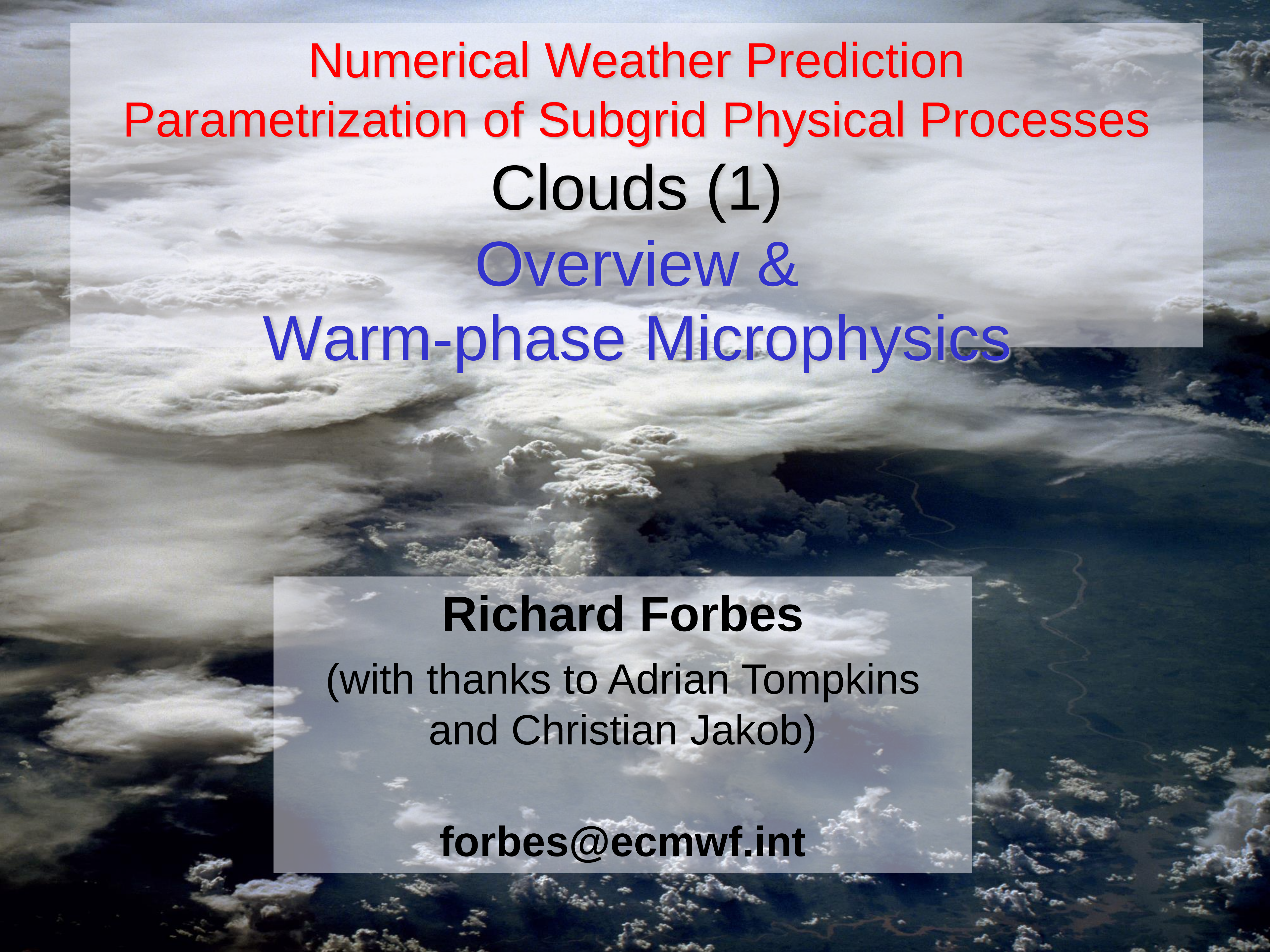


Numerical Weather Prediction
Parametrization of Subgrid Physical Processes

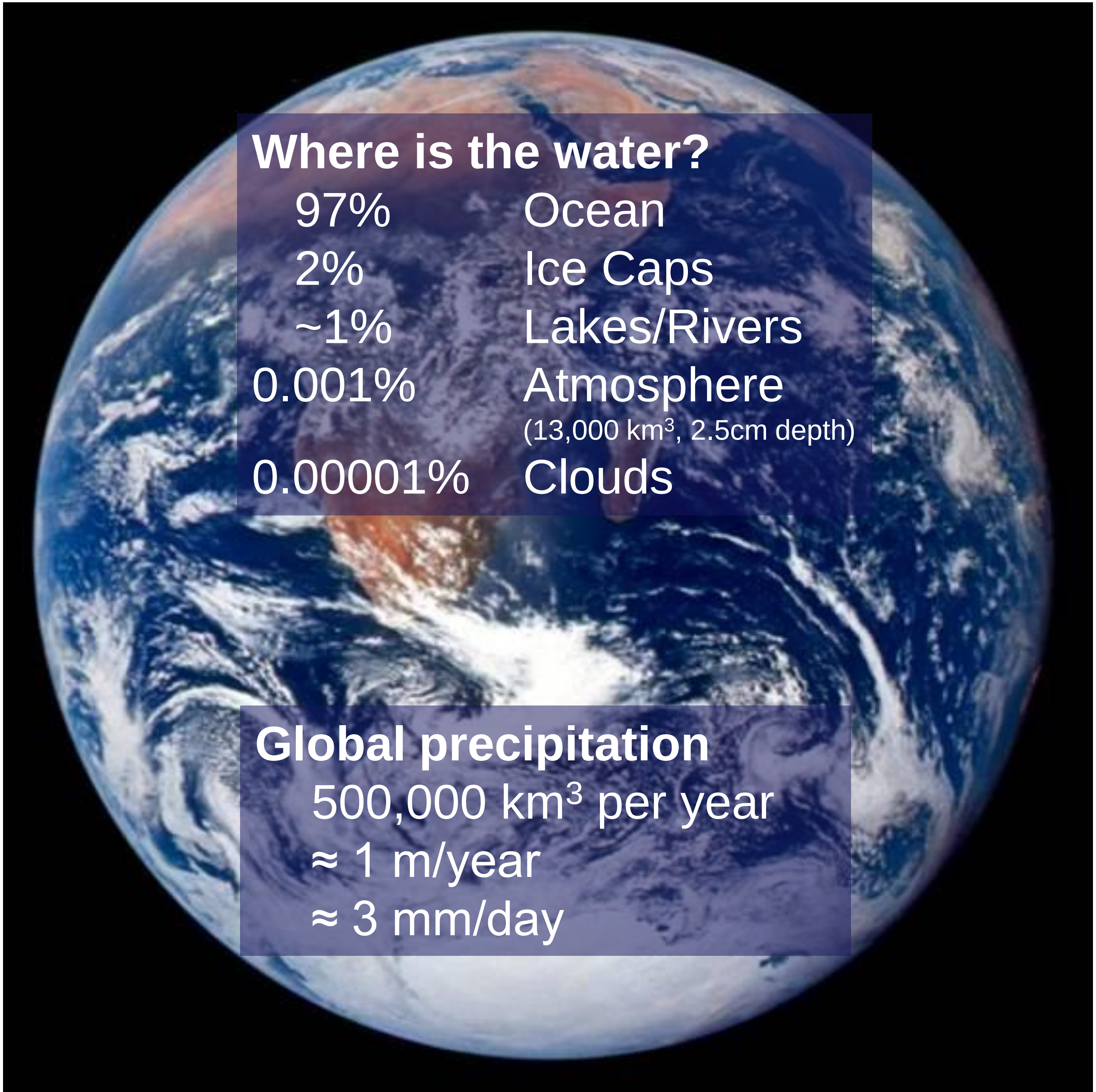
Clouds (1)

Overview & Warm-phase Microphysics

Richard Forbes

(with thanks to Adrian Tompkins
and Christian Jakob)

forbes@ecmwf.int



Where is the water?

97%	Ocean
2%	Ice Caps
~1%	Lakes/Rivers
0.001%	Atmosphere (13,000 km^3, 2.5cm depth)
0.00001%	Clouds

Global precipitation

500,000 km^3 per year

≈ 1 m/year

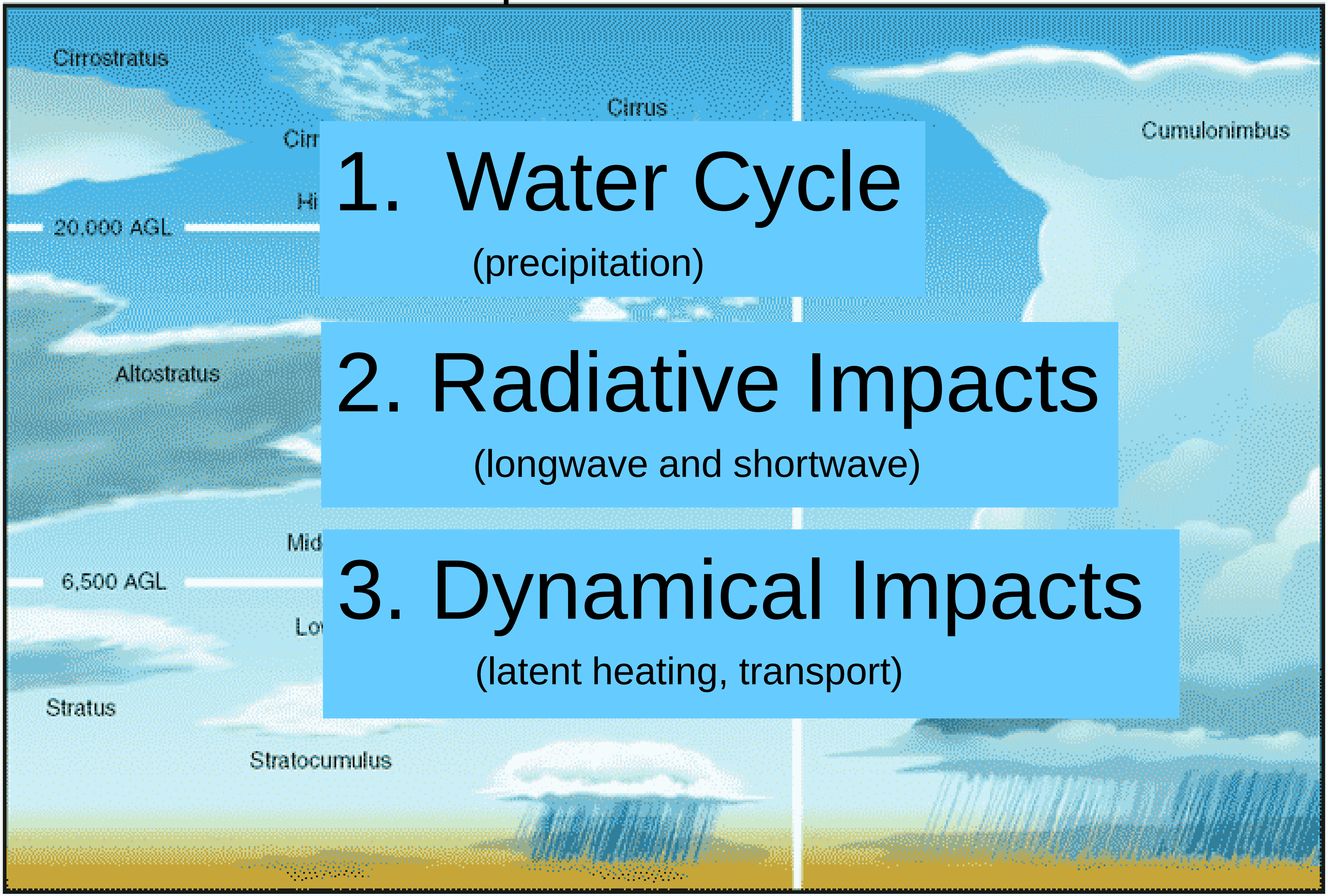
≈ 3 mm/day

Cloud Lectures - Outline

1. Overview of cloud parametrization issues **(Lecture 1)**
2. Liquid-phase microphysical processes **(Lecture 1)**
3. Ice and mixed-phase microphysical processes **(Lecture 2)**
4. Sub-grid heterogeneity **(Lecture 3)**

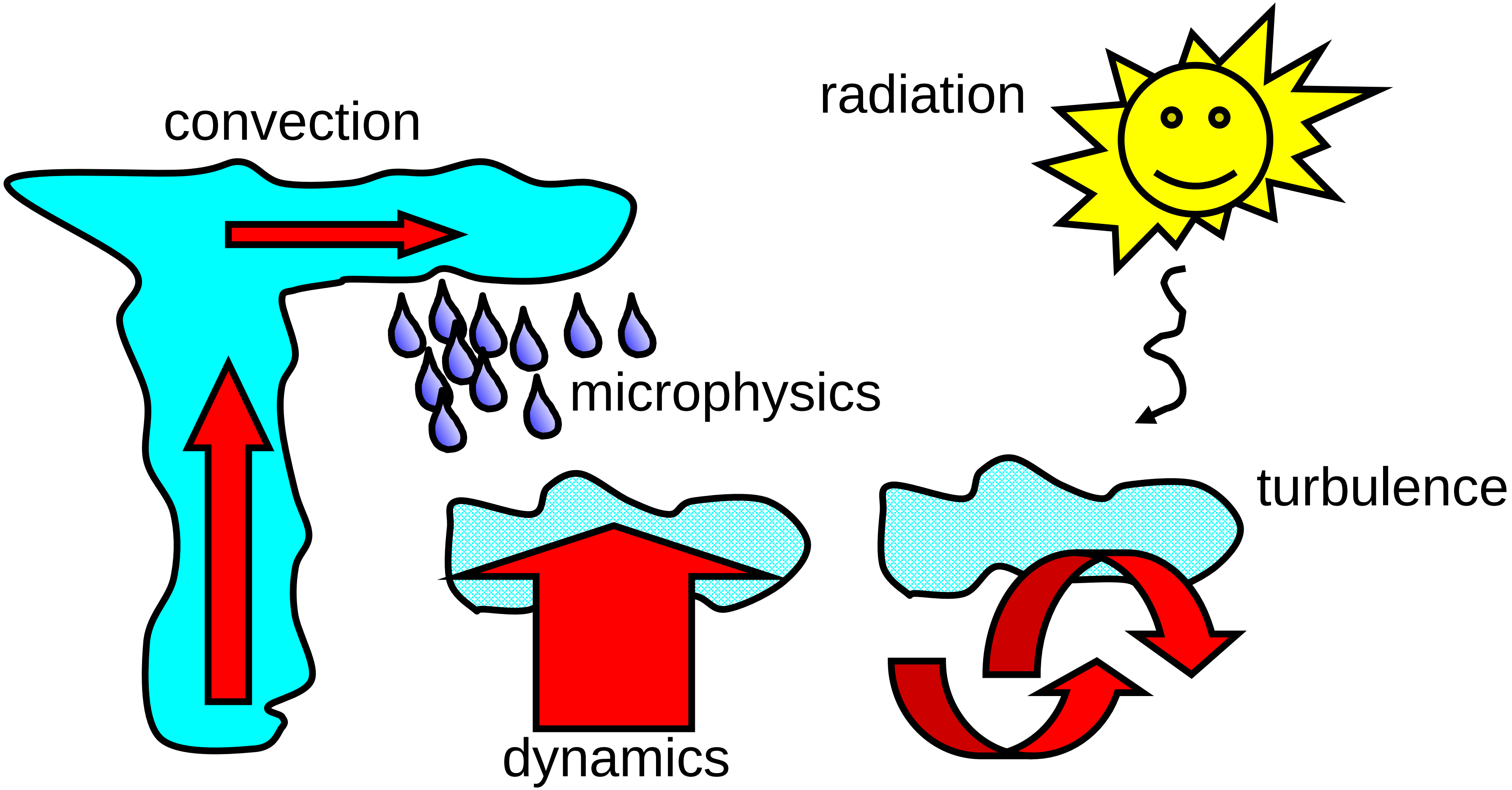
1. Overview of Cloud Parametrization Issues

The Importance of Clouds



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

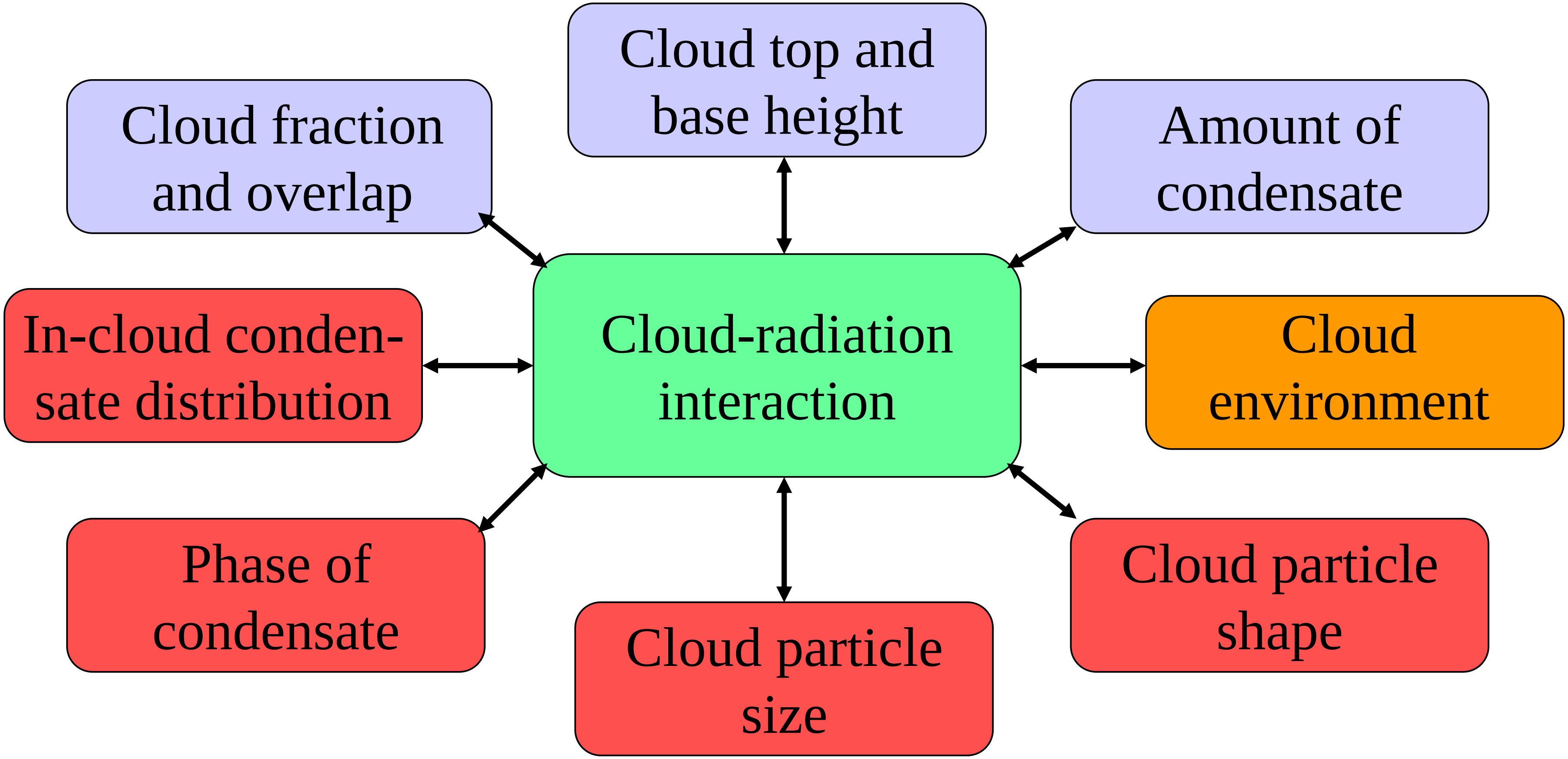
Representing Clouds in GCMs What are the problems ?



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

Representing Clouds in GCMs What are the problems ?

Example: cloud-radiation interaction – many uncertainties



Cloud-radiation interaction

Cloud fraction and overlap

Cloud top and base height

Amount of condensate

In-cloud condensate distribution

Cloud environment

Phase of condensate

Cloud particle size

Cloud particle shape

🟦 Cloud macrophysics

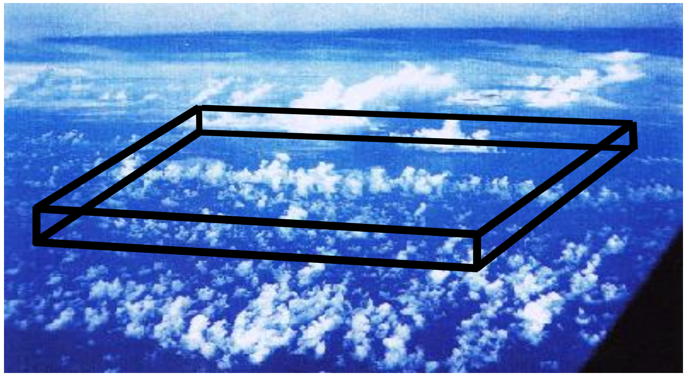
🟥 Cloud microphysics

🟧 “External” influence

Cloud Parametrization Issues:

- Microphysical processes

- Macro-physical
  - subgrid heterogeneity



- Numerical issues

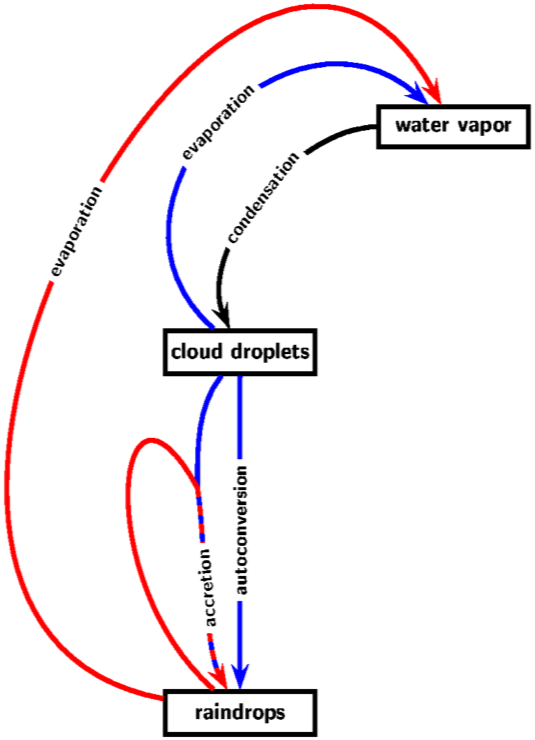
$$\boxed{\frac{\partial q_l}{\partial t} = A(q_l) + S(q_l) - D(q_l)}$$

Microphysics Parametrization Issues:
Which quantities (categories) to represent ?

- Water vapour

Warm-phase:

- Cloud water droplets
- Rain drops



From: Axel Seifert

Microphysics Parametrization Issues:
Which quantities (categories) to represent ?

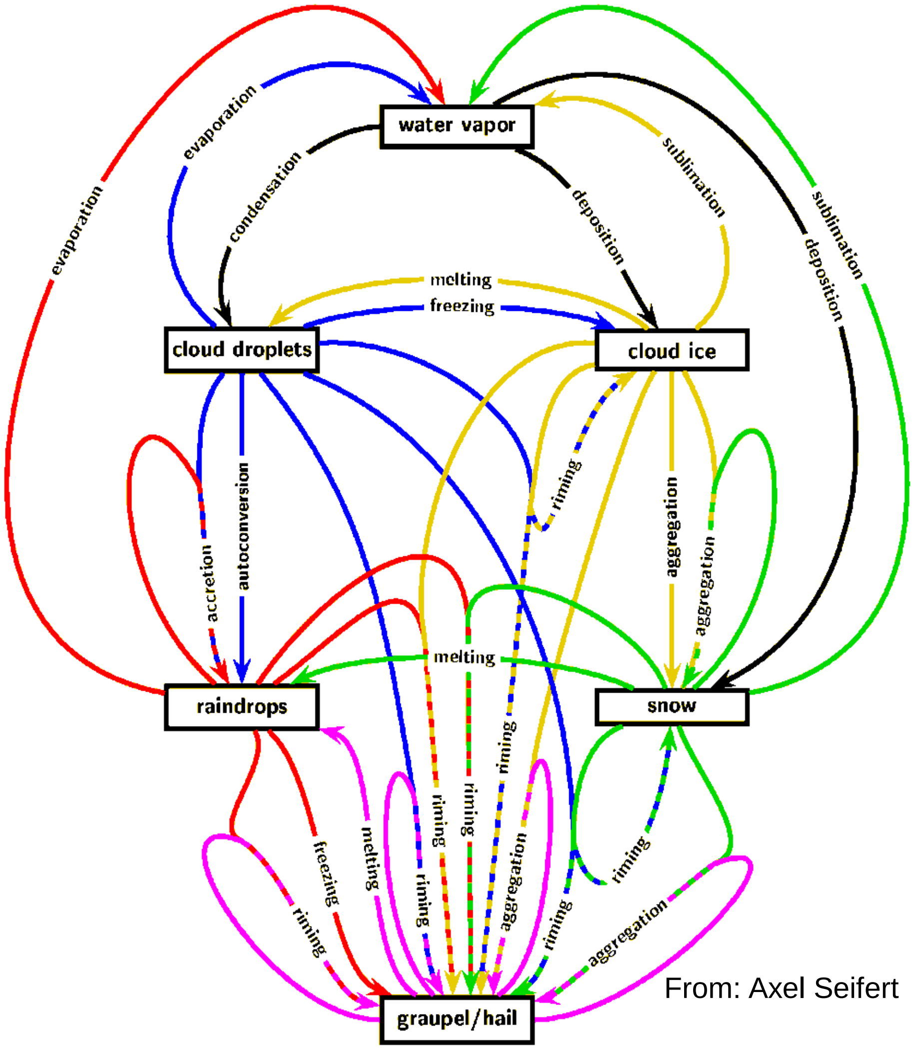
- Water vapour

Warm-phase:

- Cloud water droplets
- Rain drops

Cold-phase

- Cloud ice crystals
- Snow flakes
- Graupel pellets
- Hailstones

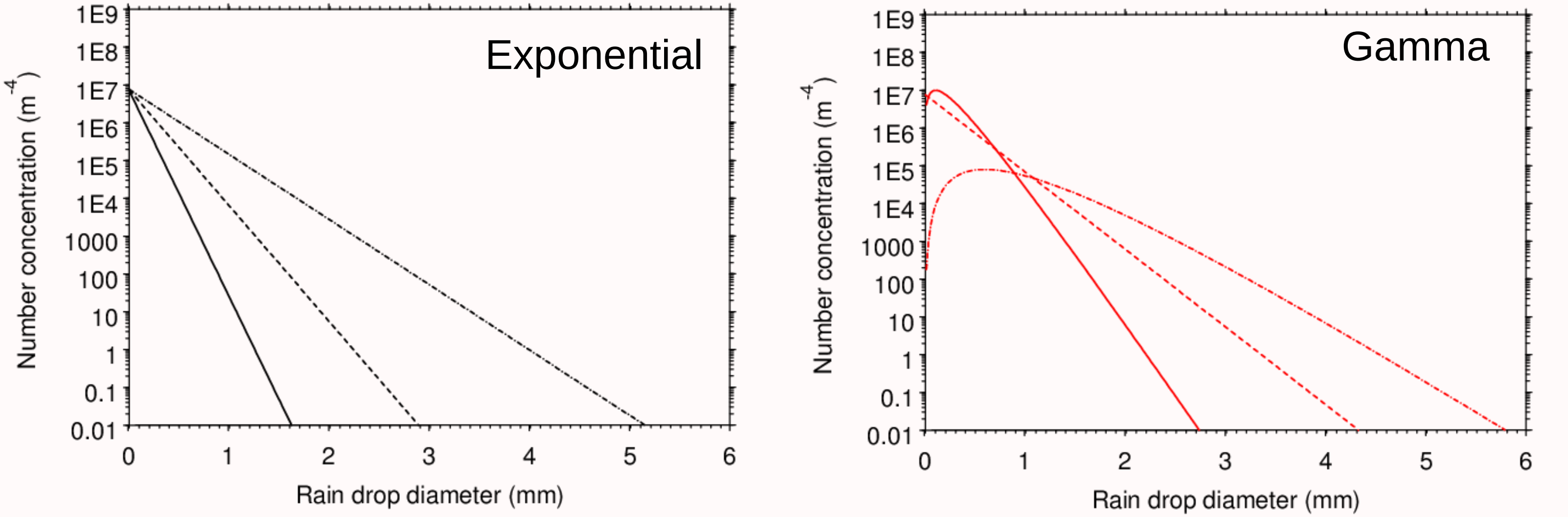


From: Axel Seifert

Microphysics Parametrization Issues:

Particle size distributions

- Each category represents a range of particle sizes defined by its particle size distribution
- This can be represented with some functional form (exponential, gamma)

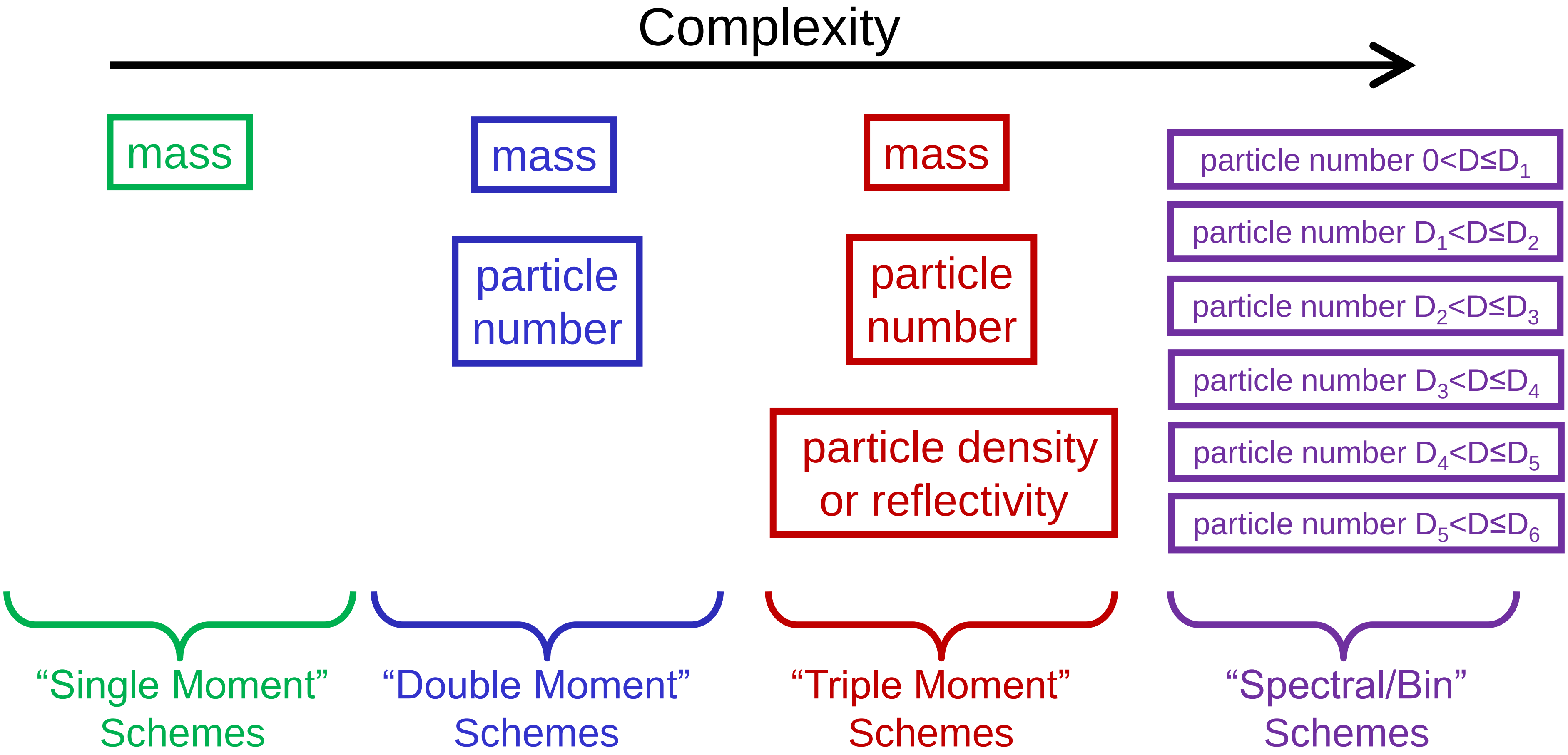


Rain drop size distributions for three different rain water contents

Three different rain drop size distributions for the same rain water content

- The particle size distributions and their evolution can be modelled with different complexities and degrees of freedom…

Microphysics Parametrization Issues:
Complexity ?



Complexity

mass

mass

particle number

mass

particle number

particle density or reflectivity

particle number $0<D\leq D_1$

particle number $D_1<D\leq D_2$

particle number $D_2<D\leq D_3$

particle number $D_3<D\leq D_4$

particle number $D_4<D\leq D_5$

particle number $D_5<D\leq D_6$

"Single Moment" Schemes

"Double Moment" Schemes

"Triple Moment" Schemes

"Spectral/Bin" Schemes

GCMs have single-moment or double-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)*

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

e.g. rain in models with long timestep (1hr) - timescale for fallout of rain << model timestep therefore can assume rain profile is in equilibrium

Prognostic approach *(parametrized sources and sinks)*

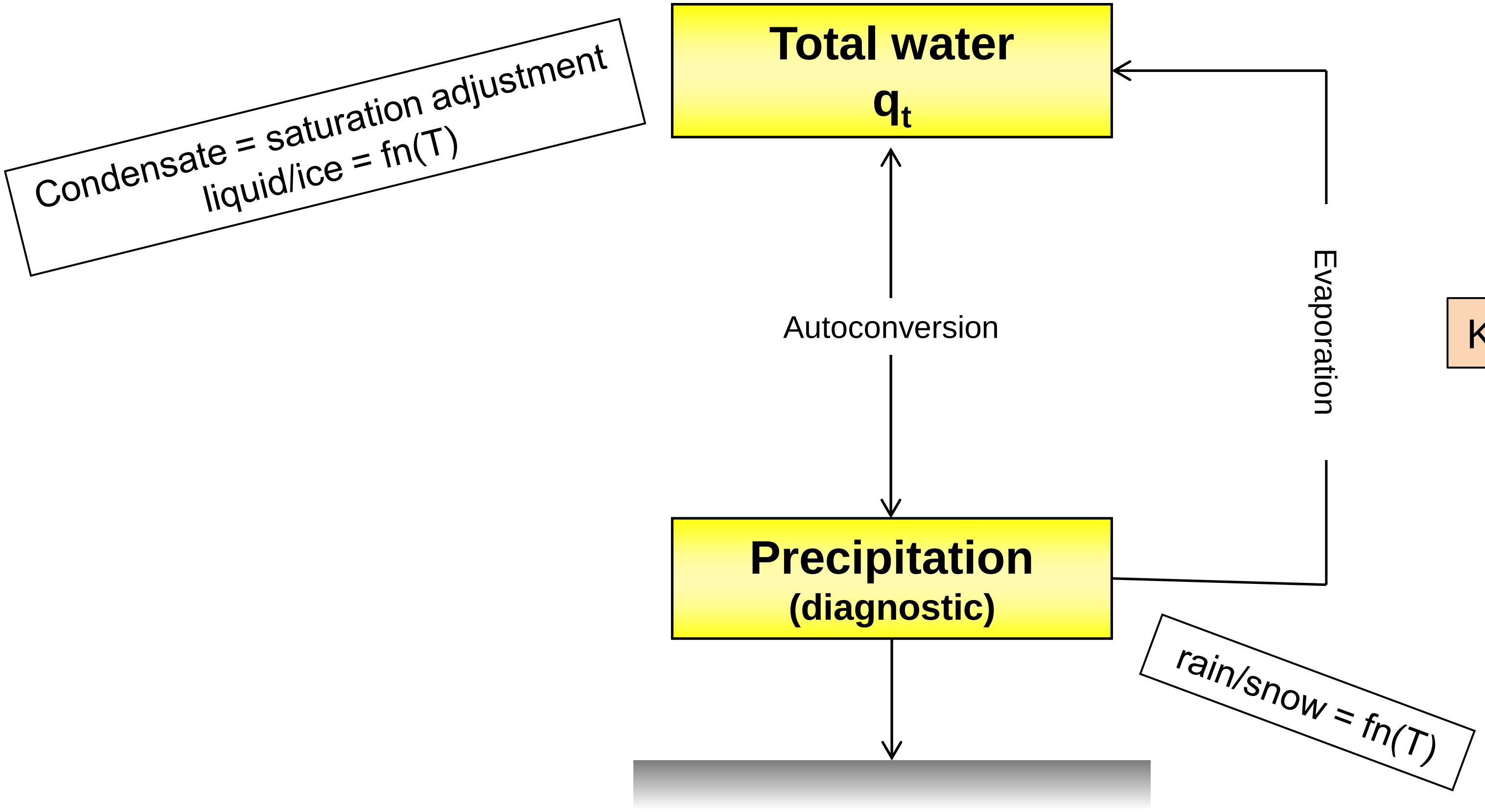
$$\frac{\partial q_l}{\partial t} = \underbrace{A(q_l)}_{\text{Advection + sedimentation}} + \overbrace{S(q_l)}^{\text{Sources}} - \underbrace{D(q_l)}_{\text{Sinks}}$$

e.g. snow has a slower fallspeed so can take many timesteps to reach the ground, can be advected many grid lengths.

CAN HAVE MIXTURE OF APPROACHES

Microphysics Parametrization: Simple schemes

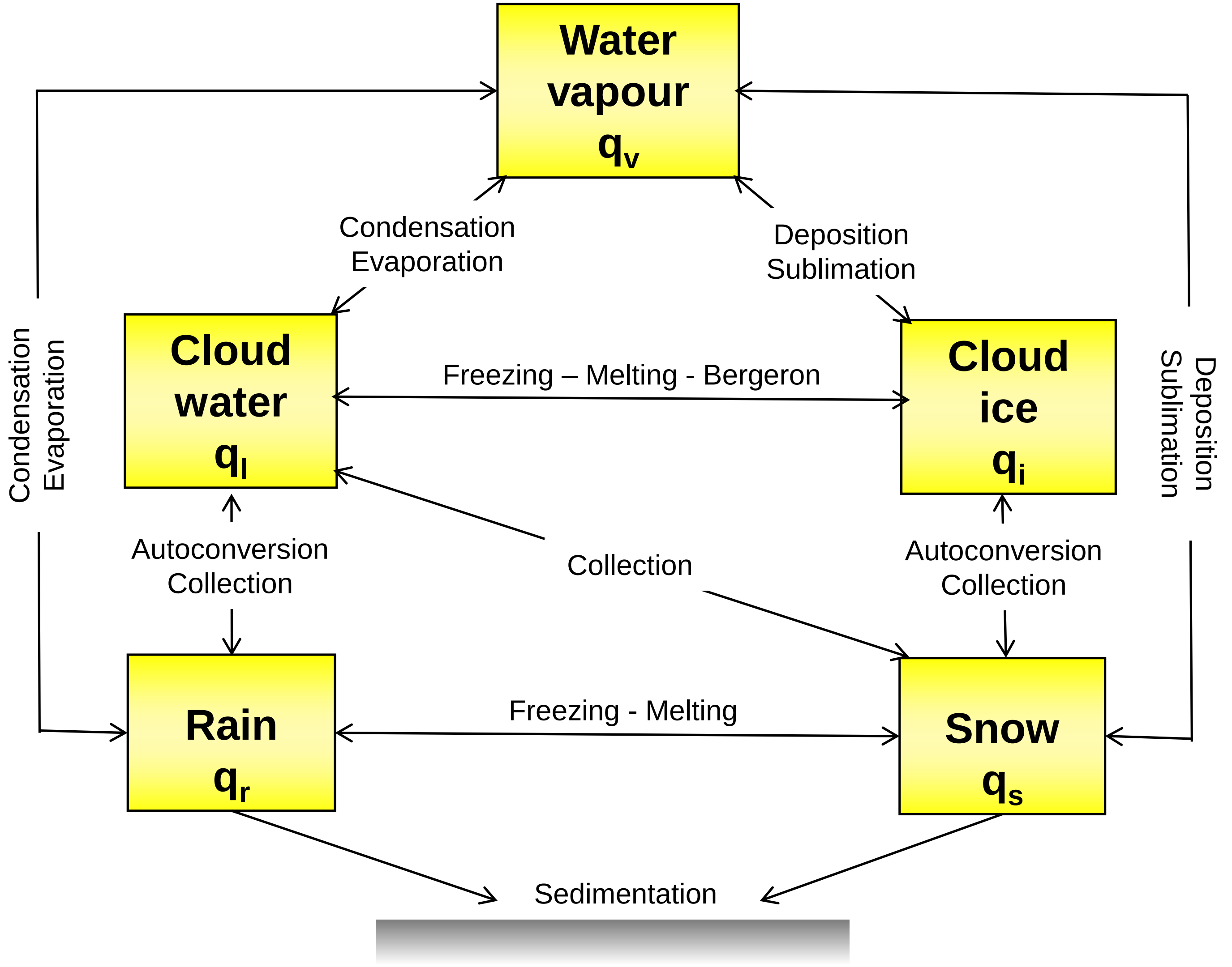
(…in many GCMs not that long ago, still some now, and in many convection parametrizations!)



Kessler (1969)

Microphysics Parametrization: *The "category" view*

Single moment schemes



Water vapour q_v

Condensation
Evaporation

Deposition
Sublimation

Cloud water q_l

Freezing – Melting - Bergeron

Cloud ice q_i

Condensation
Evaporation

Deposition
Sublimation

Autoconversion
Collection

Collection

Autoconversion
Collection

Rain q_r

Freezing - Melting

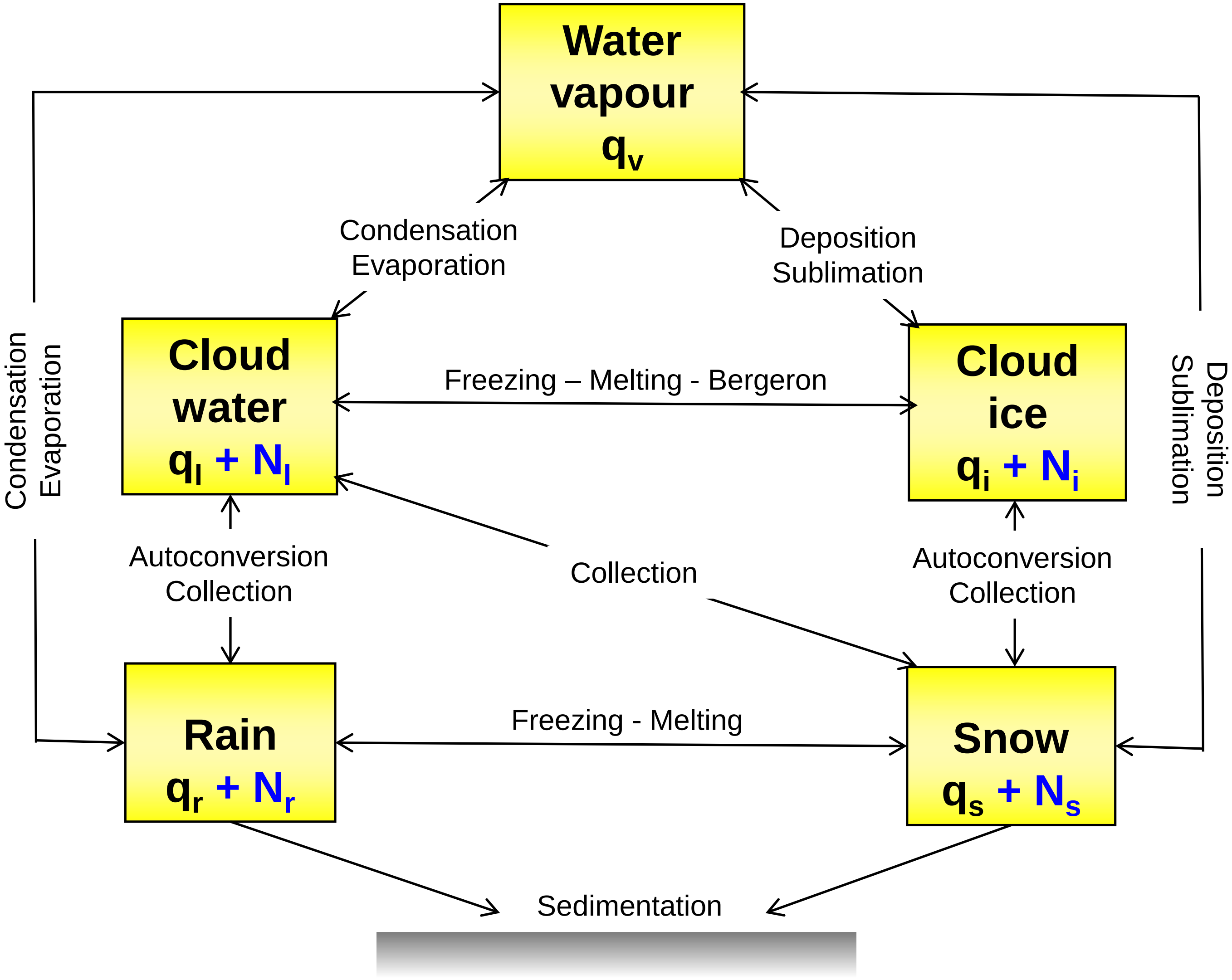
Snow q_s

Sedimentation

Rutledge and Hobbs (1983)

Microphysics Parametrization: The "category" view

Double moment schemes



Water vapour
q_v

Condensation
Evaporation

Deposition
Sublimation

Cloud water
$q_l + N_l$

Freezing – Melting - Bergeron

Cloud ice
$q_i + N_i$

Condensation
Evaporation

Deposition
Sublimation

Autoconversion
Collection

Collection

Autoconversion
Collection

Rain
$q_r + N_r$

Freezing - Melting

Snow
$q_s + N_s$

Sedimentation

e.g.

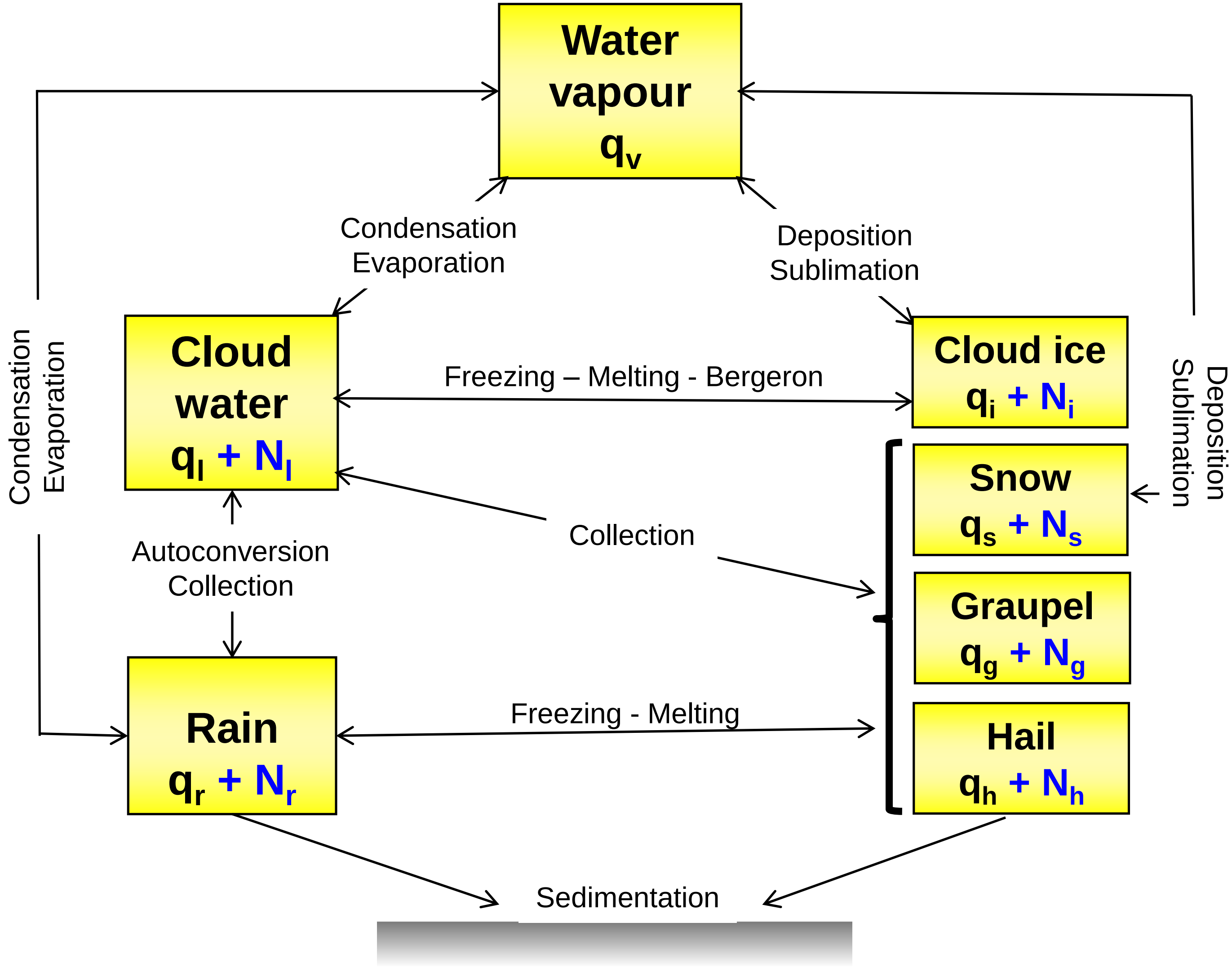
Ferrier (1994)

Seifert and Beheng (2001)

Morrison et al. (2005)

Microphysics Parametrization: The "category" view

Double moment schemes – multiple ice categories



e.g.

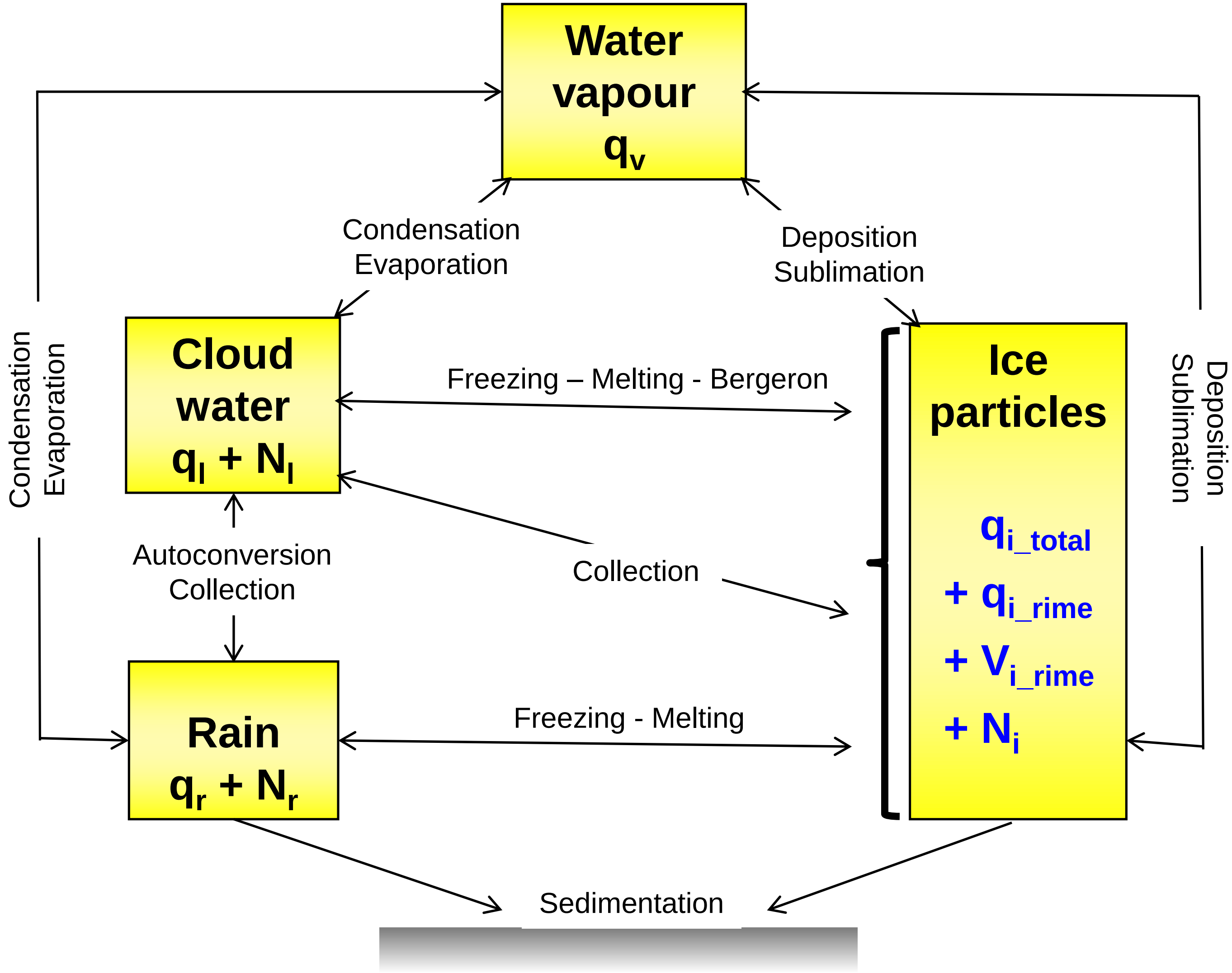
Lin et al. (1983)

Meyers et al. (1997)

Milbrandt and Yau (2005)

Microphysics Parametrization: The "category" view

Double moment + ice particle properties



Water vapour q_v

Condensation
Evaporation

Deposition
Sublimation

Condensation
Evaporation

Cloud water $q_l + N_l$

Freezing – Melting - Bergeron

Ice particles

q_{i_total}
$+ q_{i\_rime}$
$+ V_{i\_rime}$
$+ N_i$

Deposition
Sublimation

Autoconversion
Collection

Collection

Rain $q_r + N_r$

Freezing - Melting

Sedimentation

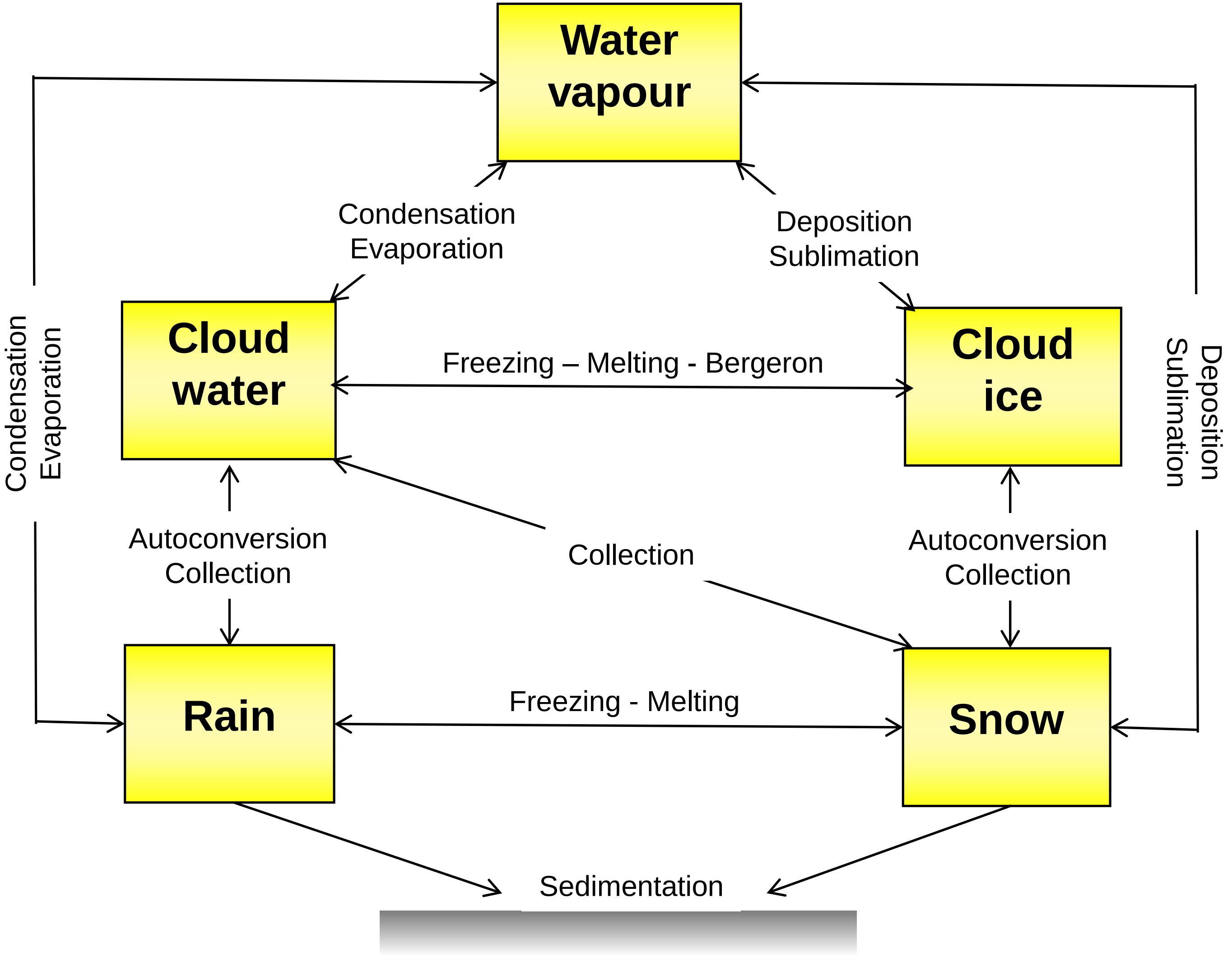
e.g.

Morrison and Grabowski (2008)

Morrison and Milbrandt (2015a,b) 'P3'

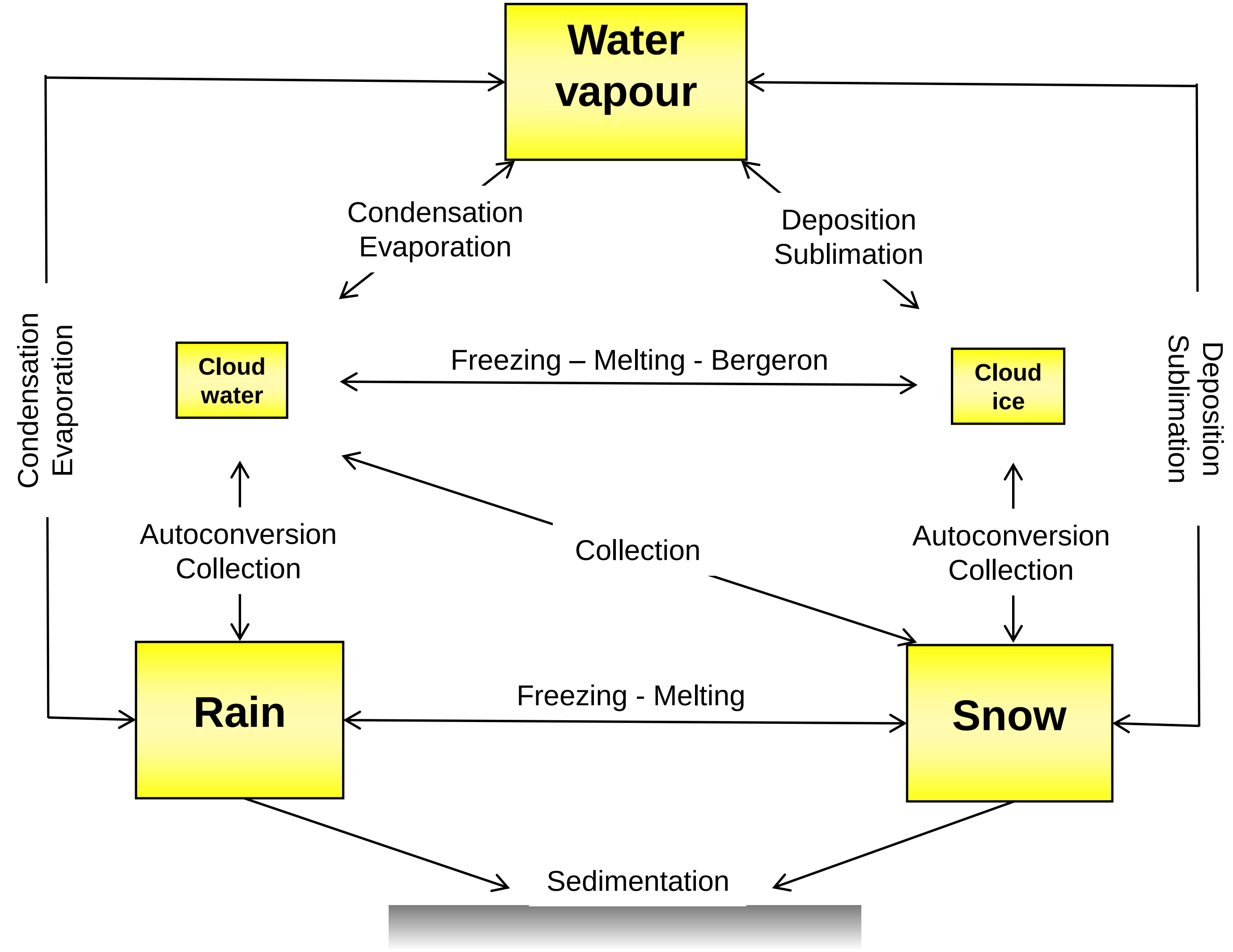
Microphysics Parametrization: The "category" view

What is important?



Microphysics Parametrization:

The hydrological perspective



Water vapour

Condensation
Evaporation

Deposition
Sublimation

Condensation
Evaporation

Cloud water

Freezing – Melting - Bergeron

Cloud ice

Deposition
Sublimation

Autoconversion
Collection

Collection

Autoconversion
Collection

Rain

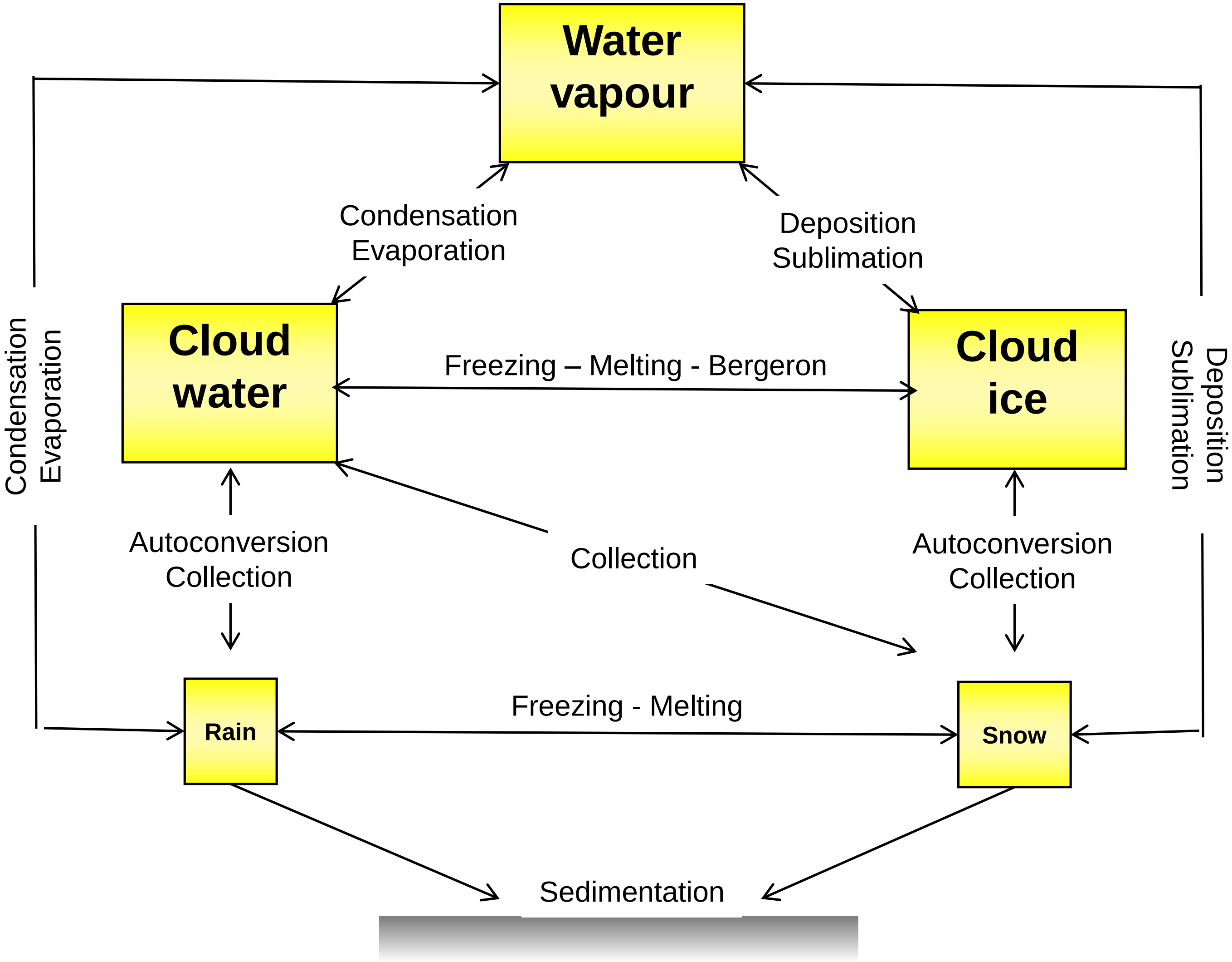
Freezing - Melting

Snow

Sedimentation

Microphysics Parametrization:

The radiative perspective



Water vapour

Condensation
Evaporation

Deposition
Sublimation

Condensation
Evaporation

Cloud water

Freezing – Melting - Bergeron

Cloud ice

Deposition
Sublimation

Autoconversion
Collection

Collection

Autoconversion
Collection

Rain

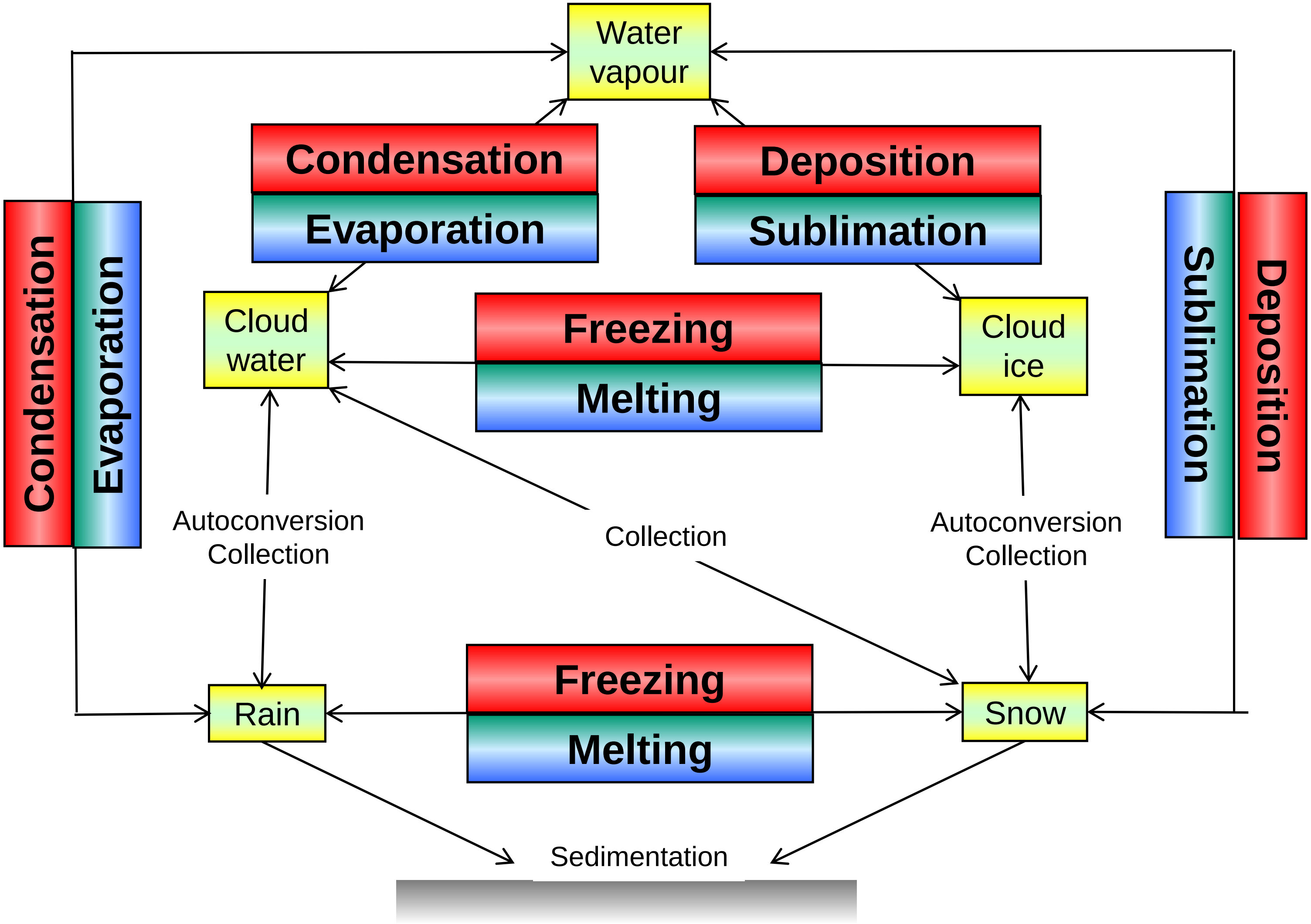
Freezing - Melting

Snow

Sedimentation

Microphysics Parametrization:

The "diabatic process" perspective



2. Warm-phase Microphysical Processes

Cloud microphysical processes

- To describe warm-phase cloud and precipitation processes in our models we need to represent:
  - Nucleation of water droplets
  - Diffusional growth of cloud droplets (condensation)
  - Collection processes for cloud drops (collision-coalescence), leading to precipitation sized particles
  - the advection and sedimentation (falling) of particles
  - the evaporation of cloud and precipitation size particles

Droplet Classification

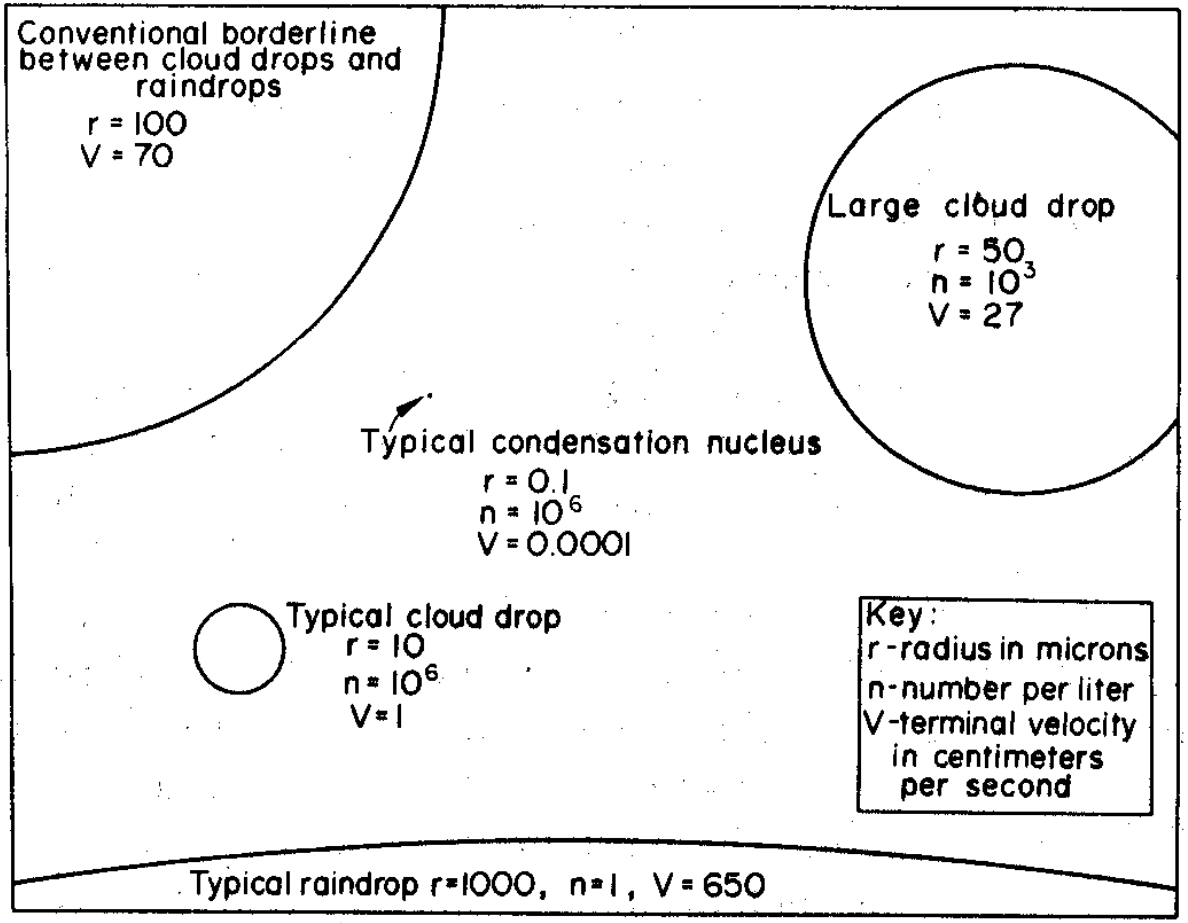
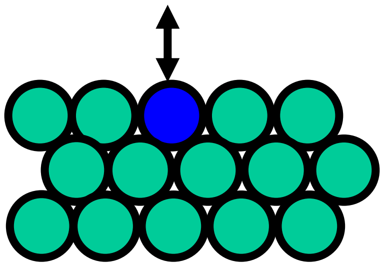


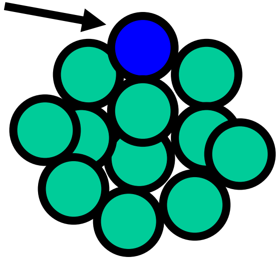
FIG. 5.1. Comparative sizes, concentrations, and terminal fall velocities of some of the particles involved in cloud and precipitation processes. (From McDonald, 1958.)

Nucleation of cloud droplets: Important effects for particle activation



Planar surface: Equilibrium when atmospheric vapour pressure = saturation vapour pressure ($e = e_s$) 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.

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

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

σ = Surface tension of droplet

r = 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).

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

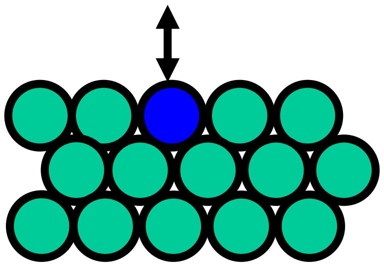
$R_c =$ Critical Radius

$\sigma =$ Surface tension of droplet

Nucleation of cloud droplets:
Heterogeneous Nucleation

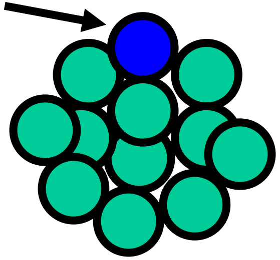
- Collection of water molecules on a foreign substance, RH > ~80% (Haze particles)
- These (hydrophilic) soluble particles are called Cloud Condensation Nuclei (CCN)
- CCN always present in sufficient numbers in lower and middle troposphere
- Nucleation of droplets (i.e. from stable haze particle to 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

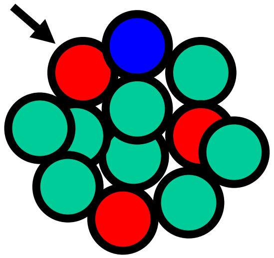
Surface molecule has fewer neighbours



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



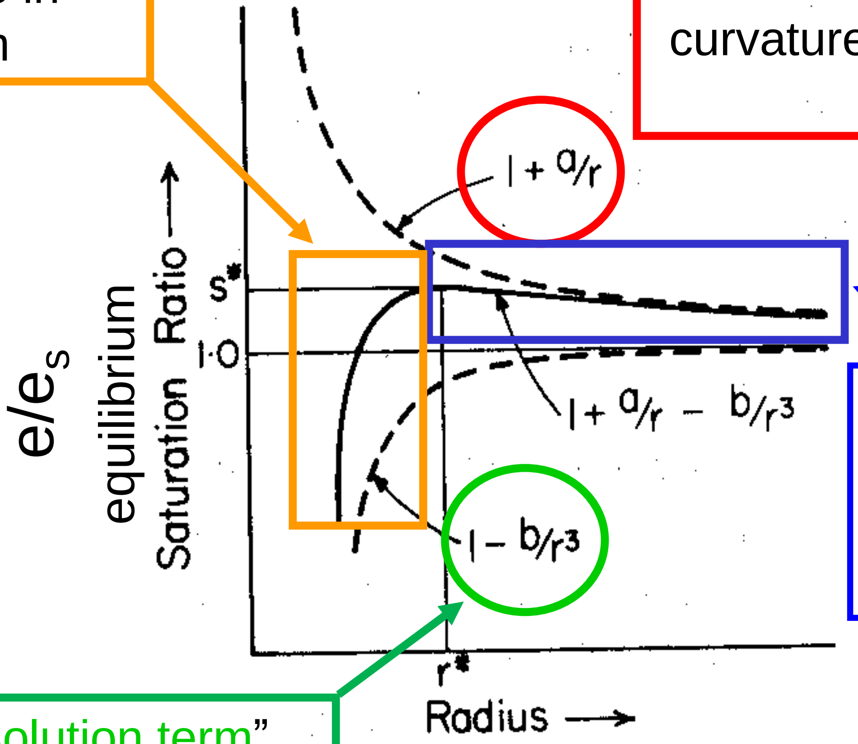
Presence of dissolved substance: saturation vapour pressure reduces with smaller drop size due to solute molecules replacing solvent on drop surface (assuming $e_{solute} < e_v$)

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

Nucleation of cloud droplets: Heterogeneous Nucleation

Haze particle in equilibrium

“Curvature term”
Small drop – high radius of curvature, easier for molecule to escape



Activation:
e / e_s = s*=1.01
r > r* = 0.12μm
(dependent on solute)

“Solution term”
Reduction in vapour pressure due to dissolved substance

“Köhler Curve”

Diffusional growth of cloud water droplets

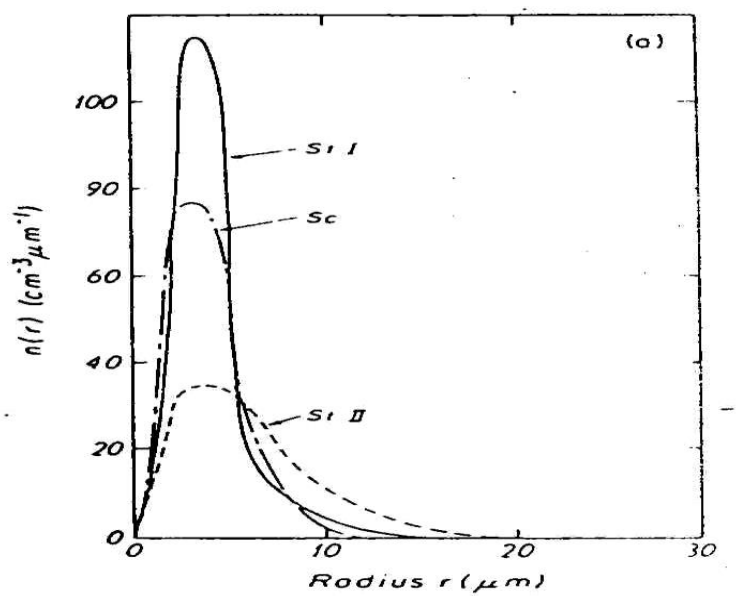
- Once droplet is activated, water vapour diffuses towards it = condensation

- 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



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

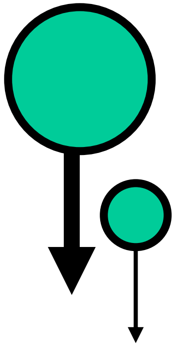
For r > 1 µm and neglecting diffusion of heat

D=Diffusion coefficient, S=Supersaturation

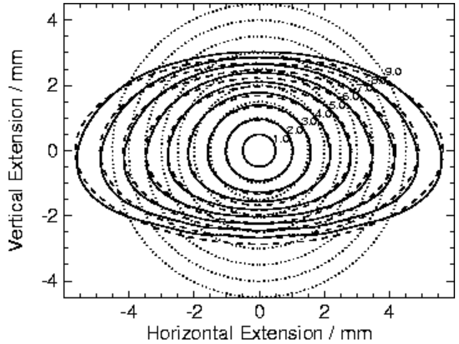
Note inverse radius dependency

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)



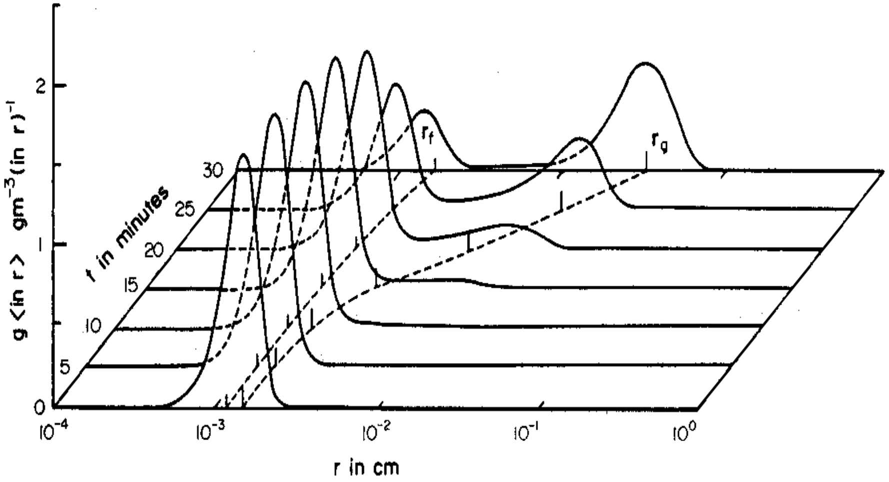


FIG. 8.10. Example of the development of a droplet spectrum by stochastic coalescence. (From Berry and Reinhardt, 1974b.)

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.

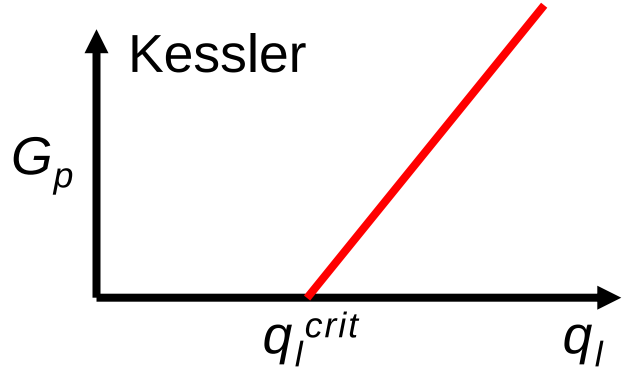
- So usually, the growth equation is not explicitly solved. In single-moment schemes simple (diagnostic) assumptions are made concerning the droplet number concentration when needed (e.g. radiation).

Parametrizing collection processes
“Autoconversion” of cloud drops to raindrops

Simplified with simple functional form, e.g.

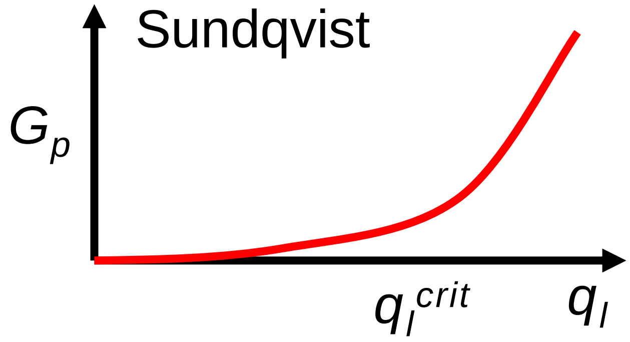
- Linear function of q_l (Kessler, 1969)

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



- 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.

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

Parametrizing collection processes
"Accretion" of cloud drops by raindrops

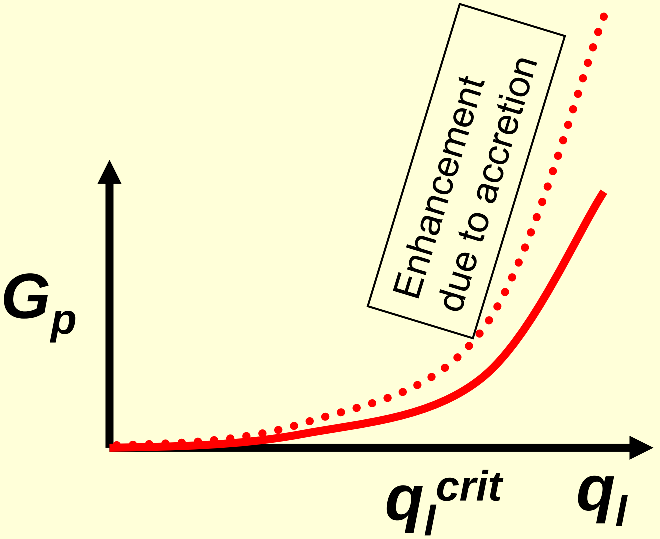
Representing autoconversion and accretion in the warm phase (liq. to rain).

Sundqvist (1978, 1989)

$$G_P = c_0 F_1 q_l \left(1 - e^{-\left(\frac{ql}{ql_{crit}} F_1\right)^2}\right)$$

G_p = autoconversion rate
P = precipitation rate

$$\boxed{F_1 = 1 + c_1 \sqrt{P} \qquad \text{Accretion}}$$



Khairoutdinov and Kogan (2000)

$$G_{aut} = 1350 q_l^{2.47} N_c^{-1.79}$$

$$\boxed{G_{acc} = 67 q_l^{1.15} q_r^{1.15}}$$

- Functional form is different
- More non-linear process
- Slower autoconversion initially, then faster
- With prognostic rain, have memory in q_r
- Then faster accretion for heavier rain.

Parametrizing evaporation - cloud and precipitation

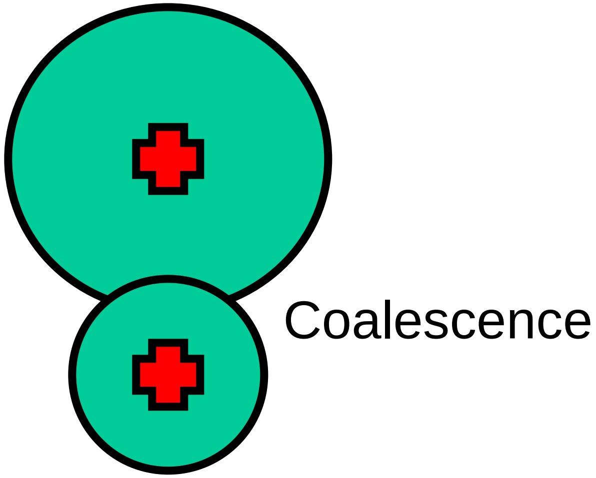
Evaporation of cloud droplets is generally assumed to be fast (instantaneous) as cloud particles are small, so as soon as the air becomes subsaturated, the cloud evaporates.

Larger precipitation size particles take longer to evaporate, so precipitation may fall into drier air below cloud base before it evaporates. Parametrized by integrating over an assumed droplet size spectrum. Evaporation is proportional to the subsaturation (e.g. Kessler 1969):

$$E_P = \alpha_1 \left(q_s - q_e \right) \rho_{rain}^{0.577}$$

which assumes an exponential drop size distribution (Marshall-Palmer), although light rain (drizzle) is found to contain many more small droplets and therefore evaporation rates are enhanced (relative to M-P).

Schematic of Warm Rain Processes



Summary

- Cloud important for it's radiative, hydrological and dynamical impacts (also transport)
- Different complexities of microphysics parametrization
- Microphysics doesn't occur in isolation – dynamics, turbulence, convection
- Warm rain – nucleation, collision-coalescence Parametrization: autoconversion, accretion, evaporation

Next Lecture:

Ice and mixed-phase processes

References

Reference books for cloud and precipitation microphysics:

Pruppacher. H. R. and J. D. Klett (1998). *Microphysics of Clouds and Precipitation* (*2nd Ed*). Kluwer Academic Publishers.

Rogers, R. R. and M. K. Yau, (1989). *A Short Course in Cloud Physics* (*3rd Ed*.) Butterworth-Heinemann Publications.

Mason, B. J., (1971). *The Physics of Clouds*. Oxford University Press.

Hobbs, P. V., (1993). *Aerosol-Cloud-Climate Interactions*. Academic Press.

Houze, Jr., R. A., (1994). *Cloud Dynamics*. Academic Press.

Straka, J., (2009). *Cloud and Precipitation Microphysics: Principles and Parameterizations*. Cambridge University Press.