Numerial Weather Prediction
Parametrization of Subgrid Physical Processes

Clouds (1)
Overview &
Warm-phase Microphysics

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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
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:

- Convection
- Radiation
- Microphysics
- Dynamics
- Turbulence
Representing Clouds in GCMs What are the problems?

Example: cloud-radiation interaction – many uncertainties

- Cloud fraction and overlap
- Cloud top and base height
- Amount of condensate
- In-cloud condensate distribution
- Cloud-radiation interaction
- Cloud environment
- Phase of condensate
- Cloud particle size
- Cloud particle shape

Legend:
- Cloud macrophysics
- Cloud microphysics
- “External” influence
Cloud Parametrization Issues:

• Microphysical processes

• Macro-physical
  – subgrid heterogeneity

• Numerical issues

\[ \frac{\partial q_l}{\partial t} = A(q_l) + S(q_l) - D(q_l) \]
**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).
- The particle size distributions and their evolution can be modelled with different complexities and degrees of freedom...

Rain drop size distributions for three different rain water contents:

- Exponential
- Gamma

Three different rain drop size distributions for the same rain water content.
Microphysics Parametrization Issues: Complexity?

Complexity

“Single Moment” Schemes

“Double Moment” Schemes

“Triple Moment” Schemes

“Spectral/Bin” Schemes

GCMs have single-moment or double-moment schemes

mass

mass

mass

particle number

particle number

particle number

particle density or reflectivity

particle number 0<D≤D₁

particle number D₁<D≤D₂

particle number D₂<D≤D₃

particle number D₃<D≤D₄

particle number D₄<D≤D₅

particle number D₅<D≤D₆
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. \( T, q \))*

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

*example: 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)*

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

*example: 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!)

Total water $q_t$

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

Autoconversion

Precipitation (diagnostic)

Evaporation

Kessler (1969)

rain/snow = $fn(T)$
Microphysics Parametrization: The “category” view

Single moment schemes

- Cloud water $q_i$
- Cloud ice $q_i$
- Rain $q_r$
- Snow $q_s$

Processes:
- Condensation
- Evaporation
- Freezing – Melting - Bergeron
- Autoconversion
- Collection
- Deposition
- Sublimation
- Sedimentation

Rutledge and Hobbs (1983)
Microphysics Parametrization: The “category” view
Double moment schemes

- Water vapour $q_v$
- Cloud water $q_l + N_l$
- Rain $q_r + N_r$
- Cloud ice $q_i + N_i$
- Snow $q_s + N_s$

Processes:
- Condensation
- Evaporation
- Freezing - Melting - Bergeron
- Collection
- Autoconversion Collection
- Deposition Sublimation
- Sedimentation

References:
- Ferrier (1994)
- Seifert and Beheng (2001)
- Morrison et al. (2005)
Microphysics Parametrization: The “category” view
Double moment schemes – multiple ice categories

- Water vapour \( q_v \)
  - Condensation
  - Evaporation
  - Deposition
  - Sublimation

- Cloud water \( q_i + N_i \)
  - Autoconversion
  - Collection

- Rain \( q_r + N_r \)
  - Freezing – Melting
  - Bergeron

- Cloud ice \( q_i + N_i \)
  - Collection

- Snow \( q_s + N_s \)
  - Freezing – Melting

- Graupel \( q_g + N_g \)

- Hail \( q_h + N_h \)

- 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 $q_v$

Cloud water $q_l + N_l$

Rain $q_r + N_r$

Ice particles $q_{i\text{ total}} + q_{i\text{ rime}} + V_{i\text{ rime}} + N_i$

Condensation Evaporation

Freezing – Melting - Bergeron

Collection

Freezing - Melting

Deposition Sublimation

Sedimentation

Condensation Evaporation

Autoconversion Collection

Deposition Sublimation

e.g. Morrison and Grabowski (2008)
Morrison and Milbrandt (2015a,b) ‘P3’
Microphysics Parametrization: The “category” view
What is important?

- Cloud water
- Cloud ice
- Rain
- Snow
- Water vapour

Processes:
- Condensation
- Evaporation
- Freezing – Melting - Bergeron
- Autoconversion
- Sublimation
- Deposition
- Condensation
- Collection
- Autoconversion
- Collection
- Freezing - Melting
- Sedimentation
Microphysics Parametrization:
The hydrological perspective

- Water vapour
  - Condensation
  - Evaporation
  - Deposition
  - Sublimation

- Cloud water
  - Autoconversion
  - Collection

- Rain
  - Freezing
  - Melting

- Cloud ice
  - Autoconversion
  - Collection

- Snow
  - Freezing
  - Melting

- Sedimentation
Microphysics Parametrization: The radiative perspective

Water vapour

Cloud water

Cloud ice

Condensation
Evaporation
Autoconversion
Collection
Collection
Freezing - Melting
Freezing - Melting
Sedimentation
Deposition
Sublimation
Deposition
Sublimation
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**

![Diagram illustrating droplet classification](image)

**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

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

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

\(\sigma = \text{Surface tension of droplet}\)
\(r = \text{drop radius}\)

i.e. easier for a molecule to escape, so \(e_s\) has to be higher to maintain equilibrium
Nucleation of cloud droplets: Homogeneous Nucleation

- Drop of pure water forms from vapour.
- Small drops require much higher supersaturations.
- 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).

\[
R_c = \frac{2\sigma}{R_v \rho_i T \ln\left(\frac{e}{e_s}\right)}
\]

- \(R_c\) = 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.

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”)

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

Surface molecule has fewer neighbours

Dissolved substance reduces vapour pressure
Nucleation of cloud droplets: Heterogeneous Nucleation

Haze particle in equilibrium

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

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

Activation:
\[
e / e_s = s^* = 1.01 \\
r > r^* = 0.12 \mu m
\]
(dependent on solute)

“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

\[
\frac{dr}{dt} \approx \frac{1}{r} \frac{D e^\infty}{\rho L R_v T} (S - 1)
\]

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?

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

$$\frac{\partial q_l}{\partial t} = \begin{cases} c_0 (q_l - q_{l,\text{crit}}) & \text{if } q_l > q_{l,\text{crit}} \\ 0 & \text{otherwise} \end{cases}$$

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

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

• 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.
Parametrizing collection processes
“Accretion” of cloud drops by raindrops

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

Sundqvist (1978, 1989)

\[ G_p = c_0 F_1 q_l \left( 1 - e^{-\left( \frac{q_l}{q_{l_{\text{crit}}}} \right)^2} \right) \]

\[ F_1 = 1 + c_1 \sqrt{P} \]

Gp = autoconversion rate
P = precipitation rate

Khairoutdinov and Kogan (2000)

\[ G_{\text{aut}} = 1350 q_l^{2.47} N_c^{-1.79} \]

\[ G_{\text{acc}} = 67 q_l^{1.15} q_r^{1.15} \]

- Functional form is different
- More non-linear process
- Slower autoconversion initially, then faster
- With prognostic rain, have memory in qr
- 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):

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

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

- RH > 78% (Haze)
- CCN ~ 10 microns
- RH > 100.6%
- "Activation"
- Diffusional Growth
- Different fall speeds
- Coalescence
**Summary**

- Cloud important for its 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**
Reference books for cloud and precipitation microphysics:


