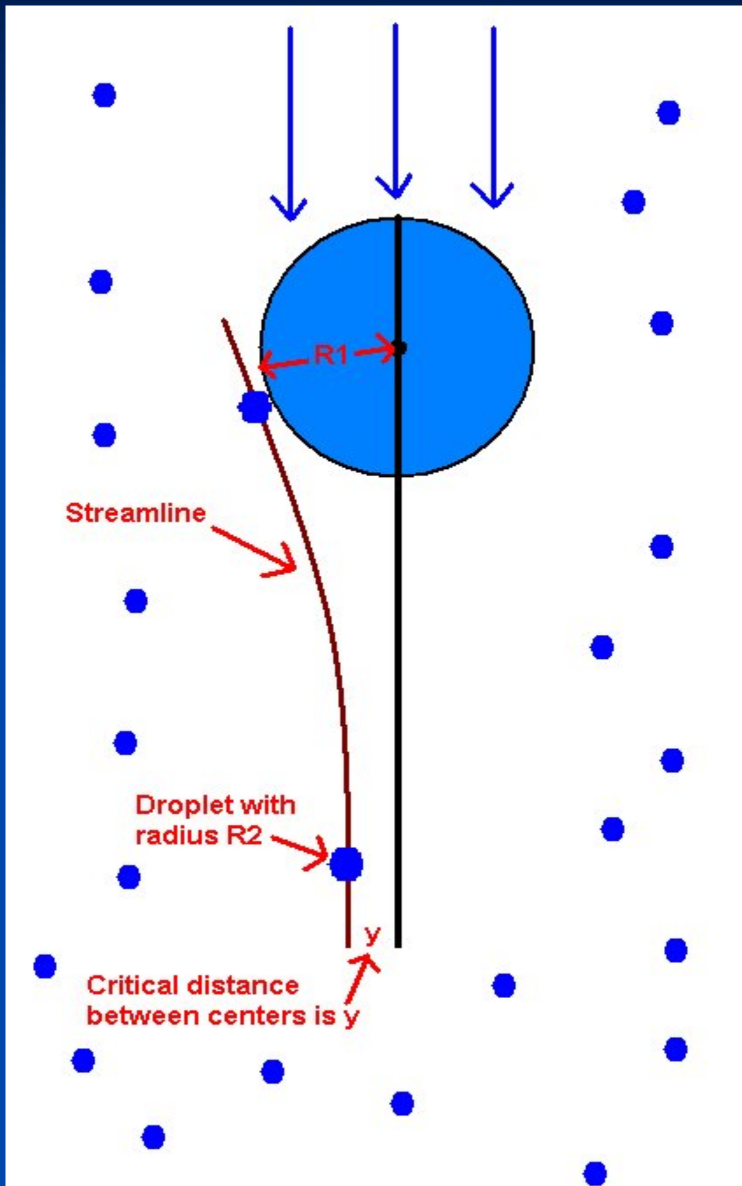




Collision and Coalescence 1



Collision efficiency 1



$$E = \frac{y^2}{(R1 + R2)^2}$$

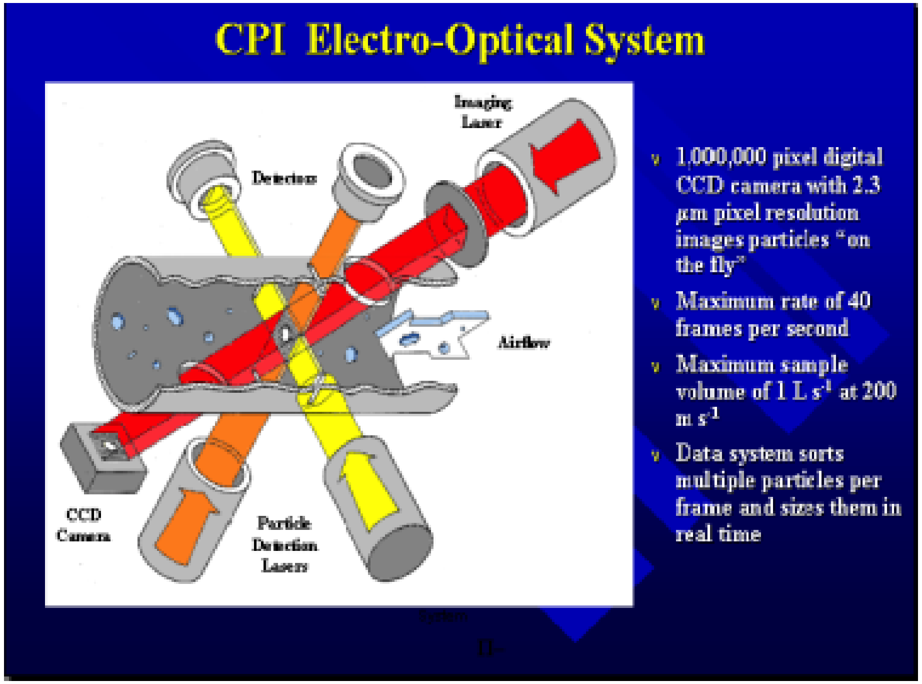
Collision efficiency

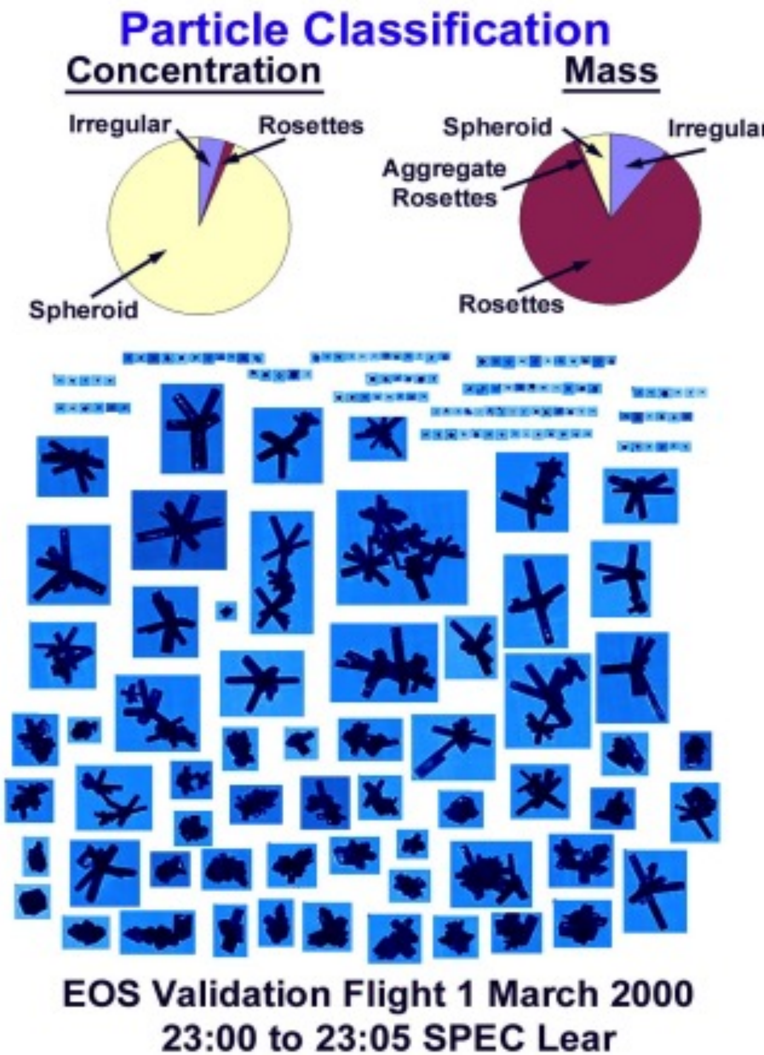
<u>Collison does not guarantee coalescence</u>

Droplets may bounce
Droplets may coalesce temporarily and break back into their original shape
Droplets may coalesce temporarily and break into many small droplets
Droplets may coalesce and stay in one bigger droplet

From Wallace & Hobbs 1977

Cloud Particle Imager (CPI, SPEC Inc.)





Cloud Particle Imager (CPI, SPEC Inc.)

Heterogeneous and homogeneous nucleation 1

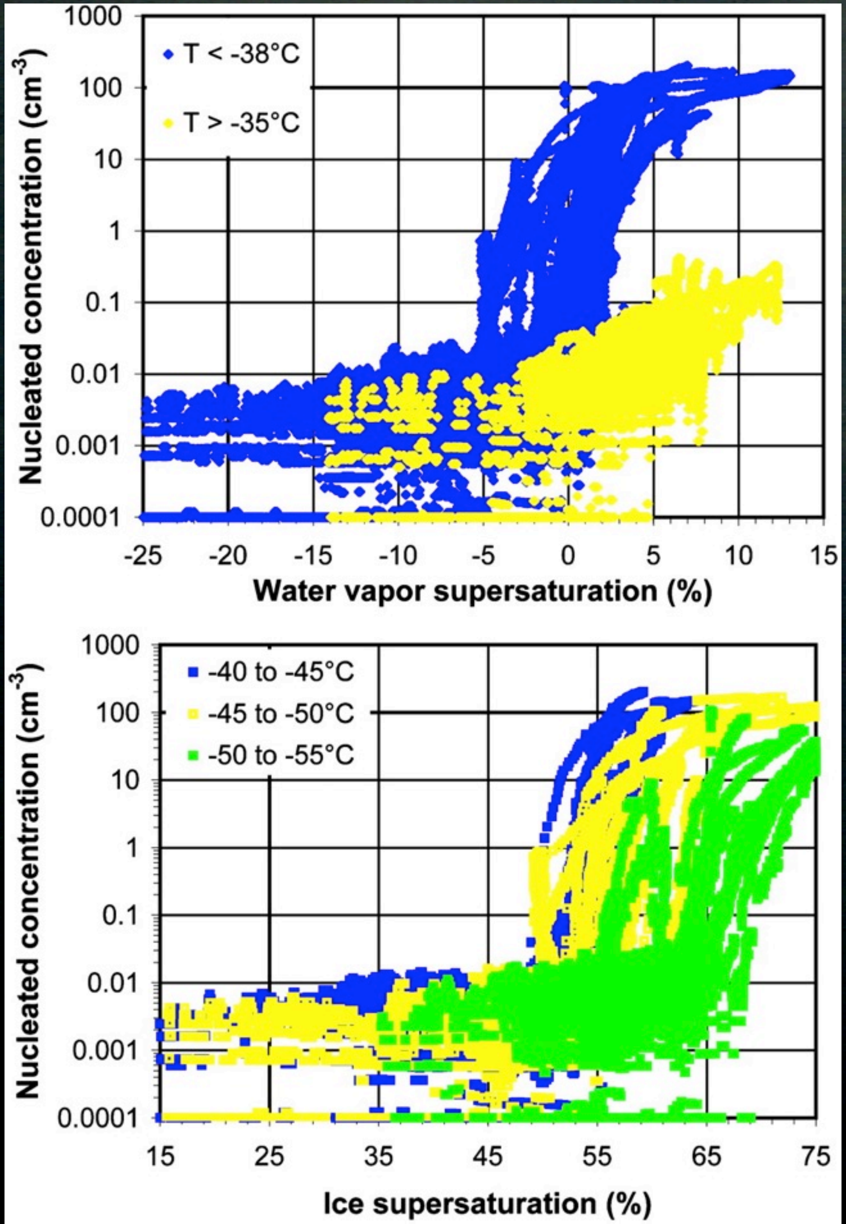
Homogeneous Nucleation

- freezing of pure water drops or liquid aerosol particles
- temperature and RH important
- theory fairly well understood

Heterogeneous Nucleation

- ice formation initiated by presence of solid particle
- by freezing (liquid to solid) or deposition (vapor to solid)
- nucleation at specific sites on substrates
- favored nuclei have lattice structure similar to ice
- also temperature and RH sensitive, but can occur at smaller S and warmer T than homogeneous nucleation

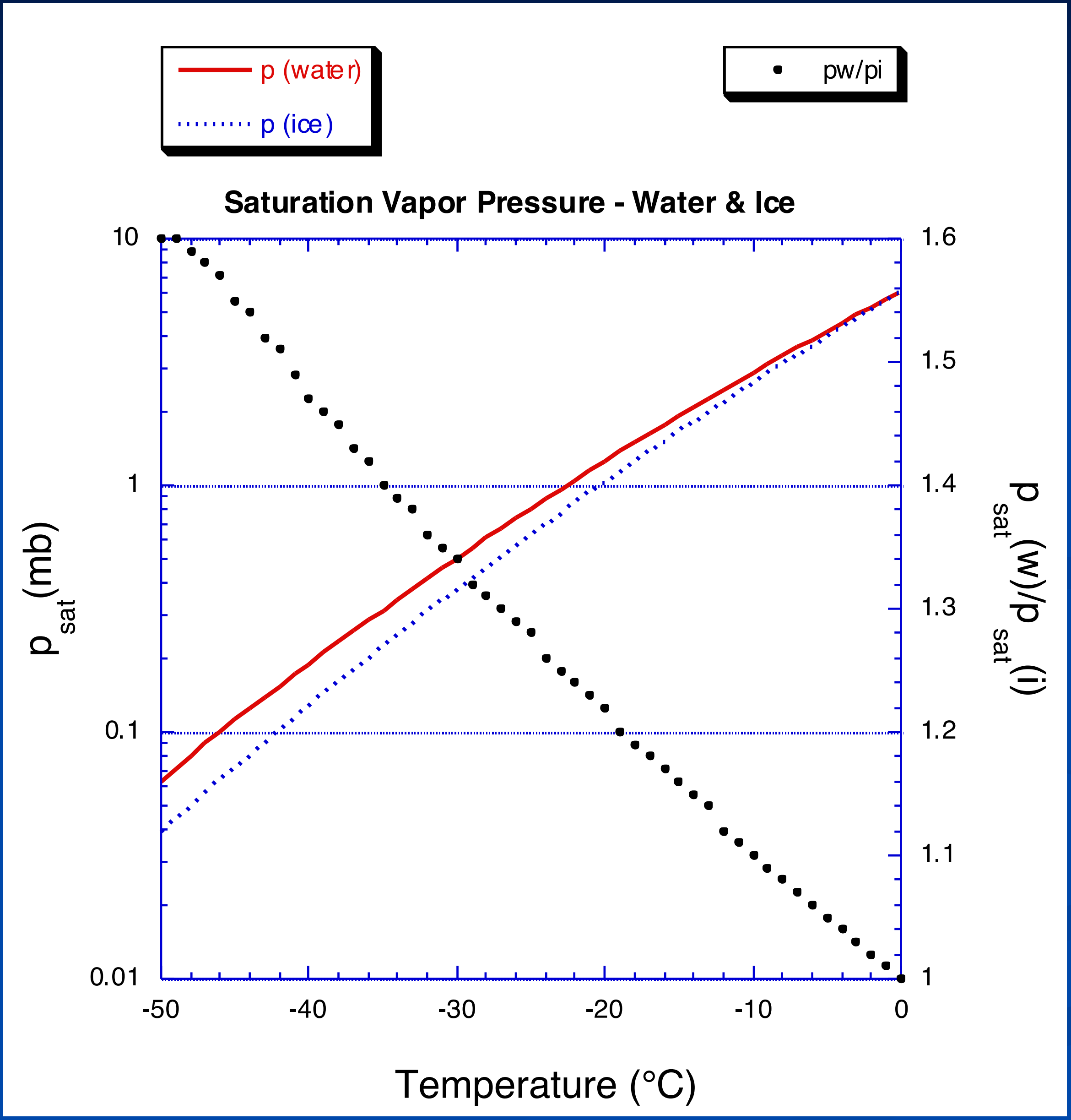
Heterogeneous and homogeneous nucleation 3



Ice concentrations nucleated by or within aerosol particles as a function of water vapor supersaturation (*Upper*) and ice supersaturation (*Lower*) for the project period. Data are color-coded to differentiate measurements in different temperature regimes. Increases in nucleated concentrations at near water saturation and at higher ice supersaturation conditions are indicative of homogeneous freezing at temperatures below –38°C.

DeMott et al, PNAS | vol. 100 | no. 25 | **14655-14660**

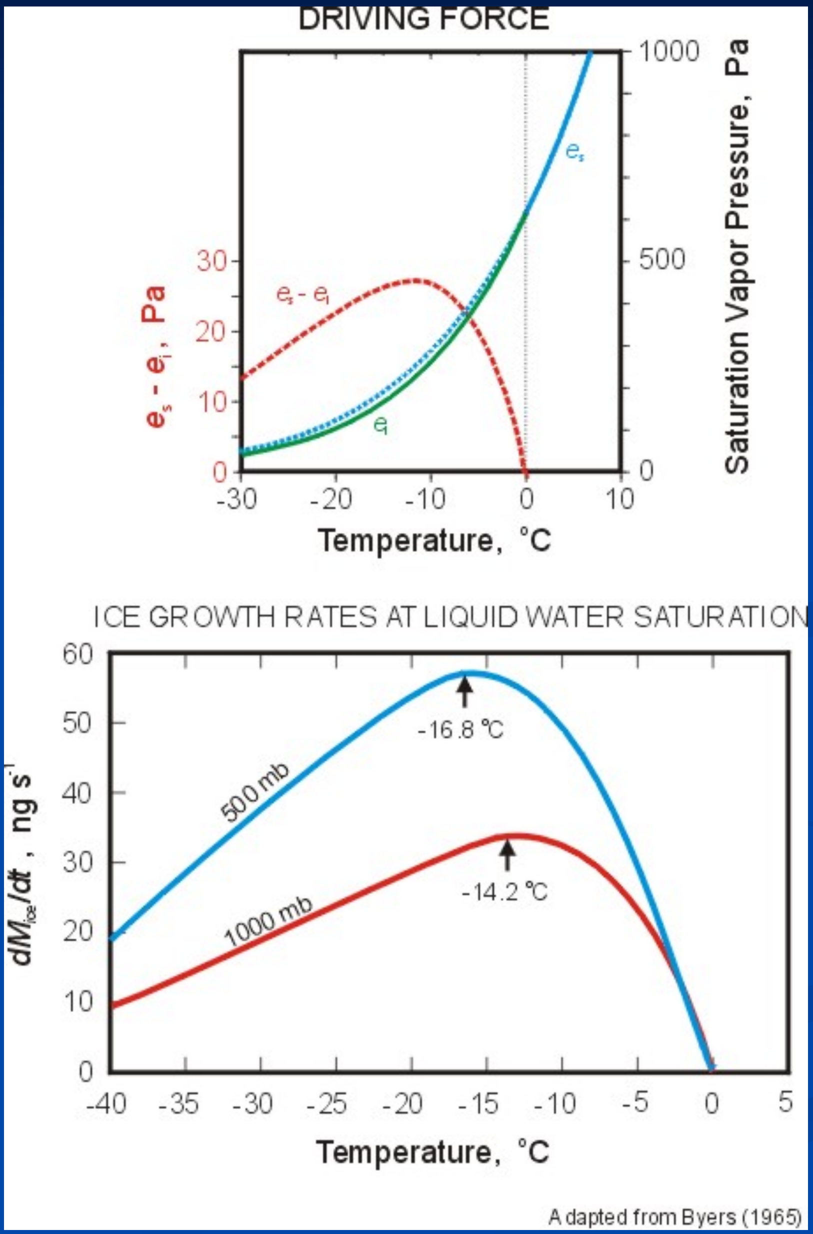
Saturation Vapor Pressures



$$S_i = \frac{e}{e_i} = \frac{e}{e_s}\frac{e_s}{e_i} = S\left(\frac{e_s}{e_i}\right)$$

$$S_i \geq S$$

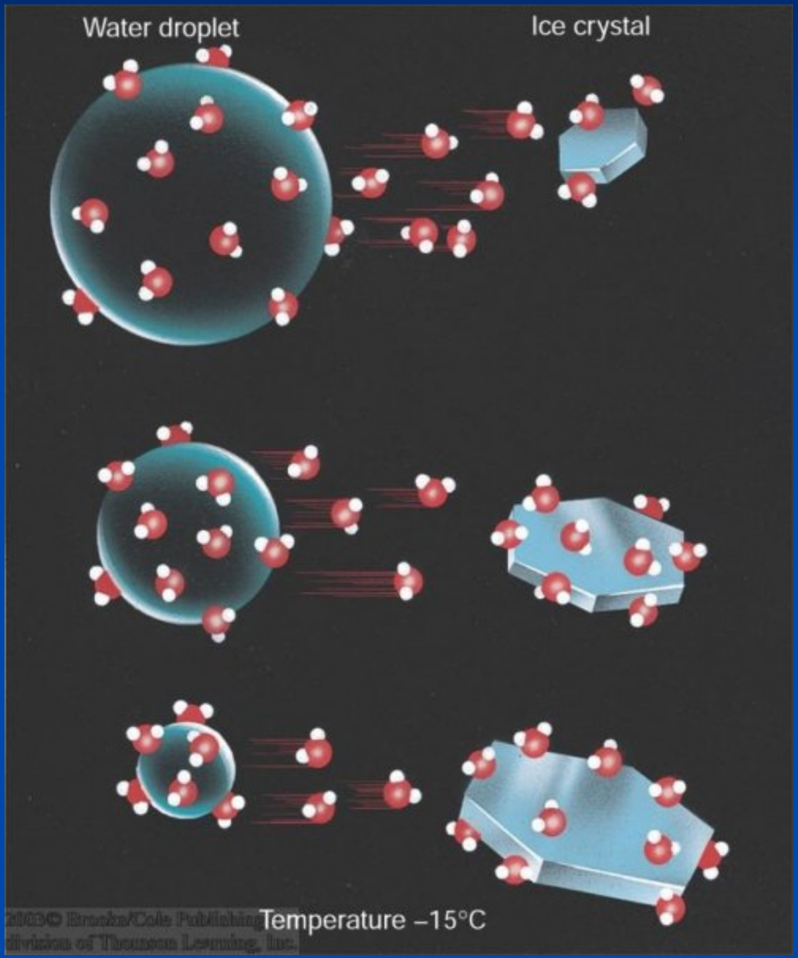
Growth of Ice Crystals



Growth of Ice Crystals – Bergeron process

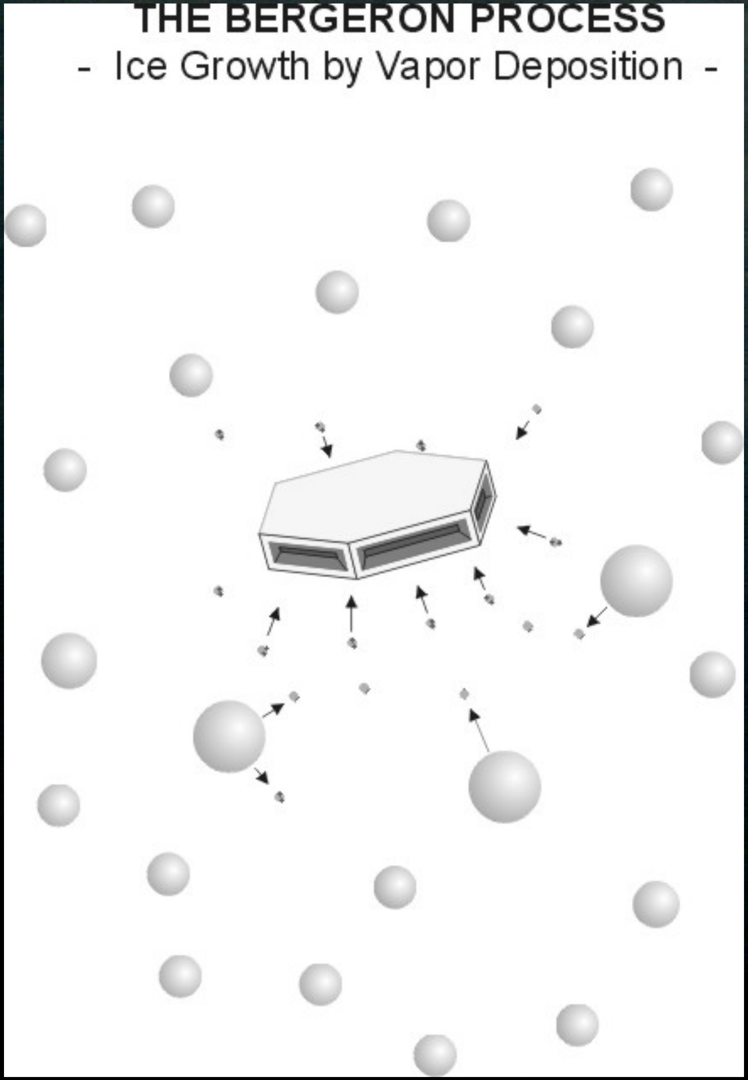
- Process of rain formation proposes that both ice crystals and liquid cloud droplets must co-exist in clouds at temperatures below freezing.
- This process is extremely important to rain formation in the middle and high latitudes where cloud tops extend above the freezing level (*cold clouds*)

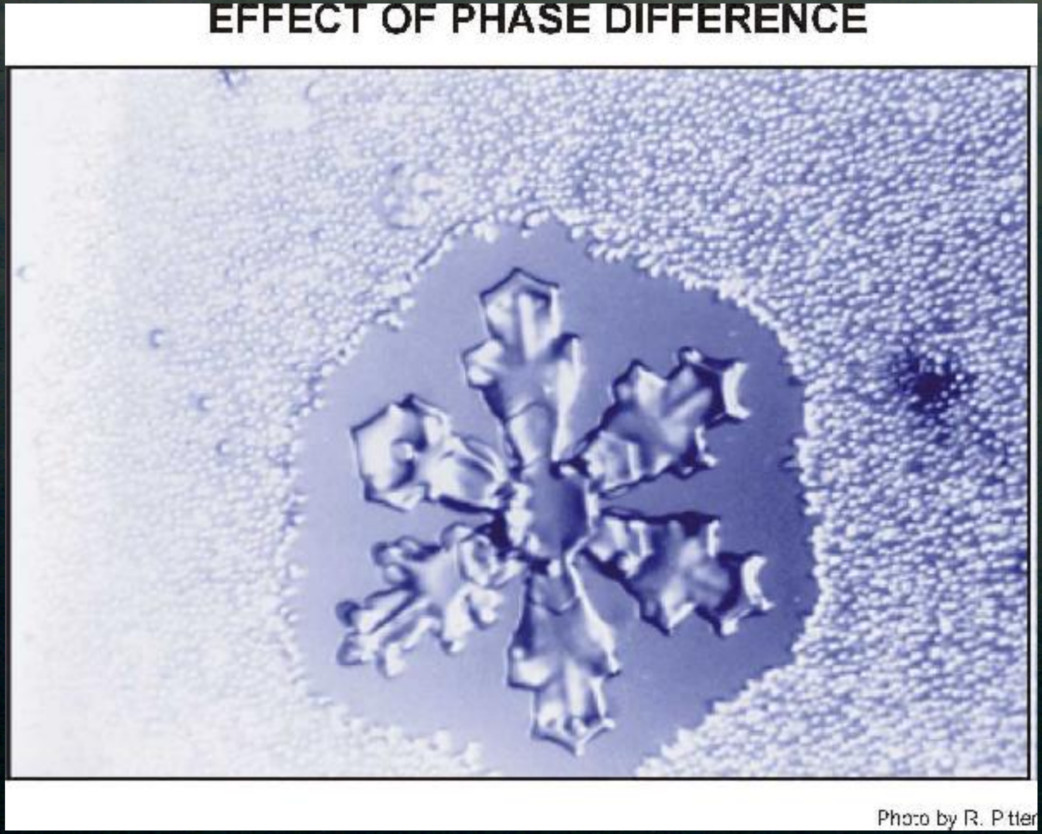
Ice Crystal (Bergeron) Process

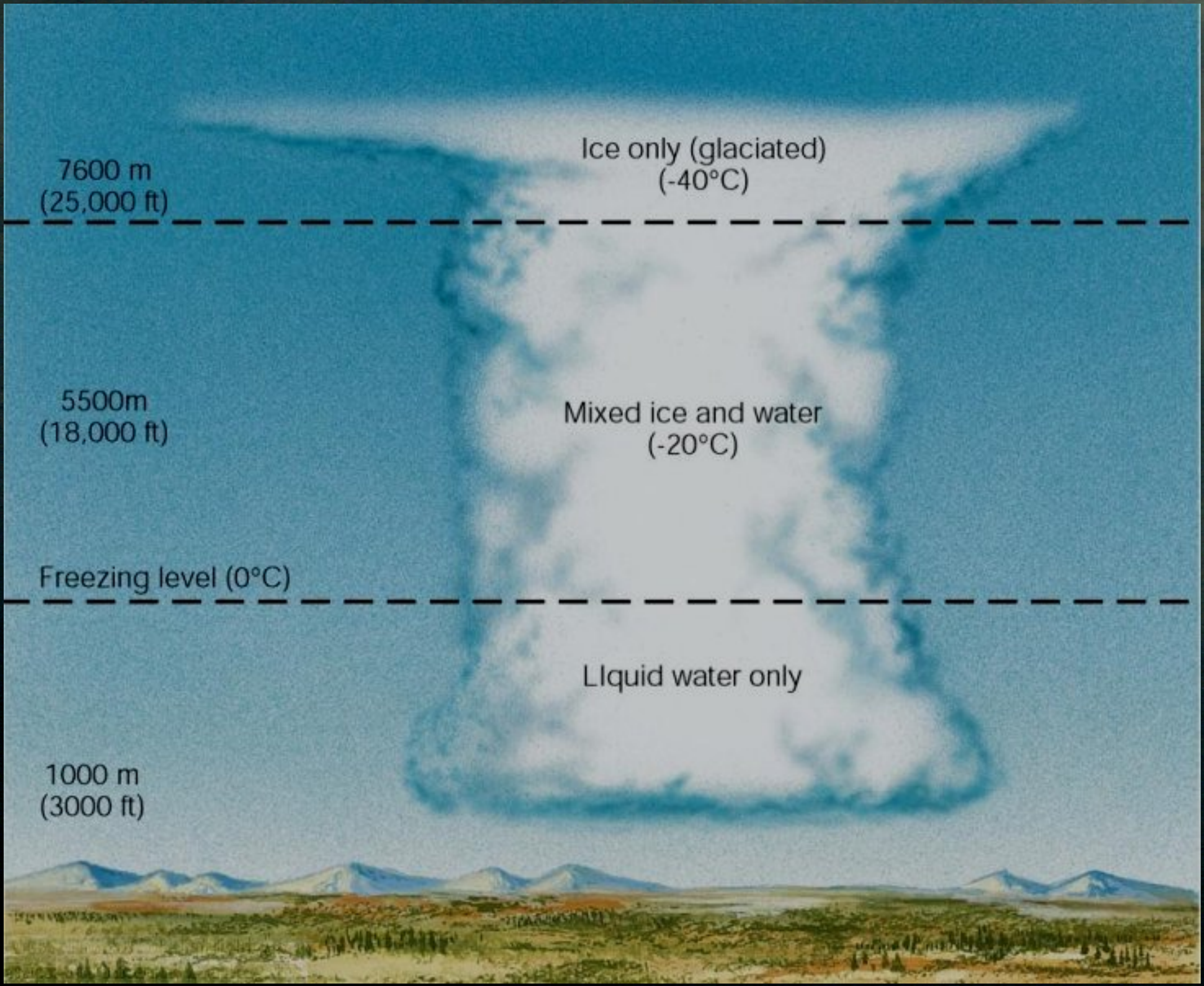


- The ice-crystal process. The greater number of water vapor molecules around the liquid droplets causes water molecules to diffuse from the liquid drops toward the ice crystals. The ice crystals absorb the water vapor and grow larger, while the water droplets grow smaller.
- It takes more vapor molecules to saturate the air directly above the water droplet than it does to saturate the air directly above the crystal.
- Ice crystals grow at the expense of the surrounding water droplets.

Growth of Ice Crystals – Bergeron process





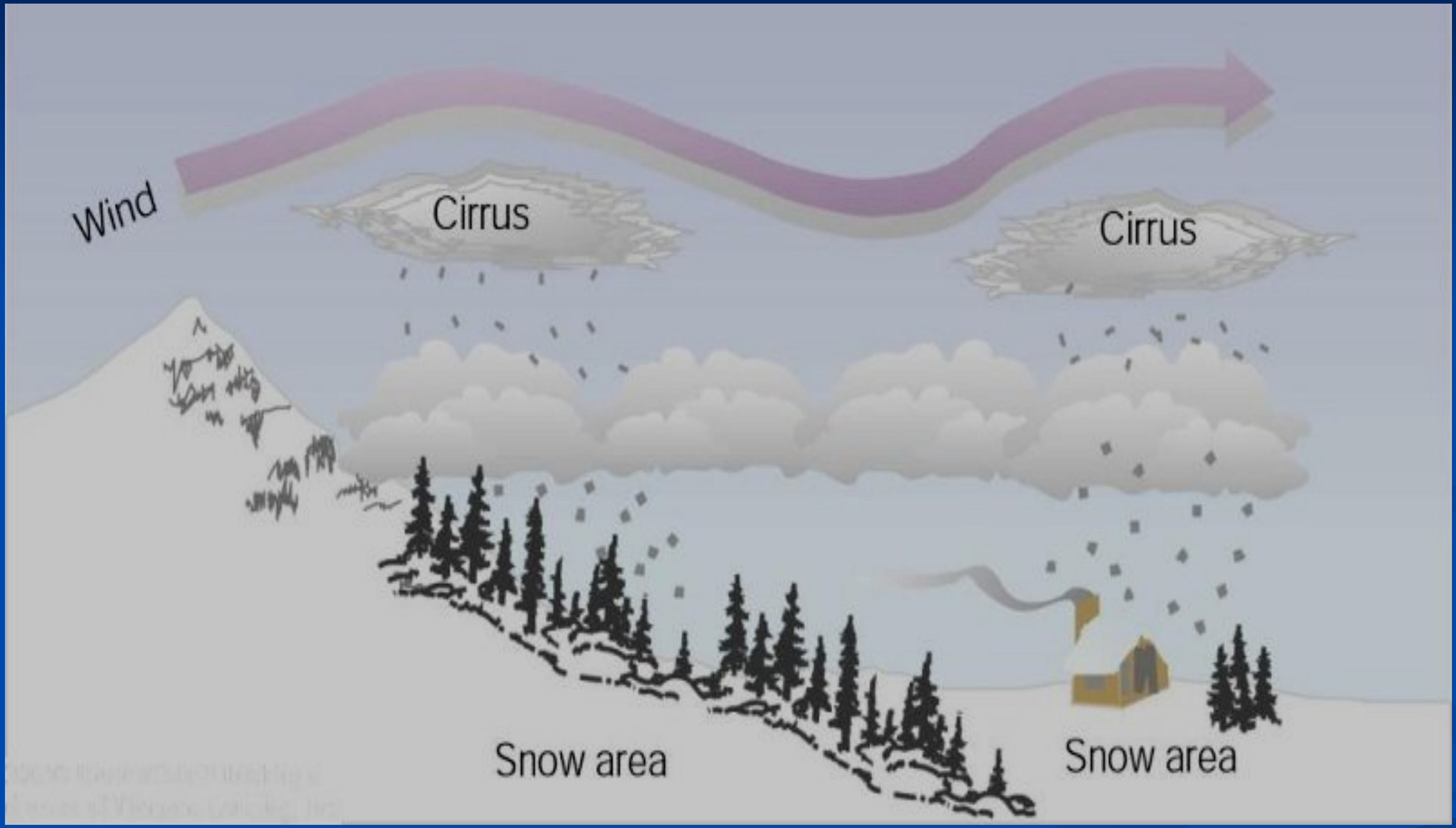


The distribution of ice and water in a cumulonimbus cloud.

Cloud Seeding

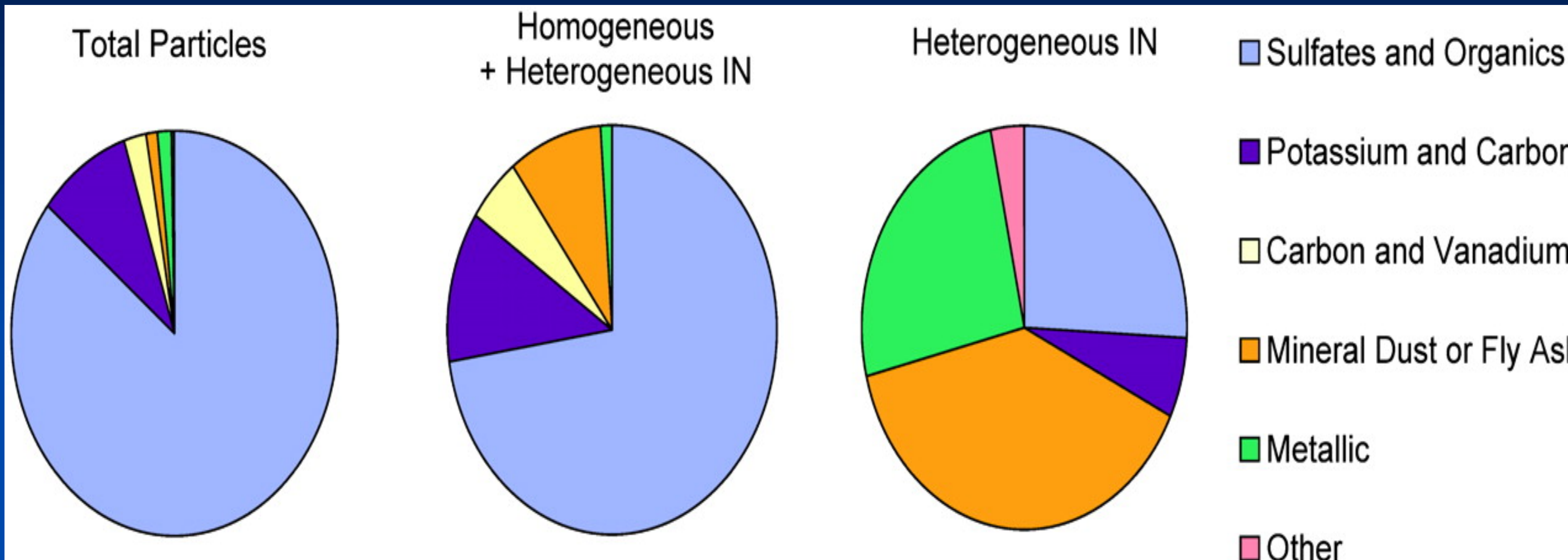
- To inject (or seed) a cloud with small particles that will act as nuclei, so that the cloud particles will grow large enough to fall to the surface as precipitation.
- First experiments in late 1940s using dry ice.
- Silver Iodide is also used today because it’s structure is similar to that of ice crystals.
- Natural seeding – cirriform clouds lie directly above a lower cloud deck, ice crystals descend into lower clouds.

Cloud Seeding



Natural seeding by cirrus clouds may form bands of precipitation downwind of a mountain chain.

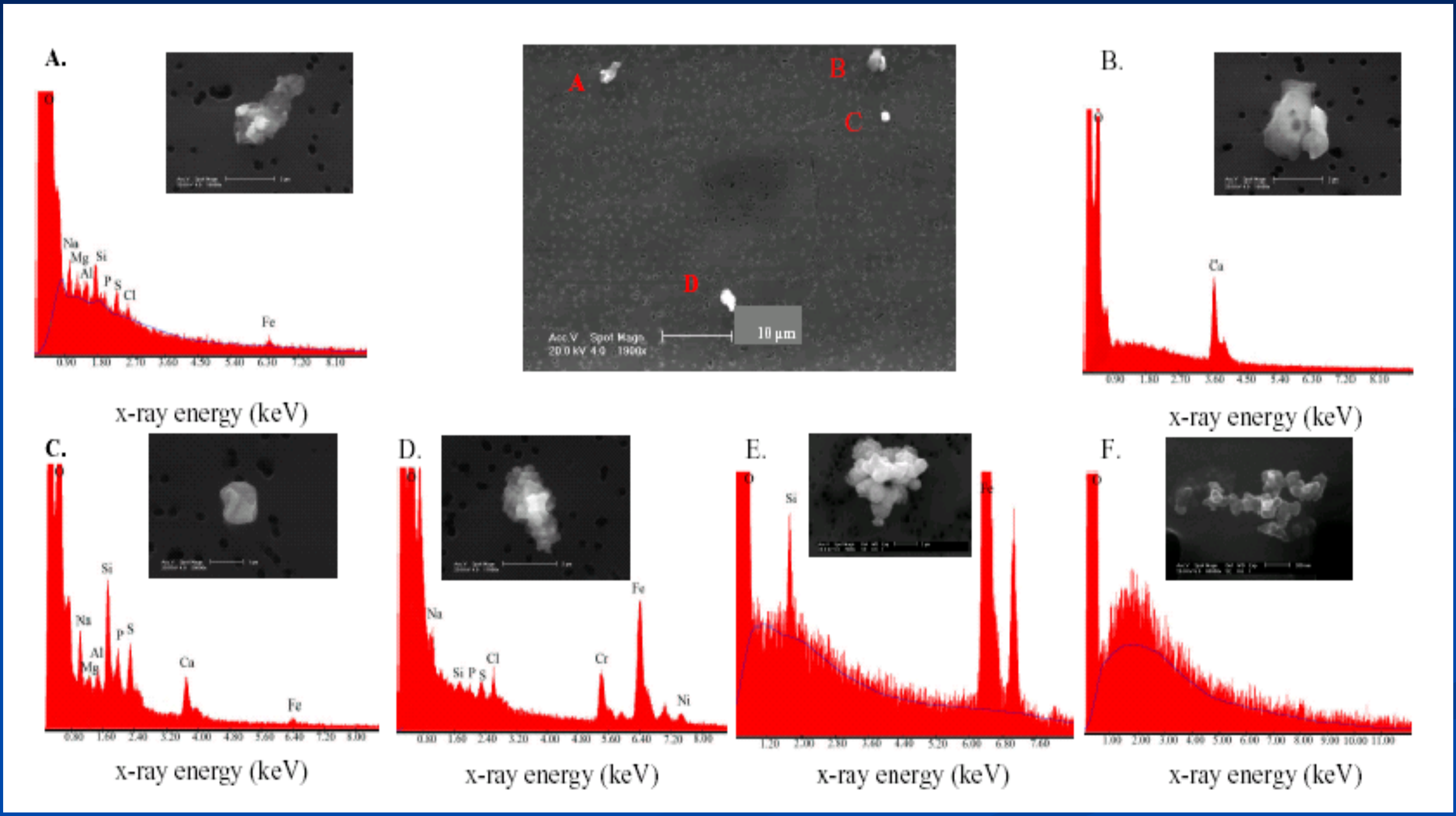
Ice nuclei compositon – Mt. Werner, Colorado



Statistics of different particle populations based on cluster analysis of PALMS mass spectra. The total aerosol composition is shown (*Left*), and the composition of nucleated ice-crystal residuals are shown in the regime under which homogeneous freezing was dominating heterogeneous nucleation (*Center*) and under conditions favorable only to heterogeneous nucleation (*Right*).

DeMott et al, PNAS | vol. 100 | no. 25 |

Supercooled Orographic Clouds



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Contrails – cirrus clouds