Microphysics Parameterization

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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 $\overline{w'\theta'}$
   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

Microphysical moments

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)

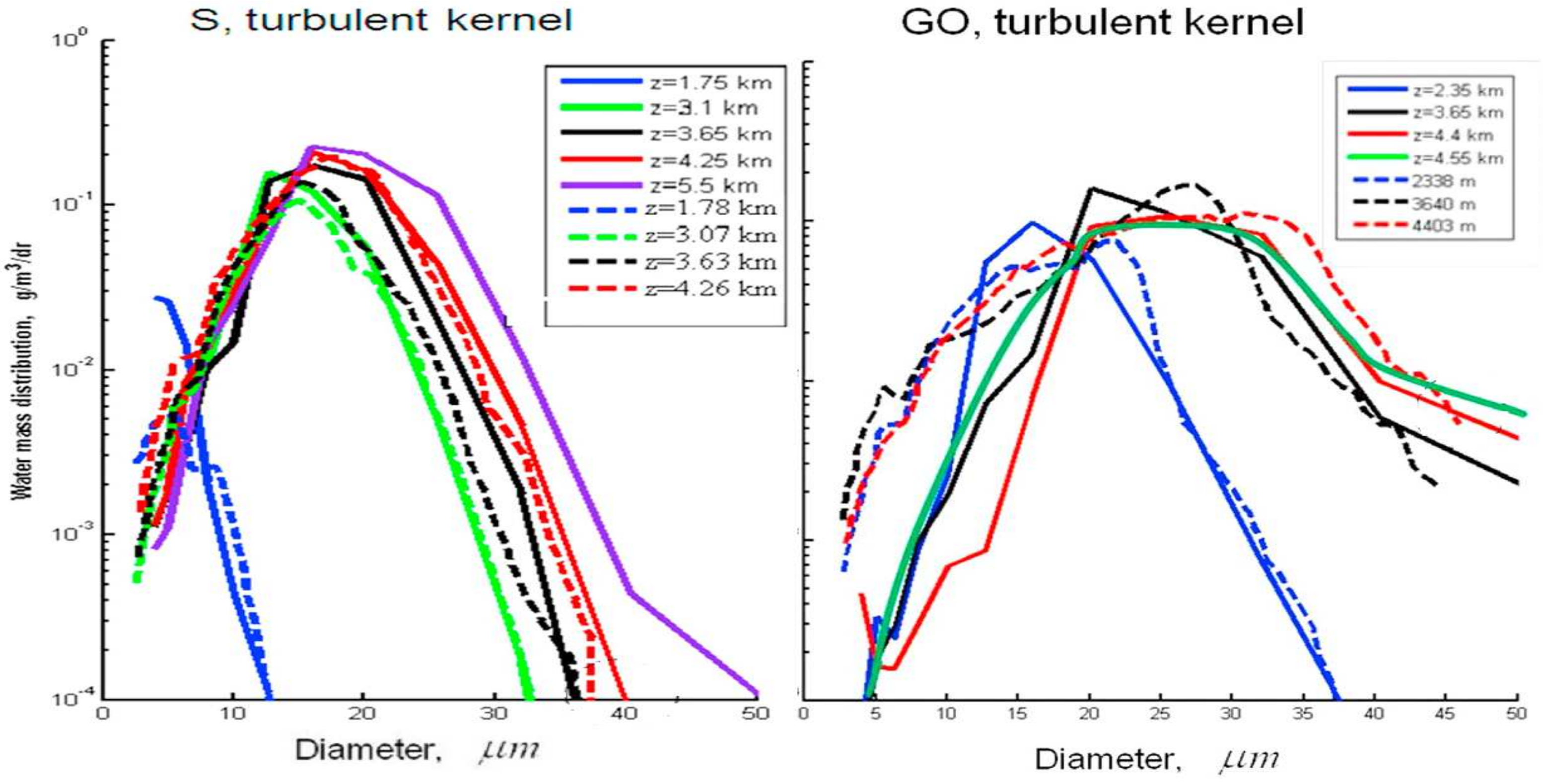
High resolutions

- 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

PSD

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

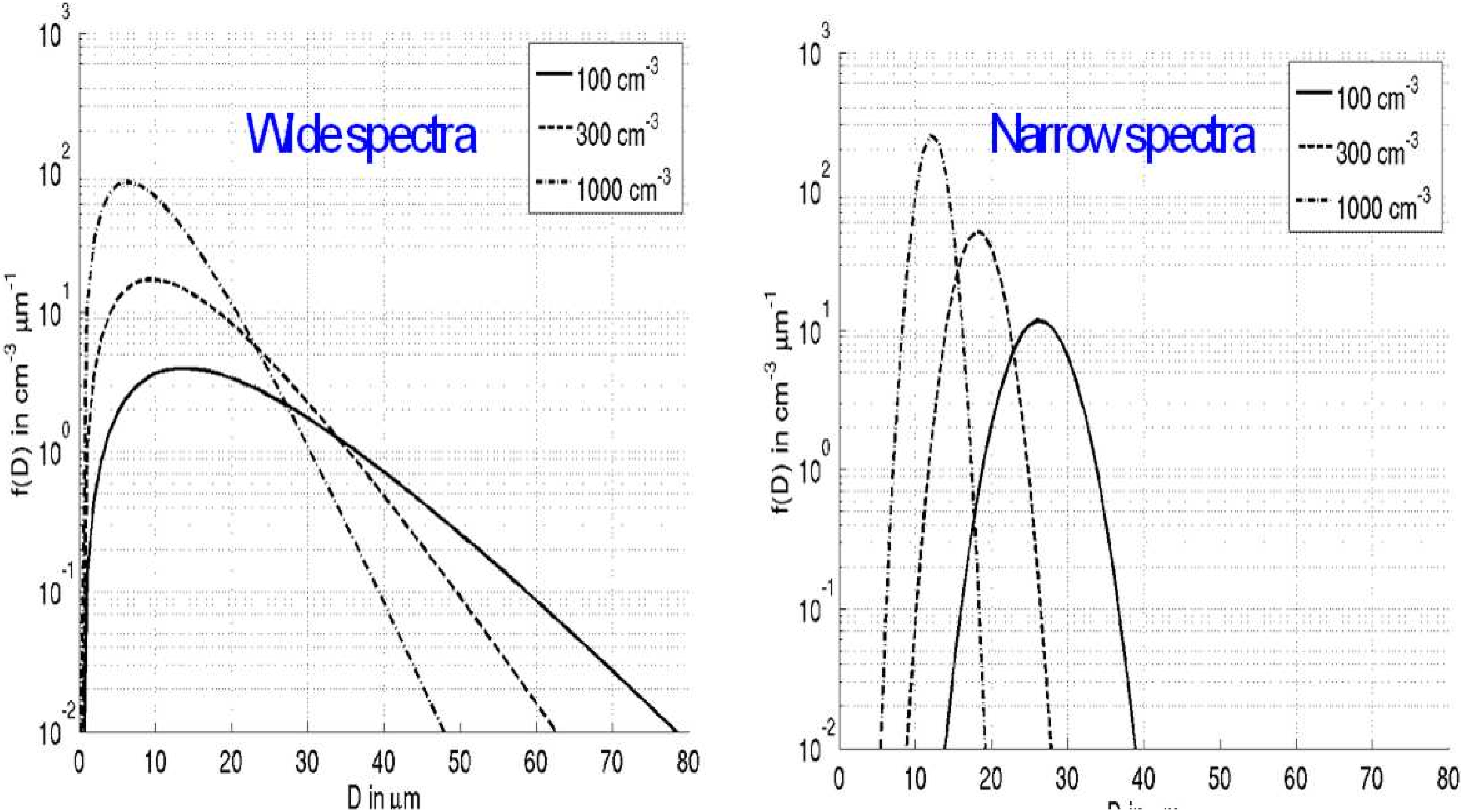
Most bulk schemes use a Gamma distribution

$$f(m) = N_0 m^{\nu} \exp(-\lambda m^{\mu})$$

where N_0 is the intercept, ν is the shape parameter, λ is the slope or scale parameter and μ is the dispersion parameter

- ν (μ) controls the shape at small (large) m
- sometimes an effective radius r or diameter D is used

Some Gamma distributions

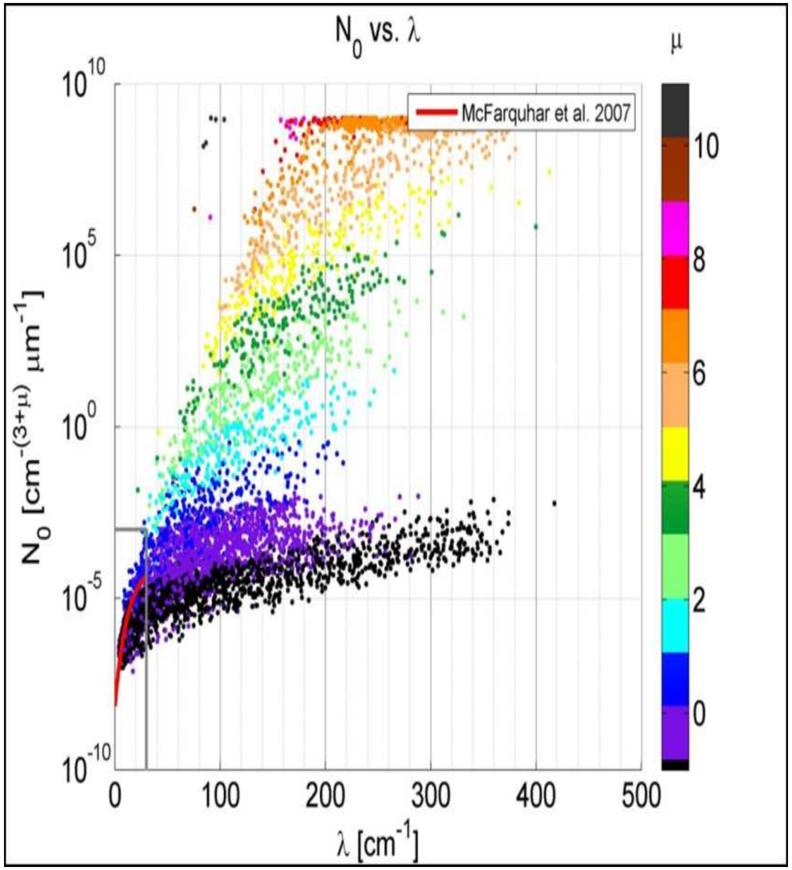


$\nu = 1, \mu = 1/3$ (left) and $\nu = 6, \mu = 1$ (right)

Modelling the PSD

- Choice of PSD is connected with choice of hydrometeor types
- All bulk schemes separate cloud droplets with $r \approx$ 10–15μm 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 $\nu = 0$, 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 λ 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

Moment evolution

Recall that we multiply by m^k and integrate over m to get k th moment...

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

where

$$\overline{v}_{t,i}^{(k)} = \frac{1}{M^{(k)}} \int_0^\infty m^k f(m) v_{t,i}(m)\, dm$$

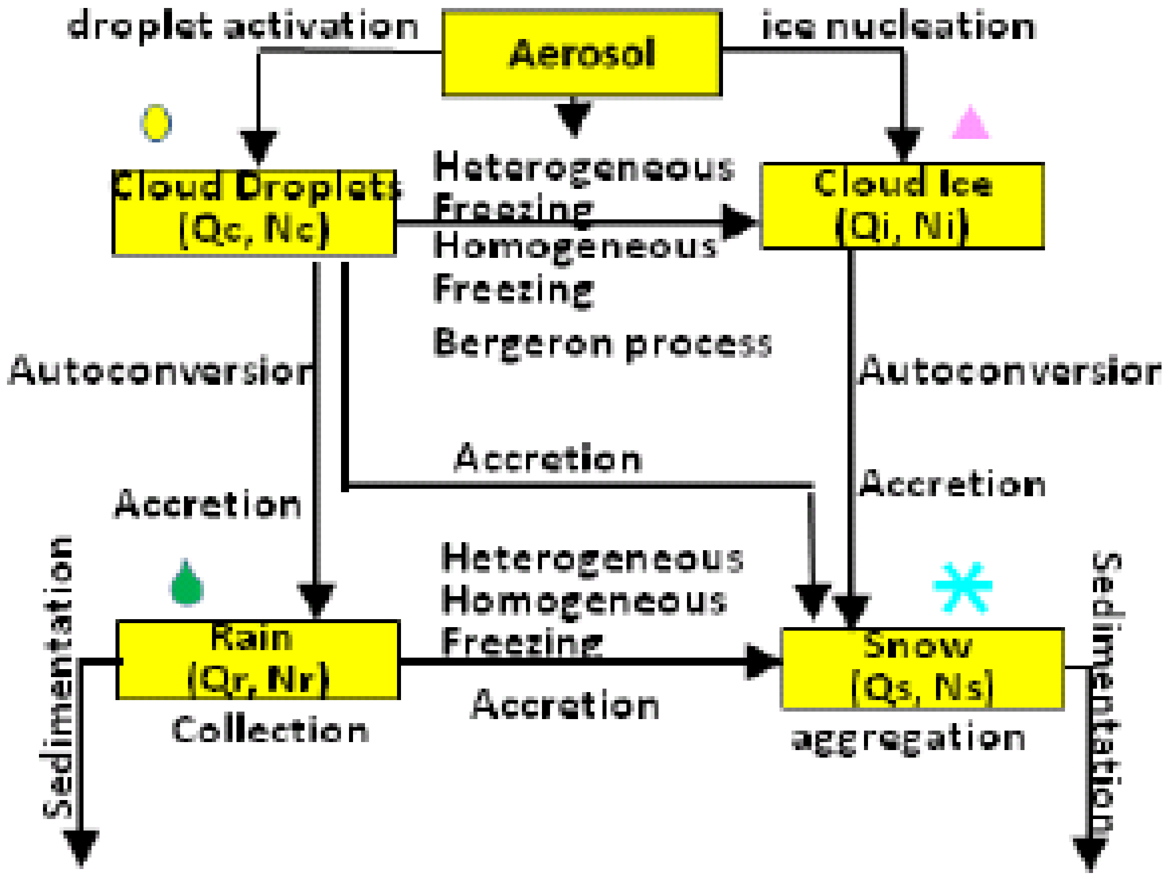
is the weighted-average fall velocity

- 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
- Morrison et al (2005): 2M scheme for droplets, cloud ice, rain, and snow.
- 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

	cloud	driz.	rain	ice	aggr.	snow	graup.	hail
Kessler 69	X		X					
Lin 83	X		X	X		X		X
Murakami 90	X		X	X		X	X	
Ferrier 94	X		X	XX		XX	XX	XX
Cohard 00	XX		XX					
Saleeby 04	XX	XX	XX	XX	XX	XX	XX	XX
Morrison 05	XX		XX	XX	XX	XX		
Milbrandt 05	XXX		XXX	XXX		XXX	XXX	XXX
Lim 10	XX		XX	X	X	X		

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

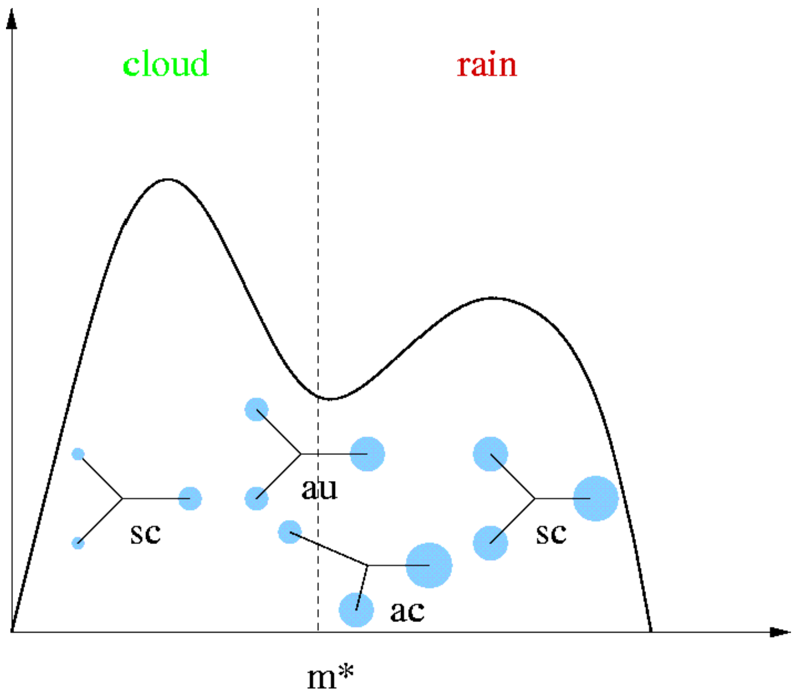
$$K_g(m_1,m_2) = \frac{\pi}{4}(D_1+D_2)^2E(m_1,m_2)|V_{t1}-V_{t2}|$$

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 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 $\longrightarrow$ droplet
- self collection (sc)
  rain + rain $\longrightarrow$ rain
- autoconversion (au)
  droplet + droplet $\longrightarrow$ rain
- accretion (ac)
  droplet + rain $\longrightarrow$ rain

Autoconversion

- Kessler formula has been widely used

$$\left(\frac{\partial M^{(1)}}{\partial t}\right)_{\mathrm{au}} = \frac{\partial q_r}{\partial t} = \begin{cases} k(q_c - q_{cr}) & \text{if } q_c > q_{cr} \\ 0 & \text{otherwise} \end{cases}$$

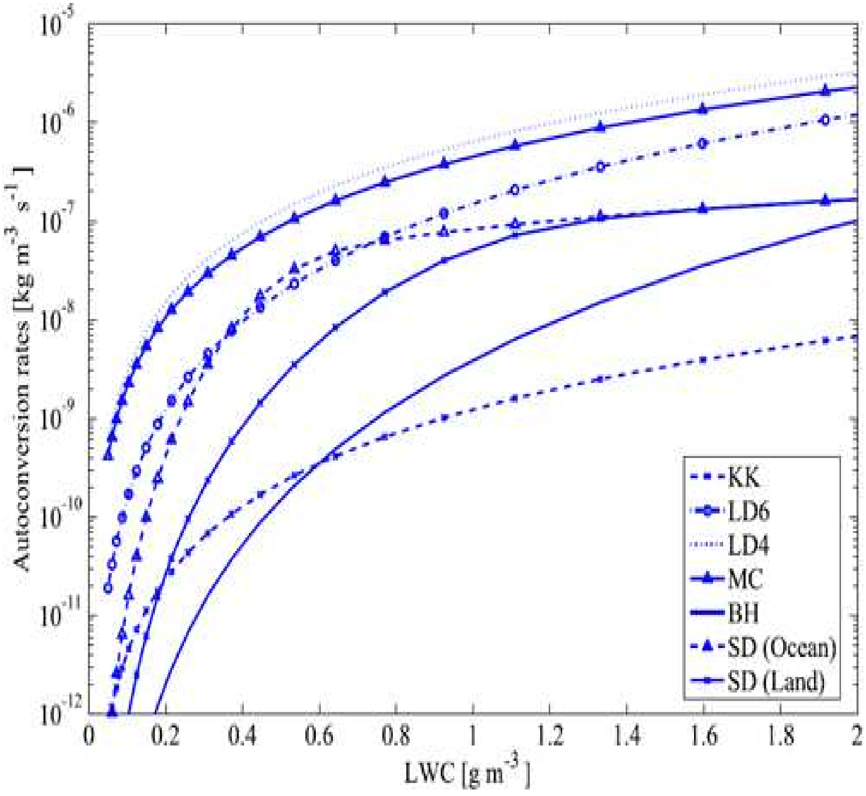
- and many variants, but this is fully empirical and no connection to solution of SCE
- However, rain production does depend strongly on droplet PSD even for given q_c

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 acretion 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:
  - $X + Y \longrightarrow Z$, snow + rain $\rightarrow$ graupel
  - $X + Y \longrightarrow X$ 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 $|\overline{\Delta V_{XY}}|$
- 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

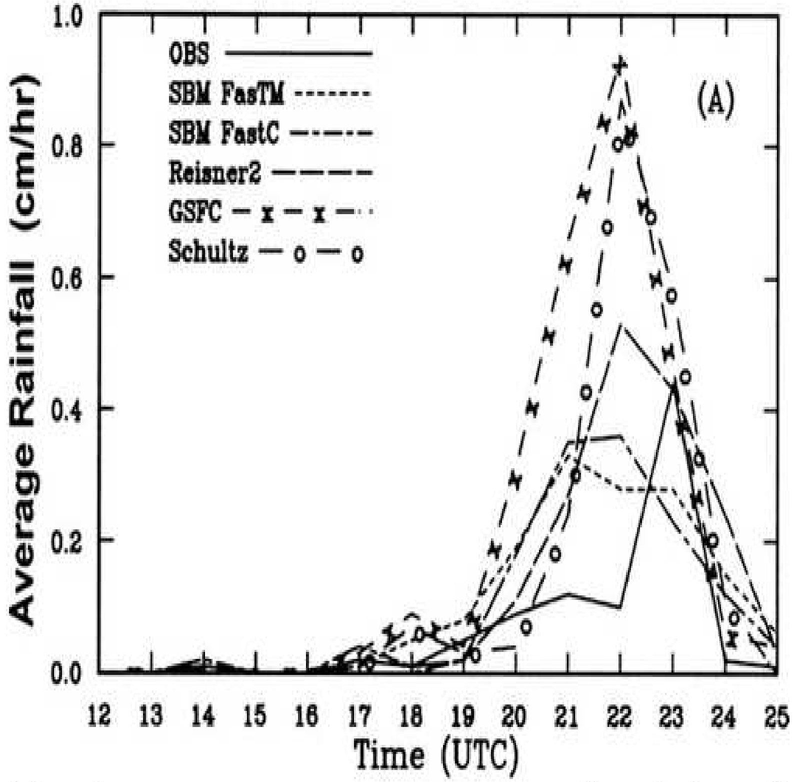
- $X + X \rightarrow X$ (eg, growth of snowflakes) is a particular problems for bulk schemes
- In reality self-collection does occur due to fall speed differences between particles of different sizes but same type
- But the averaged fall velocity speed $|\overline{\Delta V_{XX}}|$ is zero!
- In truth, 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 $|\overline{\Delta V_{XX}}|$, 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

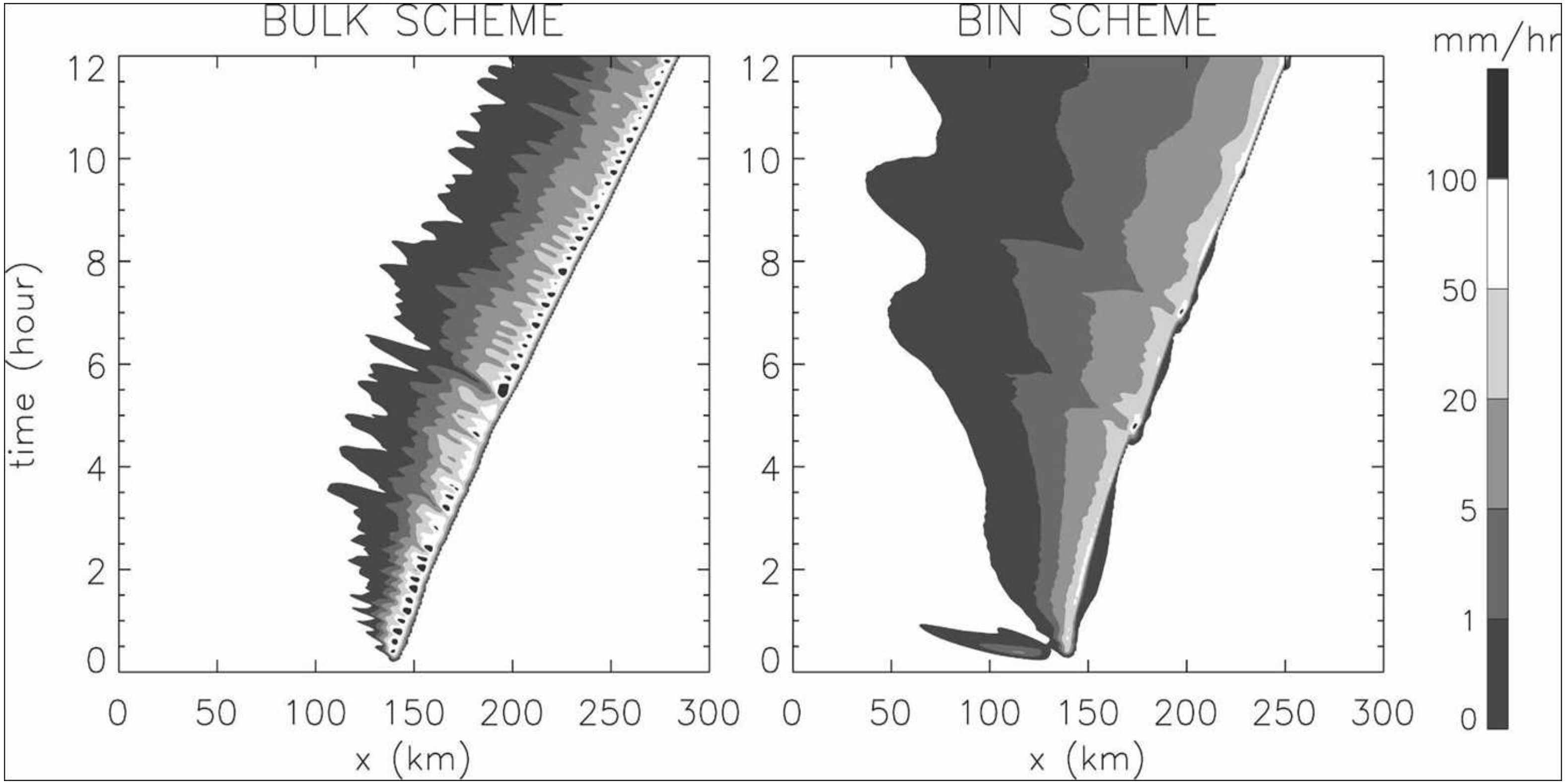


Average rain rates in large convective system over Florida, 1M schemes.
(Lynn et al 2005)

- 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

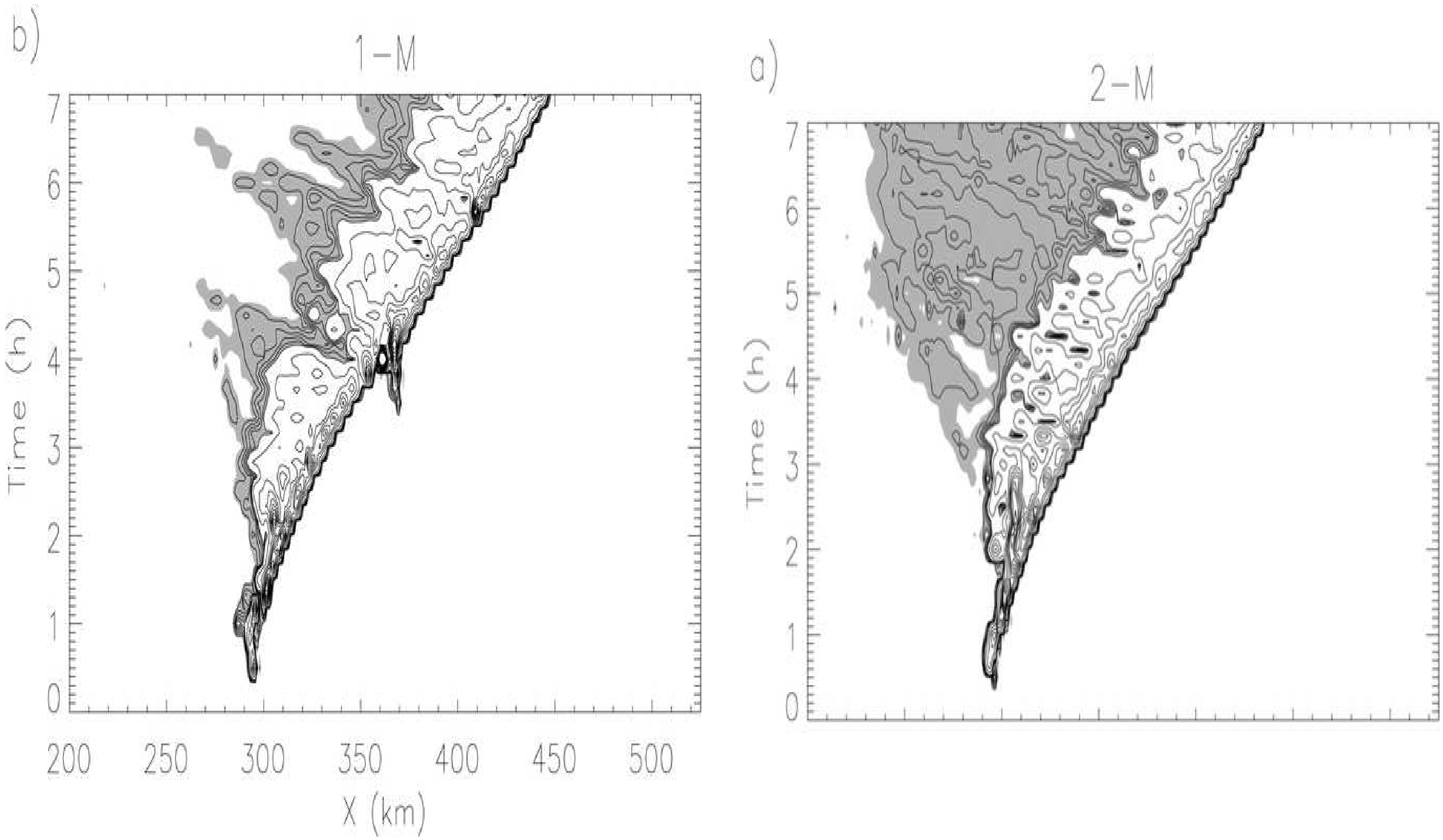
Squall line

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

  $\Longrightarrow$
- 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

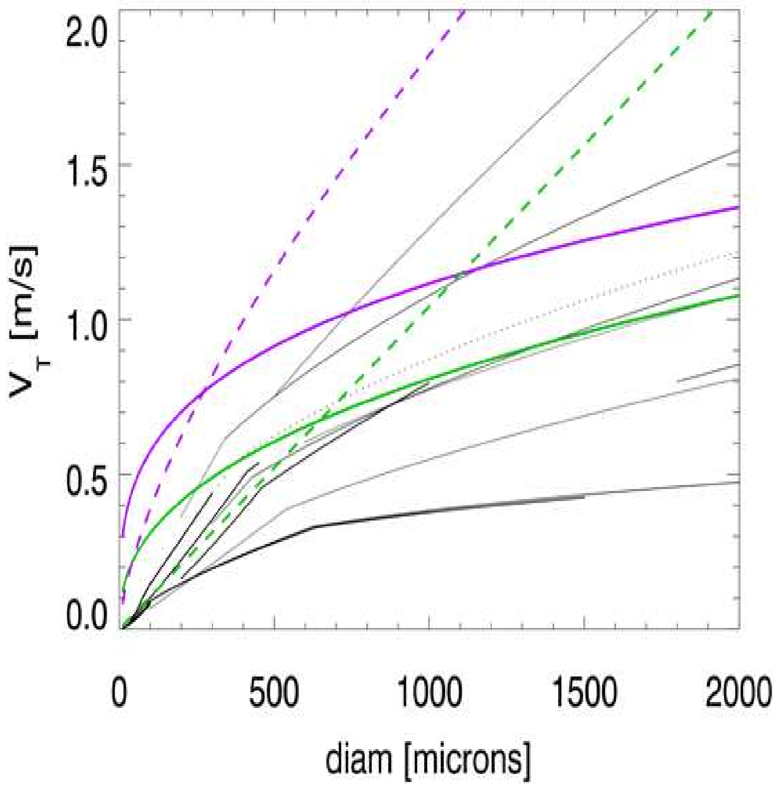
- Aerosol effects remain a major uncertainty in large-scale and climate models despite many efforts
- Aerosol-cloud effects are dependent on the relative importance of autoconversion (depends on droplet/aerosol concentration)
- But as we have seen this is not handled well by existing GCM methods
- Needs 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

Fallspeed parameterization



- Changes to ice PSD (and consistency with that assumed in radiation package) have allowed more realistic ice fall speeds
- Solid=snow, dashed=ice
- Black: data from Mitchell (1996)
- 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