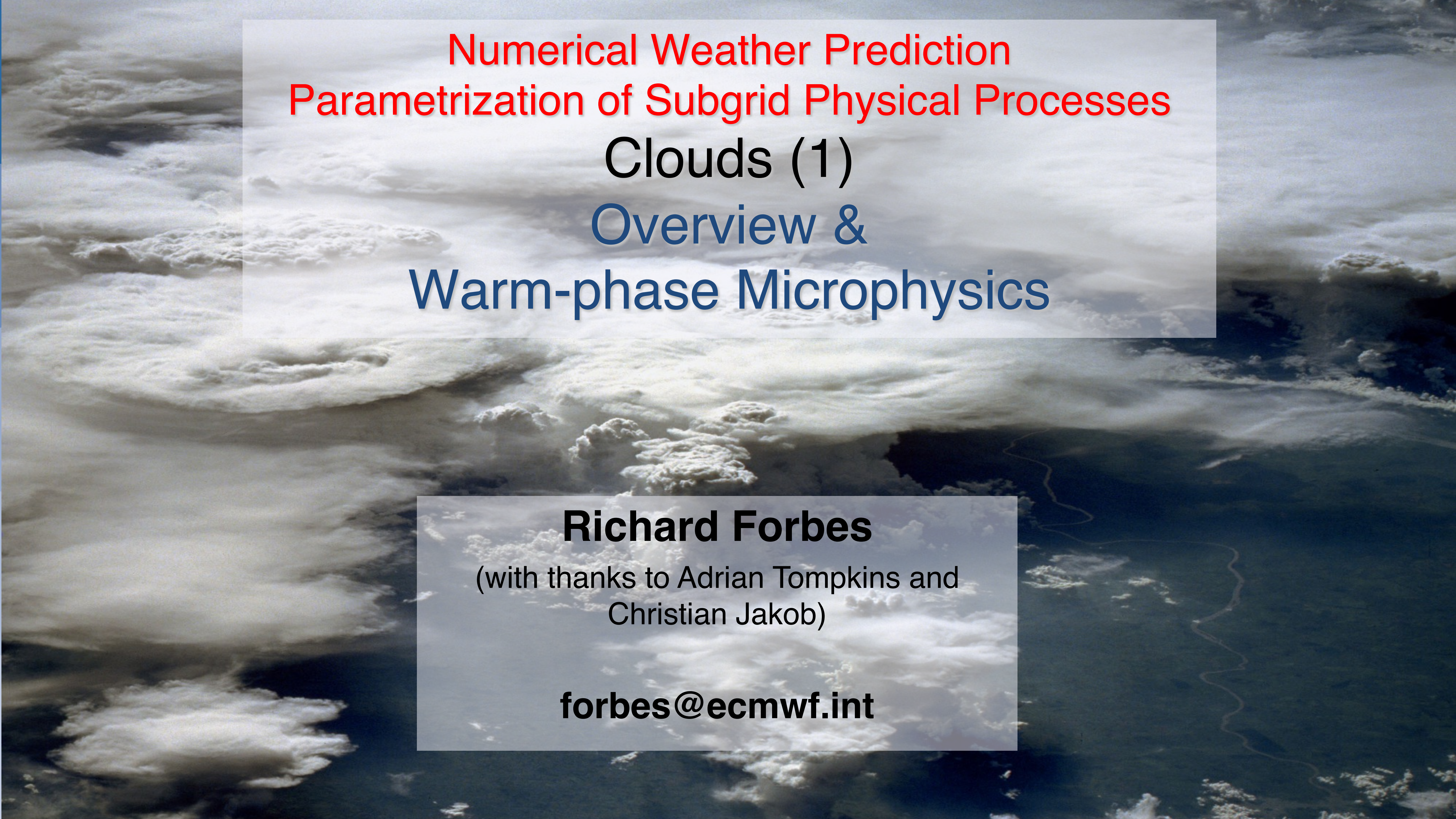


Numerical Weather Prediction
Parametrization of Subgrid Physical Processes

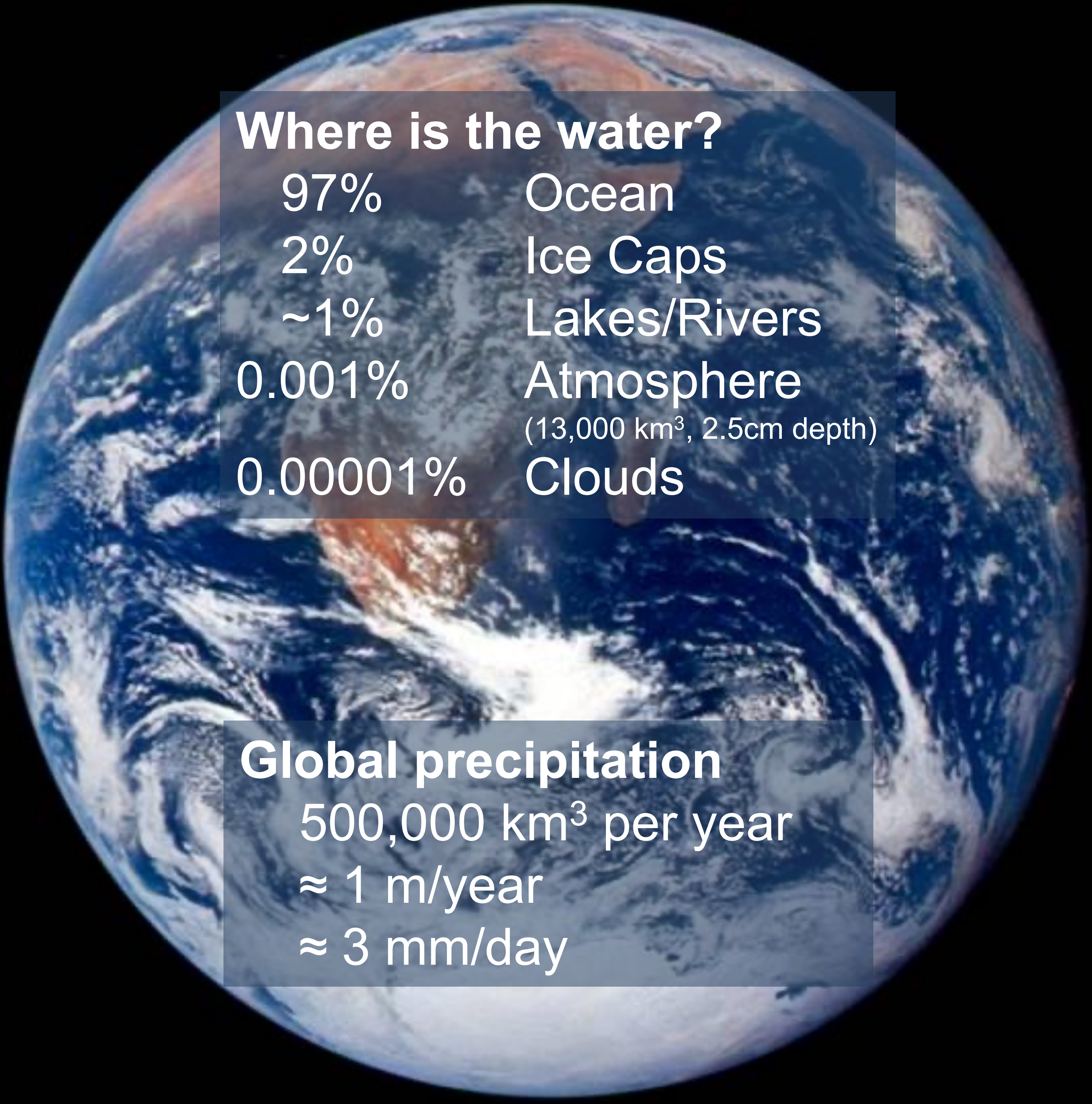
Clouds (1)

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

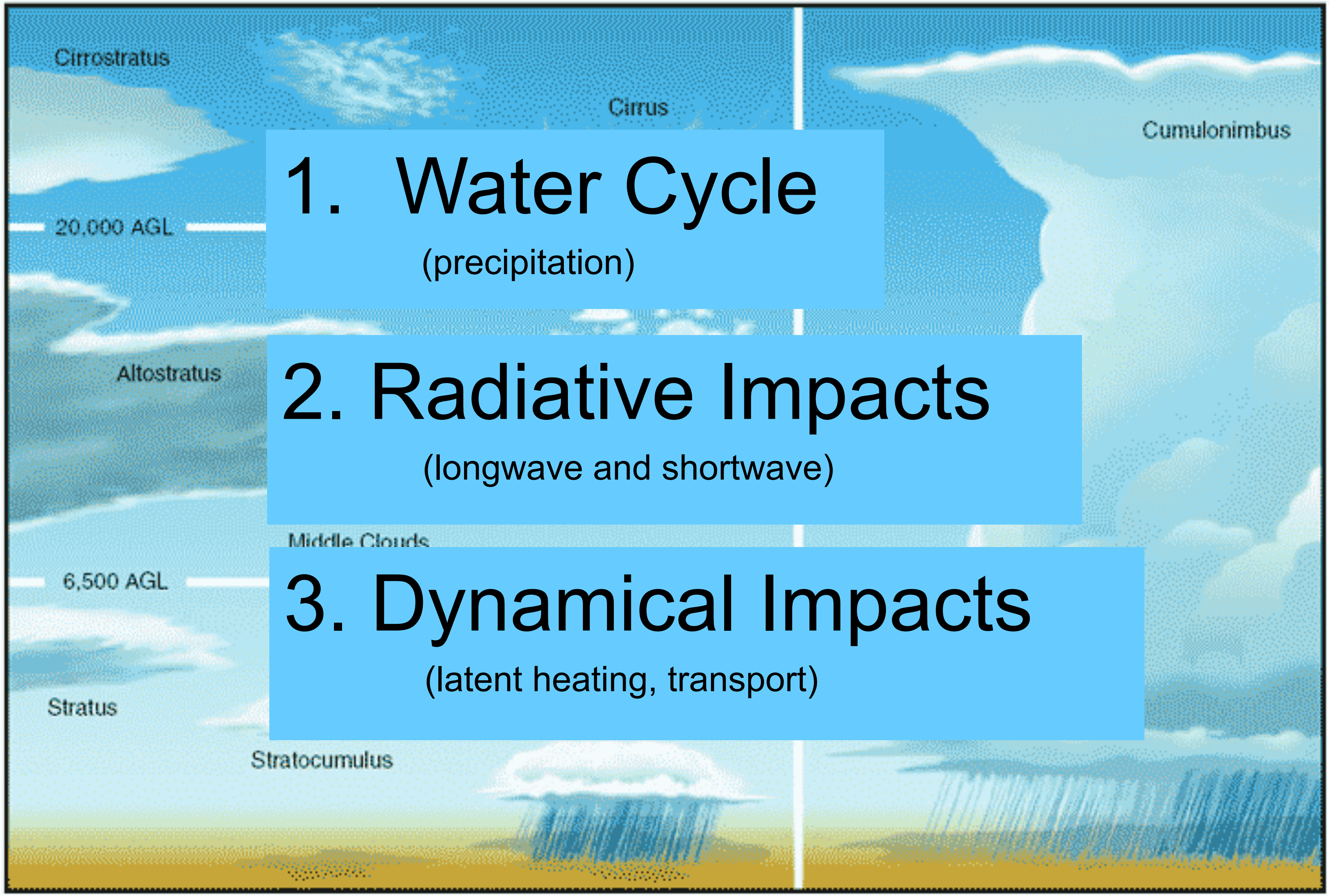
1a. Overview of cloud parametrization issues **(Lecture 1)**
1b. Liquid-phase microphysical processes **(Lecture 1)**
2. Ice and mixed-phase microphysical processes **(Lecture 2)**
3. Sub-grid heterogeneity **(Lecture 3)**
4. Model evaluation of clouds and precipitation (Lecture 4)

Learning Objectives

1. Describe the basic concepts for the design of a microphysics parametrization
2. Understand the key microphysical processes for warm-phase cloud and precipitation in the atmosphere
3. Recognise the important warm-phase microphysical processes that need to be parametrized in a numerical weather prediction model

1. Overview of Cloud Parametrization Issues

The Importance of Clouds



1. Water Cycle

   (precipitation)

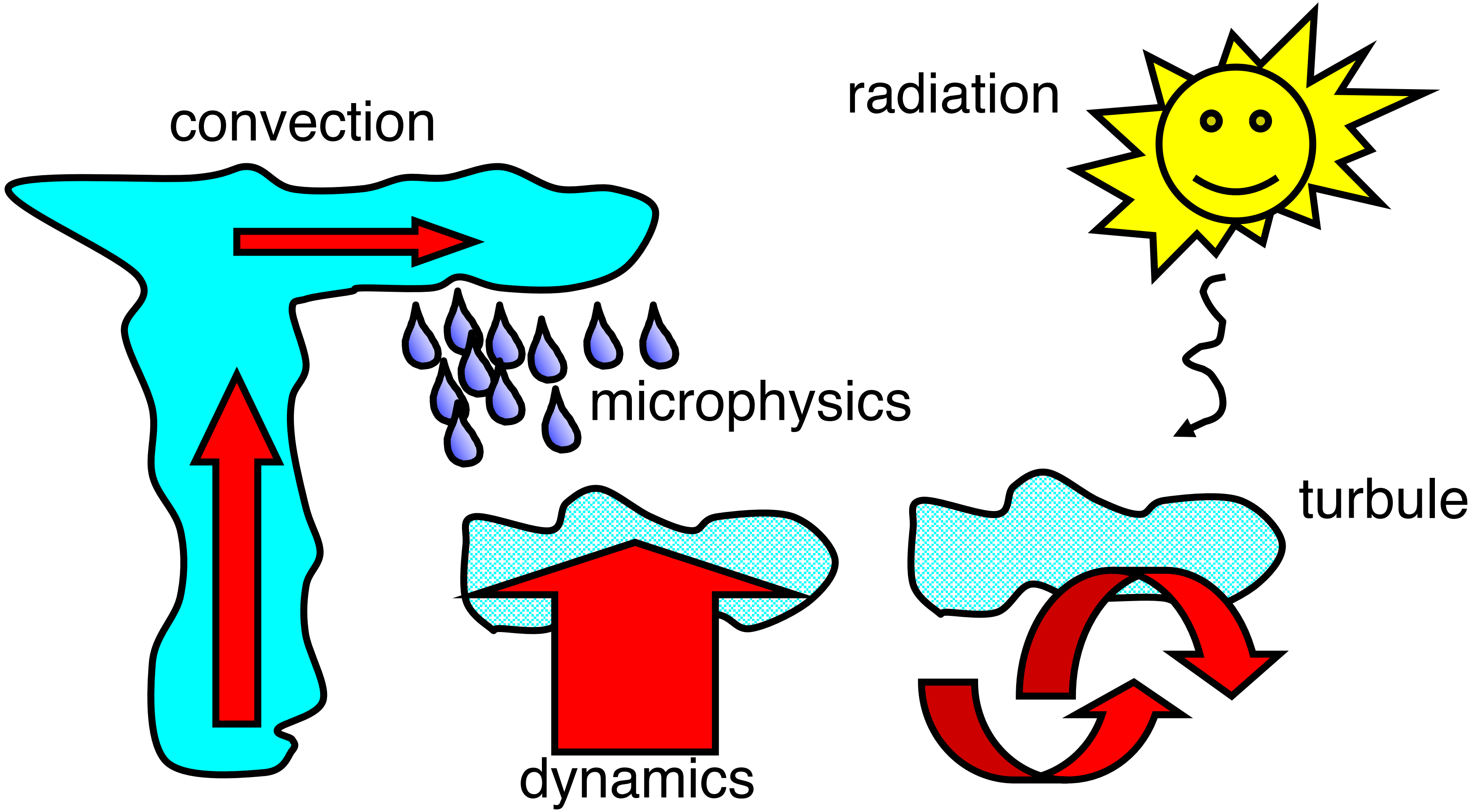
2. Radiative Impacts

   (longwave and shortwave)

3. Dynamical Impacts

   (latent heating, transport)

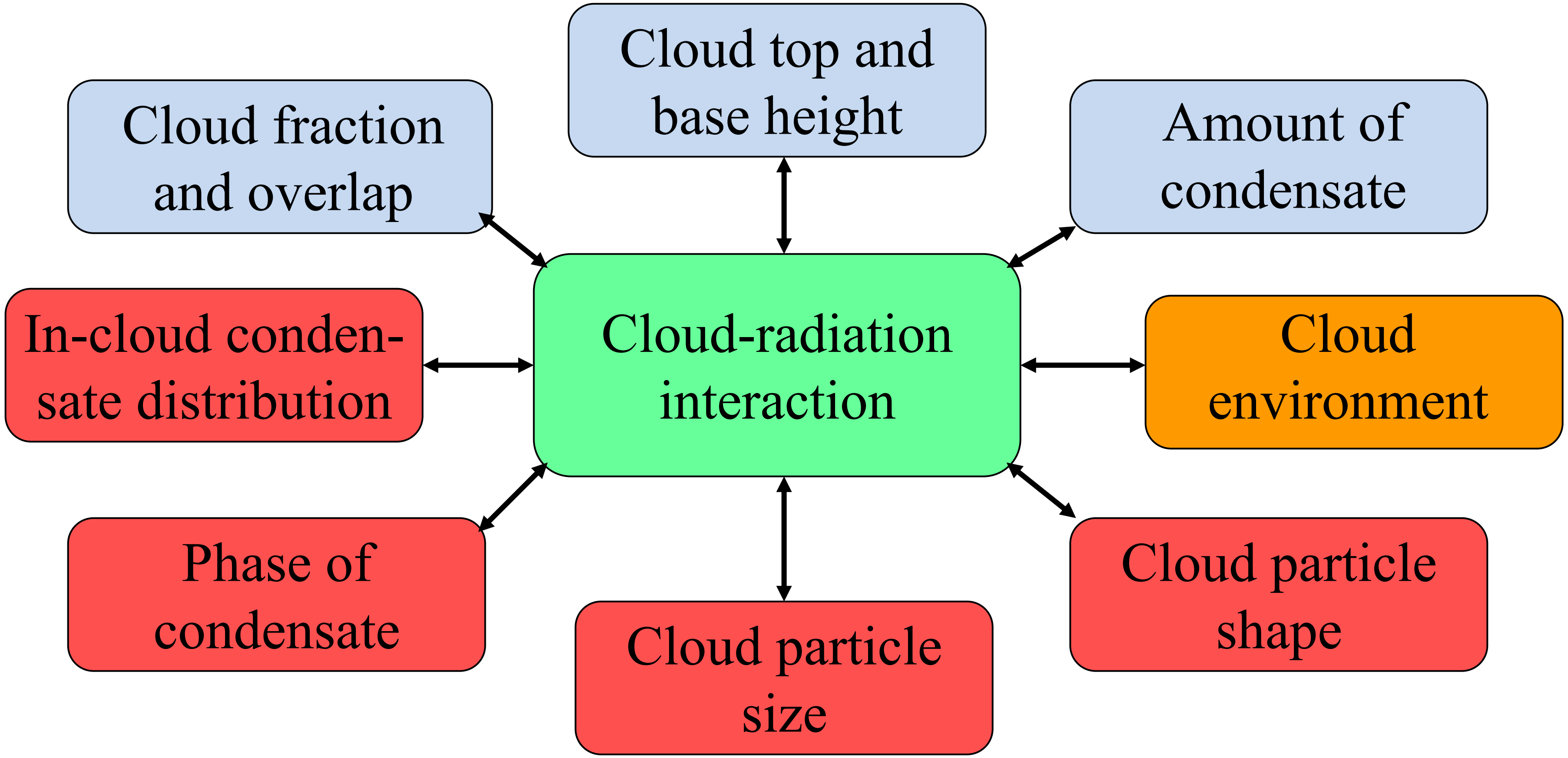
Representing Clouds in GCMs - What do we need to consider ?



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

Representing Clouds in GCMs - What do we need to consider ?

Example: cloud-radiation interaction – many uncertainties



Cloud top and base height

Cloud fraction and overlap

Amount of condensate

In-cloud condensate distribution

Cloud-radiation interaction

Cloud environment

Phase of condensate

Cloud particle size

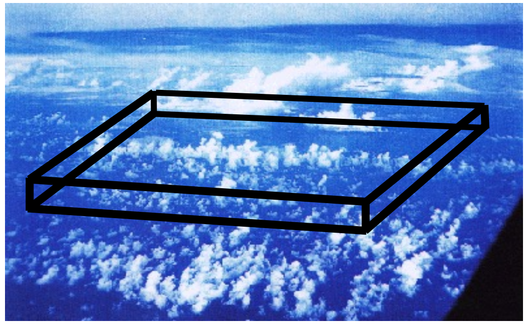
Cloud particle shape

🟦 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:

(1) Which quantities (categories) to represent ?

- Water vapour

Warm-phase:

- Cloud water droplets
- Rain drops

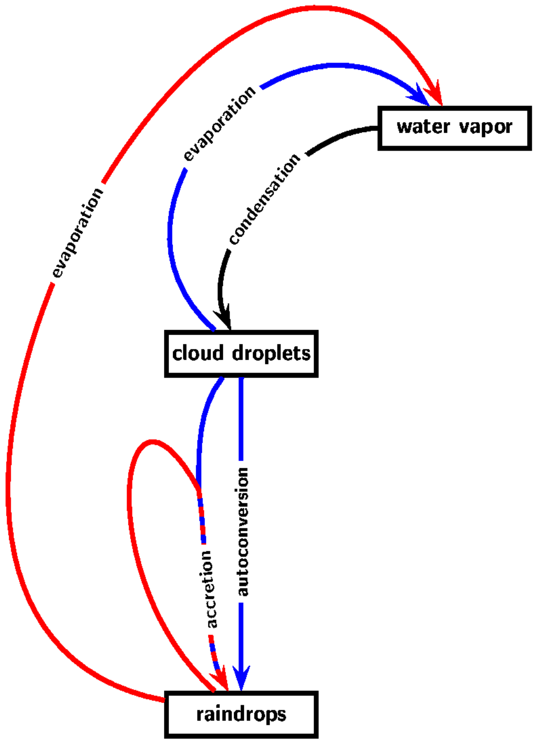


Figure courtesy of Axel Seifert

Microphysics Parametrization Issues:

(1) Which quantities (categories) to represent ?

- Water vapour

Warm-phase:

- Cloud water droplets
- Rain drops

Cold-phase

- Pristine ice crystals
- Snow particles
- Graupel pellets
- Hailstones

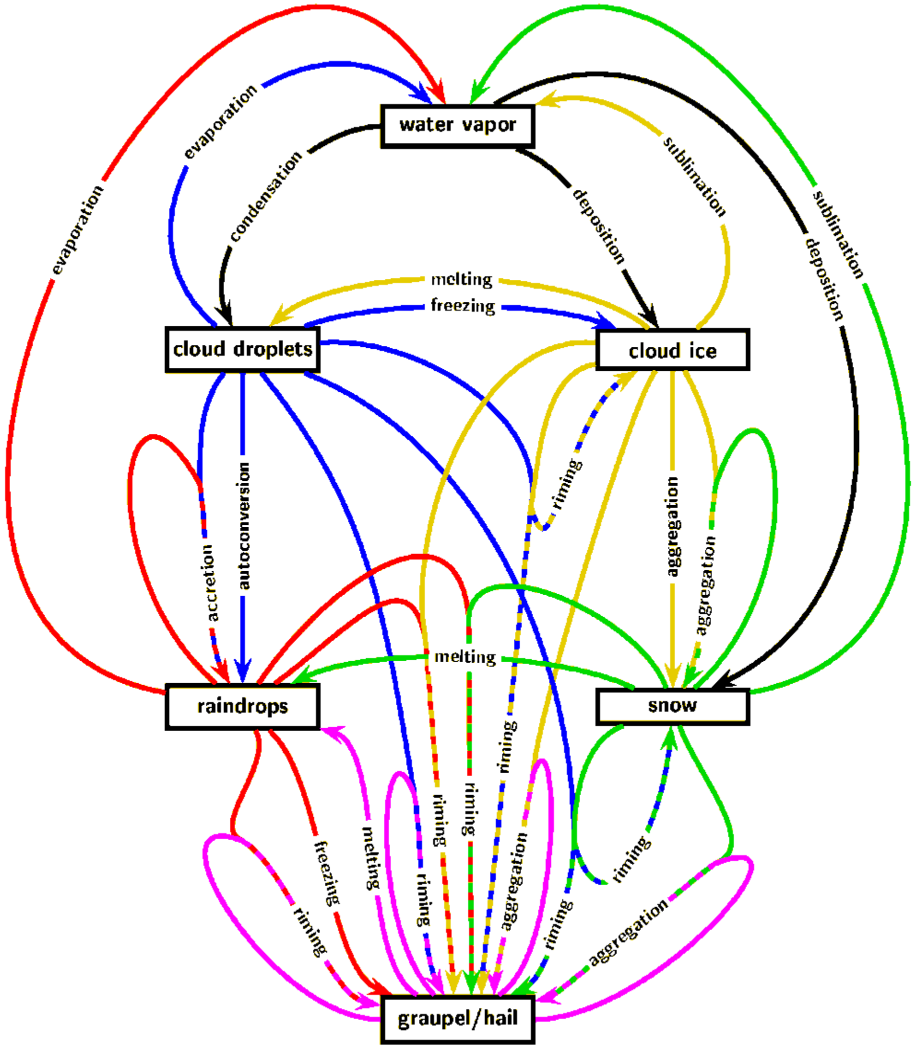
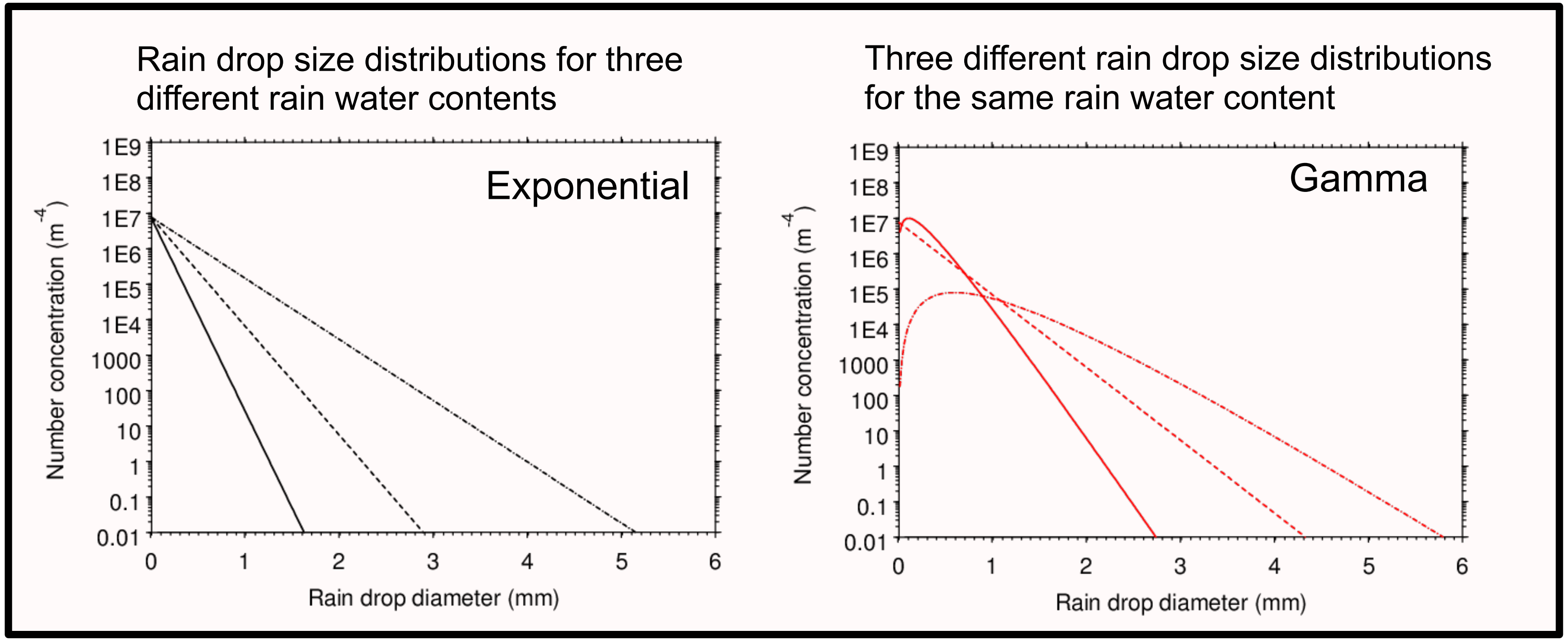


Figure courtesy of Axel Seifert

Microphysics Parametrization Issues:

(2) 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:

(2) Particle size distributions – PDF moments

The *nth* moment of the particle size distribution *f(D)* across a range of particle sizes with diameter, *D*, is defined as

$$M_n = \int_0^\infty D^n f(D) dD$$

The zeroth moment is the number concentration, *N,*

$$N = \int_0^\infty D^0 f(D) dD = \int_0^\infty f(D) dD$$

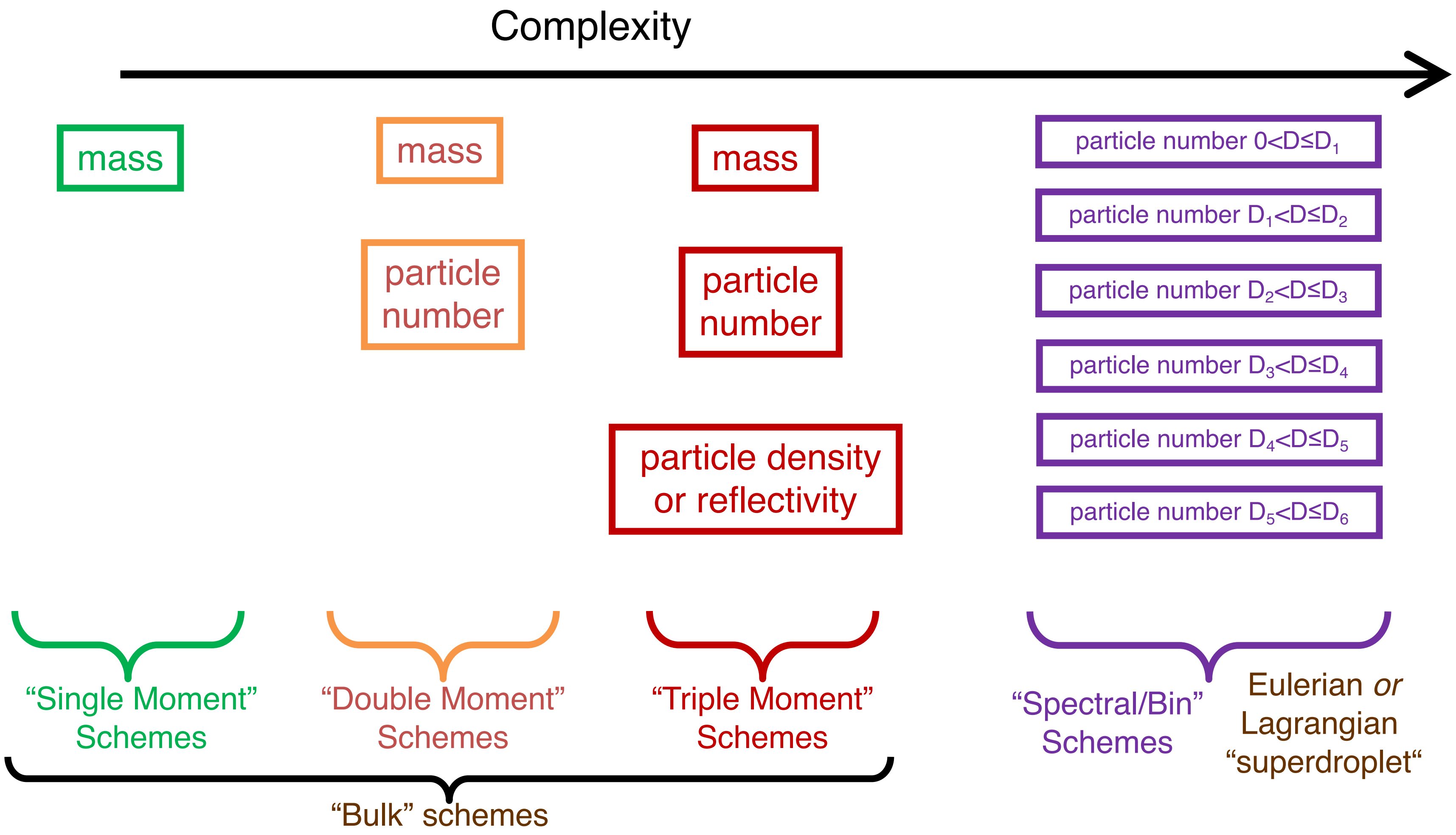
The third moment is the liquid water mass mixing ratio, *L,* (where ρ_w is the density of water)

$$L = \frac{\pi \rho_w}{6} \int_0^\infty D^3 f(D) dD$$

Other moments can be useful, e.g. the sixth moment D^6 is relevant for radar reflectivity

Microphysics Parametrization Issues:

(3) 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

Eulerian *or* Lagrangian “superdroplet“

“Bulk” schemes

GCMs typically have single-moment or double-moment schemes

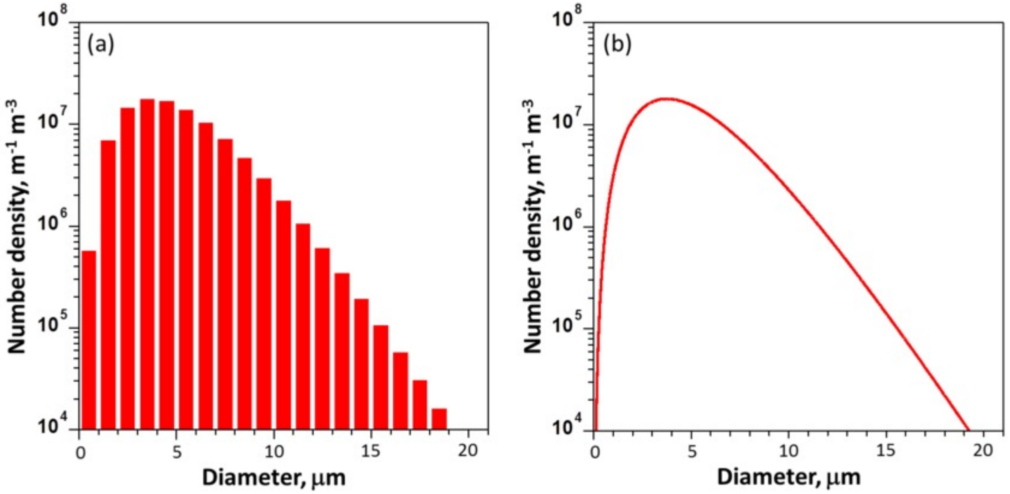
Microphysics Parametrization Issues:

(3) Complexity

- **Spectral (bin) microphysics** - divide particles into different size bins and compute evolution of each bin. Particle size distribution free to evolve rather than be subscribed. Computationally expensive.

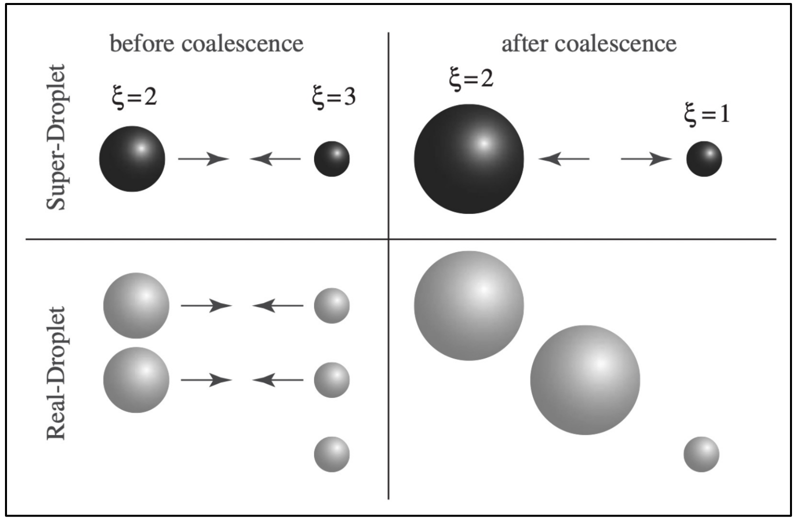
- **Super Droplet Method** (SDM) – lagrangian representation. Each super-droplet represents a multiple number of droplets with the same attributes (size) and position. Stochastic collision-coalescence.

Spectral bin microphysics



From Chen & Tsai (JAS, 2016)

Super droplet method (SDM)



From Shima et al. (QJRMS, 2009)

Microphysics Parametrization Issues:

(4) Predict or diagnose quantities?

For a bulk microphysics scheme with hydrometeor mass, q_x

Prognostic approach *(parametrized sources and sinks)*

$$\frac{\partial q_x}{\partial t} + \underbrace{\vec{v}.\nabla q_x}_{\boxed{\text{Advection}}} - \underbrace{\frac{1}{\rho}\frac{\partial}{\partial z}(\rho v_x q_x)}_{\boxed{\text{Sedimentation}}} = \underbrace{S(q_x)}_{\boxed{\text{Sources and sinks}}}$$

Diagnostic approach *(equilibrium assumed)*

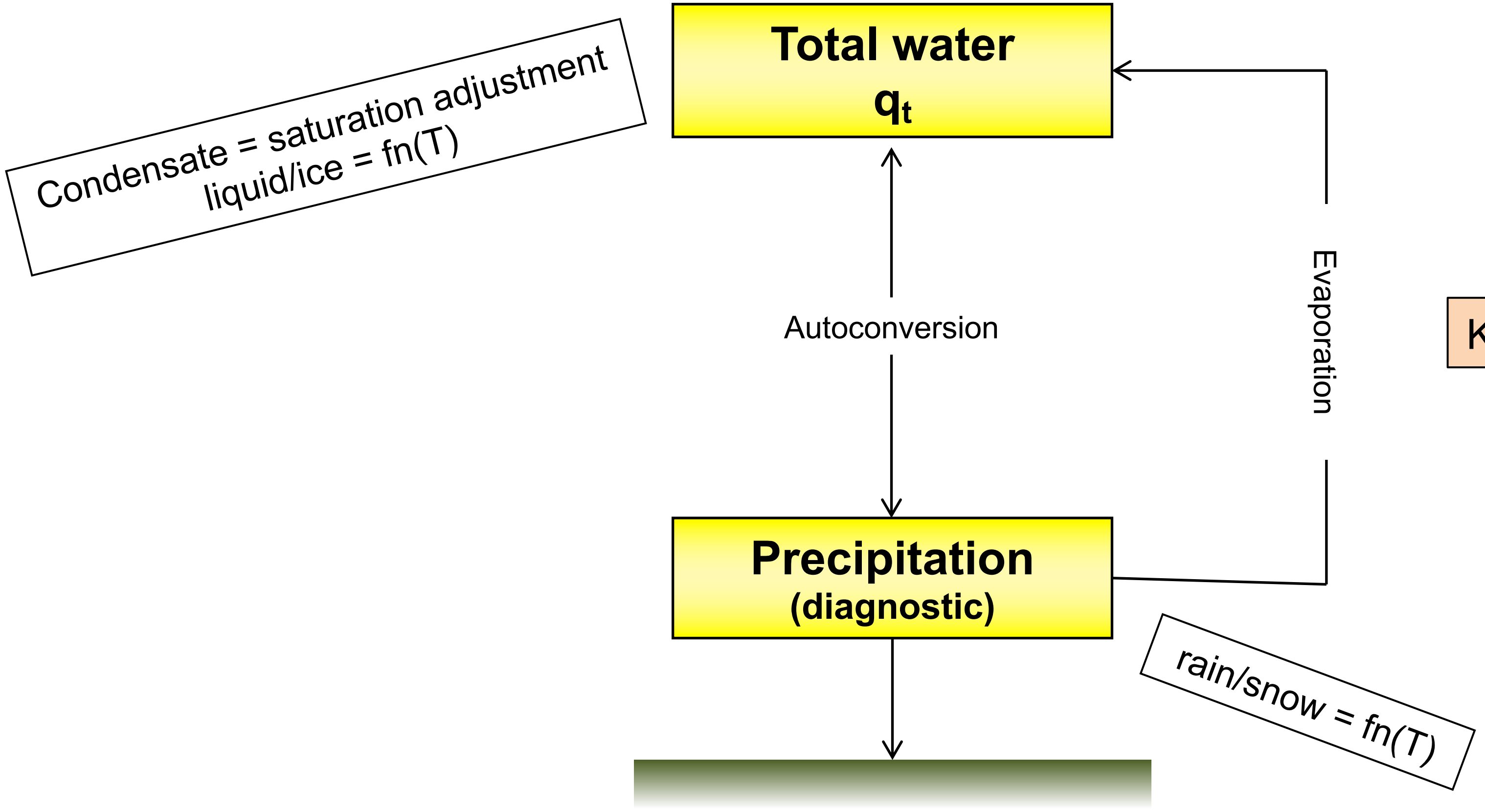
$$\xcancel{\frac{\partial q_x}{\partial t}} + \xcancel{\vec{v}.\nabla q_x} - \frac{1}{\rho}\frac{\partial}{\partial z}(\rho v_x q_x) = S(q_x)$$

> e.g. rain in models with long timestep (1hr):
> timescale for fallout of rain << model timestep
> therefore can assume rain profile is in equilibrium and can diagnose the rain flux locally every timestep

Can have a mixture of approaches for different hydrometeors

Microphysics parametrization: Simple schemes

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



Condensate = saturation adjustment
liquid/ice = fn(T)

Total water
q_t

Autoconversion

Evaporation

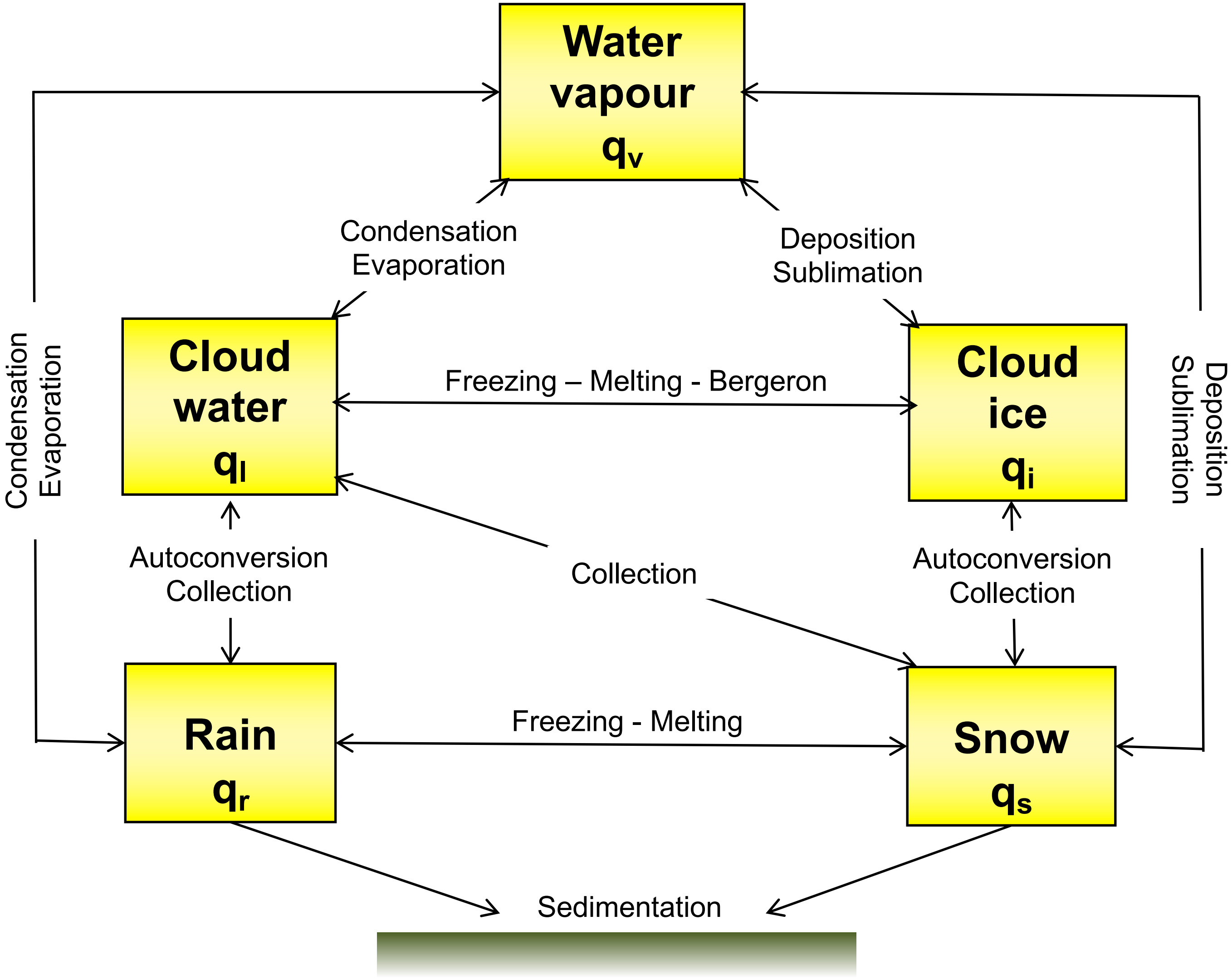
Precipitation
(diagnostic)

rain/snow = fn(T)

Kessler (1969)

Microphysics parametrization: The “category” view

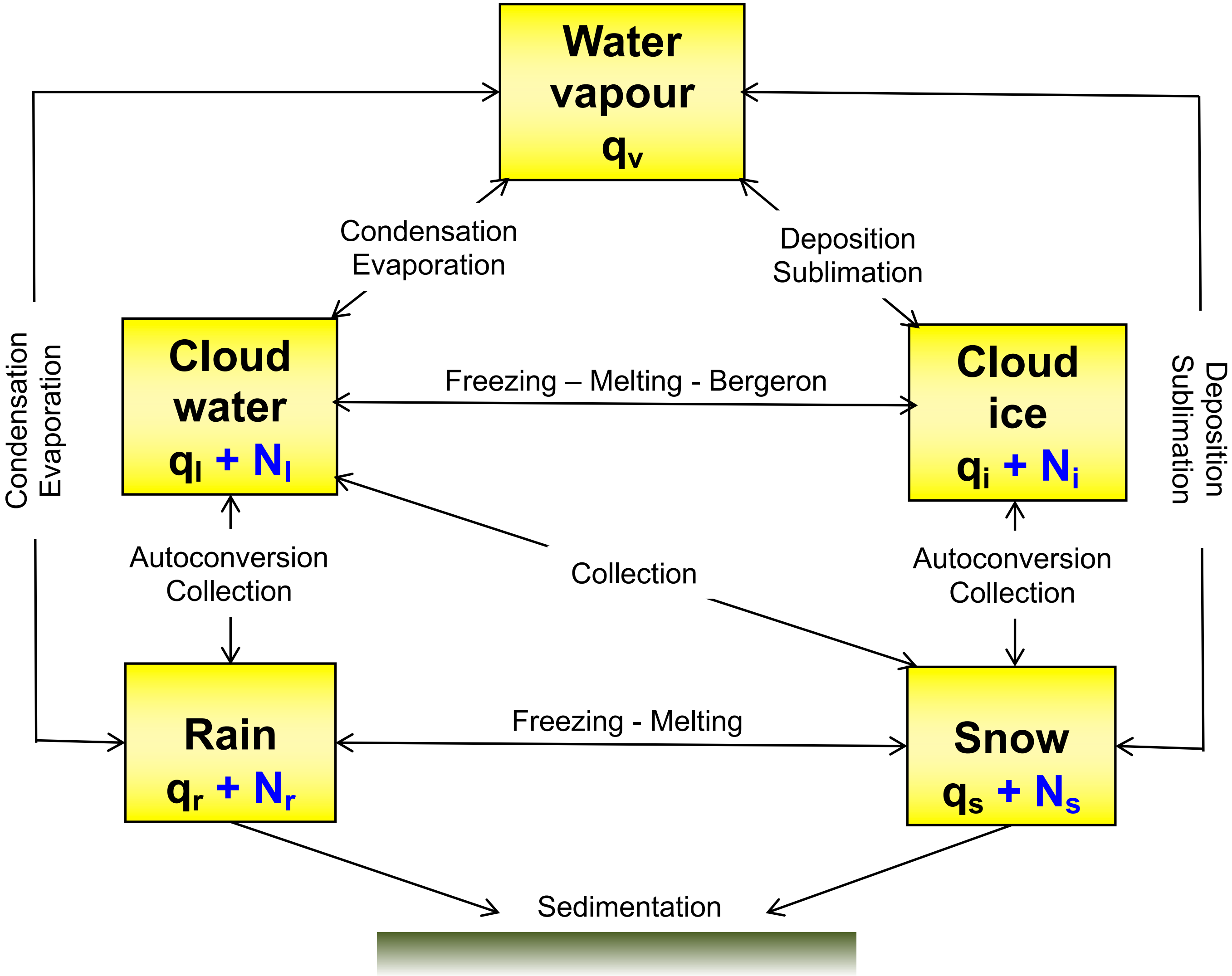
Single moment schemes



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.

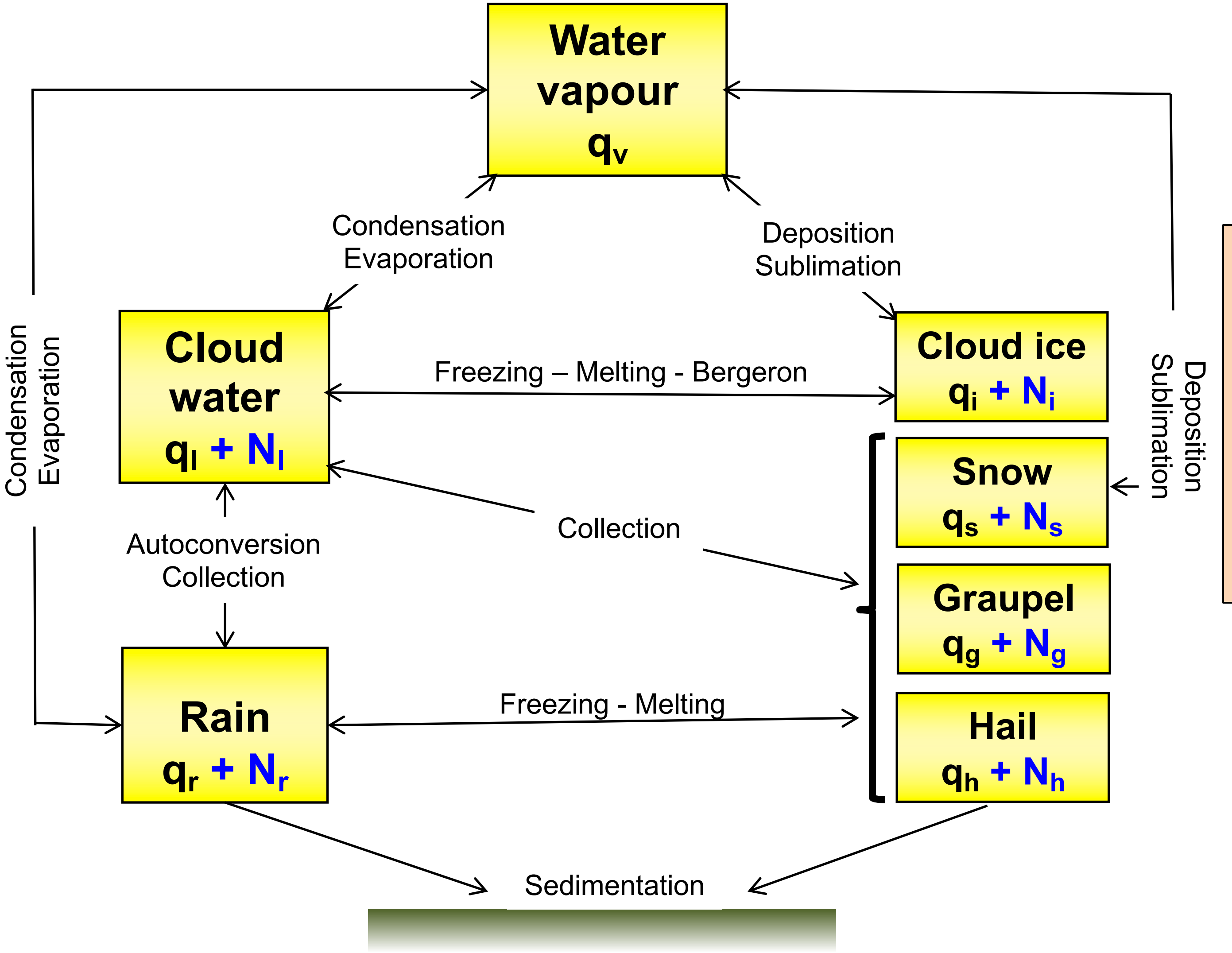
Ferrier (1994)

Seifert and Beheng (2001)

Morrison et al. (2005)

Microphysics parametrization: The “category” view

Double moment schemes – multiple ice categories



e.g.

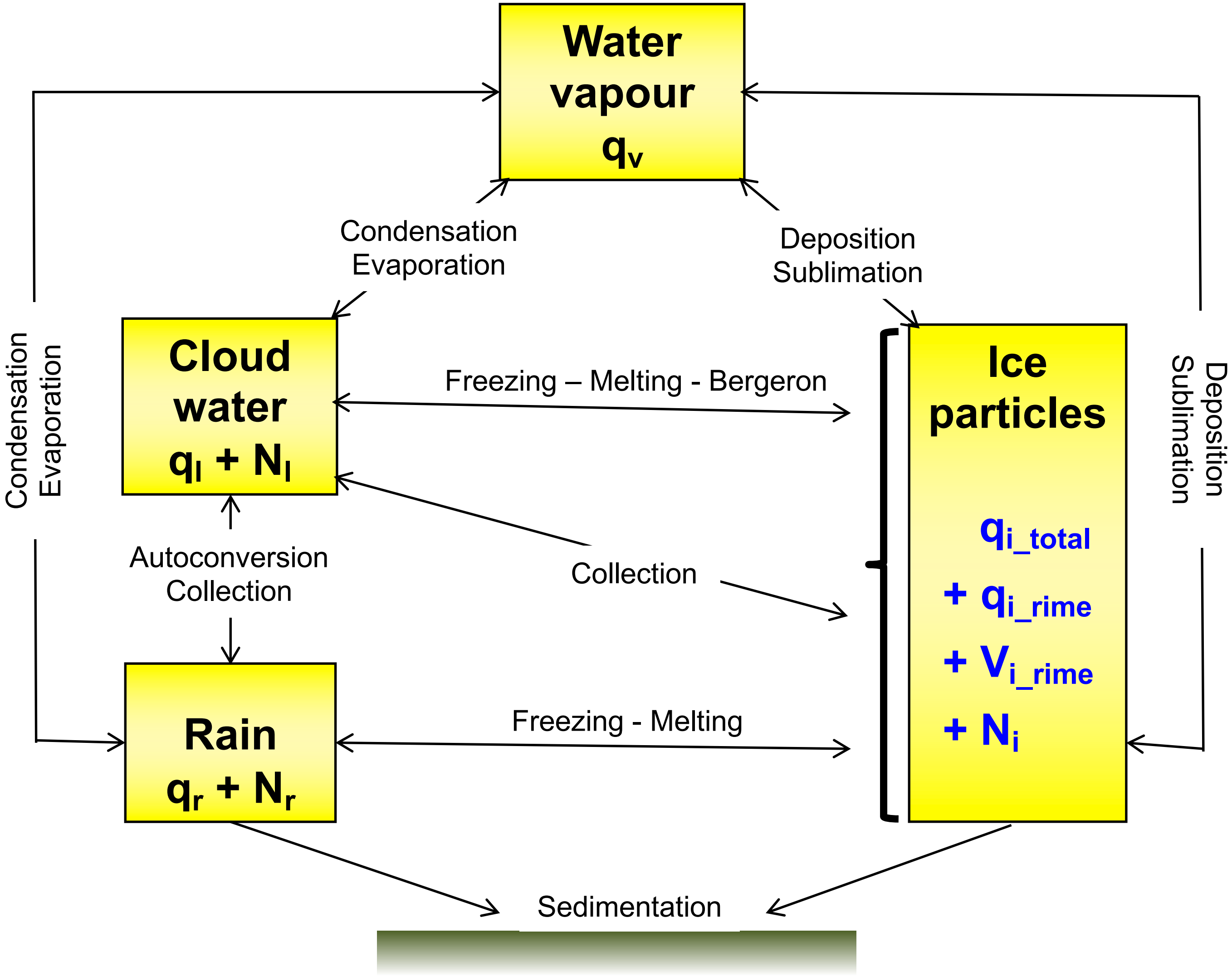
Lin et al. (1983)

Meyers et al. (1997)

Milbrandt and Yau (2005)

Microphysics parametrization: The “category” view

Double moment schemes + ice particle properties



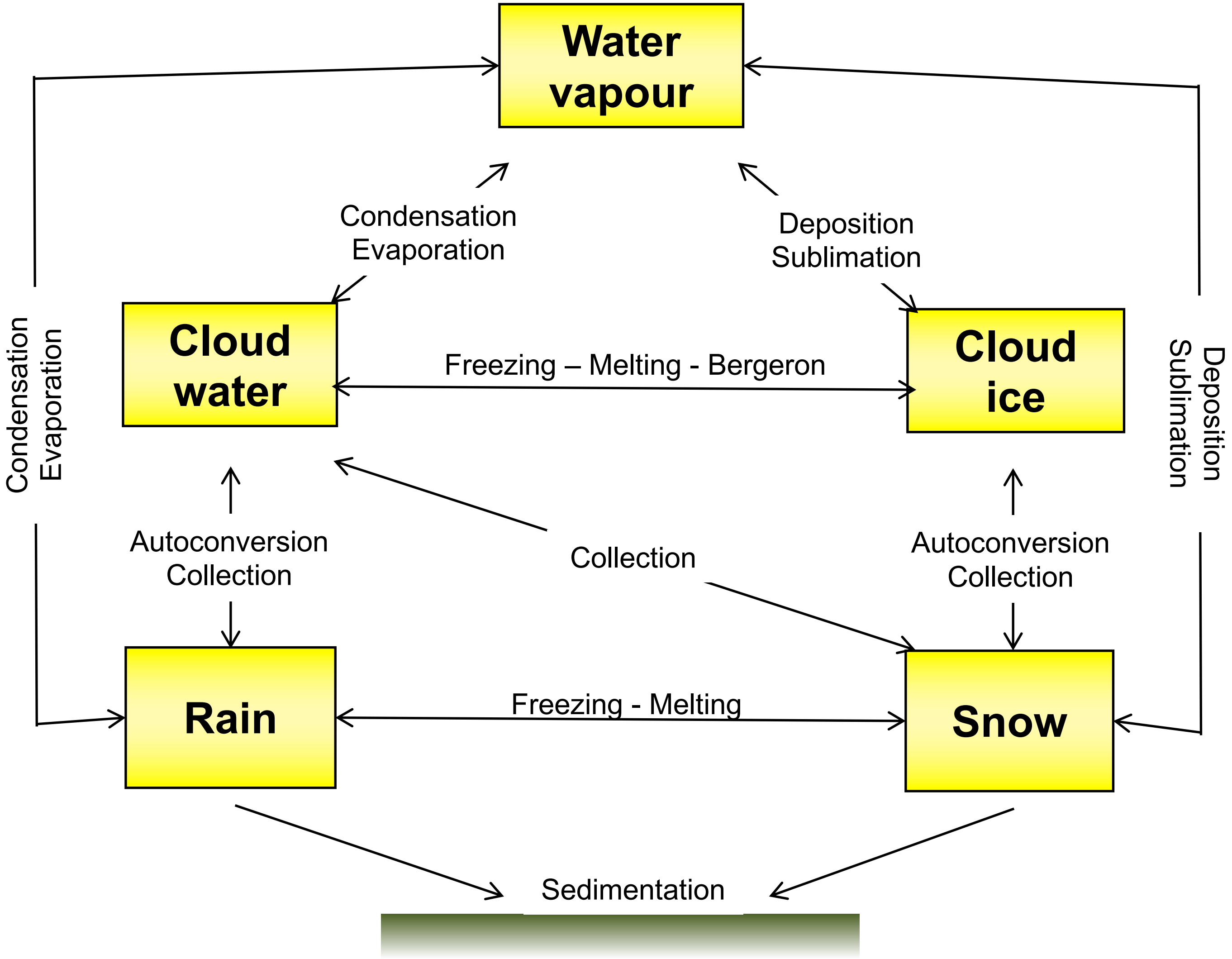
e.g.

Morrison and Grabowski (2008)

Morrison and Milbrandt (2015a,b) ‘P3’

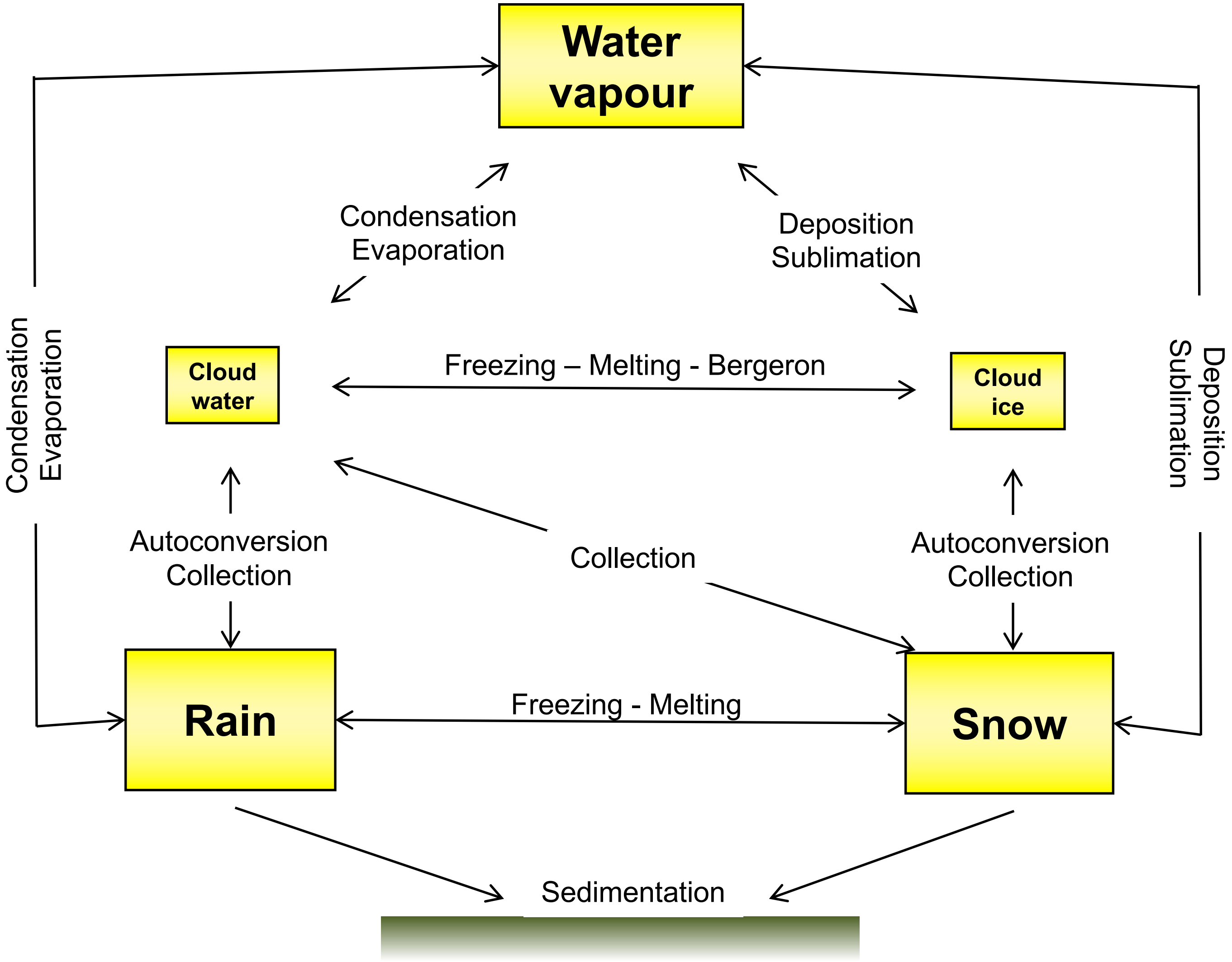
Microphysics parametrization: The “category” view

What is important?



Microphysics parametrization

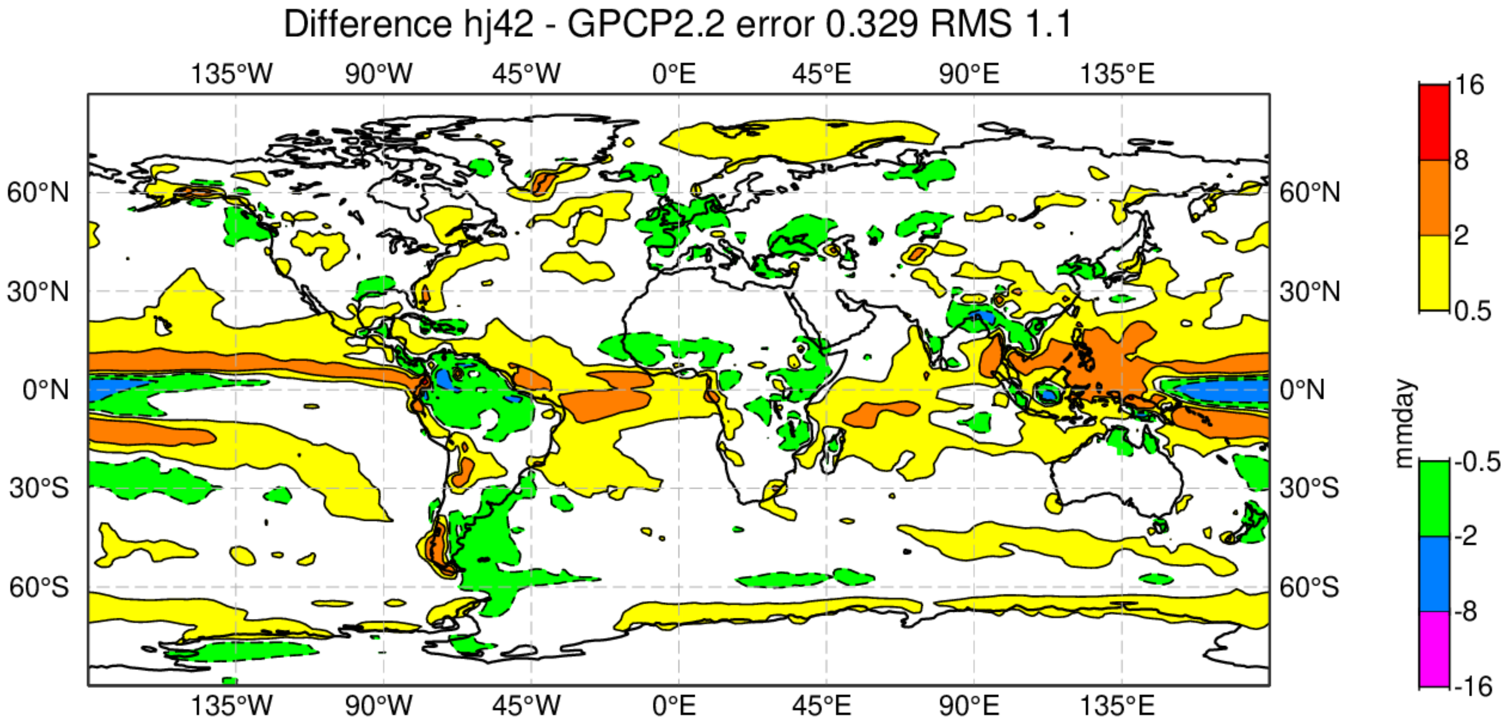
The hydrological perspective



Microphysics parametrization

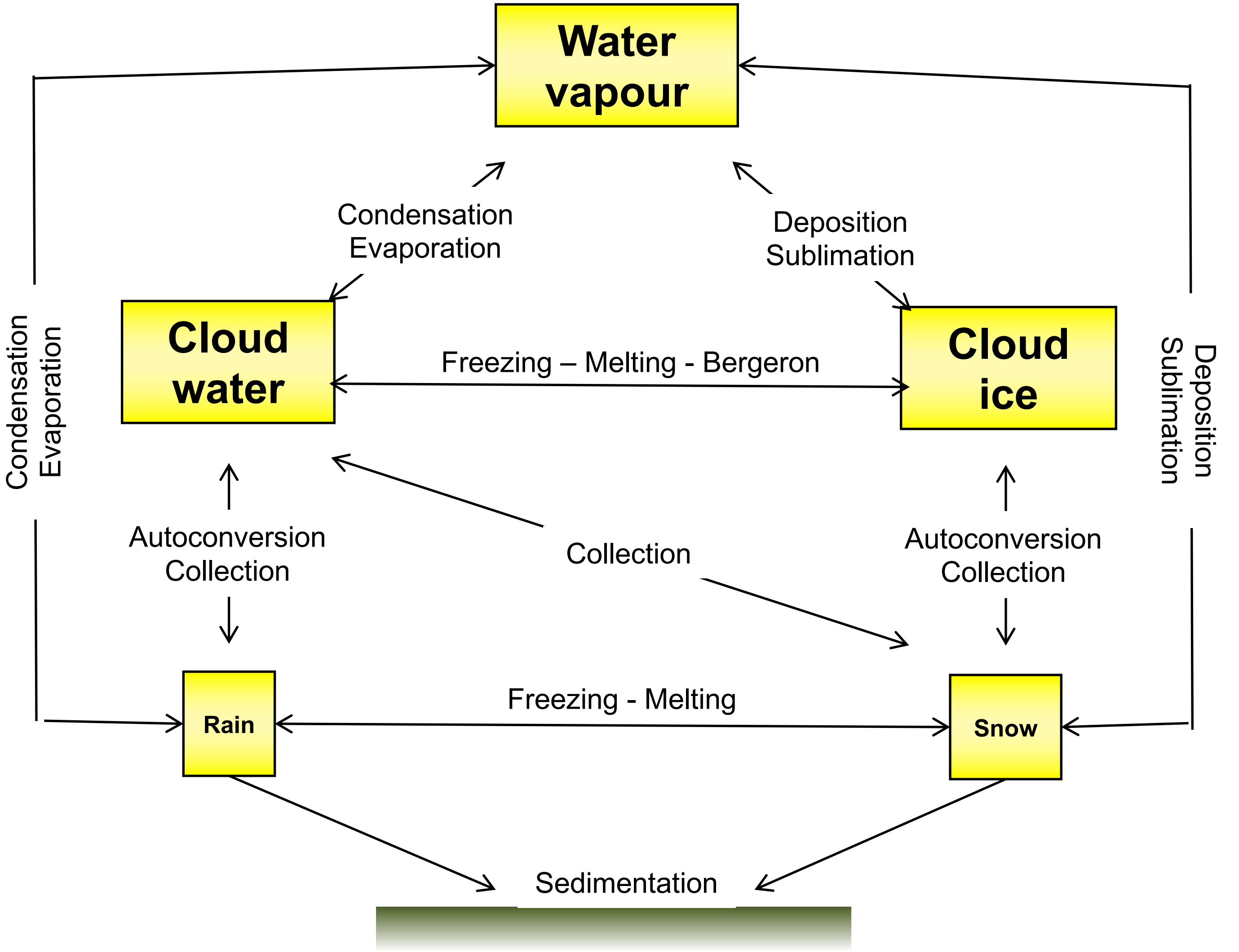
The hydrological perspective

Annual mean IFS model climatological surface precipitation bias versus GPCP observational dataset



Microphysics parametrization

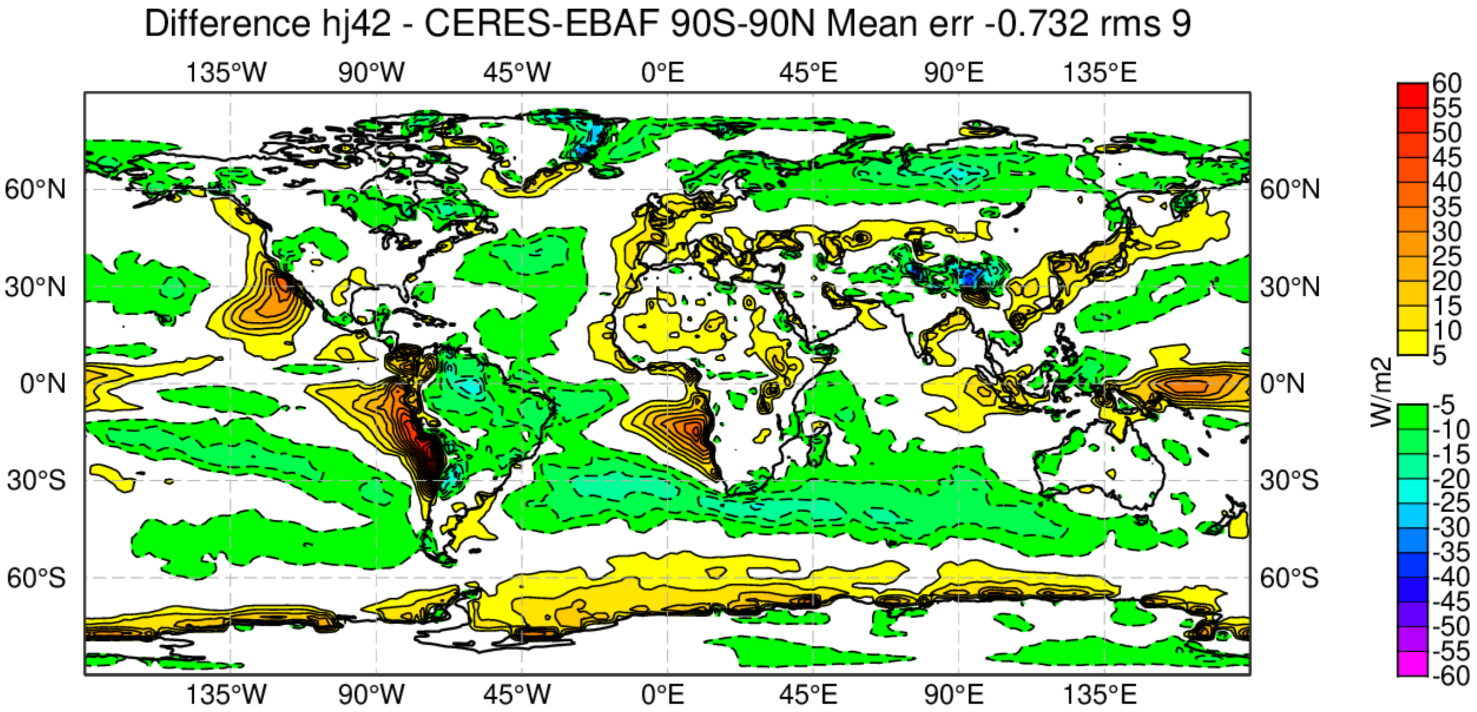
The radiative perspective



Microphysics parametrization

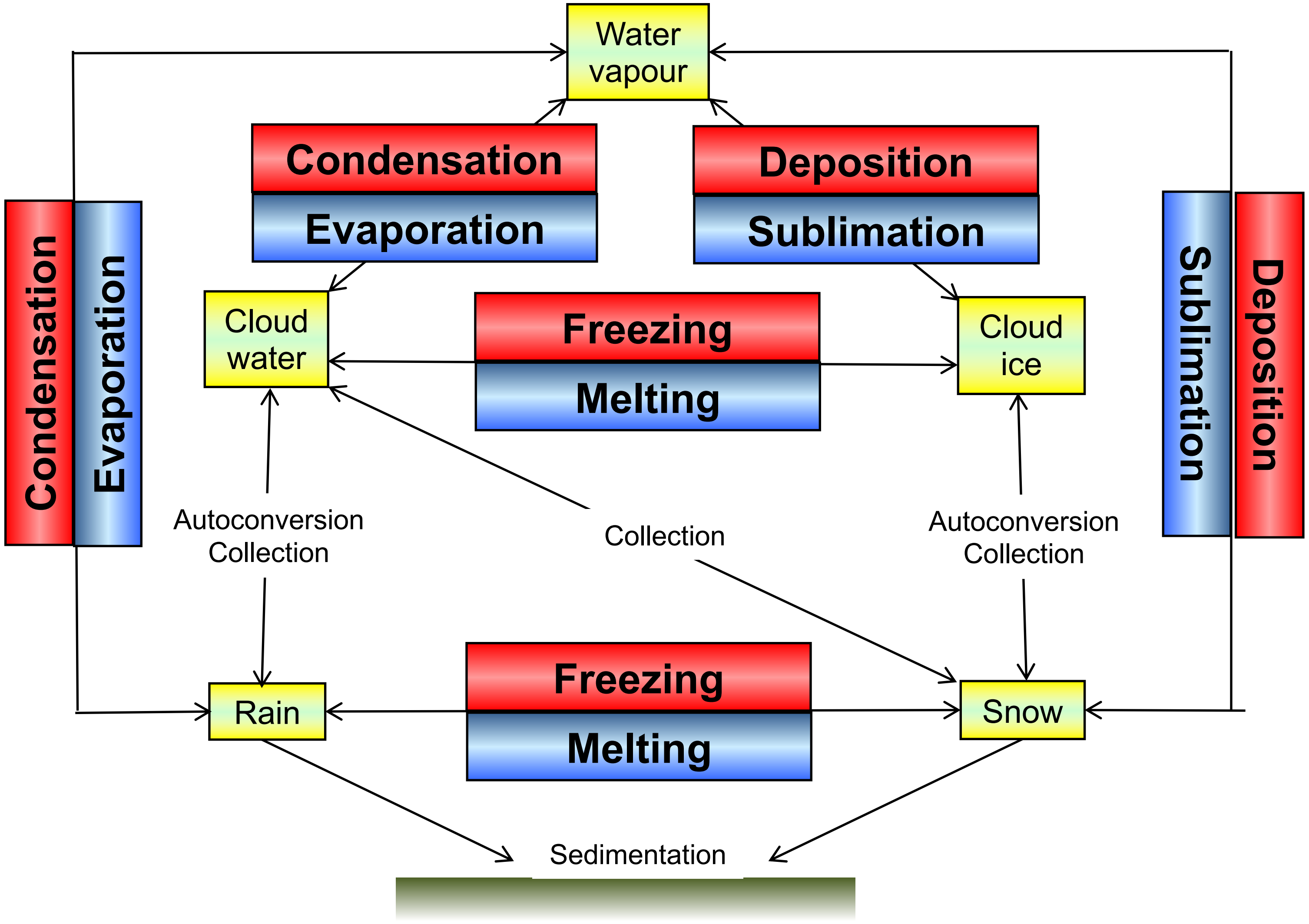
The radiative perspective

Annual mean IFS model climatological top-of-atmosphere net shortwave bias versus CERES-EBAF observations



Microphysics parametrization

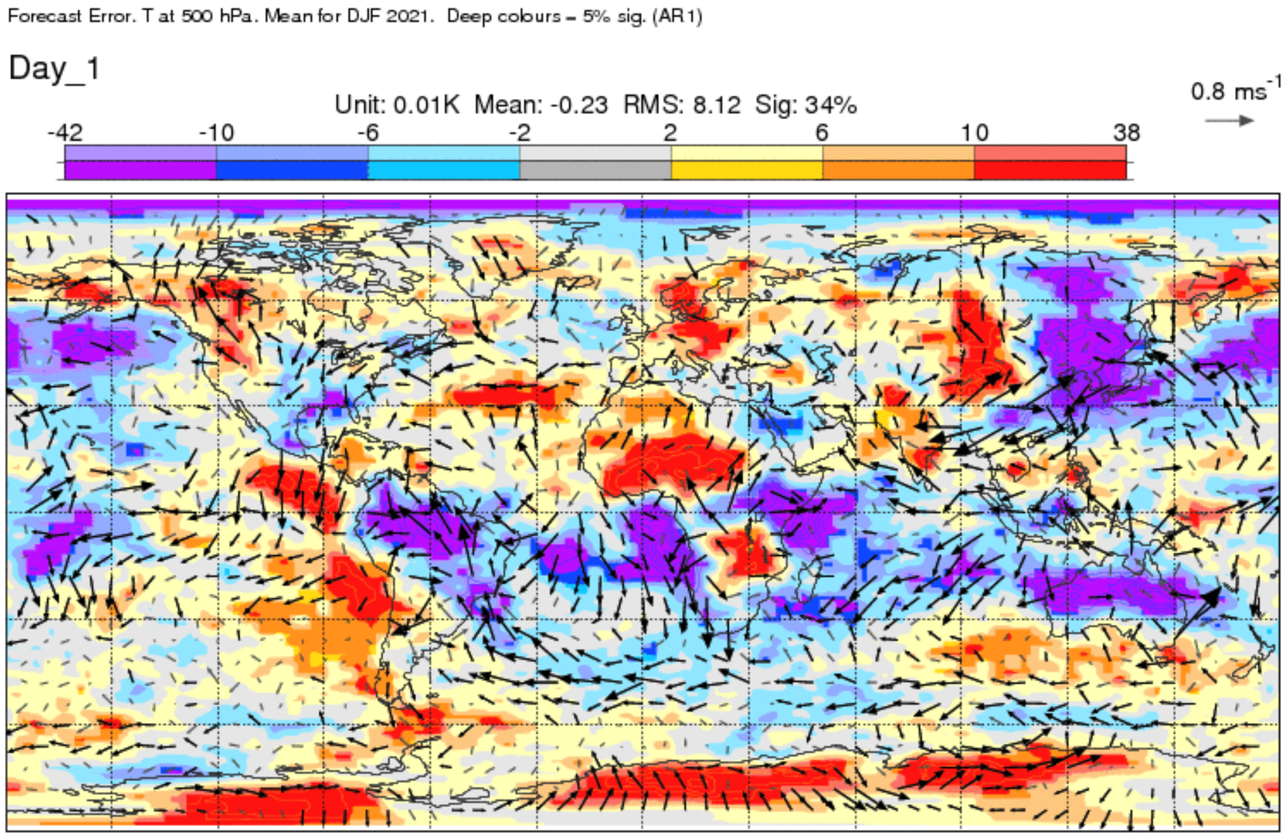
The diabatic heating/cooling perspective



Microphysics parametrization

The diabatic heating/cooling perspective

24 hour forecast mean temperature error versus analysis
at 500hPa, from the operational TCo1279 IFS



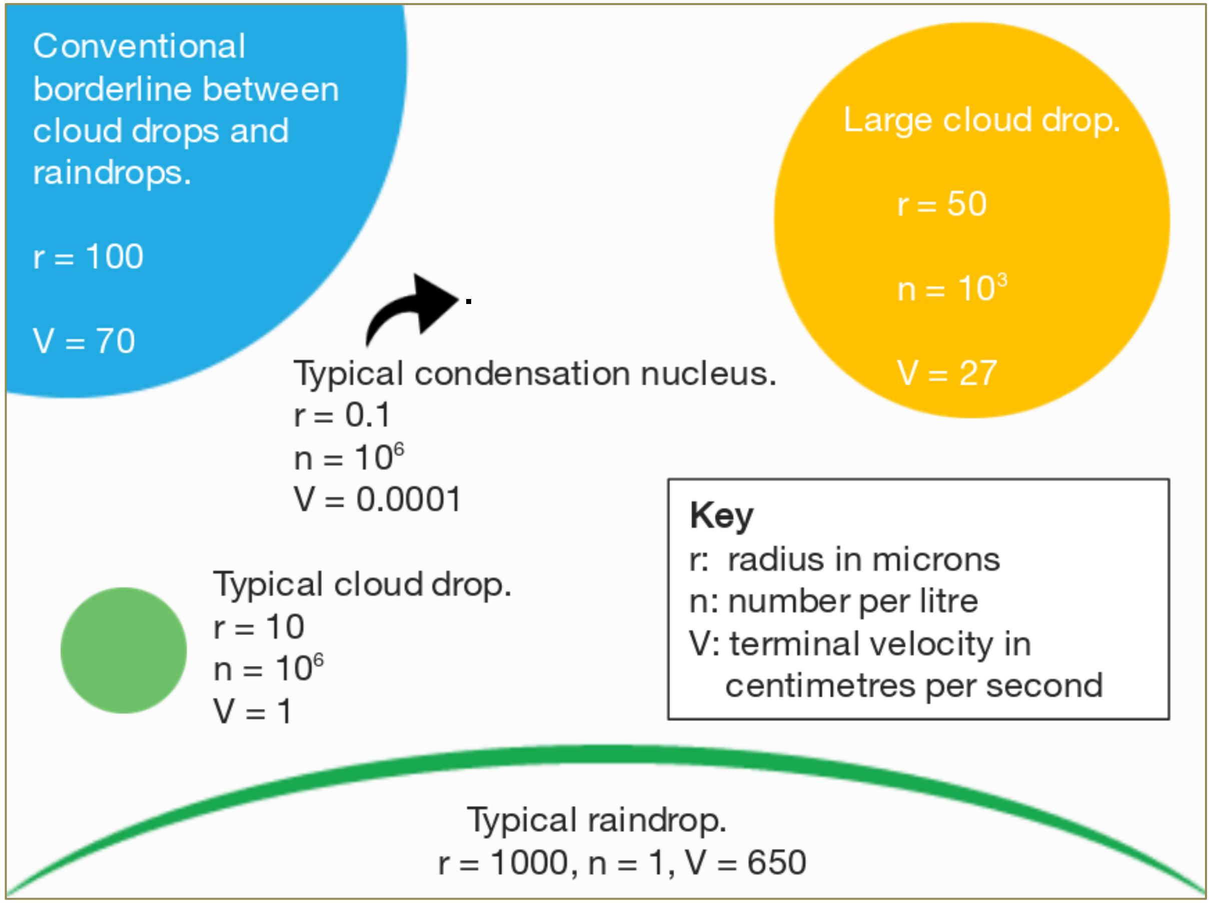
2. Warm-phase Microphysical Processes

Cloud microphysical processes

To describe warm-phase cloud and precipitation processes in our models we need to represent:

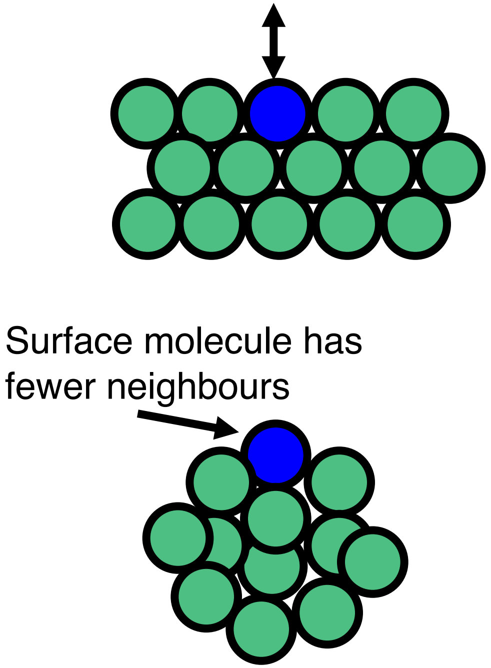
- Nucleation of water droplets
- Diffusional growth of cloud droplets (condensation)
- Collection processes for cloud drops (collision-coalescence), leading to precipitation sized particles
- the advection and sedimentation (falling) of particles
- the evaporation of cloud and precipitation size particles

Droplet Classification



Comparative sizes, concentrations and terminal fall velocities of some of the particles involved in cloud and precipitation processes (after 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

Curved surface: 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

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

$\sigma =$ Surface tension of droplet

$r =$ drop radius

Nucleation of cloud droplets: Homogeneous Nucleation

- To get a drop of pure water to form from vapour requires a high supersaturation.
- 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).
- So how do cloud droplets forming?

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

R_c = Critical radius

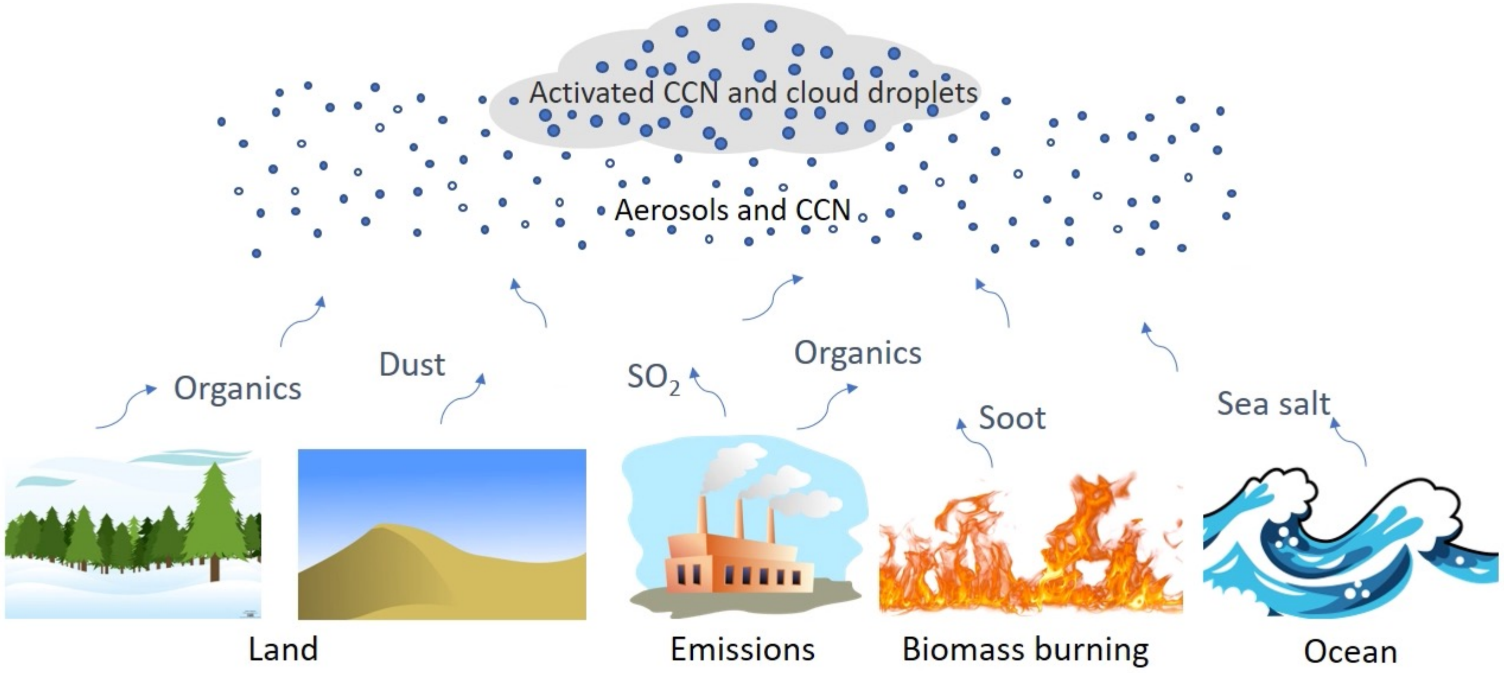
σ = Surface tension of droplet

Nucleation of cloud droplets: Heterogeneous Nucleation

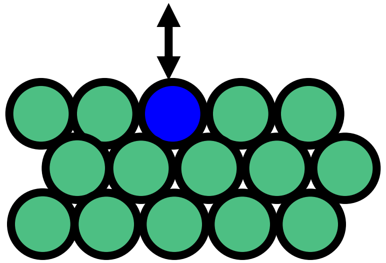
- Collection of water molecules on a foreign substance, RH > ~80% (Haze particles)
- These (hygroscopic) soluble particles are called Cloud Condensation Nuclei (CCN)
- CCN almost always present in sufficient numbers in lower and middle troposphere
- Nucleation of droplets (i.e. from stable haze particle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

Nucleation of cloud droplets: Heterogeneous Nucleation

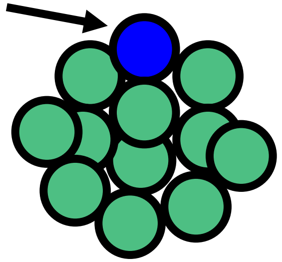
Aerosol particles are abundant in the atmosphere and many are hygroscopic (e.g. sea salt, sulphates) and readily form solute particles that become cloud condensation nuclei



Nucleation of cloud droplets: Important effects for particle activation

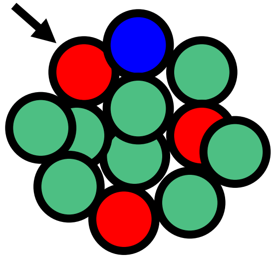


Planar surface: Equilibrium when $e=e_s$ and number of molecules impinging on surface equals rate of evaporation



Surface molecule has fewer neighbours

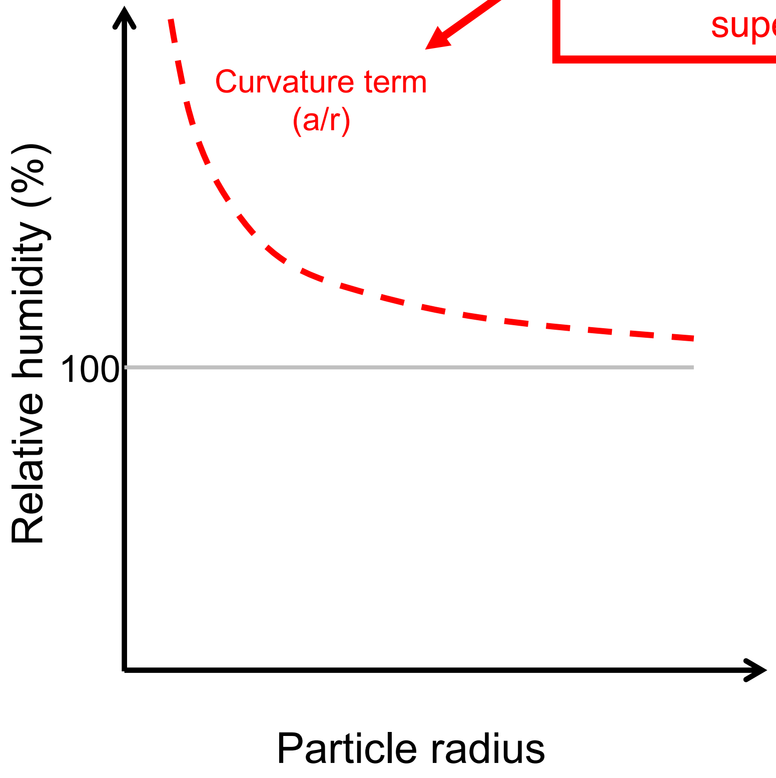
Curved surface: saturation vapour pressure increases with smaller drop size since surface molecules have fewer binding neighbours.
Effect proportional to 1/r (curvature effect or "Kelvin effect")



Dissolved substance reduces vapour pressure

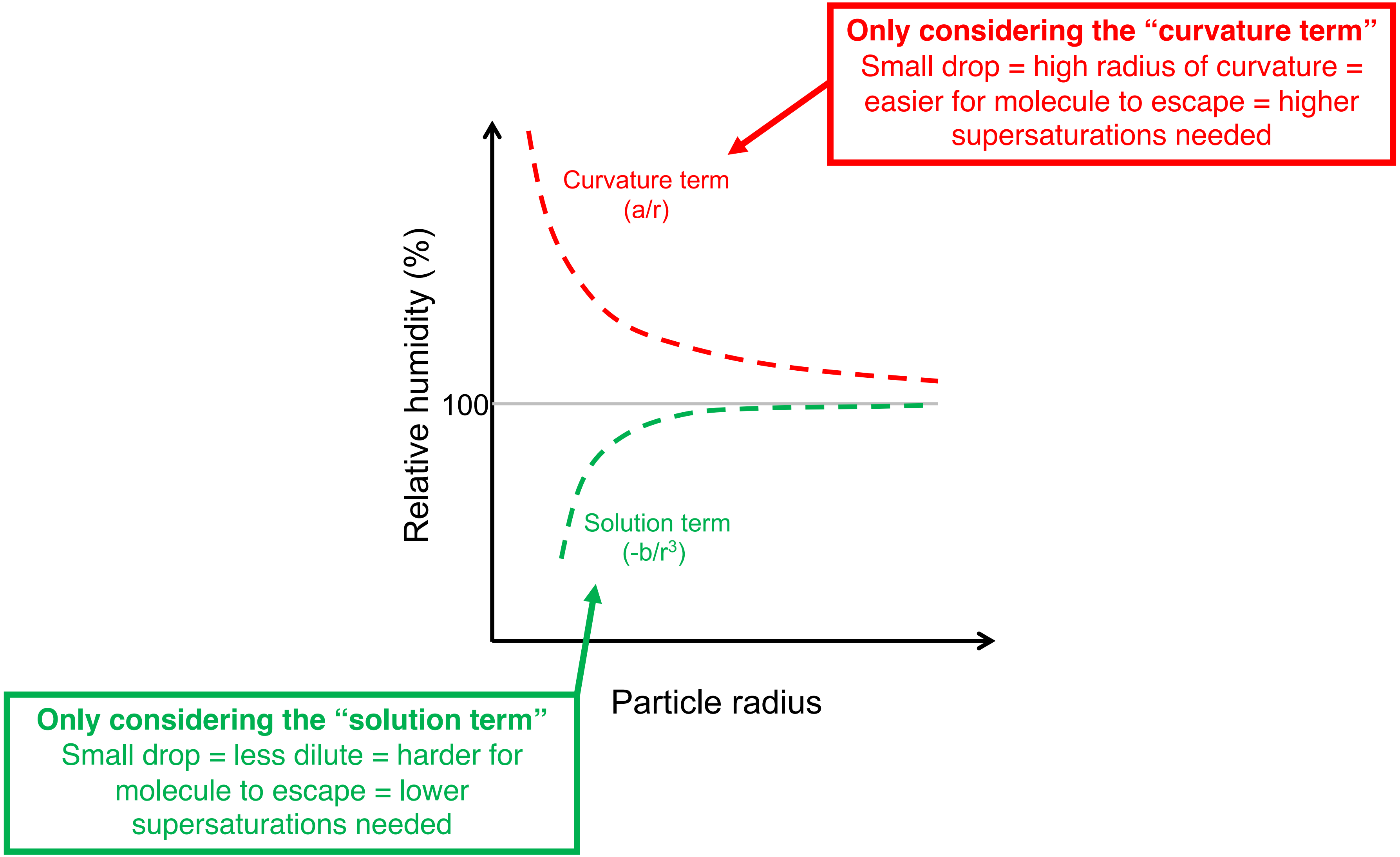
Presence of dissolved substance: saturation vapour pressure reduces with smaller drop size due to solute molecules replacing solvent on drop surface (assuming $e_{solute}<e_v$)
Effect proportional to $-1/r^3$ (solution effect or "Raoult's law")

Heterogeneous nucleation of cloud droplets (CCN activation)



Only considering the "curvature term"
Small drop = high radius of curvature = easier for molecule to escape = higher supersaturations needed

Heterogeneous nucleation of cloud droplets (CCN activation)

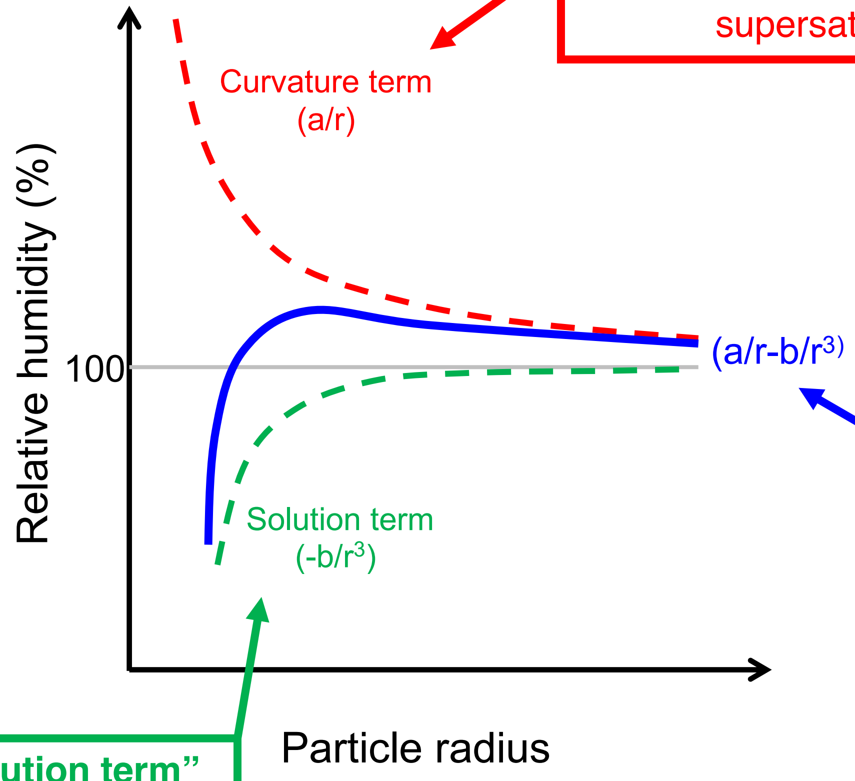


Only considering the "curvature term"
Small drop = high radius of curvature = easier for molecule to escape = higher supersaturations needed

Only considering the "solution term"
Small drop = less dilute = harder for molecule to escape = lower supersaturations needed

Heterogeneous nucleation of cloud droplets (CCN activation)

Only considering the "curvature term"
Small drop = high radius of curvature = easier for molecule to escape = higher supersaturations needed



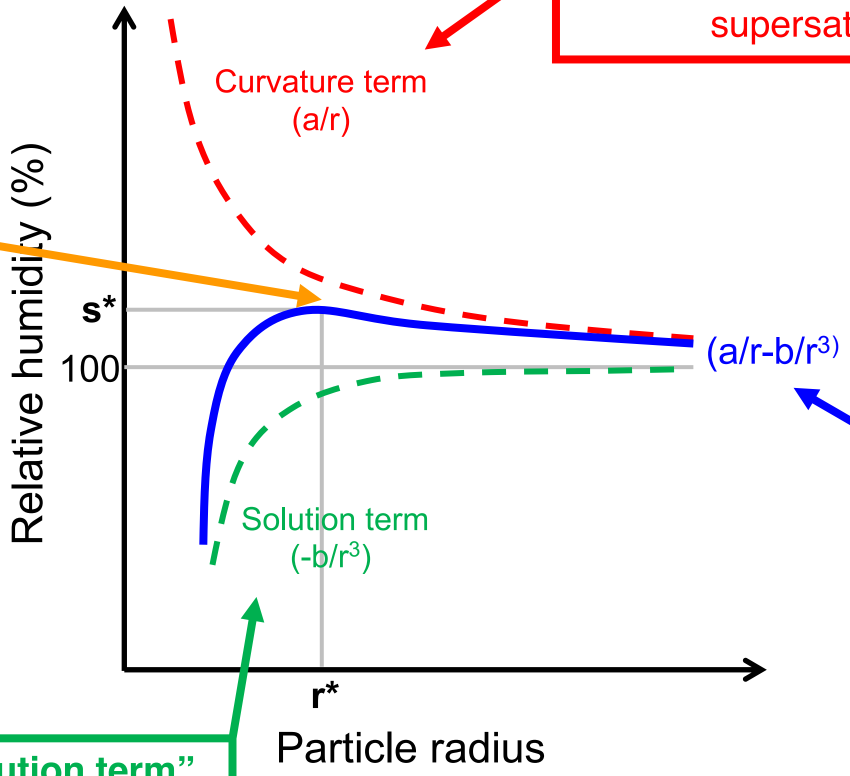
Combined "curvature" + "solution" terms = Köhler curve

Only considering the "solution term"
Small drop = less dilute = harder for molecule to escape = lower supersaturations needed

Heterogeneous nucleation of cloud droplets (CCN activation)

CCN activation at radius **r*** when supersaturation reaches critical threshold **s*** (dependent on solute)

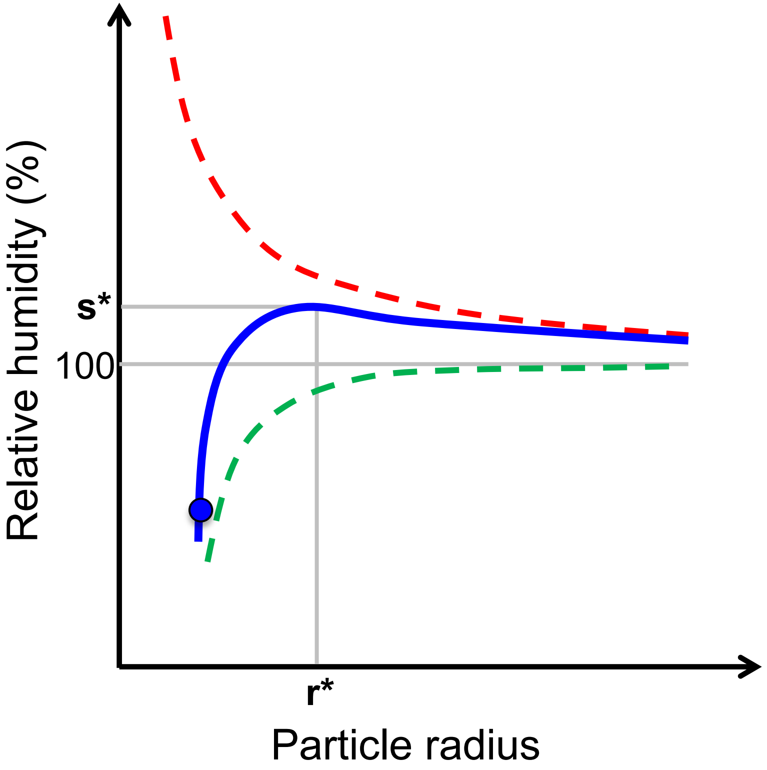
Only considering the “curvature term”
Small drop = high radius of curvature = easier for molecule to escape = higher supersaturations needed



Combined “curvature” + “solution” terms = Köhler curve

Only considering the “solution term”
Small drop = less dilute = harder for molecule to escape = lower supersaturations needed

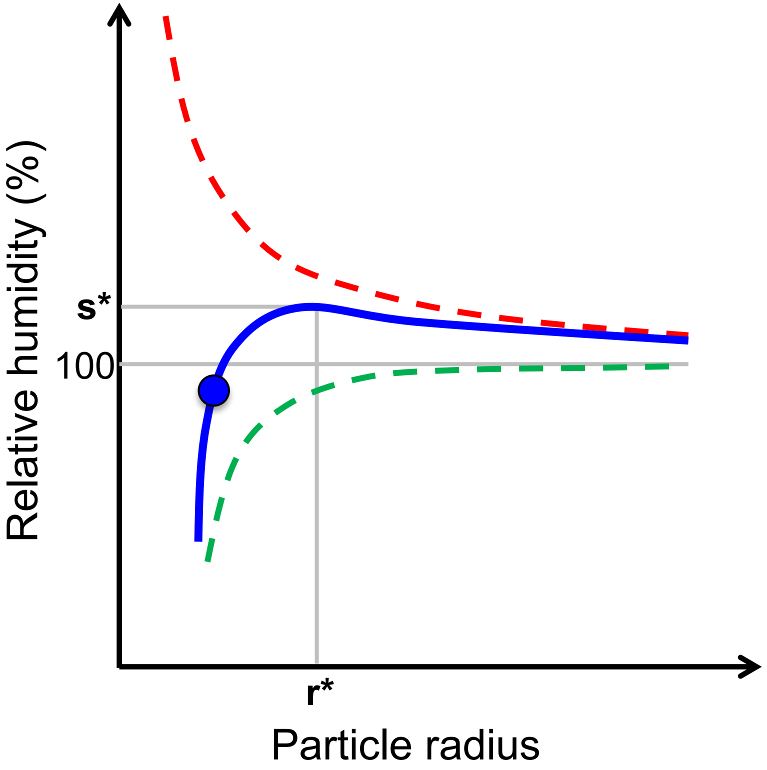
Heterogeneous nucleation of cloud droplets (CCN activation)



Haze particle in equilibrium with environment

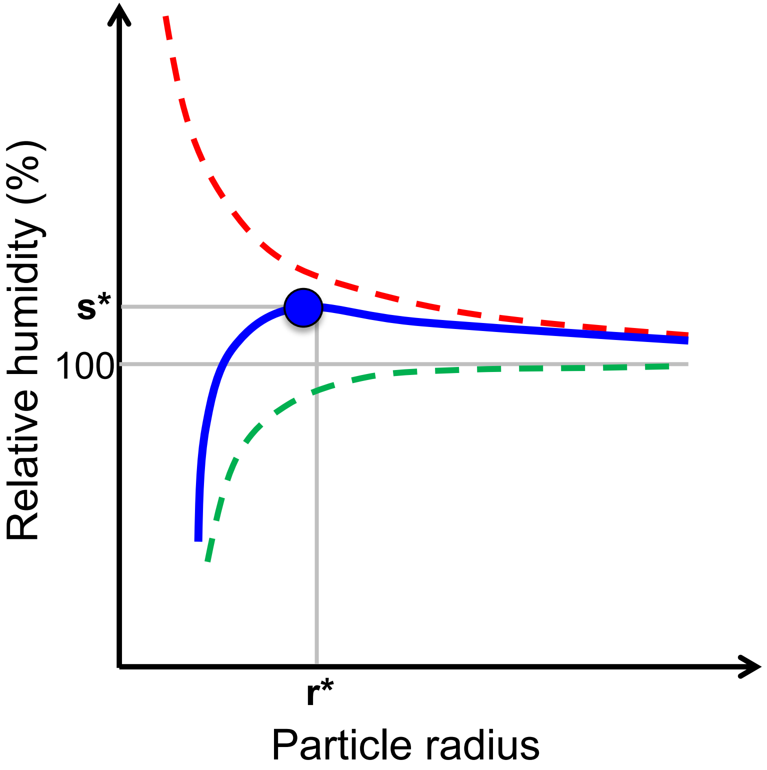
Heterogeneous nucleation of cloud droplets (CCN activation)

Relative humidity increases, particle grows but still in equilibrium with environment



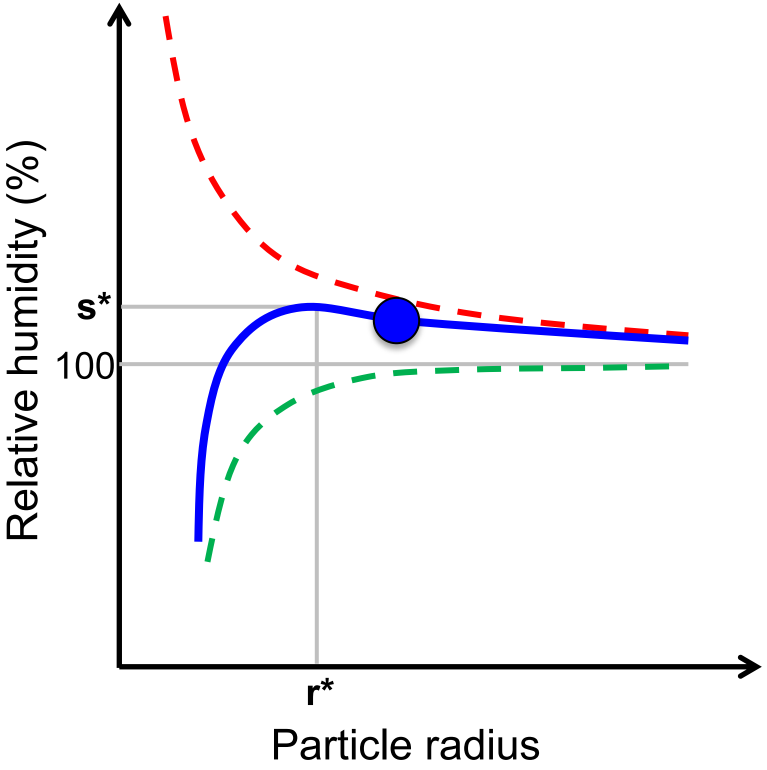
Heterogeneous nucleation of cloud droplets (CCN activation)

Relative humidity increases above saturation to critical threshold (<101%), particle “activated”



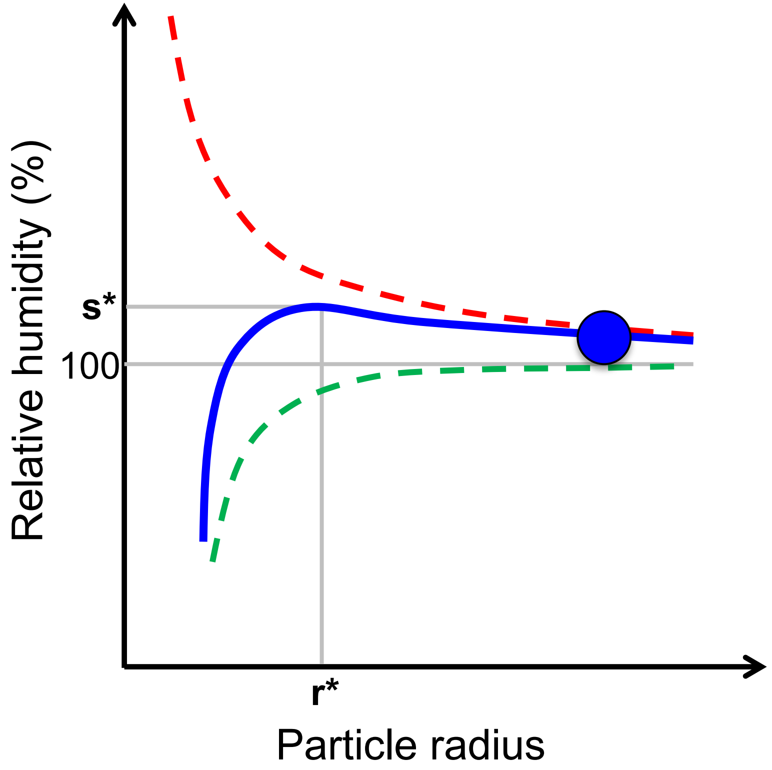
Heterogeneous nucleation of cloud droplets (CCN activation)

Particle grows rapidly reducing environmental supersaturation



Heterogeneous nucleation of cloud droplets (CCN activation)

Particle grows more slowly as radius increases and supersaturation decreases



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
- So how do rain drops form?
- Other processes must also act in precipitating clouds

Droplet growth – diffusion equation:

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

For r > $1\ \mu\text{m}$ and neglecting diffusion of heat

r = droplet radius

D = diffusion coefficient,

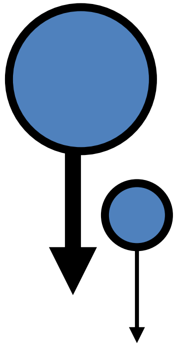
(S-1) = supersaturation

T = temperature

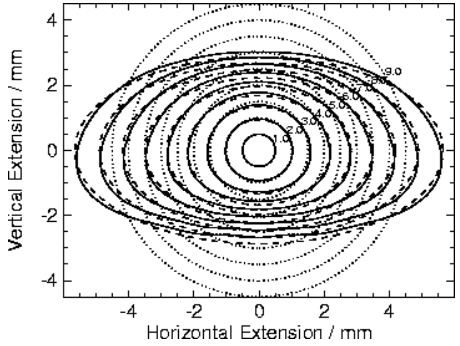
Note inverse radius dependency

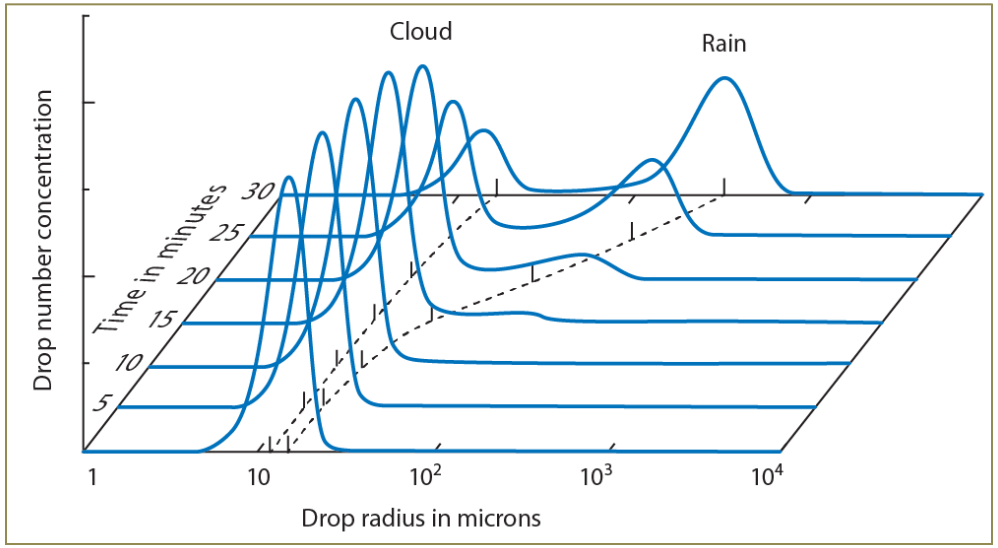
Collection processes: Collision-coalescence of water droplets

- Drops of different size move with different fall speeds - collision and coalescence
- Large drops grow at the expense of small droplets
- Collection efficiency is 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)





(After Berry and Reinhardt 1974)

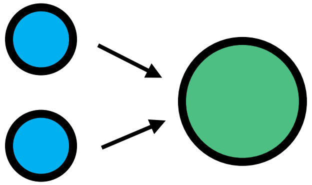
Parametrizing nucleation and water droplet diffusional growth

- Nucleation: Since CCN "activation" occurs at water supersaturations less than 1% and condensation is fast
  A good approximation is therefore to assume all supersaturation with respect to water is immediately removed to form water droplets. This is called "**saturation adjustment"**
  Many models use this simple assumption…but….
- …this doesn't provide information on cloud droplet sizes, number concentrations or the dependence on aerosol.
- In single-moment schemes (only predicting mass of cloud water), assumptions are made concerning the droplet number concentration/effective radius when needed (e.g. radiation).
- More complex schemes can explicitly represent nucleation and solve the droplet growth equation and depend on predictions of **aerosol type and number concentrations** and sub-grid vertical velocity for activation
  (important for climate change, but lots of complexities and uncertainties)

Parametrizing collision-collection process: “Autoconversion” and “Accretion”

For a bulk microphysics scheme with two warm-phase hydrometeor categories “cloud liquid droplets” (q_l) and “rain drops” (q_r)

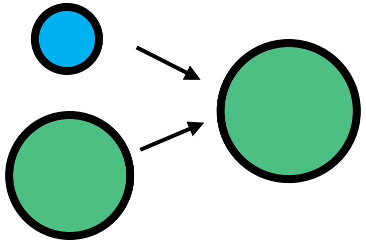
General form of “autoconversion”



$$\frac{\partial q_r}{\partial t} = a q_l{}^{b} N^{c}$$

$\partial q_r / \partial t$ = rate of change of rain water content
q_l = cloud liquid water content
N = droplet number concentration
a,b,c = parameters

General form of accretion parametrization equation



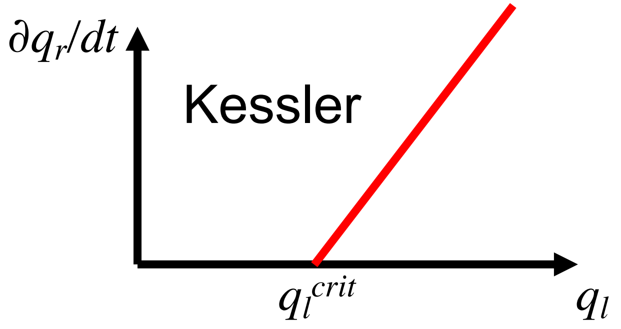
$$\frac{\partial q_r}{\partial t} = d q_l{}^{e} q_r{}^{f}$$

$\partial q_r / \partial t$ = rate of change of rain water content
q_l = cloud liquid water content
q_r = rain water content
d,e,f = parameters

Parametrizing collection processes: “Autoconversion” of cloud drops to raindrops

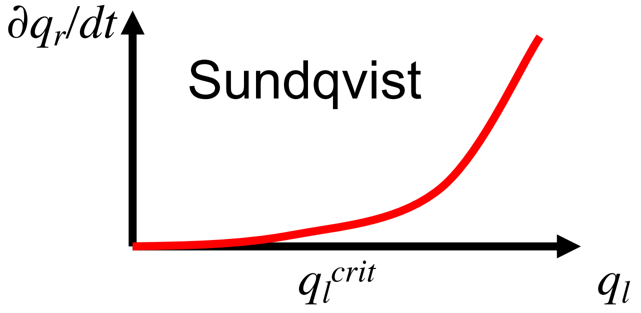
- Linear function of q_l (Kessler, 1969)

$$\frac{\partial q_r}{\partial t} = a_0\left(q_l - q_l^{crit}\right) \qquad \text{for } q_l > q_l^{crit}$$



- Function of q_l with additional term to avoid singular threshold (Sundqvist 1978)

$$\frac{\partial q_r}{\partial t} = a_0 q_l\left(1 - e^{-\left(q_l / q_l^{crit}\right)^2}\right)$$



- 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.

$$\longrightarrow \frac{\partial q_r}{\partial t} = a_0 q_l^{2.47} N^{-1.79}$$

- Or detailed bin microphysics model → machine learning/neural network (Gettelman et al. 2021)

Parametrizing collection processes: "Accretion" of cloud drops by raindrops

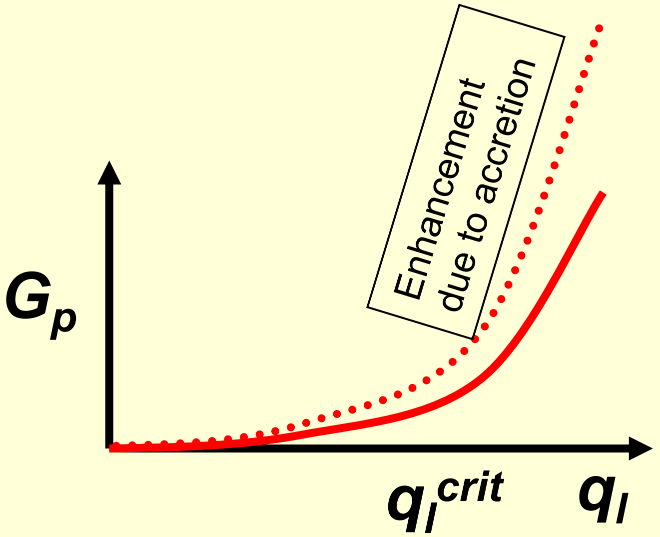
Representing autoconversion and accretion in the warm phase (cloud liquid to rain).

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

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



In the IFS pre-2010

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.

In the IFS after 2010 and now

Parametrizing evaporation - cloud and precipitation

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

However, larger precipitation size particles take longer to evaporate, so precipitation may fall into drier air below cloud base before it evaporates.

Rain evaporation is parametrized by integrating over an assumed droplet size spectrum (exponential or gamma), proportional to the subsaturation:

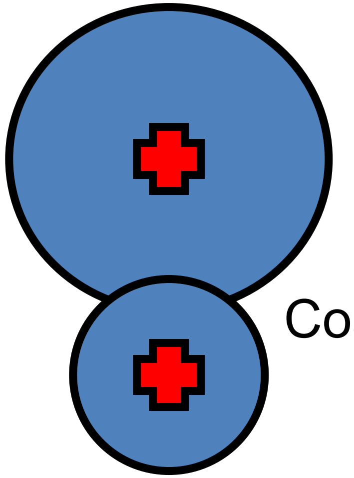
For a single rain drop of radius *r*,

$$\frac{dr}{dt} \approx \frac{1}{r} \frac{\psi e_s^{\infty}}{\rho_l R_v T}(S-1)$$

r = rain drop radius
ψ = *diffusivity of water in air*
e_s^{∞} = saturation vapour pressure for a planar surface
ρ_l = density of liquid water
R_v= *gas constant for water vapour*
T = *temperature*
S = *saturation ratio* = e/e_s^{∞}

Same as the growth (condensation) equation for a droplet with radius *r* (shown earlier), but *dr/dt* is negative because the air is subsaturated (S < 1)

Schematic of Warm Rain Processes



Coalescence

Summary

- Cloud is important for it’s radiative, hydrological and dynamical impacts (also associated with 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:

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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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