Numerical Weather Prediction
Parametrization of Subgrid Physical Processes

Clouds (1)

Cloud Microphysics

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Where is the water?

- 97% Ocean
- 2% Ice Caps
- ~1% Lakes/Rivers
- 0.001% Atmosphere
  (13000 km³, 2.5cm depth)
- 0.00001% Clouds

Global precipitation
- 500000 km³ per year
- ≈ 1 m/year
- ≈ 3 mm/day
“Clouds” Lectures

• LECTURE 1: Cloud Microphysics

• LECTURE 2: Cloud Cover in GCMs

• LECTURE 3: The ECMWF Cloud Scheme

• LECTURE 4: Validation of Cloud Schemes
• LECTURE 1: Cloud Microphysics

1. Basic concepts of cloud parametrization design

2. Microphysical processes in the atmosphere
   2.1 Warm phase
   2.2 Cold phase/mixed phase

3. Summary
1. Overview of GCM Cloud Parametrization Issues
The Importance of Clouds

1. Water Cycle
2. Radiative Impacts
3. Dynamical Impacts
Clouds in GCMs - What are the problems?

Convection

Radiation

Microphysics

Dynamics

Turbulence

Clouds are the result of complex interactions between a large number of processes.
Clouds in GCMs - What are the problems?

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

Cloud fraction and overlap

Cloud top and base height

Amount of condensate

Cloud-radiation interaction

In-cloud condensate distribution

Cloud environment

Phase of condensate

Cloud particle shape

Cloud particle size

Cloud macrophysics

Cloud microphysics

“External” influence
Cloud Parametrization Issues:

- Microphysical processes
- Macro-physical
  - subgrid heterogeneity
- Numerical issues

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

Complexity

Cloud Mass

Ice Mass

Liquid Mass

Ice mass

Ice number

Small ice

Medium ice

Large ice

“Single Moment” Schemes

“Double Moment” Schemes

“Spectral/Bin” Microphysics

Many GCMs only have single-moment schemes
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**
Evaporation
Condensation

VAPOUR
(prognostic)

Evaporation

CLOUD
(prognostic)

Autoconversion

RAIN
(diagnostic)

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

Current ECMWF scheme

Cloud resolving models may add graupel/hail 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 \( T > 0^\circ \text{C} \)
(2) Mixed Phase Microphysics \(-38^\circ \text{C} < T < 0^\circ \text{C}\)
(3) Pure ice Microphysics \( T < -38^\circ \text{C} \)
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

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.

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

\[\sigma = \text{Surface tension of droplet}\]

\[r = \text{drop radius}\]

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 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).

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

$R_c = \text{Critical Radius}$
$\sigma = \text{Surface tension of droplet}$
$e/e_s = \text{Supersaturation}$
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) at very small supersaturations.
**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 $e_{solute} < e_v$)

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

“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
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 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.

- Note that this assumption means that models can just use one “prognostic” equation for the total water mass, i.e. the sum of vapour and liquid.

- Usually, the growth equation is not explicitly solved, and 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)

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

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

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

- 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.

$$\frac{\partial q_r}{\partial t} = c_0 q_l^{2.47} N_c^{-1.79}$$
Schematic of Warm Rain Processes

Coalescence
2. Microphysical Processes
2.2 Cold Phase
“The Six-Cornered Snowflake”
Ice Microphysical Processes

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

- Droplets do not freeze at 0°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 water droplets occurs **below about -38°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°C!
• Ice nucleation processes can 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°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

I will not discuss heterogeneous ice nucleation in great detail in this course due to lack of time and the fact that these processes are only starting to be tackled in large-scale models. For example, see recent work of Ulrike Lohmann for more details.

Schematic of heterogeneous ice nucleation mechanisms (from Rogers and Yau, 1996)
Ice Nucleation:
Observed supercooled liquid water occurrence

**Observations:**
- Colder than -38°C, no supercooled liquid water.
- Supercooled liquid water increasingly common as approach 0°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°C rarely have ice.

(Hogan et al., GRL, 2004)
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

\[ \frac{\partial m}{\partial t} = \frac{4\pi sCF}{\left(\frac{L_s}{RT} - 1\right)} \frac{L_s}{k\alpha T} + \frac{RT}{\chi e_{si}} \propto s \cdot C \cdot F \]

• 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
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 subsaturated with respect to water can be supersaturated with respect to ice.
Diffusional growth of ice crystals
Mixed phase cloud Bergeron process (II)

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

Ice particles grow at the expense of water droplets
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

Model

Westbrook et al. (2008)
• Some schemes represent ice processes very simply, removing ice super-saturation (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). See Lohmann and Karcher JGR 2002(a,b) for another example of including ice microphysics in a GCM.
Collection processes: Rimming – capture of water drops by ice

- **Graupel**: formed by collecting liquid water drops in mixed phased clouds ("riming"), particularly 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)
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, but this split is rather artificial.

Degree of riming can be light or heavy.

Alternative approach:
- Morrison and Grabowski (2008) have three ice prognostics: ice number concentration, mixing ratio from deposition, mixing ratio from riming.
- 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 -5°C. Leads to increased numbers of smaller crystals.

- **Sedimentation** due to gravity. Fall speed depends on particle size (and habit/density for ice).
Falling Precipitation

Ice
Snow
Melting layer
Rain

Chilbolton 3.075 GHz radar 20 Oct 2000 10:42:51 RHI 6475/027/01 Azim 259.0°

Radar reflectivity factor (dBZ)

0 10 20 30 40
-30 -20 -10 0 10 20 30 40

Distance (km)

Height (km)

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!
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
Reference books for cloud and precipitation microphysics:


