The Representation of Cloud Microphysical Processes in NWP Models

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ECMWF, 1-4 September 2015
Role of Clouds in NATURE

• radiative forcing
• thermodynamical feedback
• redistribution of atmospheric moisture
• precipitation
• etc.
Representation of Clouds in MODELS

Treated by a combination of different physical parameterizations:

1. Grid-scale condensation (microphysics) scheme

2. Subgrid-scale schemes
   • cloud fraction
   • deep convection
   • shallow convection
   • boundary layer

3. Radiative transfer scheme
   • computes radiative fluxes SW/LW
Representation of Clouds in MODELS

Cloud Microphysics Scheme

*Three main roles:*

1. optical properties (for radiation scheme)
2. thermodynamic feedbacks (latent heating/cooling; mass loading)
3. precipitation (rates and types at surface)
Cloud Microphysical Processes

BAMS, 1967
Microphysics Parameterization Schemes

Hydrometeors are traditionally partitioned into categories:

- **Clouds**
  - Cold-based Continental Clouds
  - Deposition nucleation of the liquid phase—vapor deposition
  - Narrow cloud spectra
  - Slow broadening by coalescence aided by turbulence

- **Ice**
  - Ice deposition nucleation
  - Broad cloud droplet spectra
  - Sorption nucleation
  - Heterogeneous freezing (immersion/contact)
  - Secondary ice particles

- **Snow**
  - Frozen drops
  - Ice Pellets
  - Vapour deposition
  - Martinning
  - Continued coalescence

- **Graupel**
  - Pristine ice crystals
  - Coalescence
  - Continued coalescence

- **Rain**
  - Drizzle
  - Warm Rain
  - Sleet

- **Hail**
  - Snow Pellets
  - Hail
  - Snow Grains

BAMS, 1967
Microphysics Parameterization Schemes
The particle size distributions are modeled

For each category, microphysical processes are parameterized in order to predict the evolution of the particle size distribution, $N(D)$

**TYPES of SCHEMES:**

**Bin-resolving:**
(spectral) $N(D) = \sum_{i=1}^{I} N_i$

**Bulk:**
$N(D) = N_0 D^\alpha e^{-\lambda D}$
Approaches to parameterize cloud microphysics

**ULTIMATE GOAL:** Predict evolution of hydrometeor size distributions

![Diagram](image)

**Note:** microphysics schemes assume grid-scale homogeneity

**Bin-resolving:** (spectral)

\[ N(D) = \sum_{i=1}^{I} N_i \]

**Bulk:**

\[ N(D) = N_0 D^\alpha e^{-\lambda D} \]
**BULK METHOD**

---

**Size Distribution Function:**

\[ N_x(D) = N_{0x} D^{\alpha_x} e^{-\lambda_x D} \]

---

**3rd, 0th, 6th MOMENTS:**

- **Mass mixing ratio, \( q_x \)**
  \[ q_x \equiv \frac{\pi \rho_x}{6 \rho} \int_0^\infty D^3 N_x(D) dD = \frac{\pi \rho_x}{6 \rho} M_x(3) \]

- **Total number concentration, \( N_{T_x} \)**
  \[ N_{T_x} = \int_0^\infty N_x(D) dD = M_x(0) \]

- **Radar reflectivity factor, \( Z_x \)**
  \[ Z_x \equiv \int_0^\infty D^6 N_x(D) dD = M_x(6) \]
  (assuming spheres)

**\( p \)th moment:**

\[ M_x(p) \equiv \int_0^\infty D^p N_x(D) dD = N_{0x} \frac{\Gamma(1+\alpha_x+p)}{\lambda_x^{p+1+\alpha_x}} \]
BULK METHOD

Predict changes to specific moment(s)
  e.g. $q_x$, $N_{Tx}$, ...

Implies changes to values of parameters
  i.e. $N_{0x}$, $\lambda_x$, ...

$3^{rd}$, $0^{th}$, $6^{th}$ MOMENTS:

Mass mixing ratio, $q_x$

$$q_x \equiv \frac{\pi \rho_x}{6 \rho} \int_0^{\infty} D^3 N_x(D) dD = \frac{\pi \rho_x}{6 \rho} M_x(3)$$

Total number concentration, $N_{Tx}$

$$N_{Tx} \equiv \int_0^{\infty} N_x(D) dD = M_x(0)$$

Radar reflectivity factor, $Z_x$

$$Z_x \equiv \int_0^{\infty} D^6 N_x(D) dD = M_x(6)$$

Size Distribution Function:

$$N_x(D) = N_{0x} D^{\alpha_x} e^{-\lambda_x D}$$

$p^{th}$ moment:

$$M_x(p) \equiv \int_0^{\infty} D^p N_x(D) dD = N_{0x} \frac{\Gamma(1 + \alpha_x + p)}{\lambda_x^{p+1+\alpha_x}}$$
Traditional Approach:
PARTITIONING HYDROMETEORS INTO CATEGORIES

**BULK METHOD**

- **CLOUD**
  \[ N_c(D) = N_{0c} D^{\alpha_c} e^{-\lambda_c D} \]

- **ICE**
  \[ N_i(D) = N_{0i} D^{\alpha_i} e^{-\lambda_i D} \]

- **SNOW**
  \[ N_s(D) = N_{0s} D^{\alpha_s} e^{-\lambda_s D} \]

- **RAIN**
  \[ N_r(D) = N_{0r} D^{\alpha_r} e^{-\lambda_r D} \]

- **GRAUPEL**
  \[ N_g(D) = N_{0g} D^{\alpha_g} e^{-\lambda_g D} \]

- **HAIL**
  \[ N_h(D) = N_{0h} D^{\alpha_h} e^{-\lambda_h D} \]
Advantages of 2-moment:
More flexible representation of size distributions
→ Better calculation of process rates
→ Better representation of sedimentation
(can represent the effects of gravitational size sorting)

Advantages of 3-moment:
Independent representation of spectral dispersion – even better representation of size distributions
→ Better process rates
→ Controls excessive size sorting inherent in 2-moment schemes
The warm-rain coalescence process

Mass Density [g m\(^{-3}\) (lnr\(^{-1}\)]

Radius [cm]

Partitioning of Coalescence Processes:
- Autoconversion (cloud to rain)
- Accretion (rain collecting cloud)
- Self-collection (rain collecting rain) → multi-moment only

Bin-resolving coalescence model
SOURCE: Berry and Reinhardt (1974)
The warm-rain coalescence process

Stochastic collection equation:

\[ Q_{CL_{xy}} = \frac{1}{\rho} \pi \frac{4}{4} \int_0^\infty \int_0^\infty [V_x (D_x) - V_y (D_y)]^2 \left[ m_y (D_y) E(x, y) N_y (D_y) N_x (D_x) \right] dD_y dD_x \]

\[ N_{y CL_{xy}} = -\frac{\pi}{4} \int_0^\infty \int_0^\infty [V_x (D_x) - V_y (D_y)]^2 E(x, y) N_y (D_y) N_x (D_x) dD_y dD_x \]

Using the Long (1974) collection kernel and complete gamma functions, these can be solved analytically:

\[ Q_{CL_{xy}} = \frac{c_v \pi}{\rho} E_{xy} \Delta \overline{V} \frac{N_{T_x} N_{T_y}}{\Gamma(1 + \alpha_x) \Gamma(1 + \alpha_y)} \left[ \frac{\Gamma(3 + \alpha_x) \Gamma(4 + \alpha_y)}{x^2 \lambda_y} \frac{2 \Gamma(2 + \alpha_x) \Gamma(5 + \alpha_y)}{\lambda_x \lambda_y^4} \frac{\Gamma(1 + \alpha_x) \Gamma(6 + \alpha_y)}{\lambda_x^4} \right] \]

\[ N_{CL_{xy}} = \frac{\pi}{4} E_{xy} \Delta \overline{V} \frac{N_{T_x} N_{T_y}}{\Gamma(1 + \alpha_x) \Gamma(1 + \alpha_y)} \left[ \frac{\Gamma(3 + \alpha_x) \Gamma(1 + \alpha_y)}{x^2} \frac{2 \Gamma(2 + \alpha_x) \Gamma(2 + \alpha_y)}{\lambda_x \lambda_y^2} \right] \frac{\Gamma(1 + \alpha_x) \Gamma(3 + \alpha_y)}{\lambda_x^2} \]

Thus:

\[ \frac{dq_c}{dt} = -Q_{CN_{cr}} - Q_{CL_{cr}} \]

\[ \frac{dN_c}{dt} = -N_{CN_{cr}} - N_{CL_{cr}} \]

\[ \frac{dq_r}{dt} = Q_{CN_{cr}} + N_{CL_{cr}} \]

\[ \frac{dN_r}{dt} = N_{CN_{cr}} - N_{CL_{rr}} \]

Autoconversion is based on an empirical formulation of a bin model solution (Berry and Reinhardt, 1974)
Figure 1. Representative distributions of (a) liquid-water mass and (b) number concentration, resulting from the discrete bin integration of Eq. (13) (solid lines) and resulting from the parametrization set out in section 3(c) with two generalized gamma functions (dashed lines). Initial experimental conditions: $r_c = 1.5 \times 10^{-3}$ kg kg$^{-1}$, $D_c = 24 \mu$m, $\nu_c = 1$ and $\alpha_c = 3$ (see appendix D). Plots are made after 1200 s of integration.

Source: Cohard and Pinty (2000a)
Initial input aerosol

- Combination of **primary aerosol sources**: Sulfates, organic carbon and sea salts.
- **3-D monthly climatology** from GOCART* model with 0.5°(lon) x 1.25°(lat) grid spacing from 2001-2007.
- Mass converted to number concentration by assuming log-normal distributions.

Source: Thompson and Eidhammer, 2014

Aerosols monthly climatology at model level near the surface

*Georgia Institute of Technology
Goddard Global Ozone Chemistry Aerosol Radiation and Transport model

~ 1000 to 10 000 cm⁻³
Nucleation of Cloud Droplets \((NU_{vc})\)


- From the Köhler theory, the parameterization establishes a relationship between \(S_{\text{max}}\) reached in updraft and an critical supersaturation \((S_m)\) for the mode radius of mode \(m\):

\[
S_{\text{max}}^2 = \frac{1}{m \ S_m^2} f_m \ S_m^\frac{3}{2} + g_m \ S_m^\frac{3}{4}
\]

\(\zeta\) and \(\eta\) are two non-dimensional parameters dependant on vertical velocity, growth coefficient (accounting for diffusion of heat and moisture to particles), surface tension, etc. \(S_m\) depends on size, hygroscopicity and surface tension characteristics of the particles. \(f_m\) and \(g_m\) depends on the geometric standard deviation of mode \(m\).

- Activated aerosols concentration:

\[
N_{\text{act}} = \frac{1}{2} m N_{\text{aero}} \ \text{erf}(z_m) \ z_m \ \frac{2 \ ln(S_m/S_{\text{max}})}{3 \sqrt{2} \ ln \ m}
\]
Nucleation of Cloud Droplets \((NU_{vc})\)


- From the Köhler theory, the parameterization establishes a relationship between \(S_{\text{max}}\) reached in updraft and an critical supersaturation \((S_m)\) for the mode radius of mode \(m\):

\[
S_{\text{max}}^2 = 1 + \frac{1}{S_m^2} \frac{f_m}{S_m^2} \left( \frac{S_m^2}{m+3} \right) + g_m \left( \frac{S_m^2}{m+3} \right)^{\frac{3}{4}}
\]

<table>
<thead>
<tr>
<th>Activation depends on:</th>
<th>Implementation details:</th>
</tr>
</thead>
<tbody>
<tr>
<td>- aerosol concentration, (N_{\text{aero}})</td>
<td>- grid-scale vertical velocity</td>
</tr>
<tr>
<td>- aerosols mean radius, (r_{\text{aero}})</td>
<td>- one aerosol mode/type</td>
</tr>
<tr>
<td>- aerosol hygroscopicity, (kappa)</td>
<td>- (kappa = 0.4)</td>
</tr>
<tr>
<td>- aerosol size distribution, (\sigma)</td>
<td>- (\sigma = 1.8)</td>
</tr>
<tr>
<td>- updraft velocity, (w)</td>
<td>- (r_{\text{aero}} = 0.04) (\mu m)</td>
</tr>
<tr>
<td>- temperature and pressure, (T, p)</td>
<td>- (N_{\text{aero}}): 3-D monthly climatology</td>
</tr>
</tbody>
</table>
Ice Phase

Observed crystals:

- Complex shapes, densities, etc.
- Growth/decay processes include: deposition/sublimation, riming (wet/dry growth), ice multiplication, aggregation, gradual melting, shedding, ...

→ Difficult to represent simply
Ice Phase

Traditional bulk approach:
Partition into representative categories
with prescribed bulk physical properties
• bulk density
• shape } mass-diameter (m-D) relations
• fall speed-diameter (V-D) relations
• etc.

e.g.

CLOUD “ICE”
\[ \rho_s = 500 \, \text{kg m}^{-3} \]
\[ m = (\pi/6 \, \rho_s)D^3 \]
\[ V = a_i D^{b_i} \]

“SNOW”
\[ \rho_s = 100 \, \text{kg m}^{-3} \]
\[ m = cD^2 \]
\[ V = a_s D^{b_s} \]

GRAUPEL
\[ \rho_g = 400 \, \text{kg m}^{-3} \]
\[ m = (\pi/6 \, \rho_g)D^3 \]
\[ V = a_g D^{b_g} \]

HAIL
\[ \rho_h = 900 \, \text{kg m}^{-3} \]
\[ m = (\pi/6 \, \rho_h)D^3 \]
\[ V = a_h D^{b_h} \]
**Ice Phase**

Traditional bulk approach:

Problems with pre-defined categories:

1. Real ice particles have complex shapes
2. Conversion between categories is ad-hoc and leads to large, discrete changes in particle properties
3. Physics applied is often inconsistent

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**CLOUD “ICE”**

- $\rho_s = 500 \text{ kg m}^{-3}$
- $m = (\pi/6 \rho_s)D^3$
- $V = a_iD^{bi}$

---

**“SNOW”**

- $\rho_s = 100 \text{ kg m}^{-3}$
- $m = cD^2$
- $V = a_sD^{bs}$

---

**GRAUPEL**

- $\rho_g = 400 \text{ kg m}^{-3}$
- $m = (\pi/6 \rho_g)D^3$
- $V = a_gD^{bg}$

---

**HAIL**

- $\rho_h = 900 \text{ kg m}^{-3}$
- $m = (\pi/6 \rho_h)D^3$
- $V = a_hD^{bh}$

---

NOTE: Bin microphysics schemes have the identical problem
2014 OU CAPS Ensemble (4-km WRF)*

22-h FCST, 1-km Reflectivity, 22 UTC 8 May, 2014

* c/o Fanyou Kong
2014 OU CAPS Ensemble (4-km WRF)*

Simulated 10.7 MICRON Brightness Temperatures

* c/o Fanyou Kong
The simulation of ice-containing cloud systems is often very sensitive to how ice is partitioned among categories.

- idealized 1-km WRF simulations (em_quarter_ss)
- base reflectivity

**Microphysics Schemes:**
- **MOR**: Morrison et al. (2005, 2009)
- **MY2**: Milbrandt and Yau (2005)

Morrison and Milbrandt (2011), MWR
There is a paradigm shift in the way ice-phase microphysics is represented

→ Moving away from increased number of pre-defined categories; towards emphasis on physical properties of ice

e.g.:
- 2-moment: more info on mean-particle size
- 3-moment: info on *spectral dispersion* of size distribution
- graupel *density*: better fall speeds, etc.
- axis ratio
**Ice Phase**

**TRADITIONAL:**

- **SNOW**
  \[ \rho_s = f(D_s) \]
  \[ V = a_s D^{bs} \]

- **GRAUPEL**
  \[ \rho_g = 400 \text{ kg m}^{-3} \]
  \[ V = a_g D^{bg} \]

- **HAIL**
  \[ \rho_h = 900 \text{ kg m}^{-3} \]
  \[ V = a_h D^{bh} \]

---

**MODIFICATION:**

- **SNOW**
  \[ \rho_s = f(D_s) \]
  \[ V = a_s D^{bs} \]

- **GRAUPEL**
  \[ \rho_g \text{ is predicted} \]
  \[ V = a_g(\rho_g) D^{bg(\rho_g)} \]

- **HAIL**
  \[ \rho_h = 900 \text{ kg m}^{-3} \]
  \[ V = a_h D^{bh} \]

---

**Qg, Ng, Bg**

**Qh, Nh**

*Partial mitigation to the problems with pre-defined categories*

* Milbrandt and Morrison (2013), JAS
Which of the following is more duck-like?

- **SQUEAK!**
  - has a label that says “DUCK”
  - big, round eyes
  - plastic exterior, hollow interior
  - yellow, wing-like appendages
  - no feet
  - makes a “squeak” noise

- **DUCK**
  - has no label
  - small, round eyes
  - feathery exterior, meaty interior
  - white, wing-like appendages
  - webbed feet
  - makes a “quack” noise

**IF IT QUACKS LIKE A DUCK …**
Which of the following is more duck-like?
New Bulk Microphysics Parameterization: Predicted Particle Properties (P3)*

Based on a conceptually different approach to parameterize ice-phase microphysics.

NEW CONCEPT
“free” category – predicted properties, thus freely evolving type
“fixed” category – traditional; prescribed properties, predetermined type

Compared to traditional (ice-phase) schemes, P3:
• avoids some necessary evils (ad-hoc category conversion, fixed properties)
• has self-consistent physics
• is better linked to observations
• is more computationally efficient

* Morrison and Milbrandt (2015)
## Overview of P3 Scheme

### Prognostic Variables: (advected)

#### LIQUID PHASE:

- **2 categories, 2-moment:**
  - $Q_c$ – cloud mass mixing ratio [kg kg\(^{-1}\)]
  - $Q_r$ – rain mass mixing ratio [kg kg\(^{-1}\)]
  - $N_c$ – cloud number mixing ratio [#kg\(^{-1}\)]
  - $N_r$ – rain number mixing ratio [#kg\(^{-1}\)]

#### ICE PHASE:

- **$nCat$ categories, 4 prognostic variables each:**
  - $Q_{dep}(n)$ – deposition ice mass mixing ratio [kg kg\(^{-1}\)]
  - $Q_{rim}(n)$ – rime ice mass mixing ratio [kg kg\(^{-1}\)]
  - $N_{tot}(n)$ – total ice number mixing ratio [# kg\(^{-1}\)]
  - $B_{rim}(n)$ – rime ice volume mixing ratio [m\(^3\) kg\(^{-1}\)]
A given (free) category can represent any type of ice-phase hydrometeor

**Prognostic Variables:**

- $Q_{dep}$ – deposition ice mass mixing ratio [kg kg$^{-1}$]
- $Q_{rim}$ – rime ice mass mixing ratio [kg kg$^{-1}$]
- $N_{tot}$ – total ice number mixing ratio [# kg$^{-1}$]
- $B_{rim}$ – rime ice volume mixing ratio [m$^3$ kg$^{-1}$]

**Predicted Properties:**

- $F_{rim}$ – rime mass fraction, $F_{rim} = Q_{rim} / (Q_{rim} + Q_{dep})$ [-]
- $\rho_{rim}$ – rime density, $\rho_{rim} = Q_{rim} / B_{rim}$ [kg m$^{-3}$]
- $D_m$ – mean-mass diameter, $D_m \propto Q_{tot} / N_{tot}$ [m]
- $V_m$ – mass-weighted fall speed, $V_m = f(D_m, \rho_{rim}, F_{rim})$ [m s$^{-1}$]
- etc.

**Diagnostic Particle Types:**

Based on the predicted properties (rather than pre-defined)
**Predicting microphysical process rates ~ computing $M_x^{(p)}$**

**P3 SCHEME**

\[ M^{(p)} = \int_0^{\infty} D^p N_x(D) dD = N_{0x} \frac{\Gamma(1 + \mu_x + p)}{\lambda_x^{p+1+\mu_x}} \]

- **Fixed category** ⇒ constant $m$-$D$, $A$-$D$, $V$-$D$ parameters

- **Free category** ⇒ variable $m$-$D$, $A$-$D$, $V$-$D$ parameters

\[ Q = \frac{1}{\rho} \int_0^{\infty} m(D)N(D) dD = \frac{1}{\rho} \int_0^{\infty} \alpha D^\beta N_x(D) dD = \frac{\alpha}{\rho} M^{(p)} = \frac{\alpha}{\rho} N_{0x} \frac{\Gamma(1 + \mu_x + \beta)}{\lambda_x^{1+\mu_x+\beta}} \]

→ cannot compute moments analytically, lookup table approach is used in P3
Predicting process rates ~ computing $M_x^{(p)}$

**P3 SCHEME** – Determining $m(D) = \alpha D^\beta$ for regions of $D$:

Conceptual model of particle growth following Heymsfield (1982):

- **ICE INITIATION**
  - Spherical ice
  - $\alpha = \pi/6 \quad \rho_{\text{bulk_ice}}$
  - $\beta = 3$

- **VAPOR GROWTH**
  - Unrimed crystals
  - $\alpha = \text{const}$
  - $\beta \sim 2$

- **AGGREGATION**
  - Partially rimed crystal
  - $\alpha = f(F_{\text{rim}}, \rho_{\text{rim}})$
  - $\beta \sim 2$

- **RIME COLLECTION IN CRYSTAL INTERSTICES**
  - Spherical graupel
  - $\alpha = f(F_{\text{rim}}, \rho_{\text{rim}})$
  - $\beta = 3$
**P3 SCHEME** – Determining $m(D) = \alpha D^\beta$ for regions of $D$:

- e.g. $F_{\text{rim}} = 0$

spherical ice

$\alpha_1 = \pi/6$, $\rho_{\text{bulk_ice}}$

$\beta_1 = 3$

unrimed, non-spherical crystals

$\alpha_2 = \text{const}$

$\beta_2 \sim 2$

Based on observed crystals

*conceptual model + algebraic derivation*
**P3 SCHEME** – Determining $m(D) = \alpha D^\beta$ for regions of $D$:

- Spherical, unrimed: $m(D) = \alpha_1 D^{\beta_1}$
- Nonspherical, unrimed: $m(D) = \alpha_2 D^{\beta_2}$
- Non-spherical, partially rimed: $m(D) = \alpha_3 D^{\beta_3}$
- Spherical, completely rimed: $m(D) = \alpha_4 D^{\beta_4}$

*Predicting process rates ~ computing $M_{x(p)}$*
3D Squall Line case:
(June 20, 2007 central Oklahoma)

- WRF_v3.4.1, $\Delta x = 1$ km, $\Delta z \sim 250$-300 m, 112 x 612 x 24 km domain
- initial sounding from observations
- convection initiated by $u$-convergence
- no radiation, surface fluxes
1-km WRF Simulations with P3 microphysics (1 category):

Observations

Morrison et al. (2015) [P3, part 2]
WRF Results: Base Reflectivity (1 km AGL, t = 6 h)

- **P3**
- **MOR-H**
- **WDM6**
- **MOR-G**
- **THO**
- **MY2**
- **WSM6**

**Observations**

Morrison et al. (2015) [P3, part 2]
WRF Results: Line-averaged Reflectivity \((t = 6 \text{ h})\)

**Observations**

Line averaged KOUN reflectivity at 0759 UTC
Ice Particle Properties:

- If $F_r \sim 0-0.1$
  - $\rho \sim 900$ kg m$^{-3}$
  - $V \sim 0.3$ m s$^{-1}$
  - $D_m \sim 100$ μm
  - $\rightarrow$ small crystals

- If $F_r \sim 0$
  - $\rho \sim 50$ kg m$^{-3}$
  - $V \sim 1$ m s$^{-1}$
  - $D_m \sim 3$ mm
  - $\rightarrow$ aggregates

- If $F_r \sim 1$
  - $\rho \sim 900$ kg m$^{-3}$
  - $V > 10$ m s$^{-1}$
  - $D_m > 5$ mm
  - $\rightarrow$ hail

Vertical cross section of model fields ($t = 6$ h)

Note – only one (free) category

e etc.
$F_r \sim 0-0.1$
\[ \rho \sim 900 \text{ kg m}^{-3} \]
\[ V \sim 0.3 \text{ m s}^{-1} \]
\[ D_m \sim 100 \mu\text{m} \]
\rightarrow small crystals

$F_r \sim 0$
\[ \rho \sim 50 \text{ kg m}^{-3} \]
\[ V \sim 1 \text{ m s}^{-1} \]
\[ D_m \sim 3 \text{ mm} \]
\rightarrow aggregates

$F_r \sim 1$
\[ \rho \sim 900 \text{ kg m}^{-3} \]
\[ V > 10 \text{ m s}^{-1} \]
\[ D_m > 5 \text{ mm} \]
\rightarrow hail

etc.

- small, round eyes
- white, wing-like appendages
- feathery exterior, meaty interior
- webbed feet
- makes a “quack” noise

\rightarrow duck

QUACK!
### Timing Tests for 3D WRF Simulations

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Squall line case ($\Delta x = 1$ km)</th>
<th>Orographic case ($\Delta x = 3$ km)</th>
<th># prognostic variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>P3</td>
<td>0.436 (1.043)</td>
<td>0.686 (1.013)</td>
<td>7</td>
</tr>
<tr>
<td>MY2</td>
<td>0.621 (1.485)</td>
<td>1.012 (1.495)</td>
<td>12</td>
</tr>
<tr>
<td>MOR-H</td>
<td>0.503 (1.203)</td>
<td>0.813 (1.200)</td>
<td>9</td>
</tr>
<tr>
<td>THO</td>
<td>0.477 (1.141)</td>
<td>0.795 (1.174)</td>
<td>7</td>
</tr>
<tr>
<td>WSM6</td>
<td>0.418 (1.000)</td>
<td>0.677 (1.000)</td>
<td>5</td>
</tr>
<tr>
<td>WDM6</td>
<td>0.489 (1.170)</td>
<td>0.777 (1.148)</td>
<td>8</td>
</tr>
</tbody>
</table>

- Average wall clock time per model time step (units of seconds.)
- Times relative to those of WSM6 are indicated parenthetically.

→ P3 is one of the fastest schemes in WRF
So far – despite using only 1 ice-phase category, P3 performs well compared to detailed, established (well-tuned), traditional bulk schemes

However – with 1 category, P3 has some intrinsic limitations:

- it cannot represent more than one type of particle in the same point in time and space
- As a result, there is an inherent “dilution problem”; the properties of populations of particles of different origins get averaged upon mixing

\[
\text{LARGE GRAUPEL} + \text{INITIATION (of small crystals)} = \text{SMALL GRAUPEL}
\]

\[\text{The large (mean) sizes have been lost due to dilution}\]
**Single-Category Version**  
Morrison and Milbrandt (2015) [P3, part 1]

All ice-phase hydrometeors represented by a single category, with \( Q_{dep} \), \( Q_{rim} \), \( N_{tot} \), \( B_{rim} \)

Processes:
1. Initiation of new particles
2. Growth/decay processes
   - interactions with water vapor
   - interactions with liquid water
   - self-collection
3. Sedimentation

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**Multi-Category Version**  
Milbrandt and Morrison (2015) [P3, part 3] (under review)

All ice-phase hydrometeors represented by a \( nCat \) categories, with \( Q_{dep}(n) \), \( Q_{rim}(n) \), \( N_{tot}(n) \), \( B_{rim}(n) \) \( [n = 1..nCat] \)

Processes:
1. Initiation of new particles \( \rightarrow \) determine destination category
2. Growth/decay processes
   - interactions with water vapor
   - interactions with liquid water
   - self-collection
   - collection amongst other ice categories
3. Sedimentation
Inclusion of Hallet-Mossop (rime splintering) process with $n_{Cat} = 1$

- **H-M on $n_{Cat} = 1$**
  - Hallet-Mossop process results in excessive dilution

- **H-M off $n_{Cat} = 1$**

- **H-M on $n_{Cat} = 4$**

$\rightarrow$ With $n_{Cat} = 1$, the Hallet-Mossop process results in excessive dilution
GEM (2.5 km), P3

Reflectivity

$nCat = 1$

(1 km AGL)

$nCat = 2$

(1 km AGL)
Further Development of P3

1. Rigorously test in operational NWP context
2. Additional predicted properties
   - spectral dispersion (triple-moment)
   - liquid fraction
   - others…
3. Subgrid-scale cloud fraction
4. Optimized advection
   Morrison et al. (2015 – to be submitted)
   e.g. P3, 3-moment, prognostic $f_{liq}$, $nCat = 2$:
   - 14 prognostic variables,
   - cost of advection $\sim$ 4 prognostic variables
Summary thoughts

1. Detailed BMSs are playing an increasingly important role in NWP

2. For continued advancement, developers should embrace the new paradigm of representing ice-phase hydrometeors: *abandon the use of pre-defined categories*

3. There remain mainly uncertainties in parameterizing microphysics (e.g. ice nucleation) – ensemble systems will always play an important role (w.r.t. microphysics)
Comments to “young scientists”

1. Learn from – and profit from – stupid mistakes

2. Never take for granted the implicit wisdom in “because that’s the way it has always been done”
THANKS!

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