Microphysics Parameterization

Bob Plant

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Outline

- Overview of microphysics representations
- Particle size distributions
- Basic equation structure
- Processes associated with collisions
- Some convective-scale examples
- Some example developments: the UM
Overview of microphysics representations
Parameterization processes

Basic types of processes to be parameterized

1. Processes that contribute to the subgrid fluxes such as $w'\theta'$
   eg, boundary layer turbulence (this afternoon); convection (tomorrow)

2. Processes that contribute to the forcing on the RHS of the basic atmospheric equations, even without filtering
   eg, radiation; internal heating/cooling from microphysical processes (now)
Bin and bulk

- Spectral (bin) microphysics aim to calculate microphysics as accurately and generally as possible.
- Divide microphysical particles into bins for different sizes, and compute evolution of each bin separately.
- The particle size distribution (PSD) is an output not an input.
- **Much** too expensive for operational use.
- Bulk schemes calculate with a semi-empirical PSD.
For PSDs $f(m)$ with $m$ being the particle mass, the $k$th moment is

$$M^{(k)} = \int_0^{\infty} m^k f(m) dm$$

1. One-moment schemes $k = 1$, mass
2. Two moments, $k = 0, 1$ number concentration and mass
3. Three moments, $k = 0, 1, 2$ number concentration, mass and radar reflectivity
Hybrid schemes

- Aim for accuracy of bin schemes with efficiency of bulk schemes
- e.g. Onishi and Takahashi (2011) use bin for warm processes and bulk for ice
- This is still too expensive for practical NWP
- Bin-emulating schemes: calculate rates offline with complex bin scheme and develop lookup tables (more practical)
High resolutions

- GCMs and traditional NWP have separate treatments of “cloud” and “convection”
- Microphysics within stratiform cloud handled with various bulk microphysics methods discussed here
- Convection schemes have highly simplified microphysics (for reasons to be explained!)
- As NWP reaches convection-resolving scales, the microphysics of convection should become much more realistic
- But achieving this poses challenges to the scope of existing “cloud” microphysics designed to work well for stratiform cloud
Particle size distributions
PSDs can be accurately calculated in a bin model (solid) compared to observations (dashed)

Example capturing the change in PSD with height in developing convection (S=smoky)
The PSDs

Most bulk schemes use a Gamma distribution

\[ f(m) = N_0 m^\nu \exp(-\lambda m^\mu) \]

where \( N_0 \) is the intercept, \( \nu \) is the shape parameter, \( \lambda \) is the slope or scale parameter and \( \mu \) is the dispersion parameter

- \( \nu (\mu) \) controls the shape at small (large) \( m \)
- sometimes an effective radius \( r \) or diameter \( D \) is used
Some Gamma distributions

\[ \nu = 1, \mu = 1/3 \] (left) and \( \nu = 6, \mu = 1 \) (right)
Modelling the PSD

- Choice of PSD is connected with choice of hydrometeor types
- All bulk schemes separate cloud droplets with $r \approx 10–15\mu m$ and raindrops with $r \approx 1–4mm$
- Often use Gamma for cloud drops and exponential for raindrops
- Over large distances and many clouds, PSD for precipitating particles often taken to have $v = 0$, Marshall-Palmer
Use of a Gamma Distribution

- To determine four parameters with scheme of 1, 2 or 3 moments, some have to be fixed or use empirical relations

- eg, scatter plots of obs fits showing \( N_0 \) and \( \lambda \) with a good best fit relationship over a limited range
Basic equation structure
PSD evolution

Bin-model equations for the PSD of the $i$ th hydrometeor type are:

$$
\frac{\partial}{\partial t} \rho f_i + \frac{\partial}{\partial x} \rho u f_i + \frac{\partial}{\partial y} \rho v f_i + \frac{\partial}{\partial z} \rho (w - v_t (m)) f_i = \sum_{\text{micro}} \left( \frac{\partial}{\partial t} \rho f_i \right)_{\text{proc}}
$$

where the sum is over various microphysical processes
Recall that we multiply by \( m^k \) and integrate over \( m \) to get \( k \) th moment...

\[
\frac{\partial}{\partial t} \rho M_i^{(k)} + \frac{\partial}{\partial x} \rho u M_i^{(k)} + \frac{\partial}{\partial y} \rho v M_i^{(k)} + \frac{\partial}{\partial z} \rho (w - \overline{v}_{t,i}^{(k)}) M_i^{(k)} = \sum_{\text{micro}} \left( \frac{\partial}{\partial t} M_i^{(k)} \right)_{\text{proc}}
\]

where

\[
\overline{v}_{t,i}^{(k)} = \frac{1}{M^{(k)}} \int_{0}^{\infty} m^k f(m) v_{t,i}(m) dm
\]

is the weighted-average fall velocity

- Note that it depends on \( k \) as well as \( i \)
Processes to account for:

- Droplet nucleation (condensation)
- Droplet growth by vapour diffusion
- Collisions between droplets and between different hydrometeors
- Sedimentation (differential motion)
- Freezing/melting
- Ice multiplication
- Raindrop breakup
- Effects of aerosol on all these
Processes to account for:

Example from scheme being developed by Zhang (2014)
A partial history of schemes

Note the increase in complexity, and reducing gap between bulk and bin methods...

- Kessler (1969): First warm rain bulk parameterization
- Lin et al. (1983): 1M, includes hail
- Cotton et al. (1986): First bin parameterization (RAMS)
- Murakami (1990): 1M, snow includes crystals and aggregates
- Verlinde et al. (1990): development of lookup tables
- Ferrier (1994): 2M for ice and precipitating species
- Cohard and Pinty (2000): 2M for warm microphysics
A partial history of schemes

- Saleeby and Cotton (2004): 2M bin-emulating bulk scheme. Fully interactive with prognostic CCN and IN aerosol schemes
- Milbrandt and Yau (2005): 3M scheme for hail
- Lim and Hong (2010) WRF 2M 6 classes; prognostic treatment of cloud condensation nuclei
# Types of hydrometeor

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Processes associated with collisions
Overview

- Much “large-scale” rain originates from melting ice
- This is straightforward to parameterize at the melting layer
- Much convective rain and some large-scale rain originates from collision and coalescence of cloud droplets
- More problematic...
Drop collisions

Collisions of liquid drops described by stochastic collection equation

\[
\frac{df(m)}{dt} = \int_0^{m/2} f(m') f(m - m') K(m - m', m') dm' \\
- \int_0^\infty f(m) f(m') K(m, m') dm'
\]

Collision kernel \( K \) has a gravitational/geometric part

\[
K_g(m_1, m_2) = \frac{\pi}{4} (D_1 + D_2)^2 E(m_1, m_2) |V_{t1} - V_{t2}|
\]

where \( E \) is the collection efficiency for a collision
More aspects of kernel

- In a turbulent flow, the kernel is found to increase with collisions more likely.
- Various attempts to account for turbulent effects, which can give a factor of up to 5–10 in deep convection for some pairs.
- Bin methods solve the collection equation directly for all pair combinations.
Collisions in bulk schemes

- **self collection (sc)**
  - droplet + droplet $\rightarrow$ droplet

- **self collection (sc)**
  - rain + rain $\rightarrow$ rain

- **autoconversion (au)**
  - droplet + droplet $\rightarrow$ rain

- **accretion (ac)**
  - droplet + rain $\rightarrow$ rain
Autoconversion

- Kessler formula has been widely used
  \[
  \left( \frac{\partial M^{(1)}}{\partial t} \right)_{au} = \frac{\partial q_r}{\partial t} = \begin{cases} 
  k(q_c - q_{cr}) & \text{if } q_c > q_{cr} \\ 
  0 & \text{otherwise}
  \end{cases}
  \]

- and many variants, but this is fully empirical and no connection to solution of SCE

- However, rain production does depend strongly on droplet PSD even for given \( q_c \)
SCE approaches to autoconversion

Based on analysis of results of SCE calculations

- Berry and Reinhardt (1974): first attempt, limited number of solutions, with prescribed PSDs. Considered autoconversion and accretion together
- Saleeby and Cotton (2004): many more PSDs considered, lookup tables
- Seifert et al. (2010): $\sim 10,000$ SCE simulations including effects of turbulence on collision kernel
Autoconversion vs $q_c$

- Sensitive to tail of PSD distribution: ultra-giant CCN
- Very large spread across different bulk parametrizations
Droplet-ice collisions

Such collisions in mixed-phase clouds important for formation and growth of snow, graupel and hail. Hence for precipitation.

Bin schemes: extend SCE to collisions between hydrometeors of different type. Usually $K$ taken to be as for collisions of two spheres.

Bulk scheme, examples:
- $X + Y \rightarrow Z$, snow + rain $\rightarrow$ graupel
- $X + Y \rightarrow X$ graupel + drops $\rightarrow$ graupel growth (riming)
The generalized SCE

For \( X + Y \rightarrow Z \), equations for moments are

\[
\left( \frac{\partial M_X^{(k)}}{\partial t} \right)_{X+Y\rightarrow Z} = - \int_0^\infty \int_0^\infty K_{XY} f_X(m_X) f_Y(m_Y) m_X^k \, dm_X \, dm_Y
\]

Kernel normally extracted from integrand and replaced by a weighted-average difference of fall velocities \( |\Delta V_{XY}| \)

Different bulk schemes use many different formulae to estimate this

It is often assumed that the fall velocity of the collector particle \( \gg \) than that of the collected particles
Self-collection

- \( X + X \rightarrow X \) (eg, growth of snowflakes) is a particular problem for bulk schemes.

- In reality, self-collection does occur due to fall speed differences between particles of different sizes but same type.

- But the averaged fall velocity speed \( |\Delta V_{XX}| \) is zero!

- In truth, this is not a part of the kernel that can be properly removed from the integrand.

- In practice, the same formulation is used, including a pre-factor for \( |\Delta V_{XX}| \), but much variability of results according to the expression used.
Sedimentation

- Modification of PSD at different heights because of differences in fall speed with particle mass
- Straightforward and handled automatically in bin approach
- Recall that bulk schemes work with effective fall speeds averaged over mass distribution
- Needs 2 or 3 moment scheme to try to account for change of PSD shape in anything other than ad hoc way
- Bin emulating approaches for single moments are not sufficient
- But bin emulating approach with 2 or 3 moments can give reasonable results (Morrison 2012)
Some convective-scale examples
Some MM5 simulations

Intercomparison of 1M schemes with convection-resolving resolution

All produced too-strong rain within a narrow line of cumulus

Blamed on problems capturing precipitation sedimentation

Average rain rates in large convective system over Florida, 1M schemes.

(Lynn et al 2005)
Squall line

An example considered in a few papers inc. Khain et al. (2004); Phillips et al. (2007)

Bin scheme much larger trailing stratiform area and much larger contribution from light rain
Same case: 1 and 2 moments
Same case: 1 and 2 moments

- Two-moment scheme better captures trailing stratiform precipitation
- Main difference caused by lower rain evaporation rate in the stratiform region in 2M scheme
- Due to differences in the shape of the rain drop distribution
- The 1M scheme did not have enough freedom to vary the PSD to get this right

⇒

- spatial precipitation distribution can depend dramatically on the calculation of parameters determining the shape of PSDs
Some remarks on hail

- 1M scheme has effectively no opinion on hail sizes
- 2M schemes have difficulties with large hail in the tail of the PSD
- eg, Milbrandt and Yau, 2006: 2M is sufficient to capture rain amounts and spatial distribution but 3M needed to simulate hail formation of several cm
Remarks on aerosol

- Aerosol effects remain a major uncertainty in large-scale and climate models despite many efforts.
- Aerosol-cloud effects are dependent on the relative importance of autoconversion (depends on droplet/aerosol concentration).
- But as we have seen this is not handled well by existing GCM methods.
- Needs at least 2M and should account for aerosol advection and aerosol scavenging (due to drop activation).
- For convection, many studies of effects on a single cloud.
- But very few on effects on field of clouds.
Some example developments: the UM
UM microphysics

- Single moment, bulk scheme using mass mixing ratios for vapour, cloud liquid and cloud ice/snow
- PSD and fall speeds diagnosed each time step
- Basic reference is Wilson and Ballard (1999) with various modifications since
  - Recent changes: ice and liquid PSDs, ice fall speed, improved drizzle and fog package, working on autoconversion
- Prognostic rain variable introduced with UKV (1.5km)
- Prognostic graupel scheme new in January 2013
Changes to ice PSD (and consistency with that assumed in radiation package) have allowed more realistic ice fall speeds

- Solid=snow, dashed=ice
- Purple: global model
- Green: proposed new UKV suite
Future UM developments

- New bulk scheme under development
- Initially for high-resolution (km-scale) forecasting
- Species represented are: cloud droplets, rain, ice, snow and graupel
- Options for up to 3 moments to be selected
- New scheme will be common to the UM and the Met Office CRM/LES
Conclusions

- Microphysics processes are complex but can be modelled very effectively with a bin approach.
- A research tool only: much too expensive for use in NWP.
- Practical schemes use assumed PSDs and explicitly consider 1, 2 or 3 moments of several microphysical species.
- This is problematic for particle-collision processes and issues related to fallspeed variations.
- Need to rethink schemes as resolution increases and convective clouds no longer parameterized.