# Numerical Weather Prediction
# Parametrization of Subgrid Physical Processes
# Clouds (1)
# Cloud Microphysics

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(with thanks to Adrian Tompkins and Christian Jakob)

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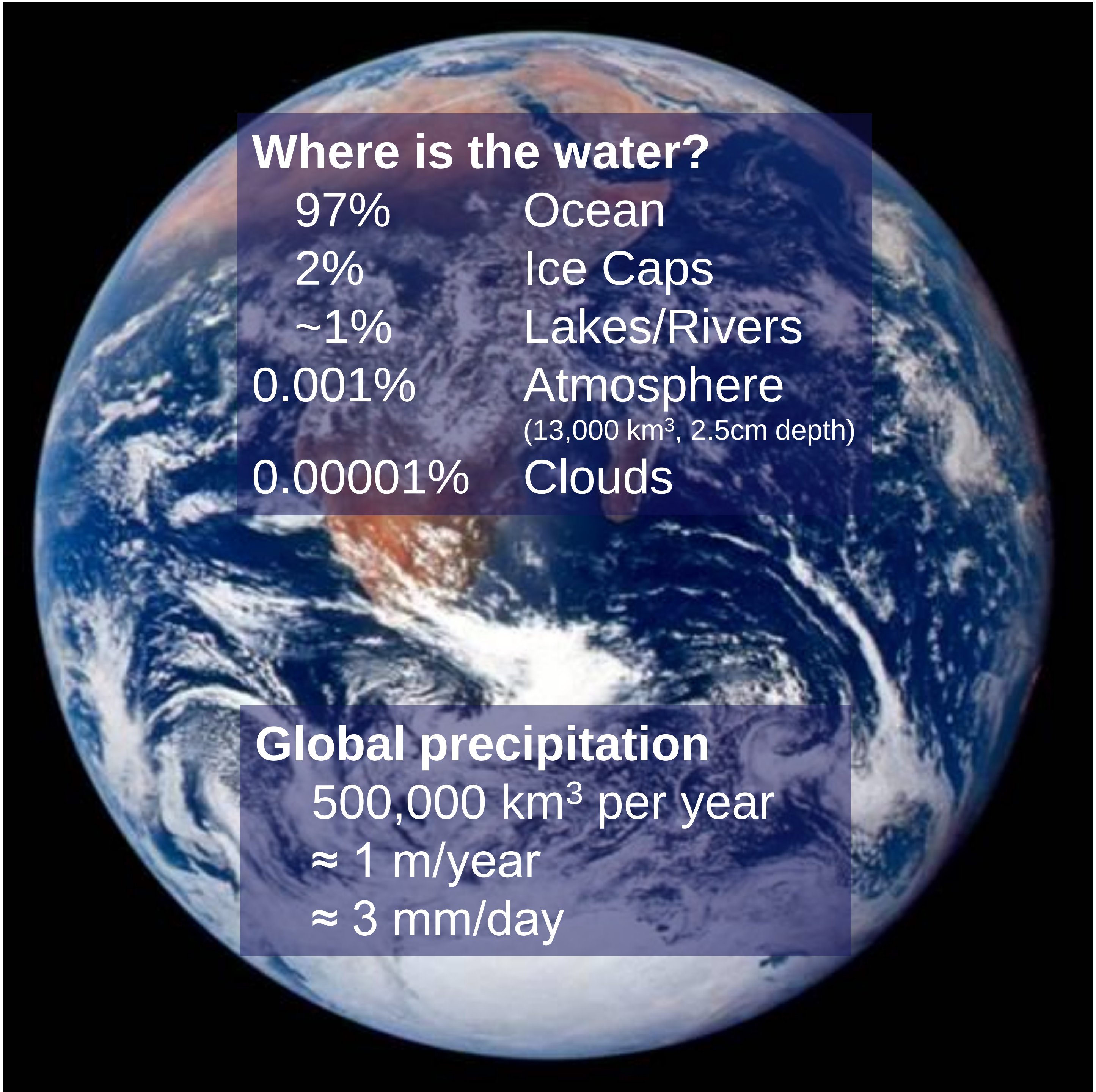
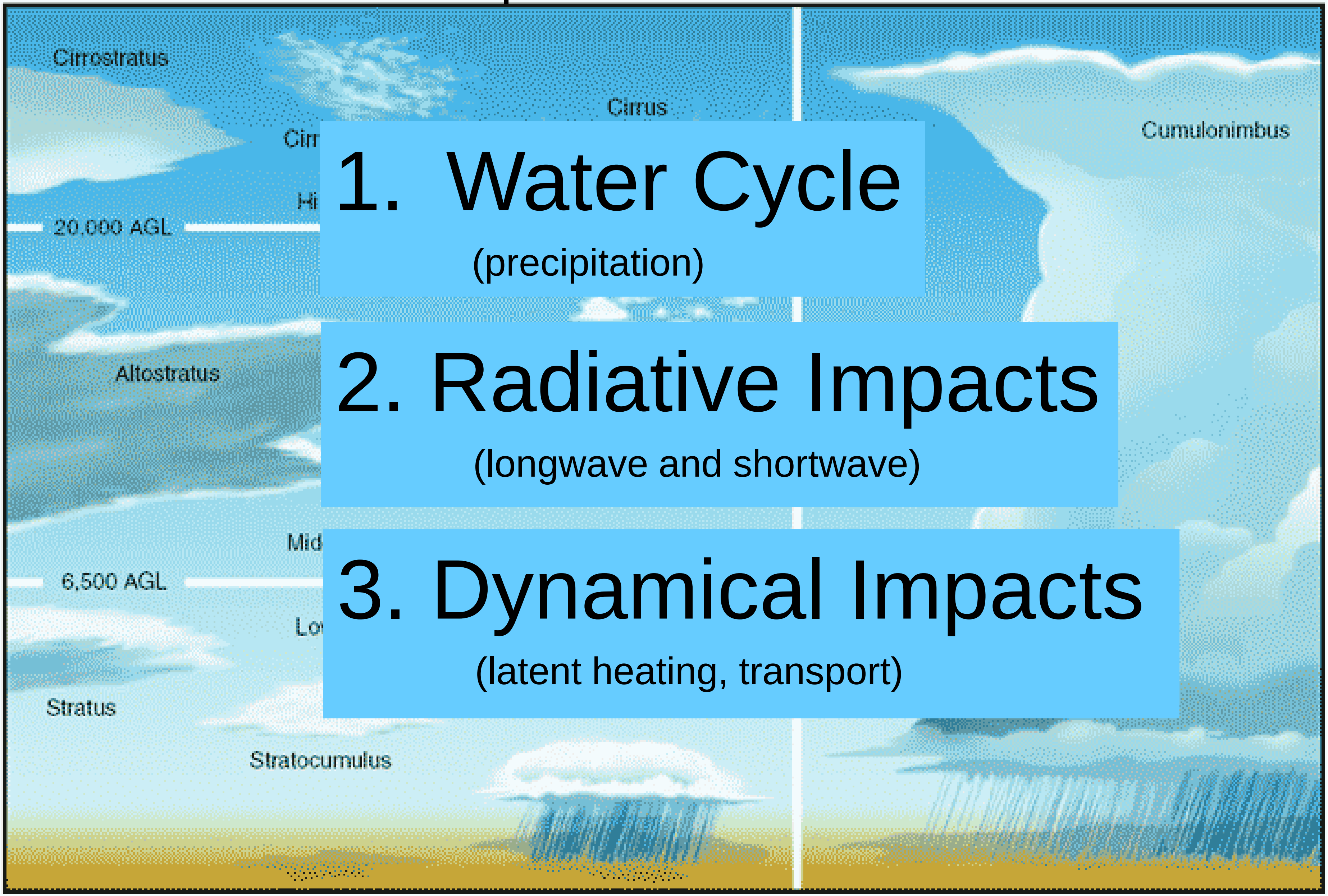

Where is the water?
97% Ocean
2% Ice Caps
~1% Lakes/Rivers
0.001% Atmosphere
(13,000 km3, 2.5cm depth)
0.00001% Clouds
Global precipitation
500,000 km3 per year
≈ 1 m/year
≈ 3 mm/day

# *Outline*

- LECTURE 1: Cloud Microphysics
  1. Overview of cloud parametrization issues
  2. Microphysical processes
     2.1 Warm phase
     2.2 Cold phase
  3. Summary
- LECTURE 2: Subgrid Cloud Cover in GCMs
- LECTURE 3: The ECMWF Cloud Scheme
- LECTURE 4: Validation of Cloud Schemes

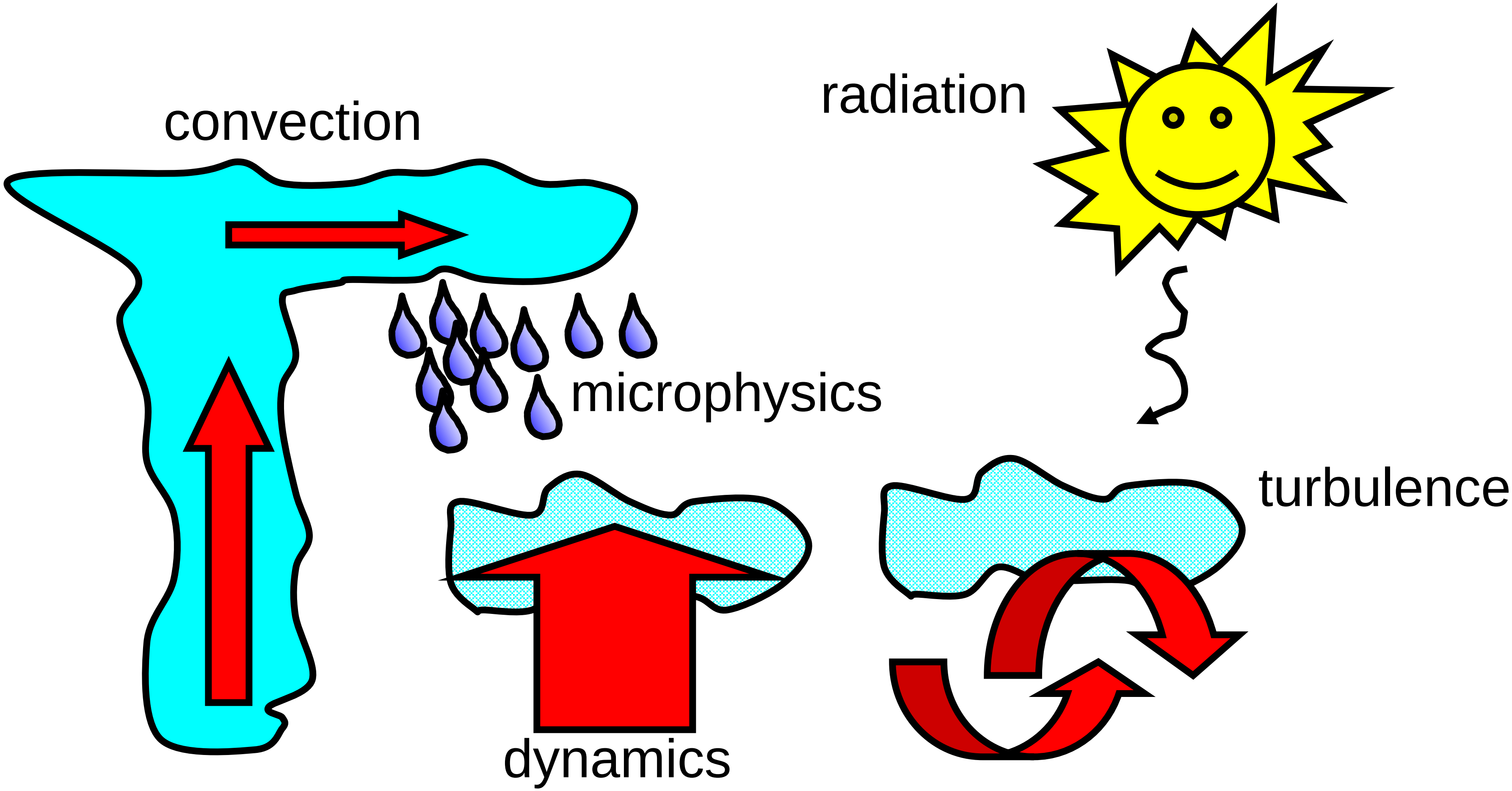

1. Overview of GCM Cloud
Parametrization Issues

# The Importance of Clouds




1. Water Cycle
   (precipitation)
2. Radiative Impacts
   (longwave and shortwave)
3. Dynamical Impacts
   (latent heating, transport)

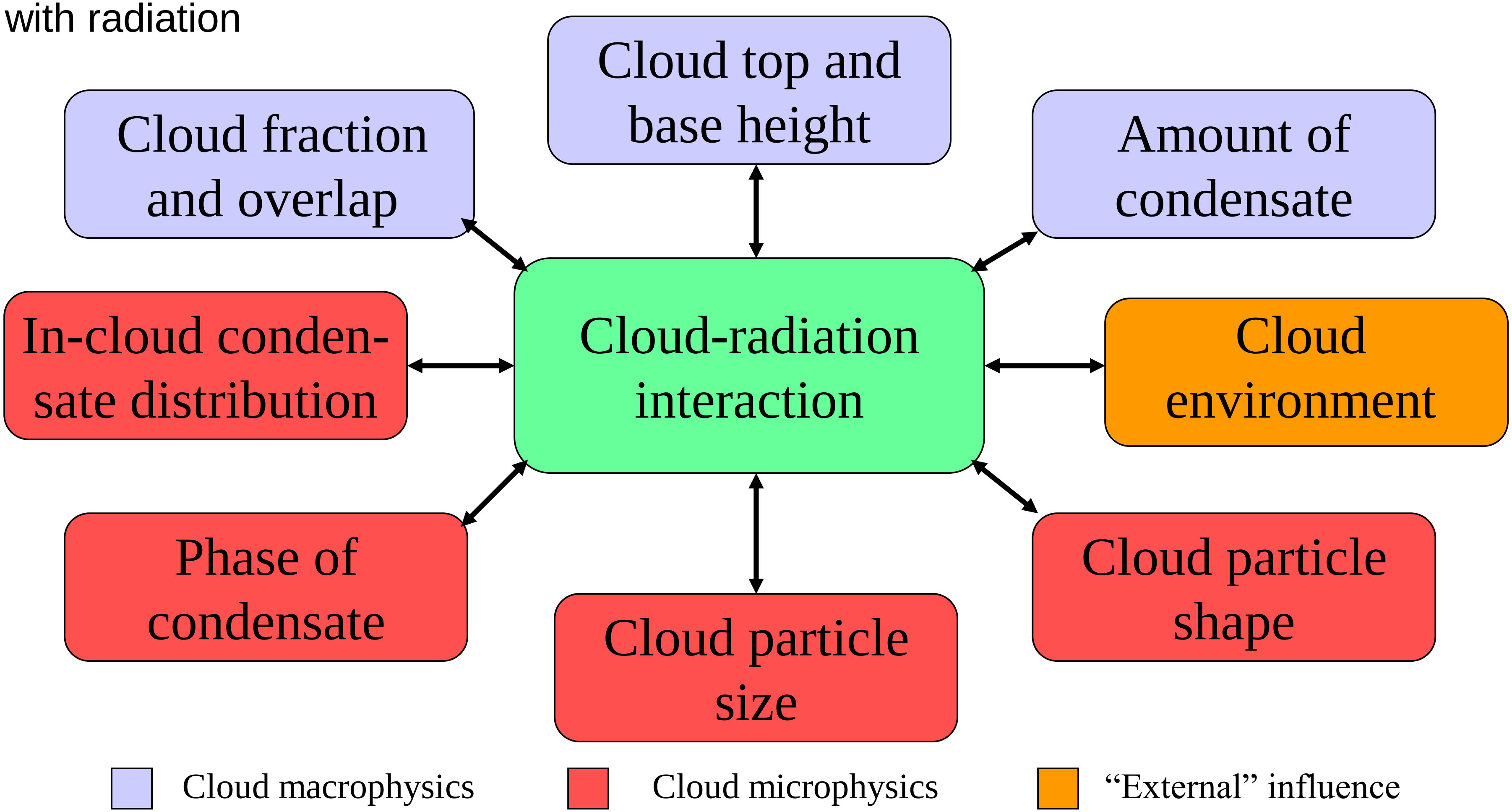
# Representing Clouds in GCMs
# What are the problems ?




Clouds are the result of complex interactions between a large number of processes

# *Representing Clouds in GCMs*
# *What are the problems ?*

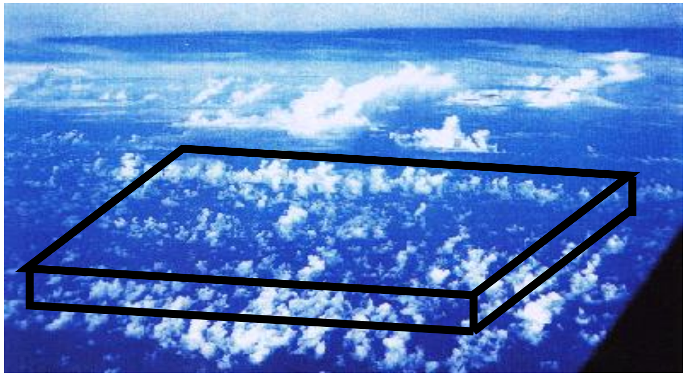
Many of these processes are only partially understood - For example, the interaction with radiation



# Cloud Parametrization Issues:

- Microphysical processes

- Macro-physical
  - subgrid heterogeneity

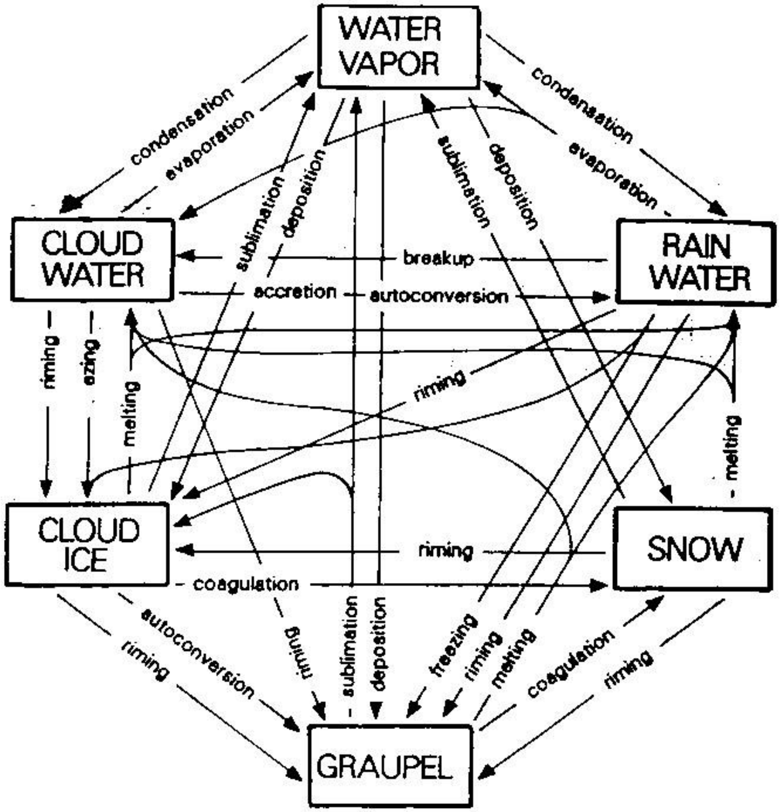


- Numerical issues

$$\frac{\partial q_l}{\partial t} = A(q_l) + S(q_l) - D(q_l)$$

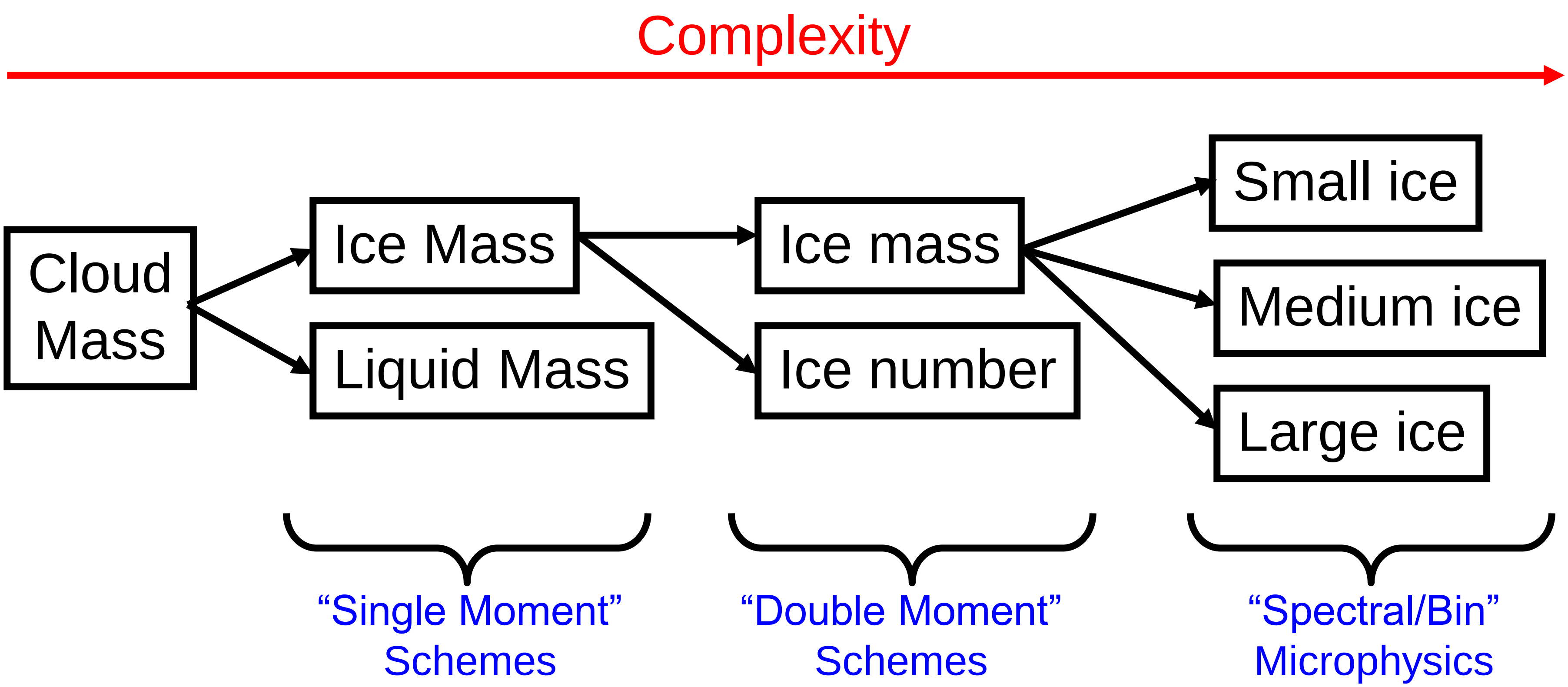
# *Cloud Parametrization Issues:*
# *Which quantities to represent ?*

- Water vapour
- Cloud water droplets
- Rain drops
- Pristine ice crystals
- Aggregate snow flakes
- Graupel pellets
- Hailstones




- Note for ice phase particles:
  - Additional latent heat.
  - Terminal fall speed of ice hydrometeors significantly less.
  - Optical properties are different (important for radiation).

# Cloud Parametrization Issues: Complexity ?




Many GCMs only have single-moment schemes

# Cloud Parametrization Issues: Diagnostic or prognostic variables ?

Cloud condensate mass (cloud water and/or ice), $q_l$

Diagnostic approach *(dependent on large scale variables e.g. T,q)*

$$q_l = f\left(\Phi_1 \ldots \Phi_n, \frac{\partial \Phi_1}{\partial t} \ldots \frac{\partial \Phi_n}{\partial t}, \ldots\right)$$

Prognostic approach *(parametrized sources and sinks)*

$$\frac{\partial q_l}{\partial t} = A(q_l) + S(q_l) - D(q_l)$$

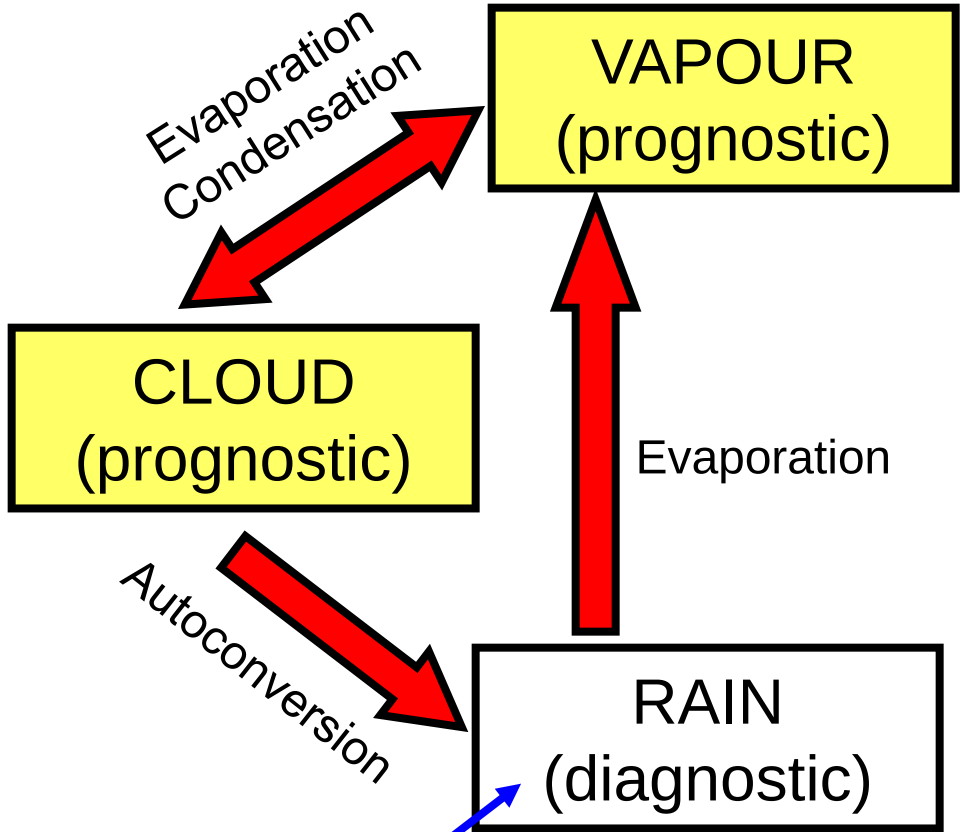
Sources

Advection + sedimentation

Sinks

**CAN HAVE MIXTURE OF APPROACHES**

# *Simple Bulk Microphysics*




Why ?

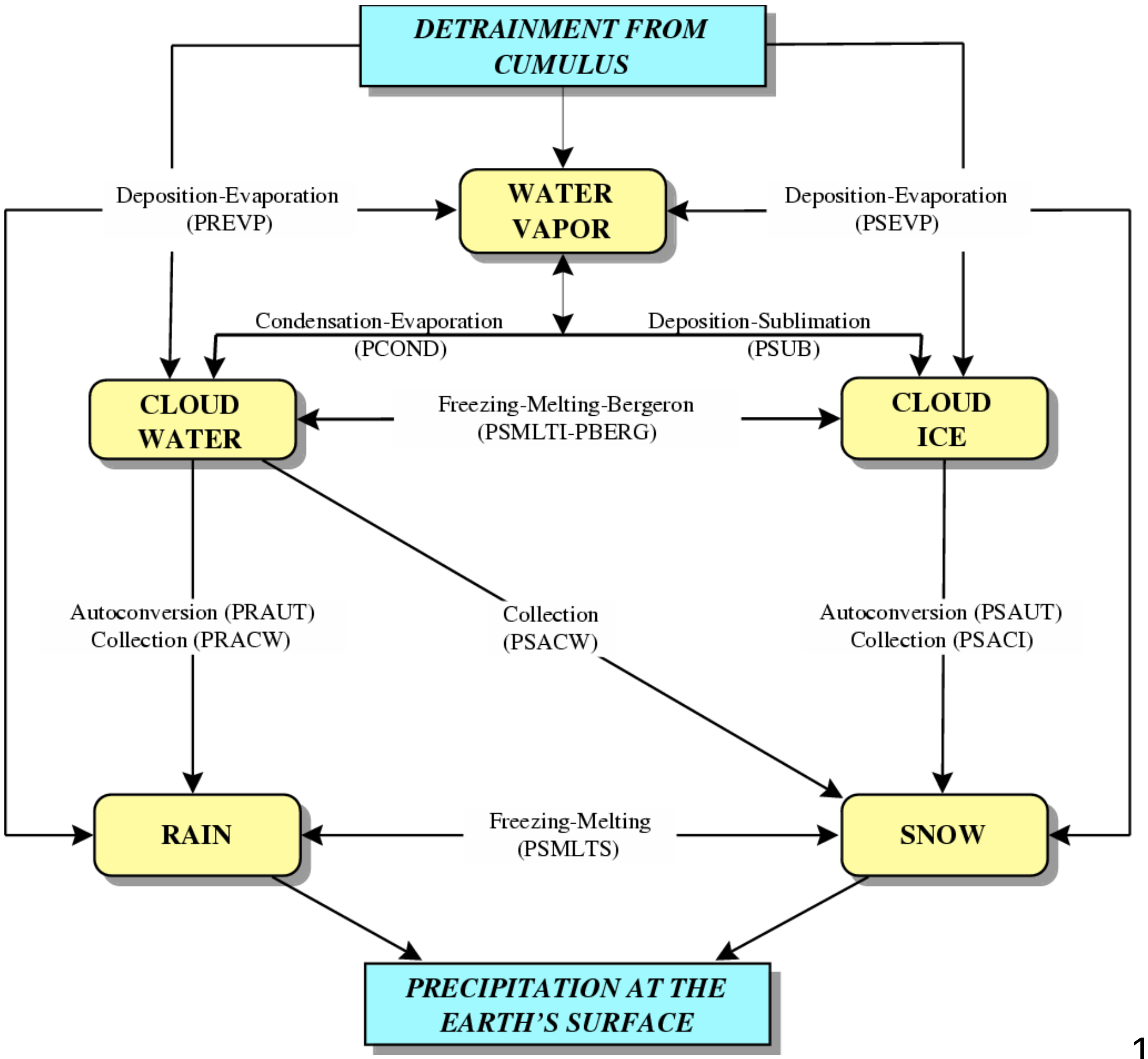
Timescale for fallout of rain is shorter than the model timestep therefore can assume that rain profile is in equilibrium

# Microphysics - a more complex GCM scheme

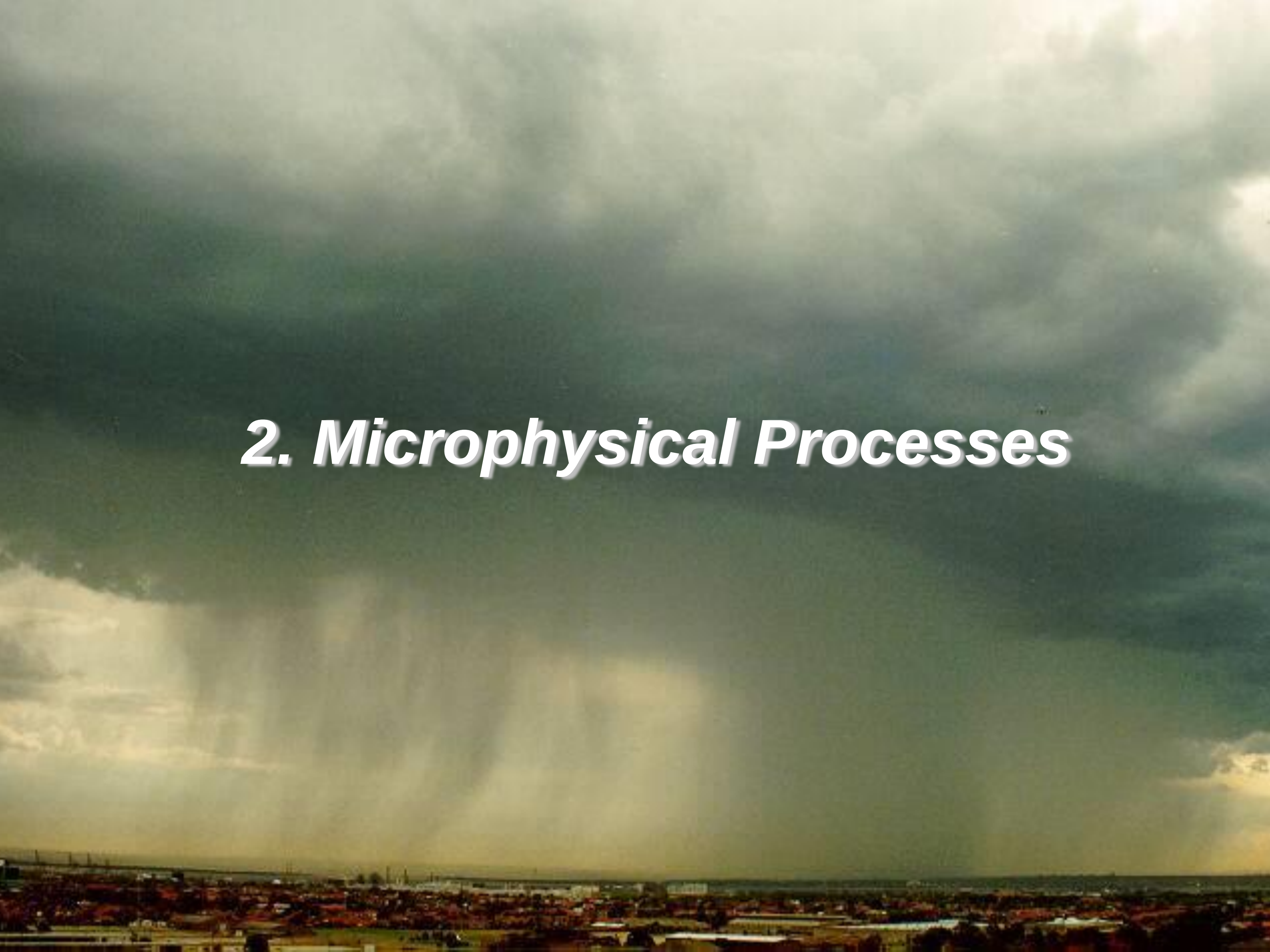
Fowler et al., JCL, 1996

Current ECMWF scheme

Cloud resolving models may add graupel and double moment representation…



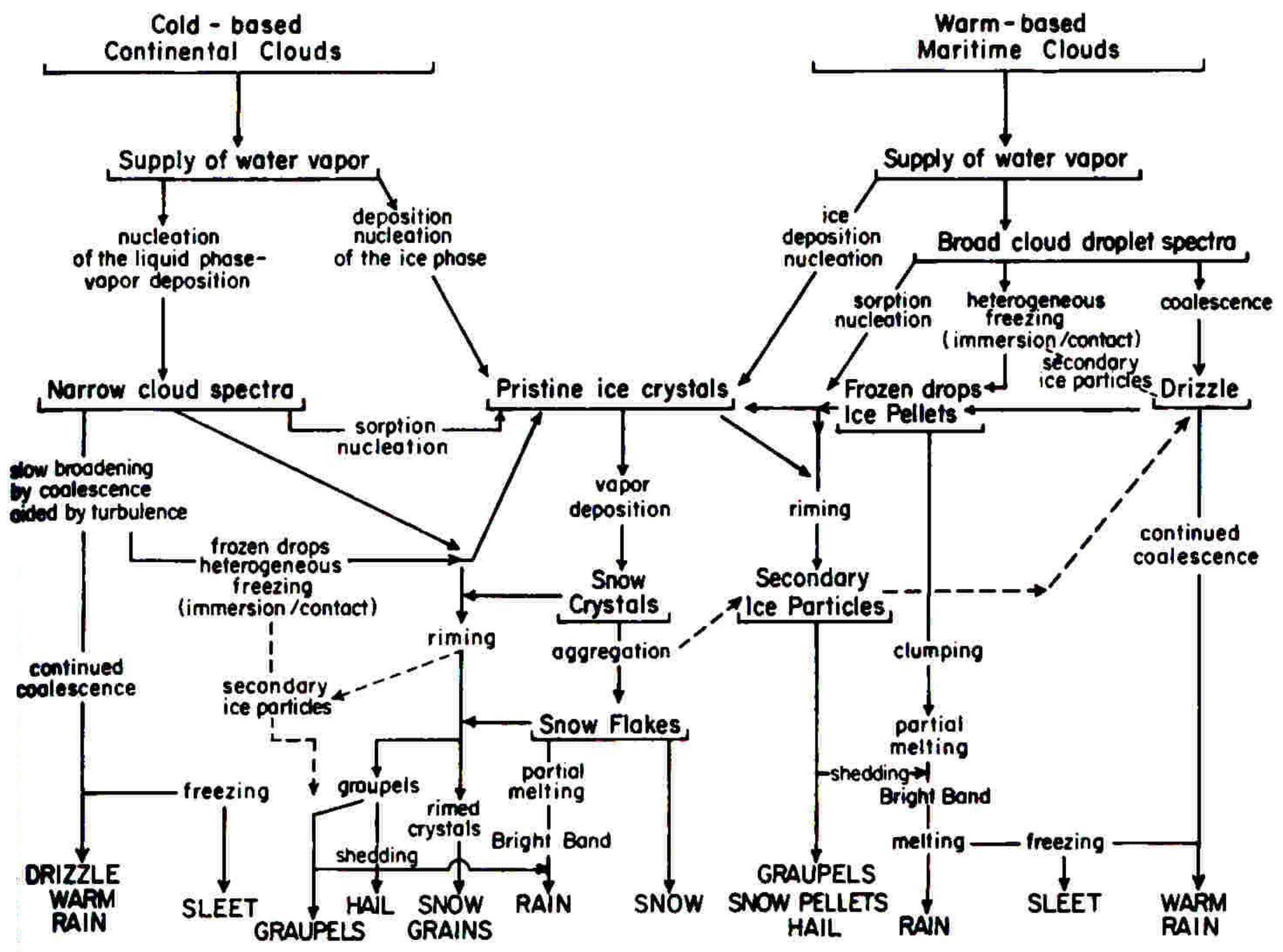
# 2. Microphysical Processes



# *Cloud microphysical processes*

- To describe cloud and precipitation processes in our models we need to represent:
  - Nucleation of water droplets and ice crystals from water vapour
  - Diffusional growth of cloud droplets (condensation) and ice crystals (deposition)
  - Collection processes for cloud drops (collision-coalescence), ice crystals (aggregation) and ice and liquid (riming) leading to precipitation sized particles
  - The advection and sedimentation (falling) of particles
  - the evaporation/sublimation/melting of cloud and precipitation size particles

Microphysics: A complex system!




→ *simplify, but need to understand processes first*

(1) Warm Phase Microphysics T > 0° C

(2) Mixed Phase Microphysics -38° C < T < 0° C

(3) Pure ice Microphysics T < -38° C

# 2. Microphysical Processes
## 2.1 Warm Phase

# Droplet Classification

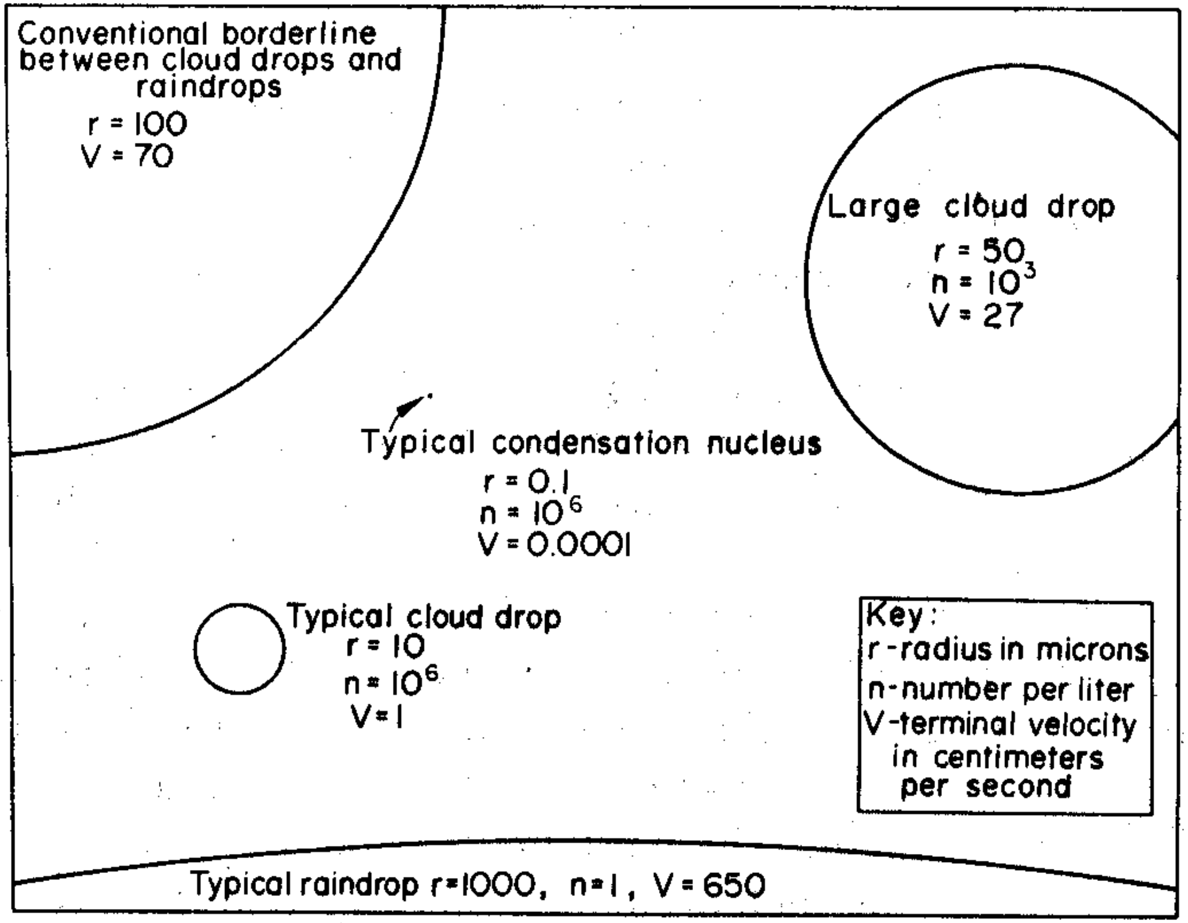
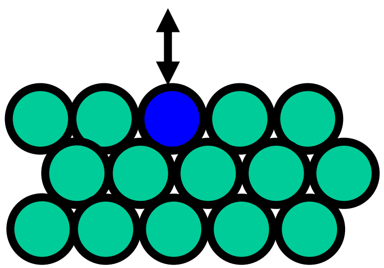
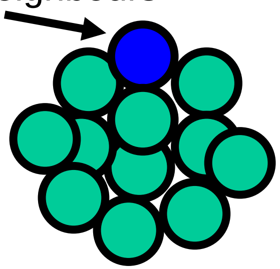



FIG. 5.1. Comparative sizes, concentrations, and terminal fall velocities of some of the particles involved in cloud and precipitation processes. (From McDonald, 1958.)

# *Nucleation of cloud droplets: Important effects for particle activation*



Surface molecule has fewer neighbours



<u>Planar surface</u>: Equilibrium when atmospheric vapour pressure = saturation vapour pressure ($e$=$e_s$) and number of molecules impinging on surface equals rate of evaporation

<u>Curved surface</u>: saturation vapour pressure increases with smaller drop size since surface molecules have fewer binding neighbours.

i.e. easier for a molecule to escape, so $e_s$ has to be higher to maintain equilibrium

$$\frac{e_s(r)}{e_s(\infty)} = \exp\left(\frac{2\sigma}{rR_v\rho_l T}\right)$$

$$\sigma = \text{Surface tension of droplet}$$

$$r = \text{drop radius}$$

# *Nucleation of cloud droplets:*
## *Homogeneous Nucleation*

- Drop of pure water forms from vapour.
- Small drops require much higher super saturations.
- Kelvin's formula for critical radius ($R_c$) for initial droplet to "survive".
- Strongly dependent on supersaturation ($e/e_s$)
- Would require several hundred percent supersaturation (not observed in the atmosphere).

$$R_c = \frac{2\sigma}{R_v \rho_l T \ln\left( e/e_s \right)}$$

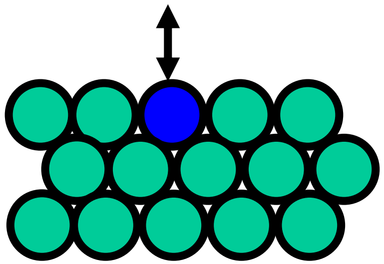
$R_c$ = Critical Radius

$\sigma$ = Surface tension of droplet

# *Nucleation of cloud droplets: Heterogeneous Nucleation*

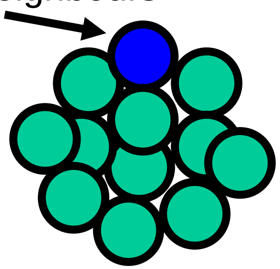
- Collection of water molecules on a foreign substance, RH > ~80% (Haze particles)
- These (hydrophilic) soluble particles are called Cloud Condensation Nuclei (CCN)
- CCN always present in sufficient numbers in lower and middle troposphere
- Nucleation of droplets (i.e. from stable haze particle to unstable regime of diffusive growth) can occur at very small supersaturations (e.g. < 1%)

# *Nucleation of cloud droplets: Important effects for particle activation*



Planar surface: Equilibrium when $e=e_s$ and number of molecules impinging on surface equals rate of evaporation

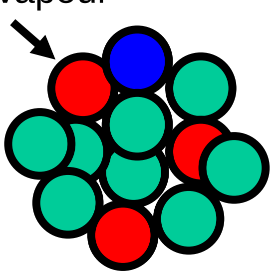
Surface molecule has fewer neighbours



Curved surface: saturation vapour pressure increases with smaller drop size since surface molecules have fewer binding neighbours.

Effect proportional to $1/r$ (curvature effect or “Kelvin effect”)

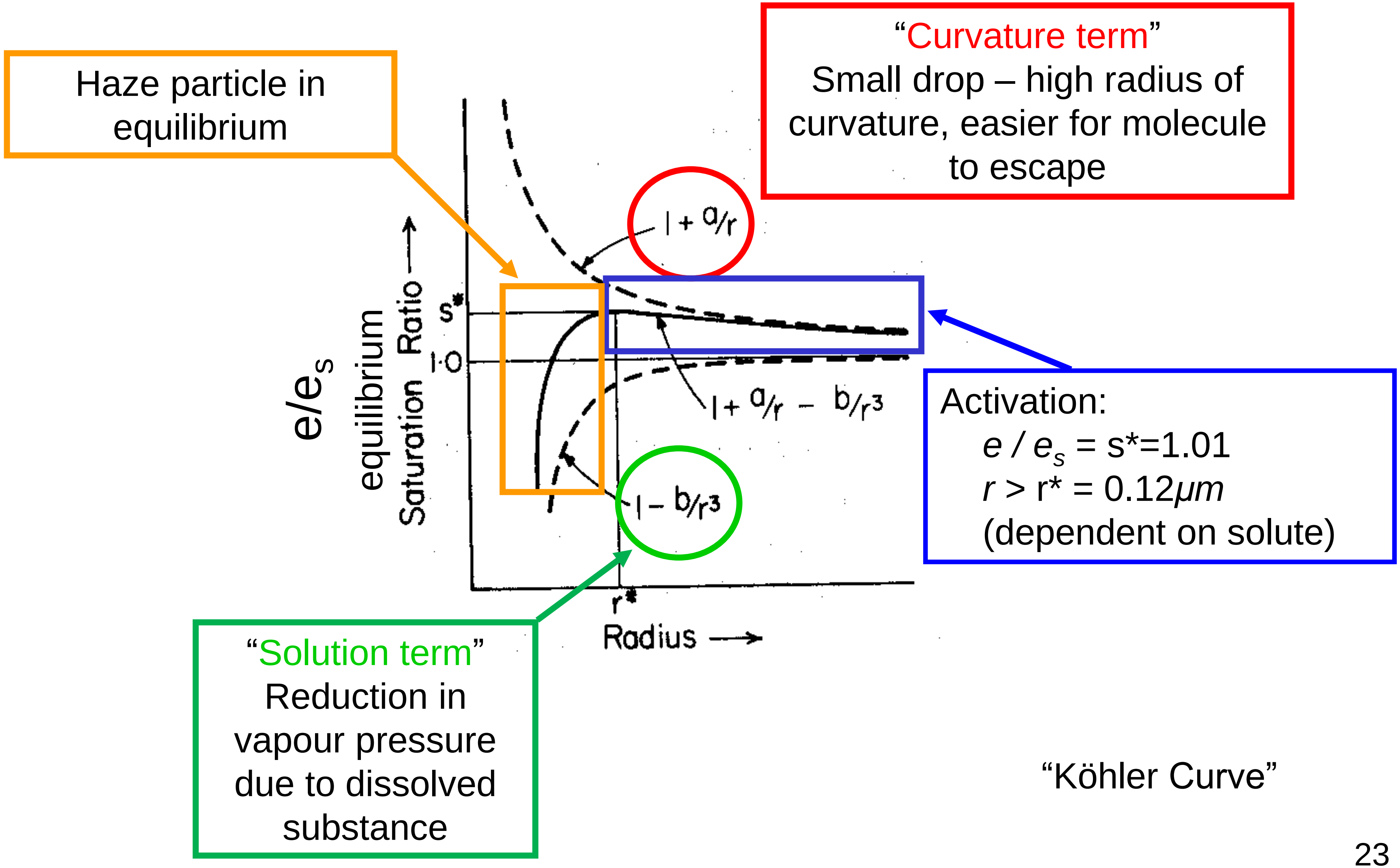
Dissolved substance reduces vapour pressure



Presence of dissolved substance: saturation vapour pressure reduces with smaller drop size due to solute molecules replacing solvent on drop surface (assuming $e_{solute}<e_v$)

Effect proportional to $-1/r^3$ (solution effect or “Raoult’s law”)

# Nucleation of cloud droplets: Heterogeneous Nucleation



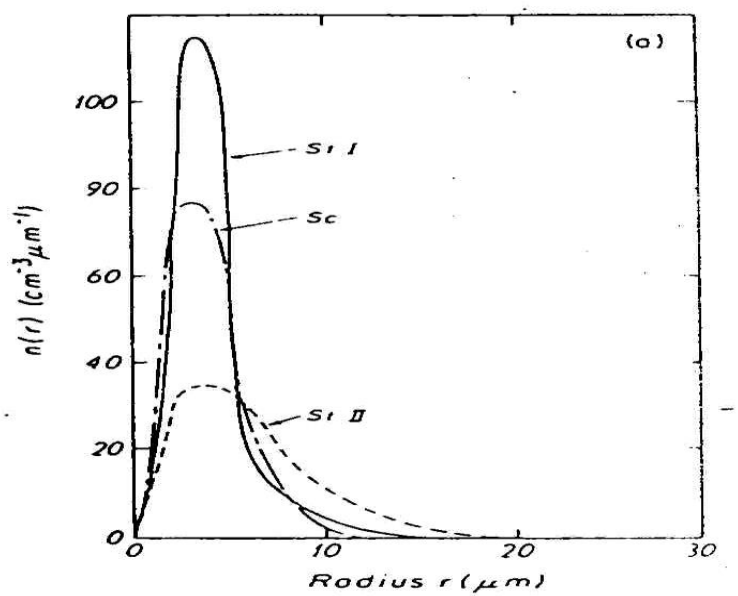

"Köhler Curve"

# Diffusional growth of cloud water droplets

- Once droplet is activated, water vapour diffuses towards it = condensation
- Reverse process = evaporation
- Droplets that are formed by diffusion growth attain a typical size of 0.1 to 10 μm
- Rain drops are much larger

  -drizzle: 50 to 100 μm

  -rain: >100 μm
- Other processes must also act in precipitating clouds




$$\frac{dr}{dt} \approx \frac{1}{r} \frac{De_s^{\infty}}{\rho_L R_v T}(S-1)$$

**For r > 1 μm and neglecting diffusion of heat**

**D=Diffusion coefficient, S=Supersaturation**

**Note inverse radius dependency**

# Collection processes
# Collision-coalescence of water drops

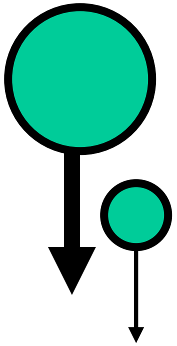
- Drops of different size move with different fall speeds - collision and coalescence

- Large drops grow at the expense of small droplets

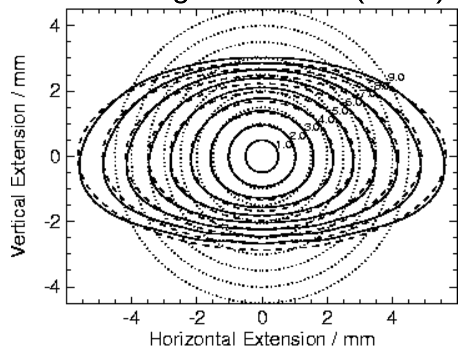
- Collection efficiency low for small drops

- Process depends on width of droplet spectrum and is more efficient for broader spectra – paradox – how do we get a broad spectrum in the first place?

- Large drops can only be produced in clouds of large vertical extent – Aided by turbulence (differential evaporation), giant CCNs ?



Rain drop shape
Chuang and Beard (1990)



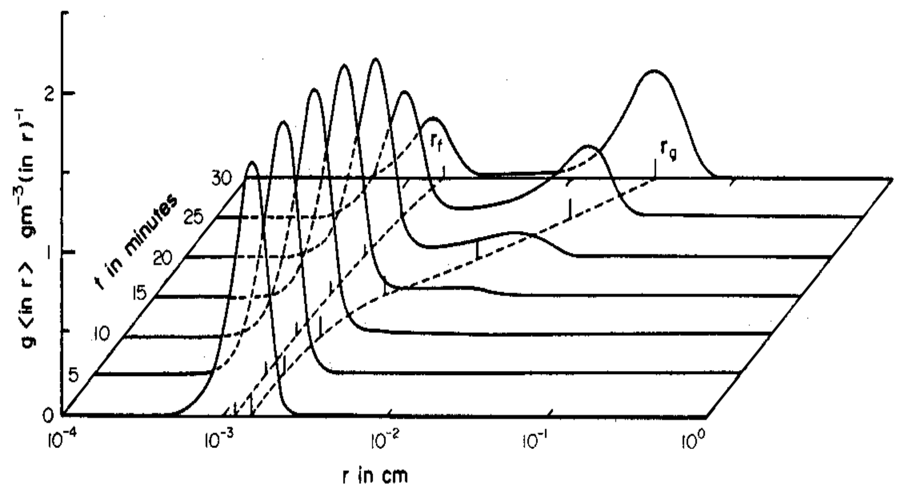




FIG. 8.10. Example of the development of a droplet spectrum by stochastic coalescence. (From Berry and Reinhardt, 1974b.)

# *Parametrizing nucleation and water droplet diffusional growth*

- Nucleation: Since CCN “activation” occurs at water supersaturations less than 1%, most schemes assume all supersaturation with respect to water is immediately removed to form water droplets.

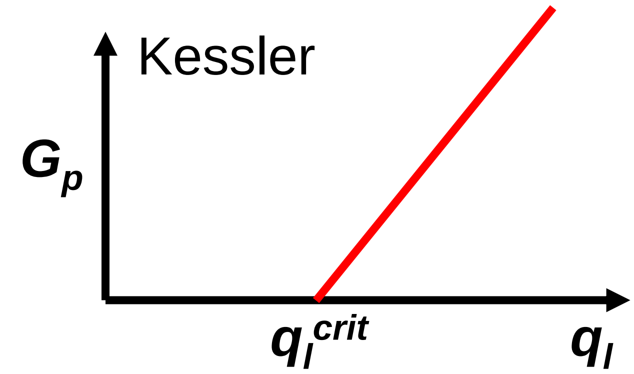
- So usually, the growth equation is not explicitly solved. In single-moment schemes simple (diagnostic) assumptions are made concerning the droplet number concentration when needed (e.g. radiation).

# Parametrizing collection processes
# "Autoconversion" of cloud drops to raindrops

## Simplified with simple functional form, e.g.

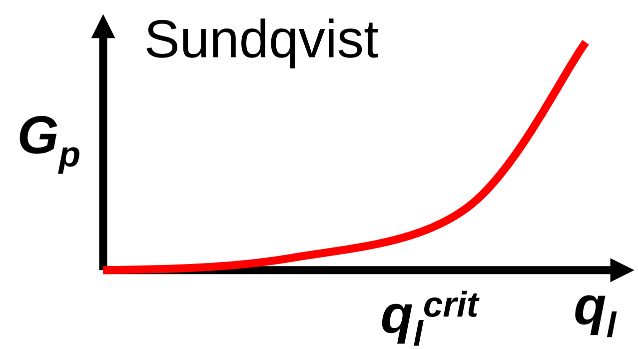
- Linear function of $q_l$ (Kessler, 1969)

$$\frac{\partial q_l}{\partial t} = \begin{cases} c_0 \left( q_l - q_l^{crit} \right) & \text{if } q_l > q_l^{crit} \\ 0 & \text{otherwise} \end{cases}$$




- Function of $q_l$ with additional term to avoid singular threshold and non-local precipitation term (Sundqvist 1978)

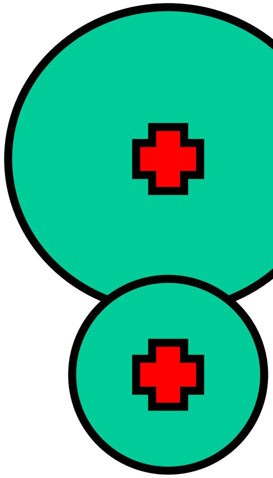
$$\frac{\partial q_l}{\partial t} = c_0 \, F_1 \, q_l \left( 1 - e^{-\left( \frac{q_l}{q_l^{crit}} F_1 \right)^2} \right)$$




- Or more non-linear, double moment functions such as Khairoutdinov and Kogan (2000), or Seifert and Beheng (2001) derived directly from the stochastic collection equation. →

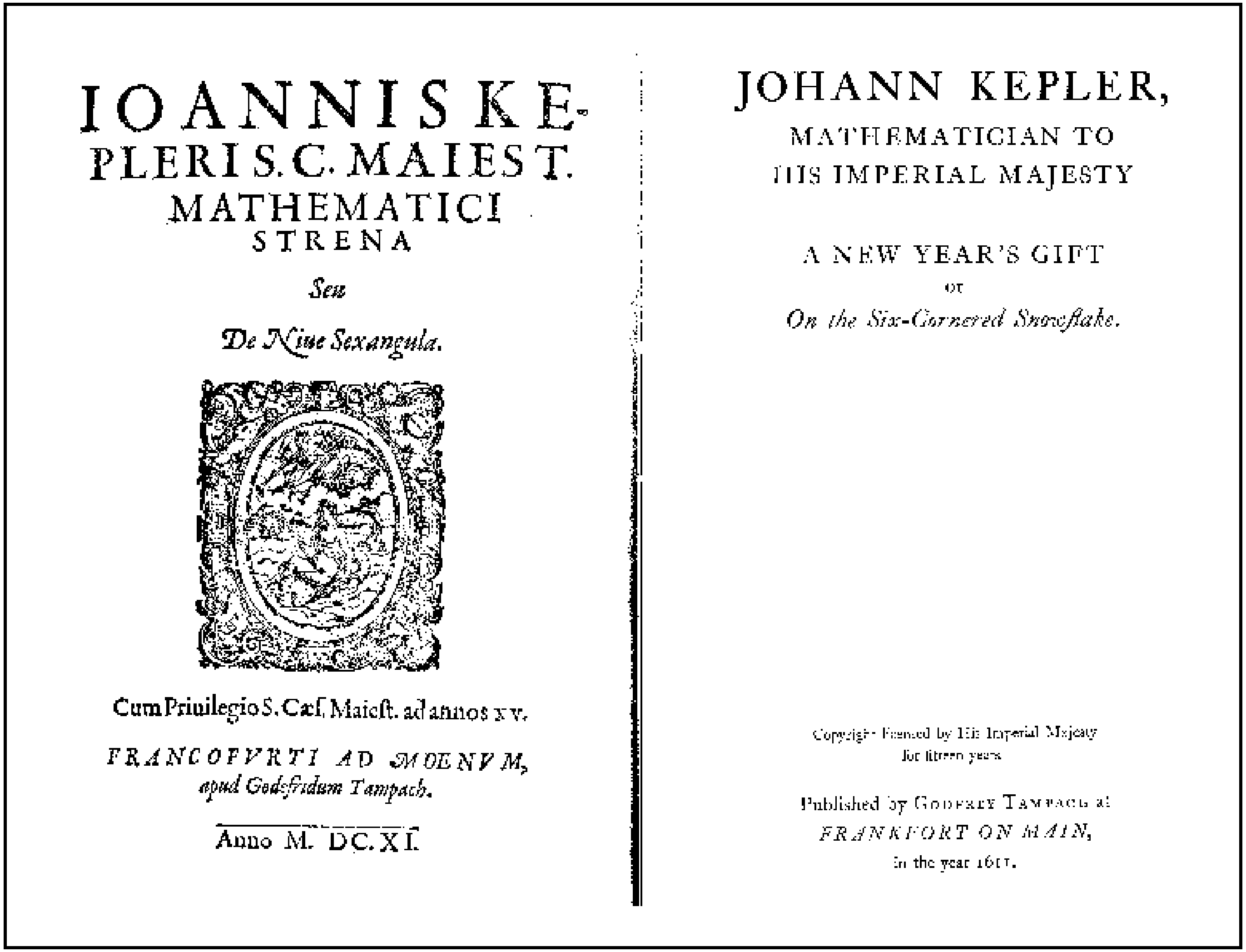
$$\frac{\partial q_l}{\partial t} = c_0 q_l^{2.47} N_c^{-1.79}$$

# *Schematic of Warm Rain Processes*



# 2. Microphysical Processes
## 2.2 Cold Phase

# *First recorded mention of the "six-cornered snowflake" - Kepler (1611)*



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Cum Priuilegio S. Cæs. Maiest. ad annos XV.

*FRANCOFVRTI AD MOENVM,*
*apud Godefridum Tampach.*

Anno M. DC. XI.

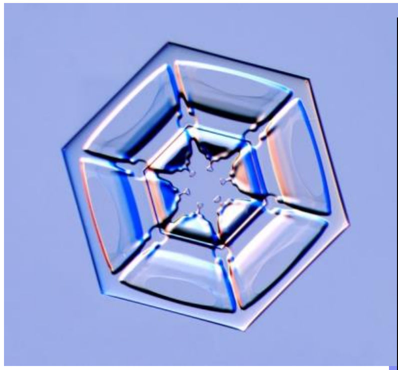
JOHANN KEPLER,
MATHEMATICIAN TO
HIS IMPERIAL MAJESTY

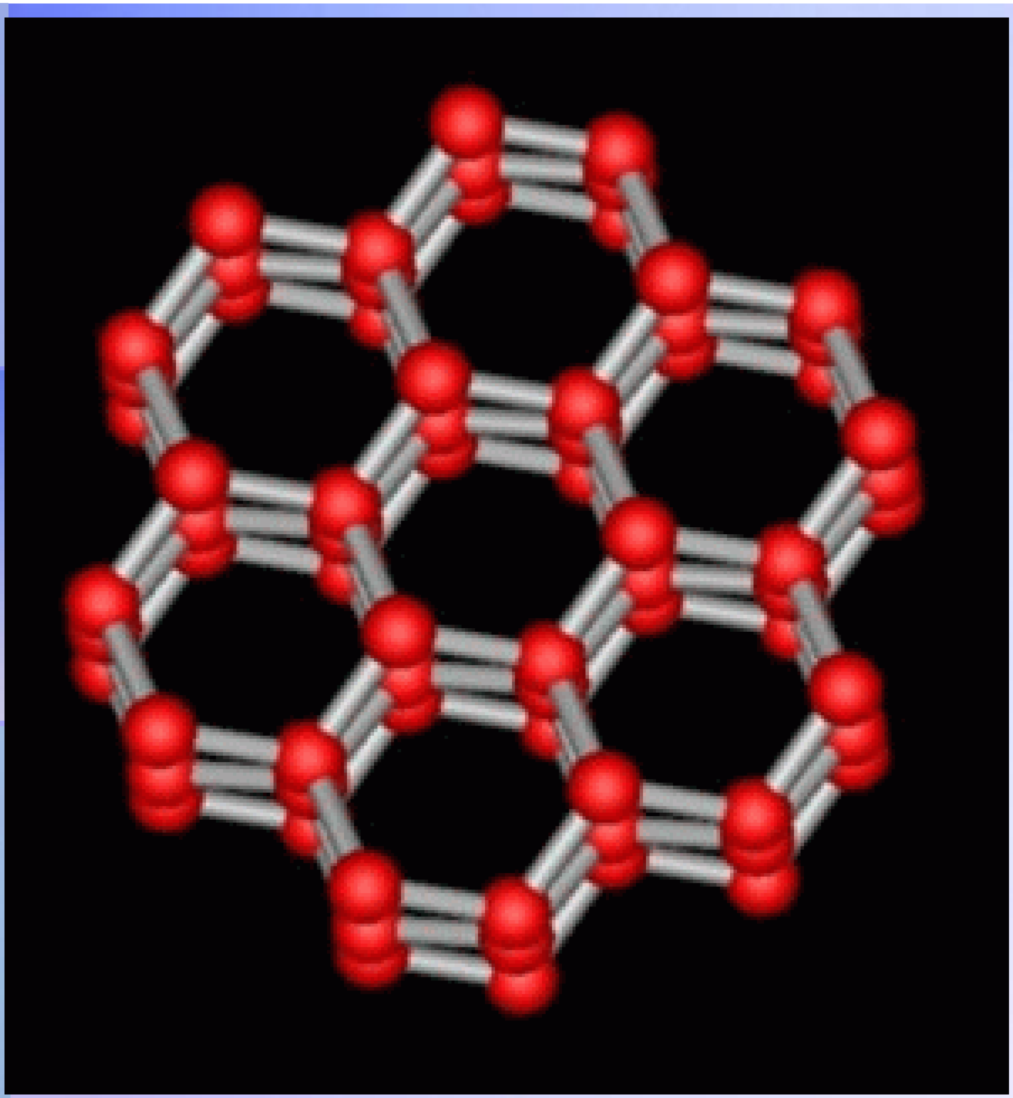
A NEW YEAR'S GIFT
or
*On the Six-Cornered Snowflake.*

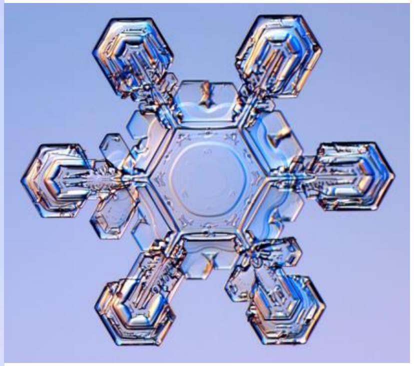
Copyright Granted by His Imperial Majesty
for fifteen years

Published by Godfrey Tampach at
*FRANKFORT ON MAIN,*
in the year 1611.

# "The Six-Cornered Snowflake"







www.snowcrystals.com
Ken Libbricht

# Ice Microphysical Processes

- Ice nucleation
- Depositional Growth (and sublimation)
- Collection (aggregation/riming)
- Splintering
- Melting

# *Ice Nucleation*

- Droplets do not freeze at 0$^{o}$C !
- Ice nucleation processes can be split into homogeneous and heterogeneous processes

**Homogeneous nucleation**

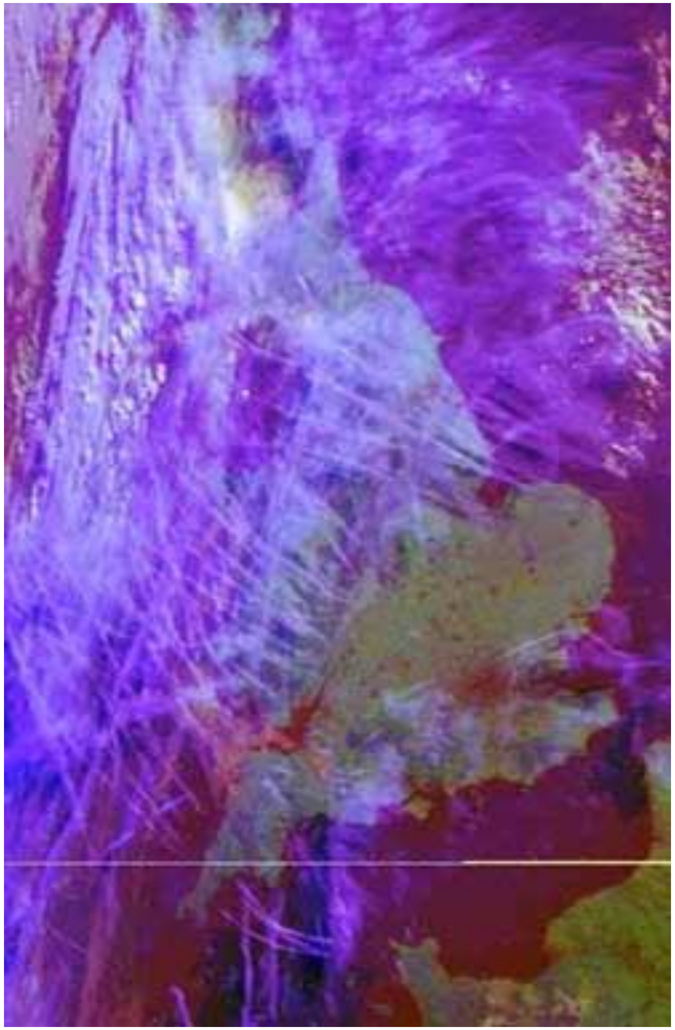
- No preferential nucleation sites (i.e. pure water or solution drop)
- Homogeneous freezing of cloud water droplets occurs below about -38$^{o}$C, so all ice below this temperature (e.g. water droplets carried upward by convective updraughts).
- Homogeneous nucleation of ice crystals from small aqueous solution drops (haze particles), which have a lower freezing temperature, is dependent on a critical relative humidity (function of temperature, Koop et al. 2000). So new ice cloud formation needs high supersaturations.
- Observations of clear air supersaturation are common…

# *Ice Nucleation: Homogeneous Nucleation*

- At cold temperatures (e.g. upper troposphere) ratio between liquid and ice saturation vapour pressures is large (can support large ice supersaturations).

- If air mass is lifted, and does not contain significant liquid particles or ice nuclei, high supersaturations with respect to ice can occur, reaching 160 to 170%.

- Long lasting contrails are a signature of supersaturation.

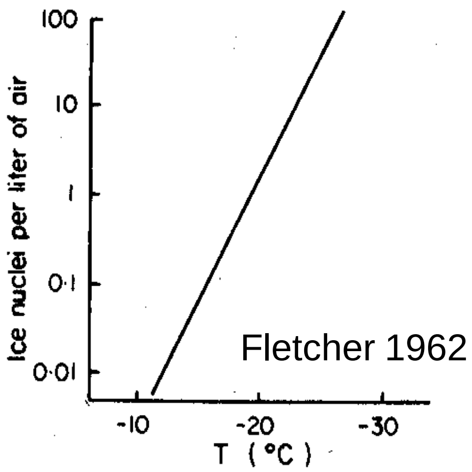


# *Ice Nucleation*

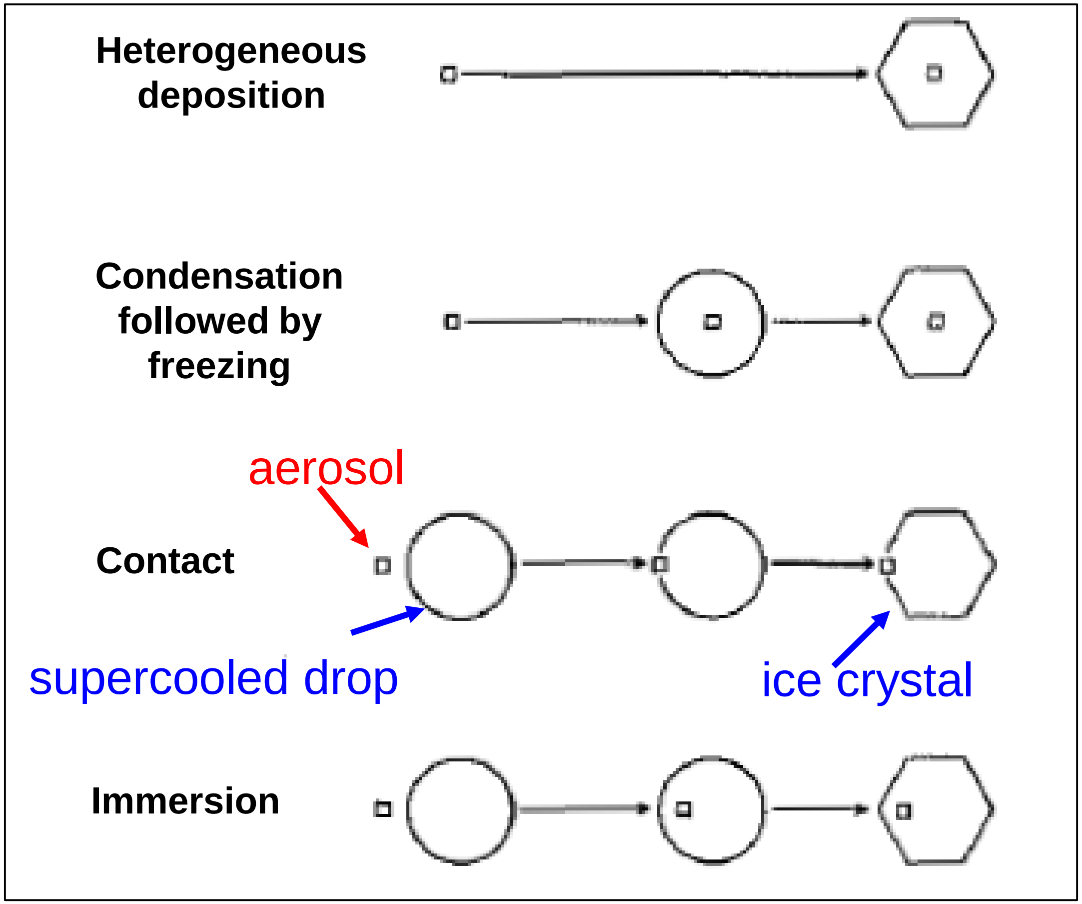
- Droplets do not freeze at 0$^o$C !
- Ice nucleation processes can also be split into homogeneous and heterogeneous.

**Heterogeneous nucleation**

- Preferential sites for nucleation (interaction with solid aerosol particles – ice nuclei)
- Frequent observation of ice between 0$^o$C and colder temperatures indicates heterogeneous processes are active.
- Number of activated ice nuclei increases with decreasing temperature so heterogeneous nucleation more likely with increasing altitude, e.g. Fletcher (1962); Meyers (1991); DeMott et al (2010)



# *Ice Nucleation: Heterogeneous nucleation*



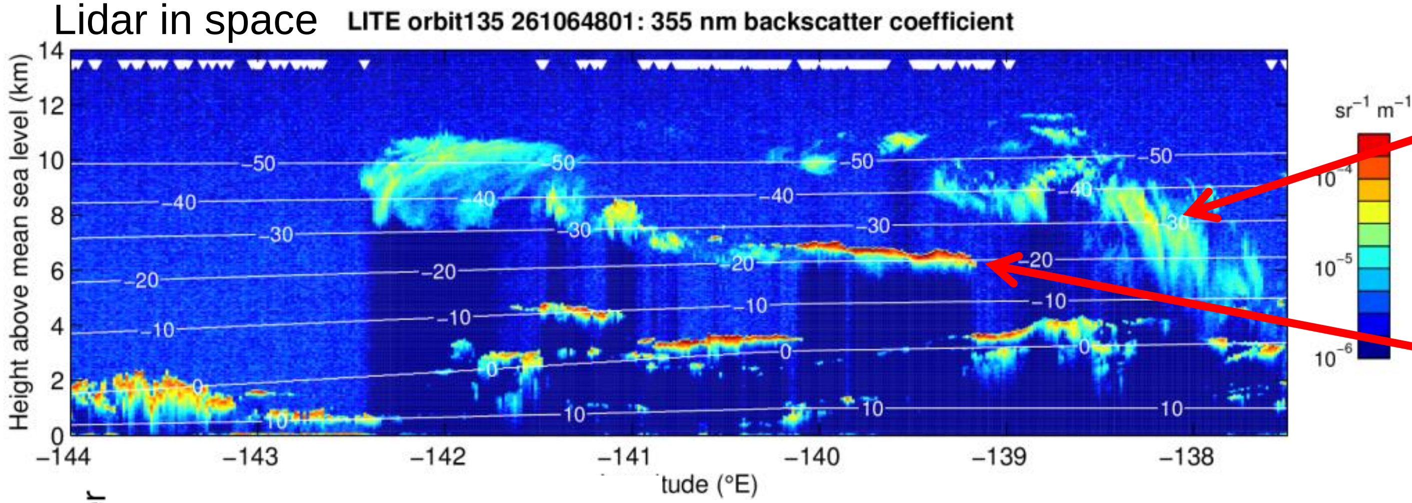

**Schematic of heterogeneous ice nucleation mechanisms**
(from Rogers and Yau, 1996)

Still many uncertainties in heterogeneous ice nucleation processes in the atmosphere and their impacts!

# *Ice Nucleation:*

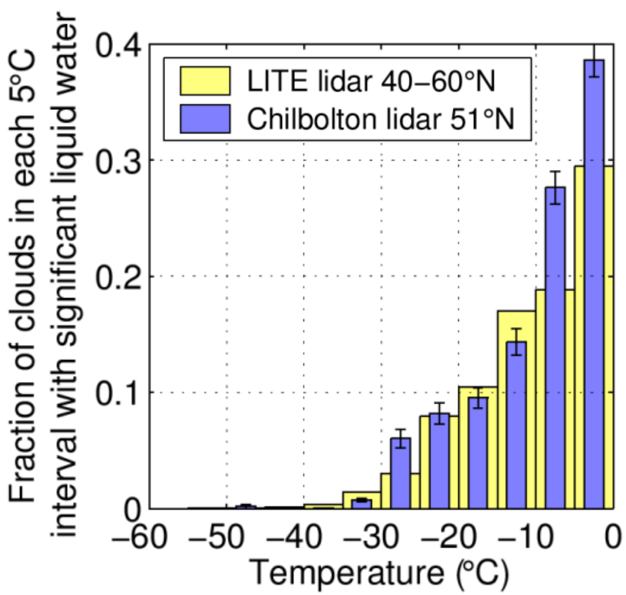
## *Observed supercooled liquid water occurrence*

Lidar in space




Lidar: lower backscatter from ice cloud

Lidar: high backscatter from liquid water layers




(Hogan et al., GRL, 2004)

Observations:

- Colder than -38$^{o}$C, no supercooled liquid water.
- Supercooled liquid water increasingly common as approach 0$^{o}$C.
- Often in shallow layers at cloud top, or in strong updraughts associated with convection
- Often mixed-phase cloud – liquid and ice present
- Convective clouds with tops warmer than -5$^{o}$C rarely have ice.

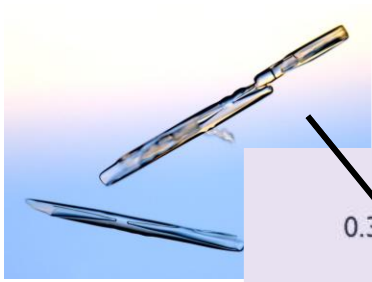
# Diffusional growth of ice crystals
# Deposition

Equation for the rate of change of mass for an ice particle of diameter D due to deposition (diffusional growth), or evaporation

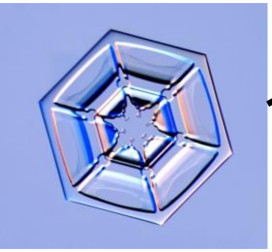
$$\frac{\partial m}{\partial t} = \frac{4\pi sCF}{\left(\frac{L_s}{RT} - 1\right)\frac{L_s}{k_a T} + \frac{RT}{\chi e_{si}}} \qquad \propto s\,C\,F$$

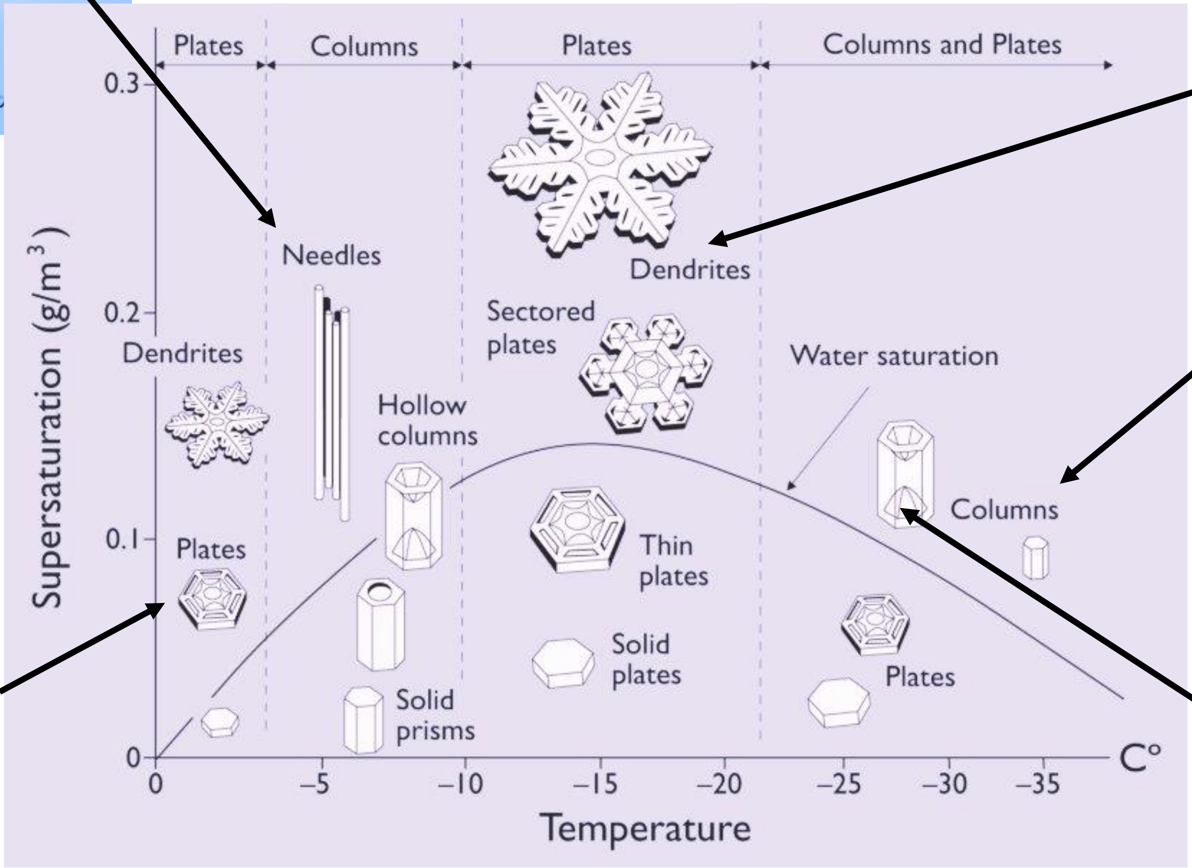
- Deposition rate depends primarily on
  - the supersaturation, *s*
  - the particle shape (habit), *C* (*plate, column, aggregate*)
  - the ventilation factor, *F* (*particle falling through air*)
- The particular mode of growth (edge growth *vs* corner growth) is sensitive to the temperature and supersaturation

# Diffusional growth of ice crystals
## Ice Habits



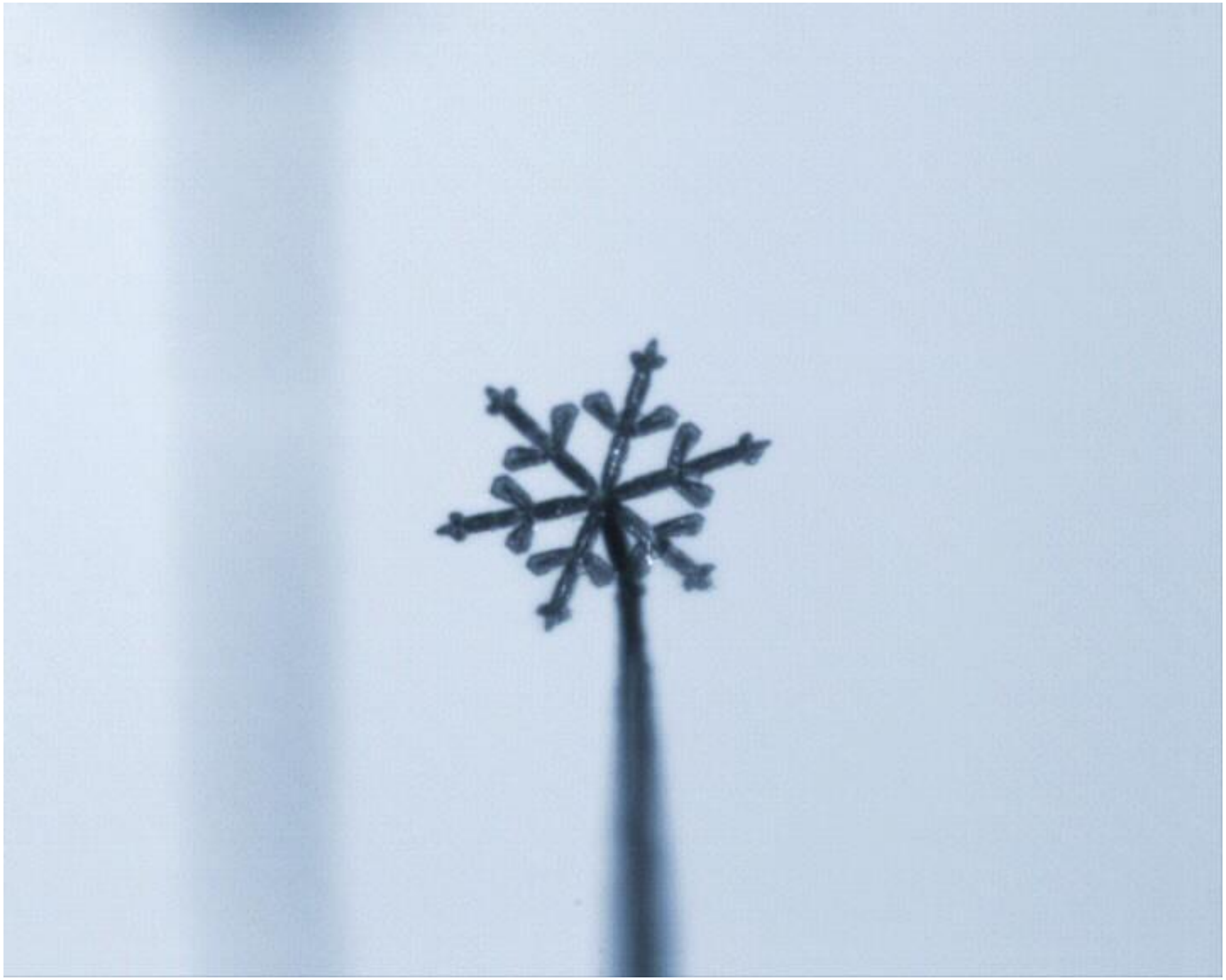
Ice habits can be complex, depend on temperature: influences fall speeds and radiative properties






http://www.its.caltech.edu/~atomic/snowcrystals/

# Diffusional growth of ice crystals
## Animation of crystal growth

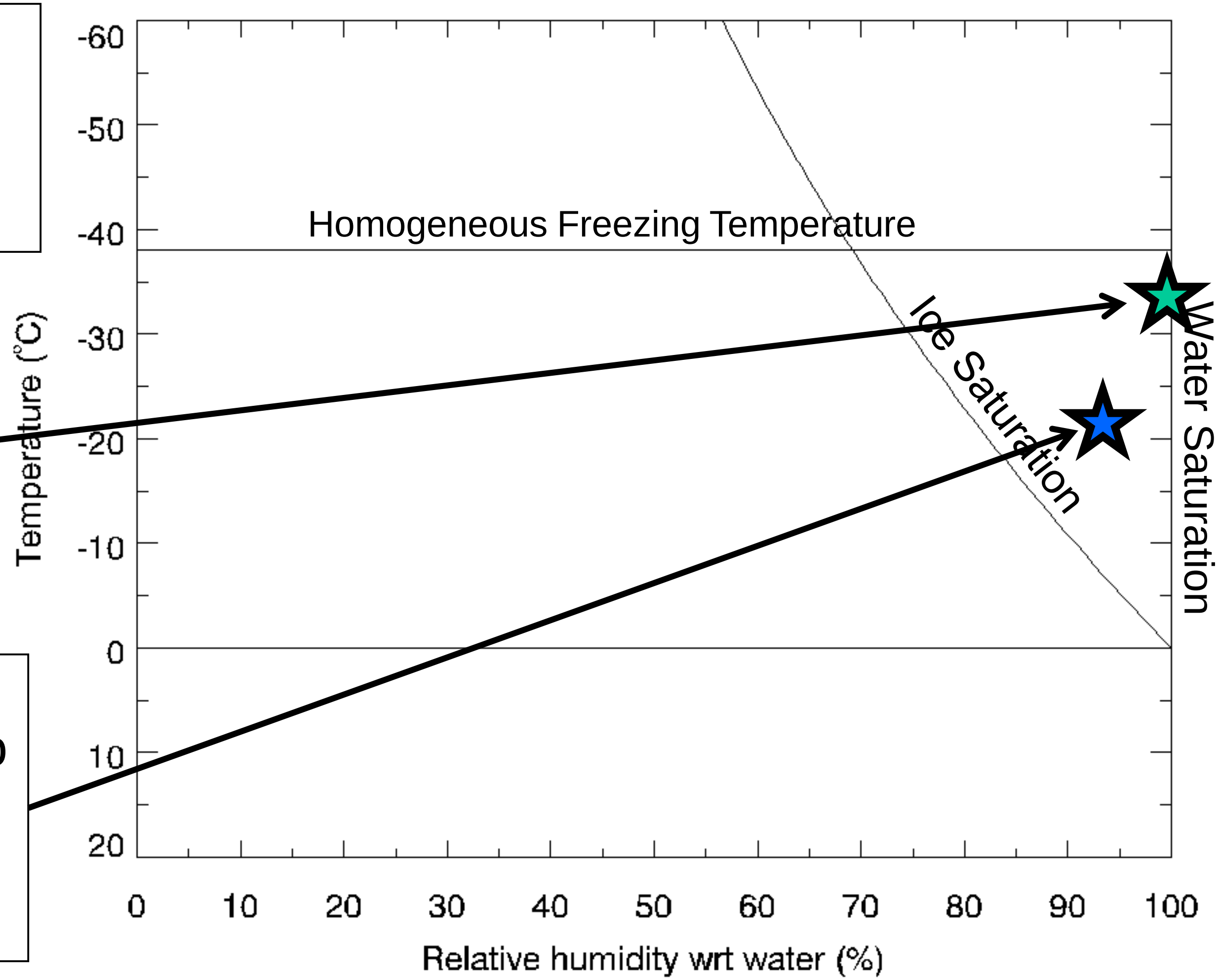


# Diffusional growth of ice crystals
# Mixed Phase Clouds: Bergeron Process (I)

The saturation vapour pressure with respect to ice is smaller than with respect to water.

A cloud which is saturated with respect to water is supersaturated with respect to ice.

A cloud which is sub-saturated with respect to water can be supersaturated with respect to ice.



# *Diffusional growth of ice crystals*
# *Mixed phase cloud Bergeron process (II)*

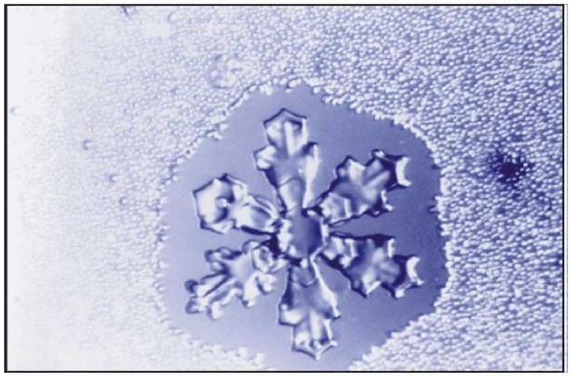
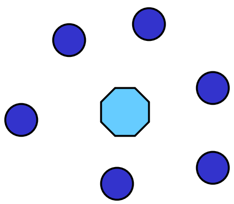


Photo by R. Pitter

Ice particles grow at the expense of water droplets

Ice particle enters water cloud →

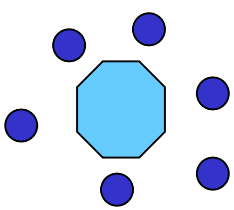


↓

Cloud is supersaturated with respect to ice

↓

Diffusion of water vapour onto ice particle →

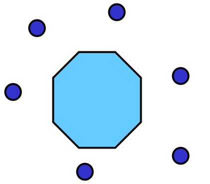


↓

Cloud will become sub-saturated with respect to water

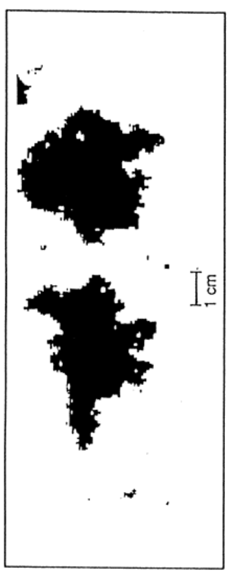
↓

Water droplets evaporate to increase water vapour →



# *Collection processes:*
# *Ice Crystal Aggregation*

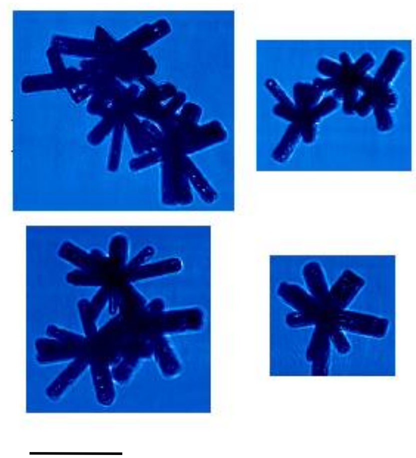
- Ice crystals can aggregate together to form “snow”
- “Sticking” efficiency increases as temperature exceeds –5° C
- Irregular crystals are most commonly observed in the atmosphere (e.g. Korolev et al. 1999, Heymsfield 2003)




Lawson, JAS’99

Field & Heymsfield ‘03

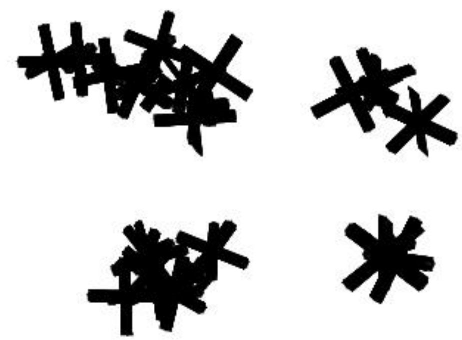
CPI



500 μm

T=-46°C

Model

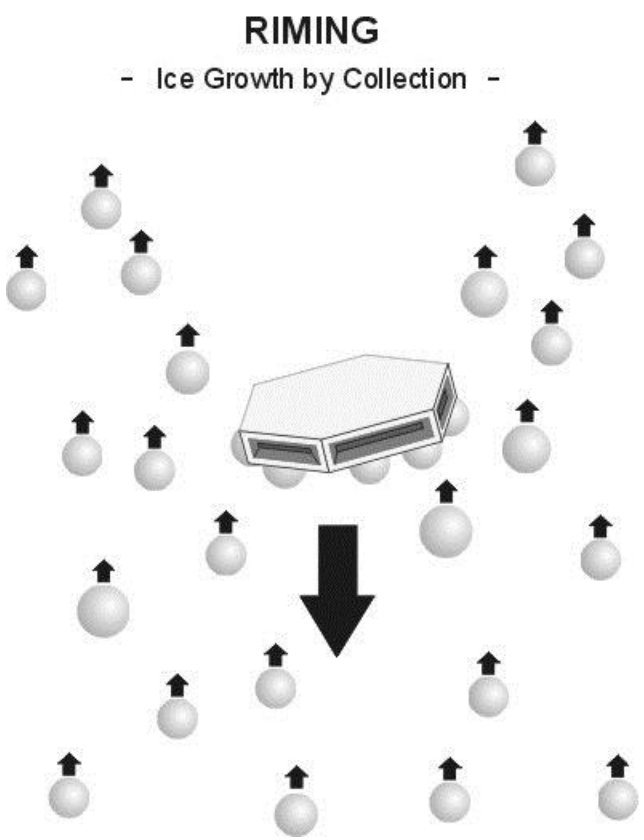


Westbrook et al. (2008)

# *Parametrization of ice crystal diffusion growth and aggregation*

- Some schemes represent ice processes very simply, converting any ice supersaturation to ice (as for warm rain process).
- Others, have a slightly more complex representation allowing ice supersaturation (e.g. current ECMWF scheme).
- Increasingly common are schemes which represent ice supersaturation and the diffusional growth equation, and aggregation, represented as an autoconversion to snow or parametrization of an evolving particle size distribution (e.g. Wilson and Ballard, 1999).

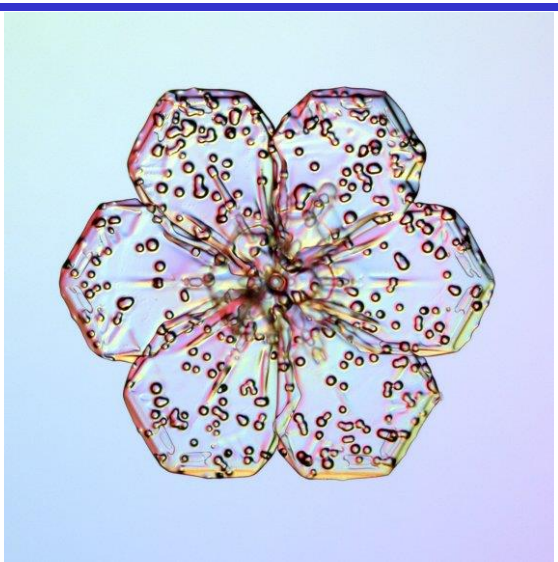
# *Collection processes:*
# *Riming – capture of water drops by ice*

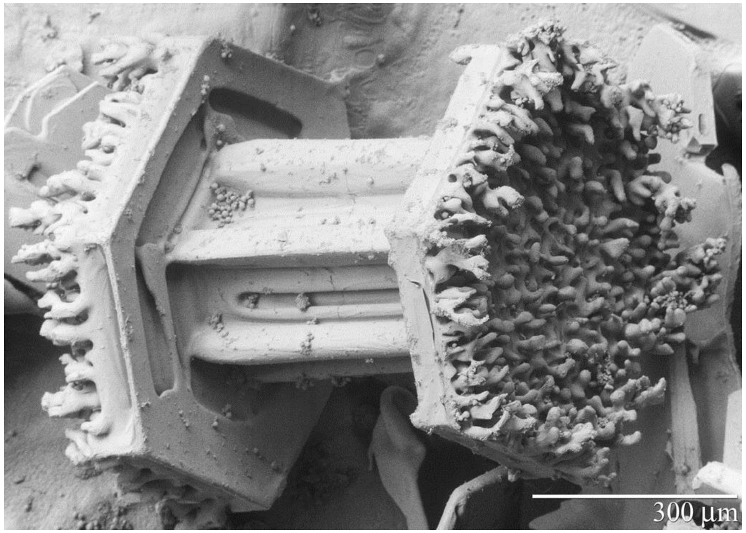


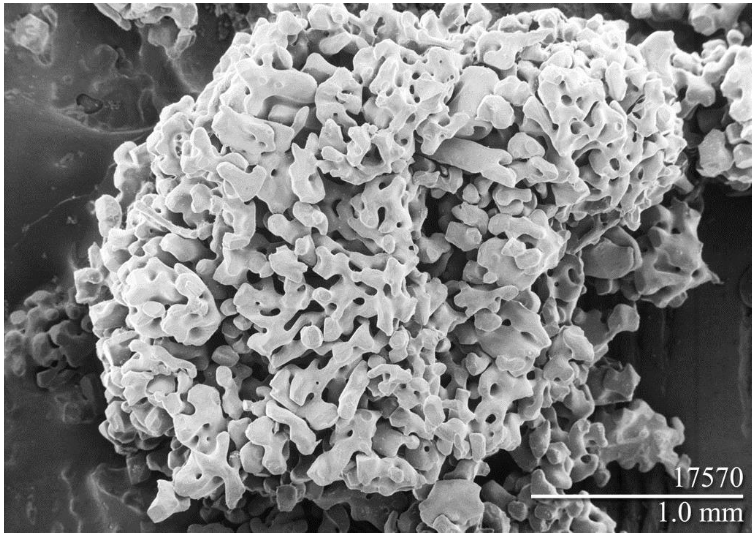

- Graupel formed by collecting liquid water drops in mixed phased clouds ("riming"), particulaly when at water saturation in strong updraughts (convection). Round ice crystals with higher densities and fall speeds than snow dendrites.

- Hail forms if particle temperature close to 273K, since the liquid water "spreads out" before freezing.  Generally referred to as "Hail" – The higher fall speed (up to 40 m/s) imply hail only forms in convection with strong updraughts able to support the particle long enough for growth.

# Rimed Ice Crystals






http://www.its.caltech.edu/~atomic/snowcrystals

Electron micrographs (emu.arsusda.gov)

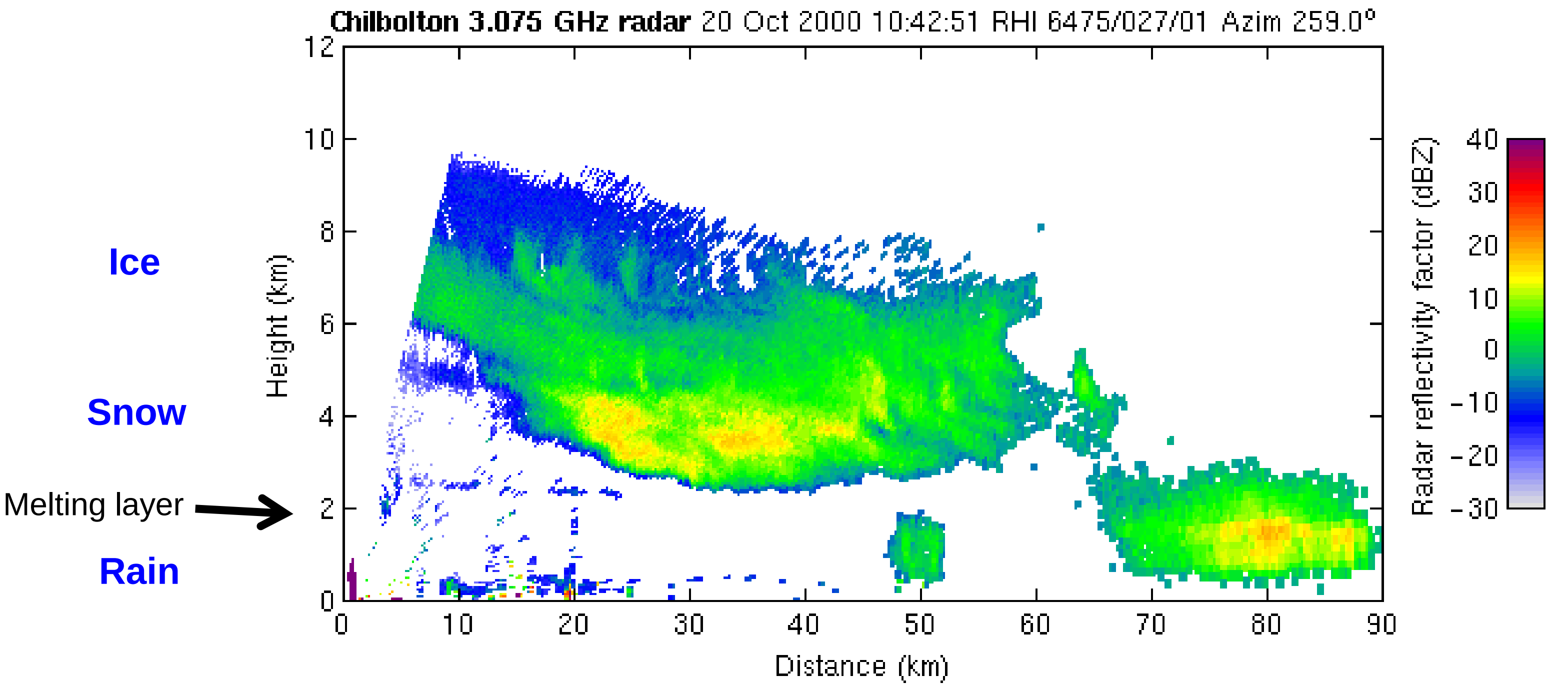
# Parametrization of rimed ice particles

- Most GCMs with parametrized convection don't explicitly represent graupel or hail (too small scale)
- In cloud resolving models, traditional split between ice, snow and graupel and hail as prognostic variables, but this split is rather artificial.
- Degree of riming can be light or heavy, particle density can vary smoothly.
- Alternative approach is to have ice particle properties as the prognostic variables, e.g.
  - Morrison and Grabowski (2008) have 3 ice variables: deposition mass, rime mass and number.
  - Morrison and Milbrandt (2015) have 4 ice variables to also represent hail-type particles: total ice mass, rime mass, rime volume and number.
  - Avoids artificial thresholds between different categories.

# Other microphysical processes
## *Splintering, Shedding, Evaporation, Melting*

- Other processes include evaporation (reverse of condensation), ice sublimation (reverse of deposition) and melting.
- Shedding: Large rain drops break up – shedding to form smaller drops, places a limit on rain drop size.
- Splintering of ice crystals, Hallet-Mossop splintering through riming around -5ºC. Leads to increased numbers of smaller crystals.
- Sedimentation due to gravity. Fall speed depends on particle size (and habit/density for ice).

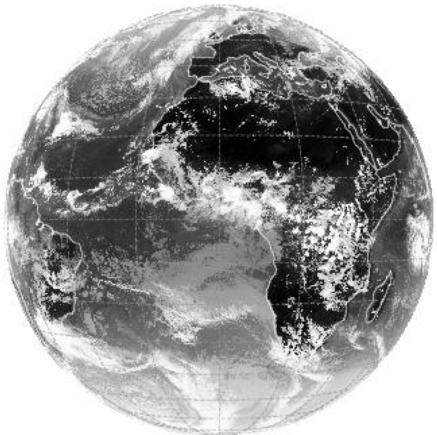
# Falling Precipitation

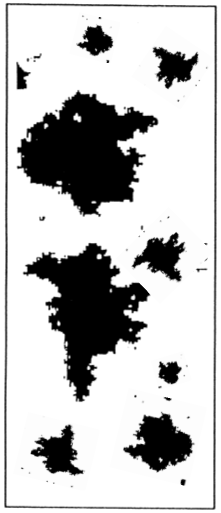



Courtesy R Hogan, University of Reading, www.met.rdg.ac.uk/radar

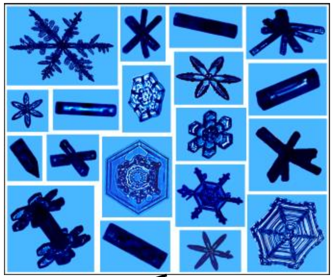
# 3. Summary

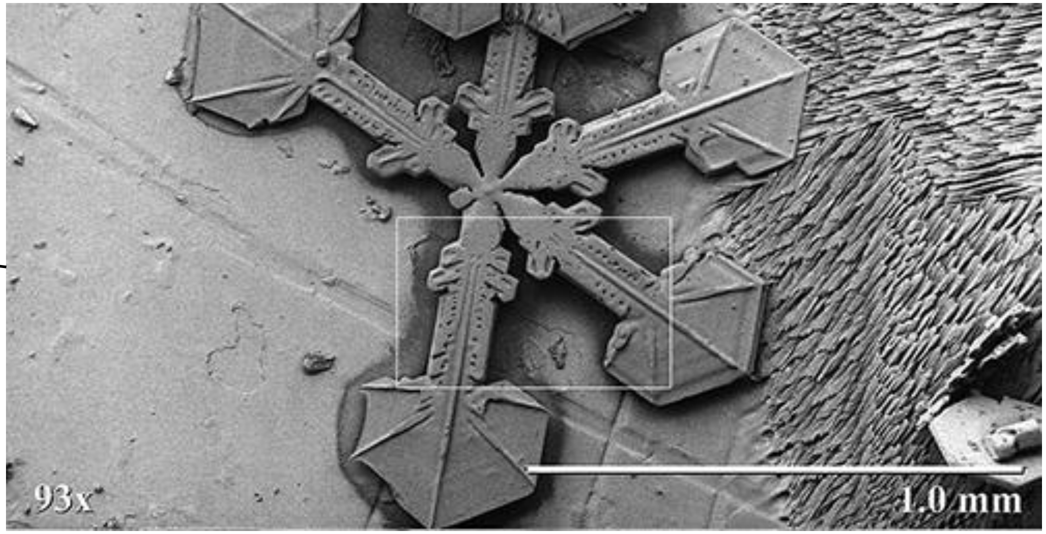
# *From global to micro-scales*

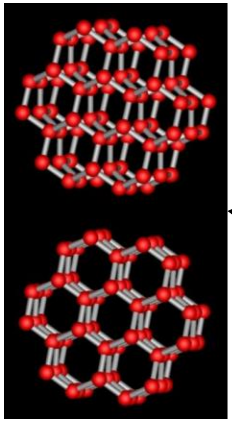




Hugely complex system.
Need to simplify!





emu.arsusda.gov

# Summary

- Parametrization of cloud and precipitation microphysical processes:
  - Need to simplify a complex system
  - Accuracy vs. complexity vs. computational efficiency trade off
  - Appropriate for the application and no more complexity than can be constrained and understood
  - Dynamical interactions (latent heating), radiative interactions
  - Still many uncertainties (particularly ice phase)
  - Particular active area of research is aerosol-microphysics interactions.
  - Microphysics often driven by small scale dynamics – how do we represent this in models…..
- Next lecture: Cloud Cover
  - Sub-grid scale heterogeneity
  - Linking the micro-scale to the macro-scale

# References

Reference books for cloud and precipitation microphysics: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Rogers, R. R. and M. K. Yau, (1989). *A Short Course in Cloud Physics* (*3rd Ed*.) Butterworth-Heinemann Publications.

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