The Representation of
Cloud Microphysical Processes
in NWP Models

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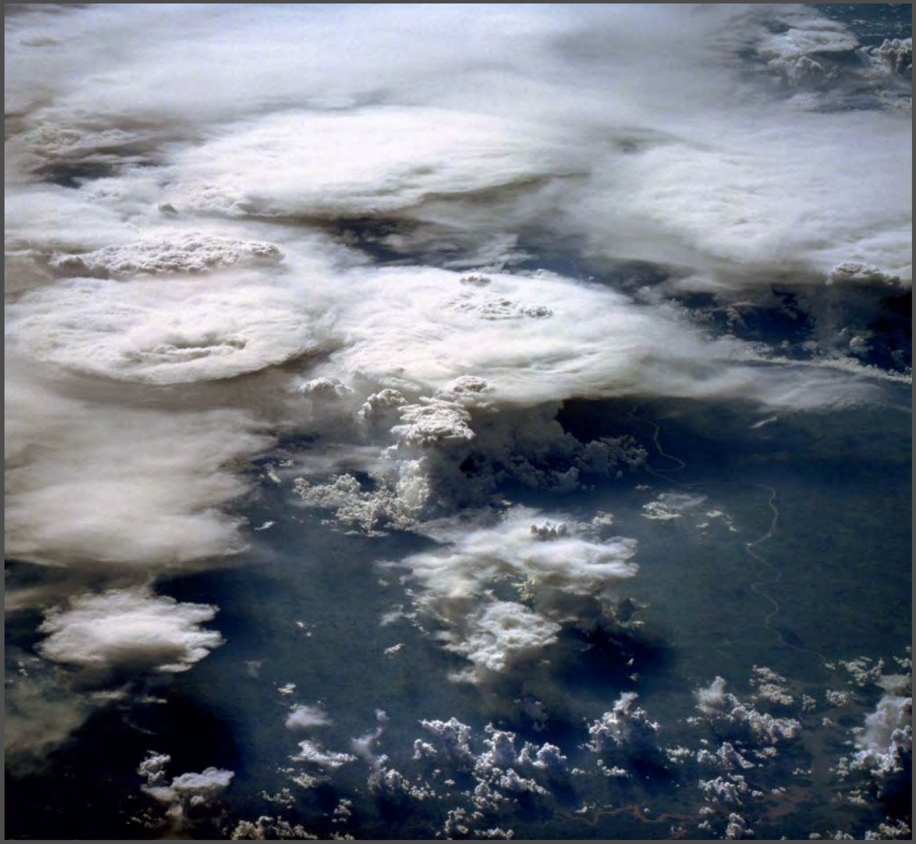
ECMWF, 1-4 September 2015

Environment Canada   Environnement Canada

RPN Service through science

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

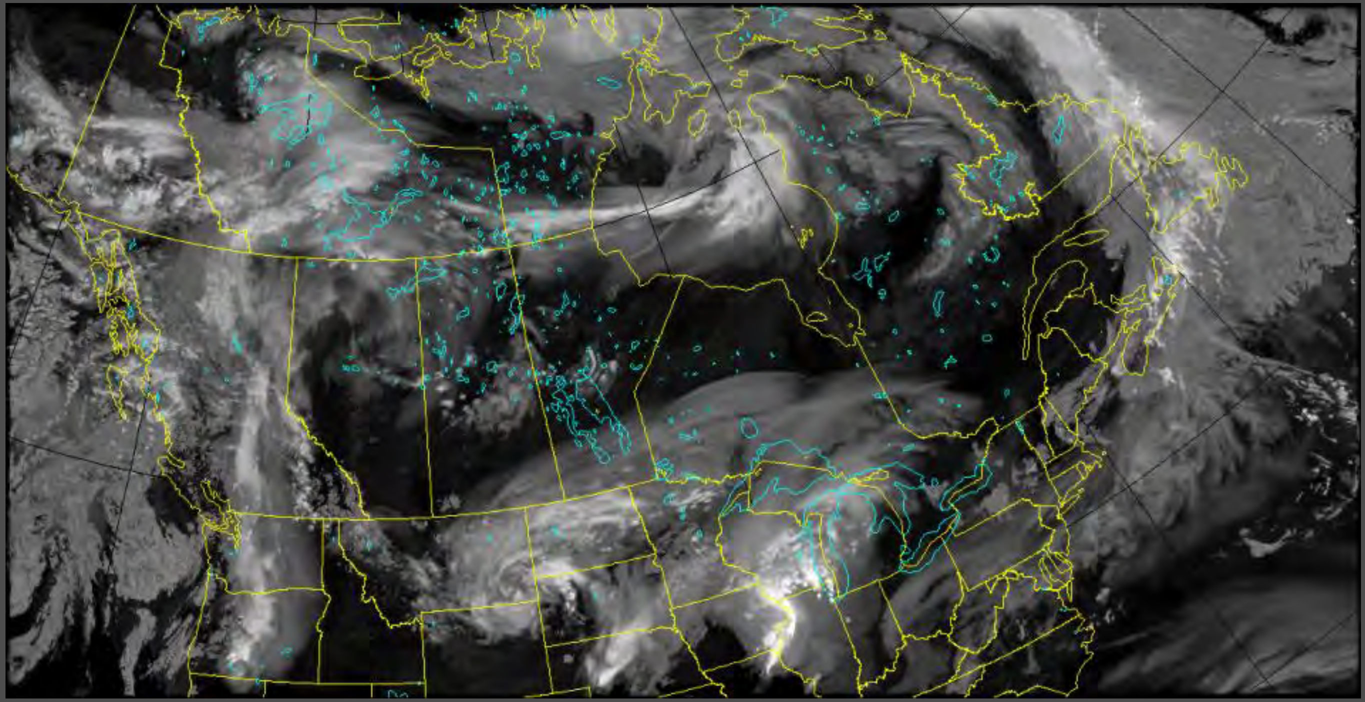
- computes radiative fluxes SW/LW

Representation of Clouds in MODELS

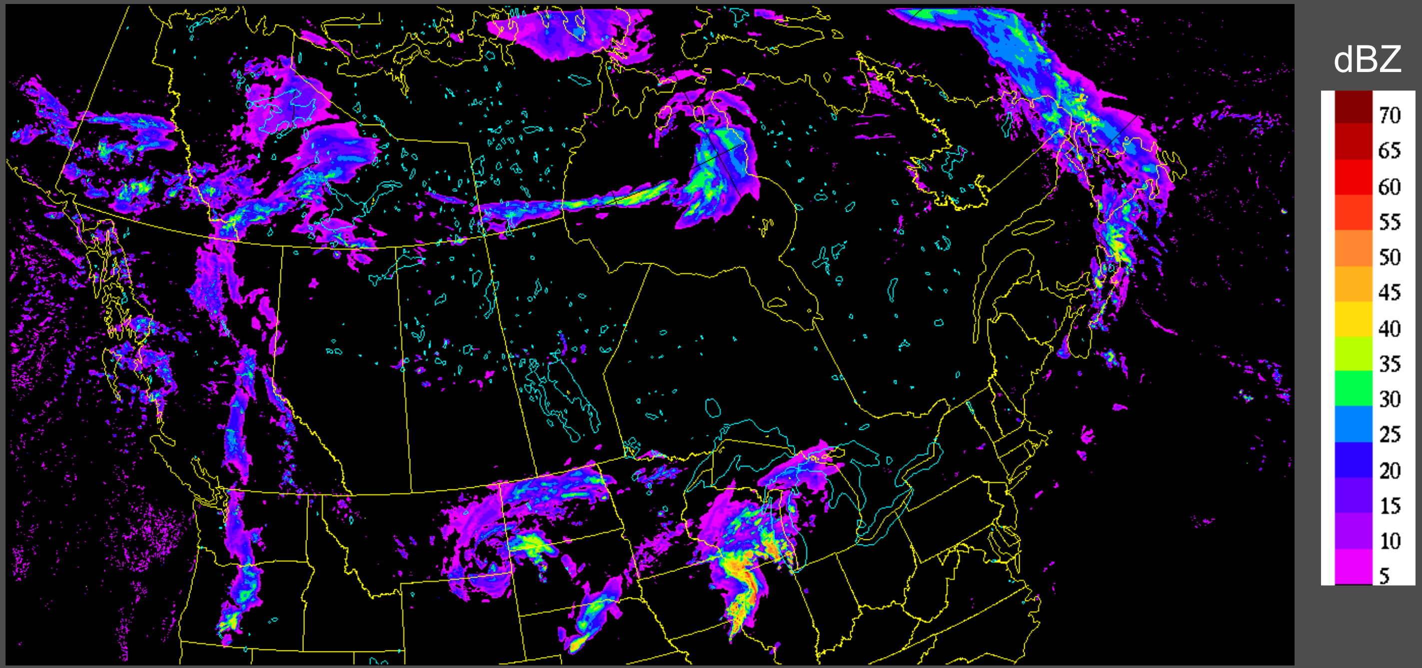
Cloud Microphysics Scheme

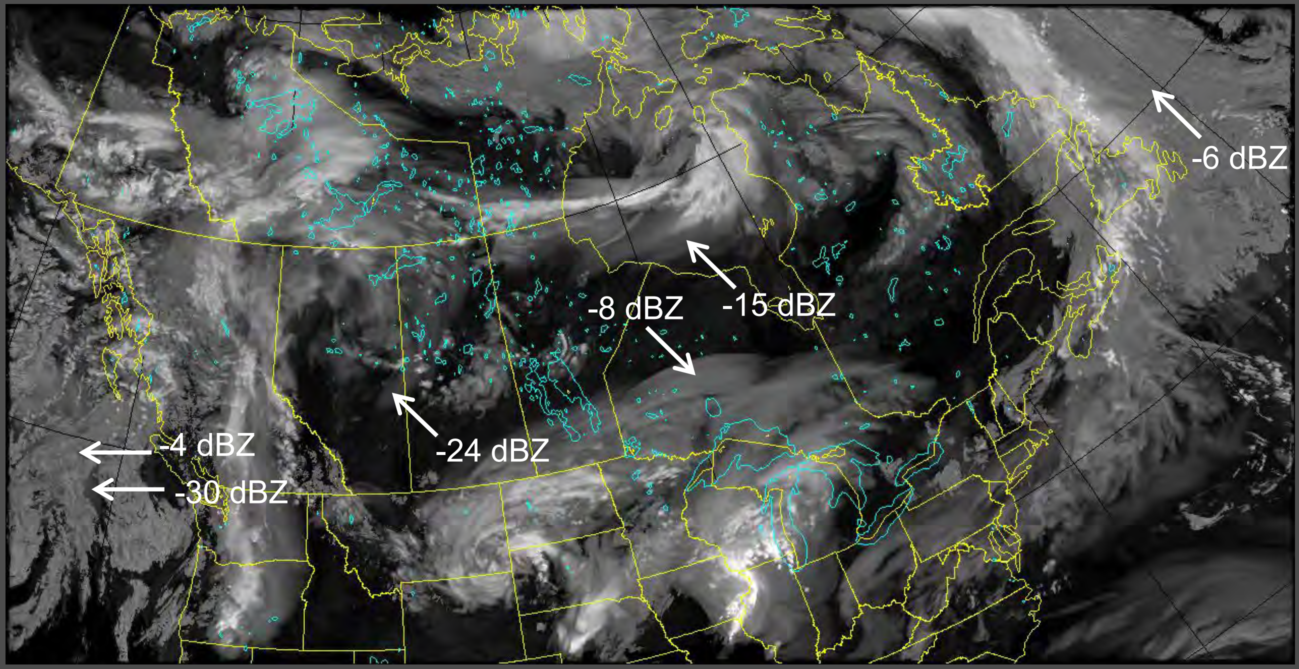
Three main roles:

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

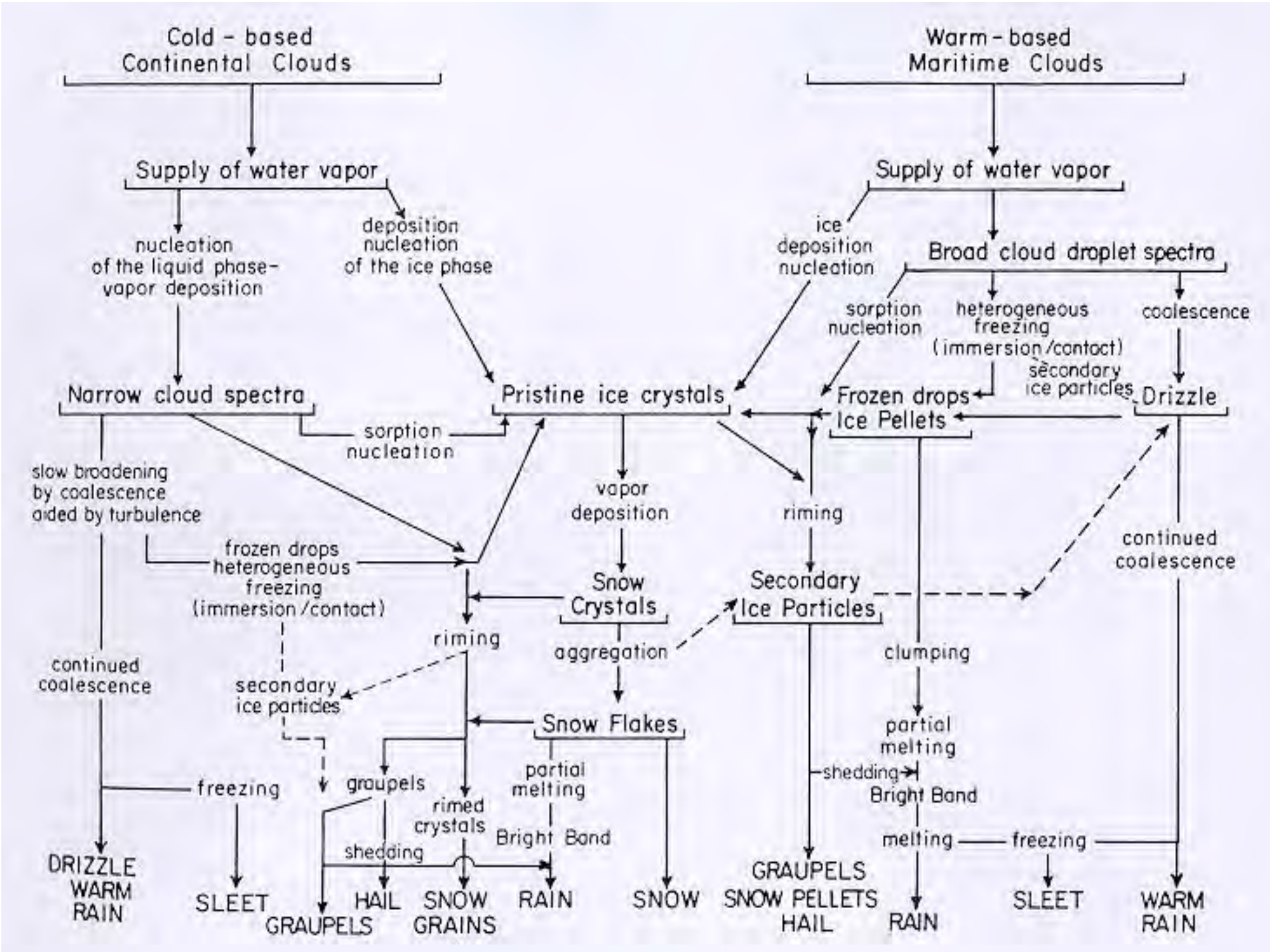


Column-Maximum Model Reflectivity





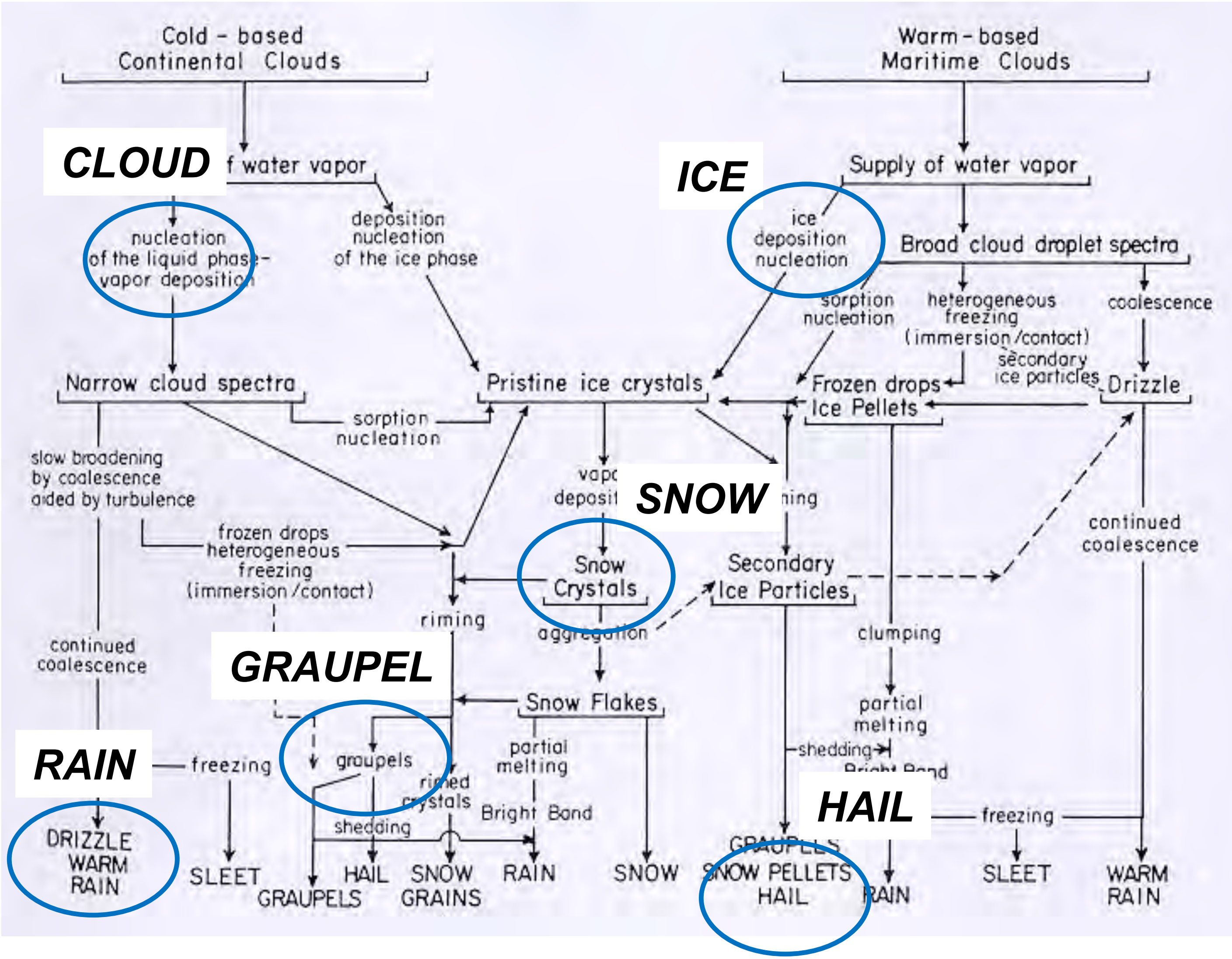
Cloud Microphysical Processes



***BAMS*, 1967**

Microphysics Parameterization Schemes

Hydrometeors are traditionally partitioned into categories



***BAMS*, 1967**

Microphysics Parameterization Schemes

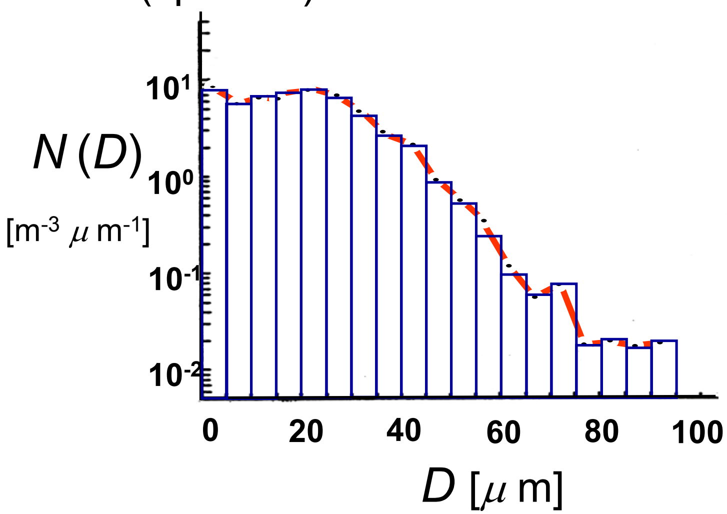
The particle size distributions are modeled

e.g. ***SNOW***

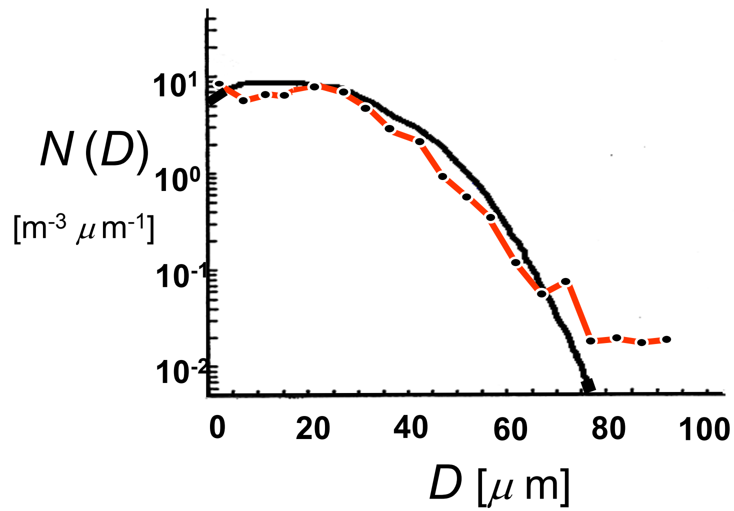
For each category, microphysical processes are parameterized in order to predict the evolution of the *particle size distribution, $N(D)$*

TYPES of SCHEMES:

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

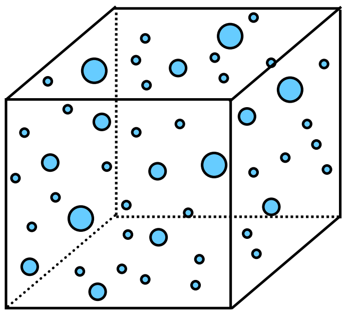


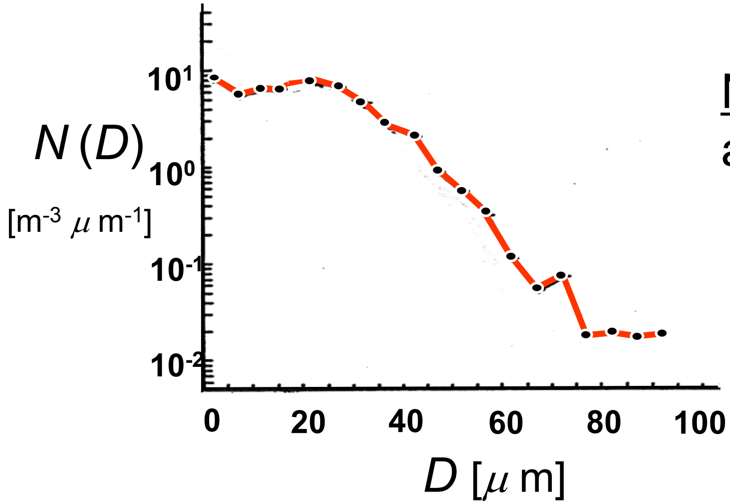
Bulk: $$N(D) = N_0 D^{\alpha} e^{-\lambda D}$$



Approaches to parameterize cloud microphysics

ULTIMATE GOAL: Predict evolution of hydrometeor size distributions

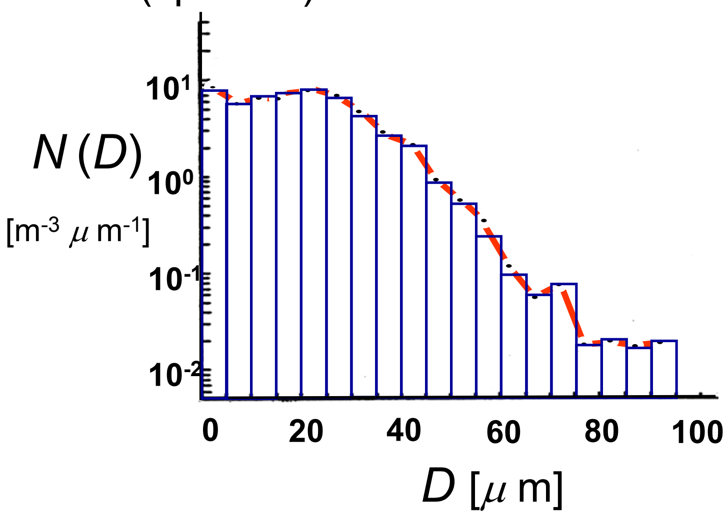




Note: microphysics schemes assume grid-scale homogeneity

Bin-resolving:
(spectral)

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



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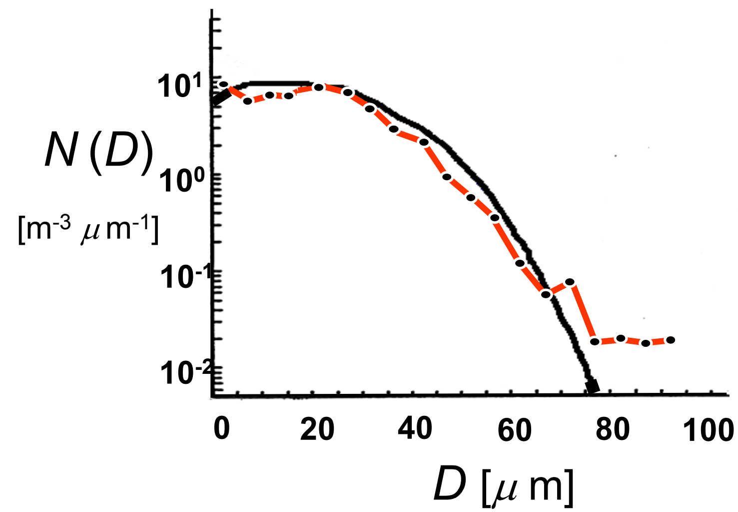
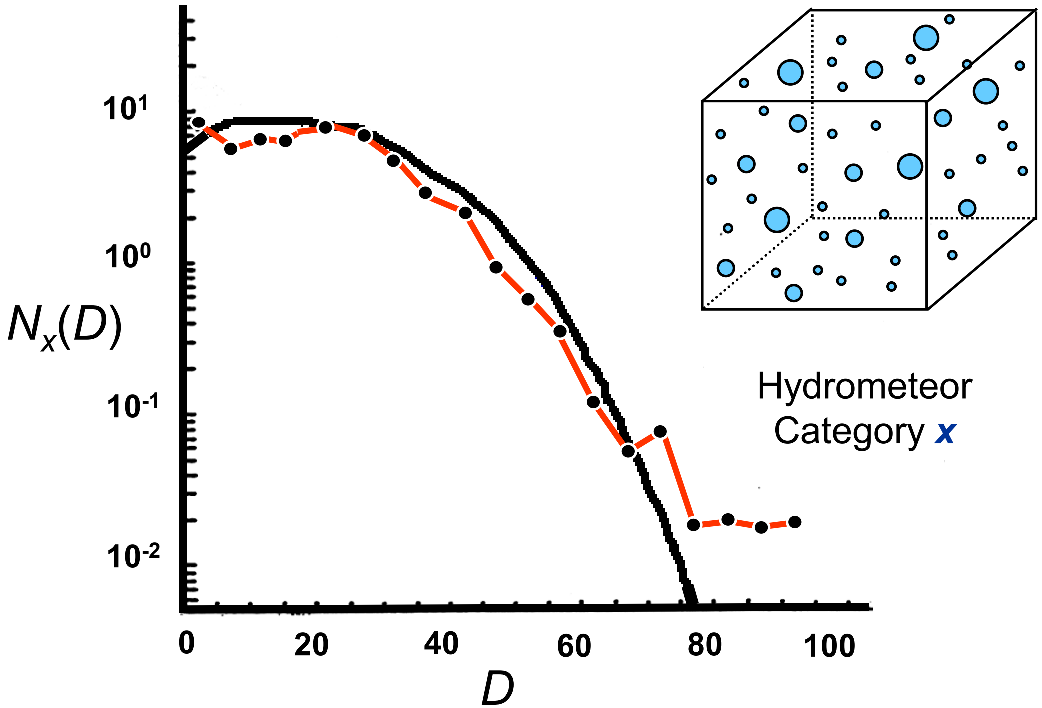


BULK METHOD



Hydrometeor Category *x*

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_{Tx}

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

Radar reflectivity factor, Z_x

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

(assuming spheres)

***Size Distribution Function*:**

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

p^{th} moment:

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

BULK METHOD

Predict changes to specific moment(s)

e.g. q_x, N_{Tx}, ...

↓

Implies changes to values of parameters

i.e. N_{0x}, λ_x, ...

Size Distribution Function:

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

p^{th} moment:

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

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}

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Radar reflectivity factor, Z_x

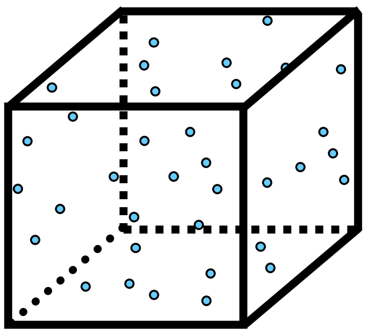
$$Z_x \equiv \int_0^\infty D^6 N_x(D) dD = M_x(6)$$

BULK METHOD

Traditional Approach:

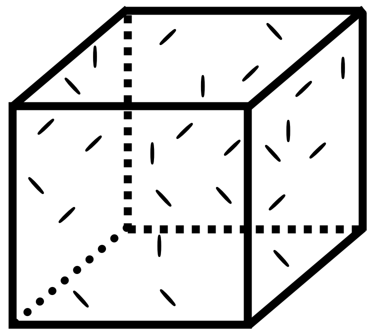
PARTITIONING HYDROMETEORS INTO CATEGORIES

CLOUD



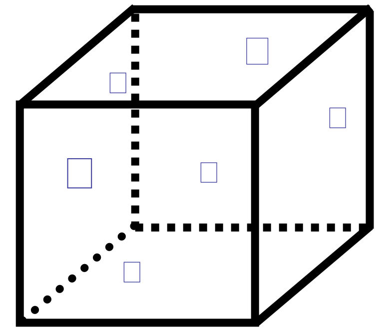
$$N_c(D) = N_{0c} D^{\alpha_c} e^{-\lambda_c D}$$

ICE



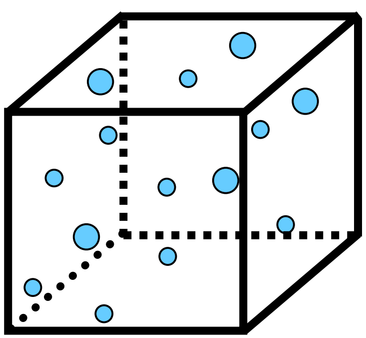
$$N_i(D) = N_{0i} D^{\alpha_i} e^{-\lambda_i D}$$

SNOW



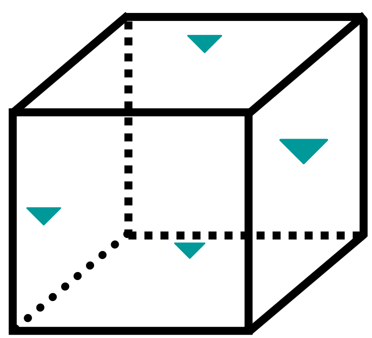
$$N_s(D) = N_{0s} D^{\alpha_s} e^{-\lambda_s D}$$

RAIN



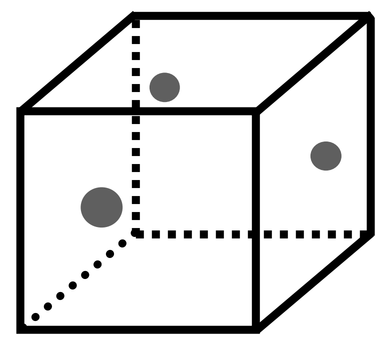
$$N_r(D) = N_{0r} D^{\alpha_r} e^{-\lambda_r D}$$

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)

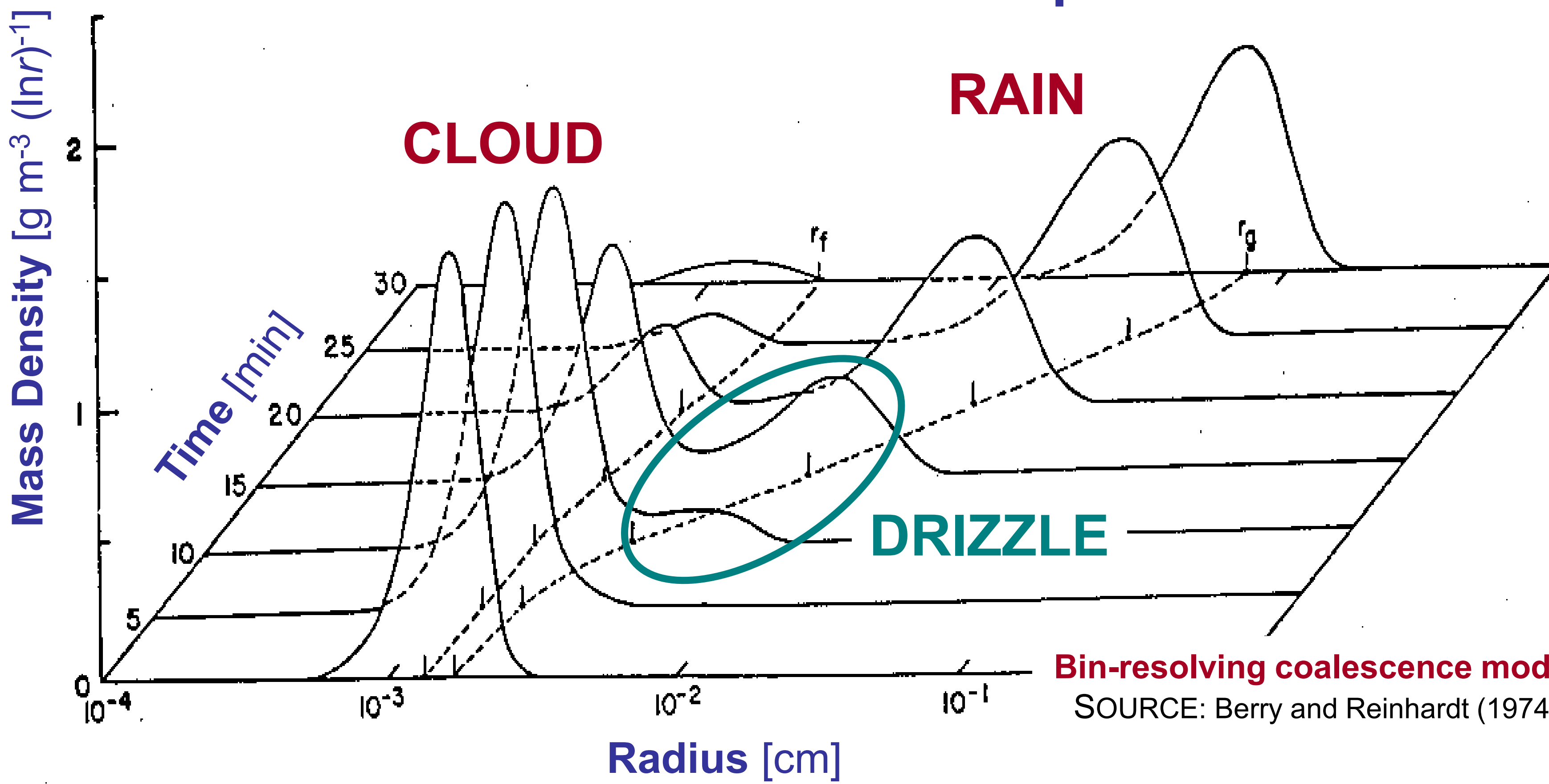
Advantages of 3-moment:

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



Bin-resolving coalescence model
SOURCE: Berry and Reinhardt (1974)

Partitioning of Coalescence Processes:

- Autoconversion (*cloud* to *rain*)
- Accretion (*rain* collecting *cloud*)
- Self-collection (*rain* collecting *rain*) → *multi-moment only*

The warm-rain coalescence process

Stochastic collection equation:

$$QCL_{yx} = \frac{1}{\rho}\frac{\pi}{4}\int_0^\infty\int_0^\infty \left|V_x(D_x) - V_y(D_y)\right|\left(D_x + D_y\right)^2 m_y(D_y)E(x,y)N_y(D_y)N_x(D_x)dD_y dD_x$$

$$N_y CL_{yx} = -\frac{\pi}{4}\int_0^\infty\int_0^\infty \left|V_x(D_x) - V_y(D_y)\right|\left(D_x + D_y\right)^2 E(x,y)N_y(D_y)N_x(D_x)dD_y dD_x$$

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

$$QCL_{yx} = \frac{c_y}{\rho}\frac{\pi}{4}E_{xy}\Delta\overline{V}\frac{N_{Tx}N_{Ty}}{\Gamma(1+\alpha_x)\Gamma(1+\alpha_y)}\left[\frac{\Gamma(3+\alpha_x)\Gamma(4+\alpha_y)}{\lambda_x^2\lambda_y^3} + \frac{2\Gamma(2+\alpha_x)\Gamma(5+\alpha_y)}{\lambda_x\lambda_y^4} + \frac{\Gamma(1+\alpha_x)\Gamma(6+\alpha_y)}{\lambda_y^5}\right]$$

$$NCL_{yx} = \frac{\pi}{4}E_{xy}\Delta\overline{V}\frac{N_{Tx}N_{Ty}}{\Gamma(1+\alpha_x)\Gamma(1+\alpha_y)}\left[\frac{\Gamma(3+\alpha_x)\Gamma(1+\alpha_y)}{\lambda_x^2} + \frac{2\Gamma(2+\alpha_x)\Gamma(2+\alpha_y)}{\lambda_x\lambda_y} + \frac{\Gamma(1+\alpha_x)\Gamma(3+\alpha_y)}{\lambda_y^2}\right]$$

Thus:

CLOUD

$$dq_c/dt = -QCN_{cr} - QCL_{cr}$$

$$dN_c/dt = -NCN_{cr} - NCL_{cr}$$

RAIN

$$dq_r/dt = QCN_{cr} + NCL_{cr}$$

$$dN_r/dt = NCN_{cr} - NCL_{rr}$$

accretion

autoconversion ***self-collection***

Autoconversion is based on an empirical formulation of a bin model solution (Berry and Reinhardt, 1974)

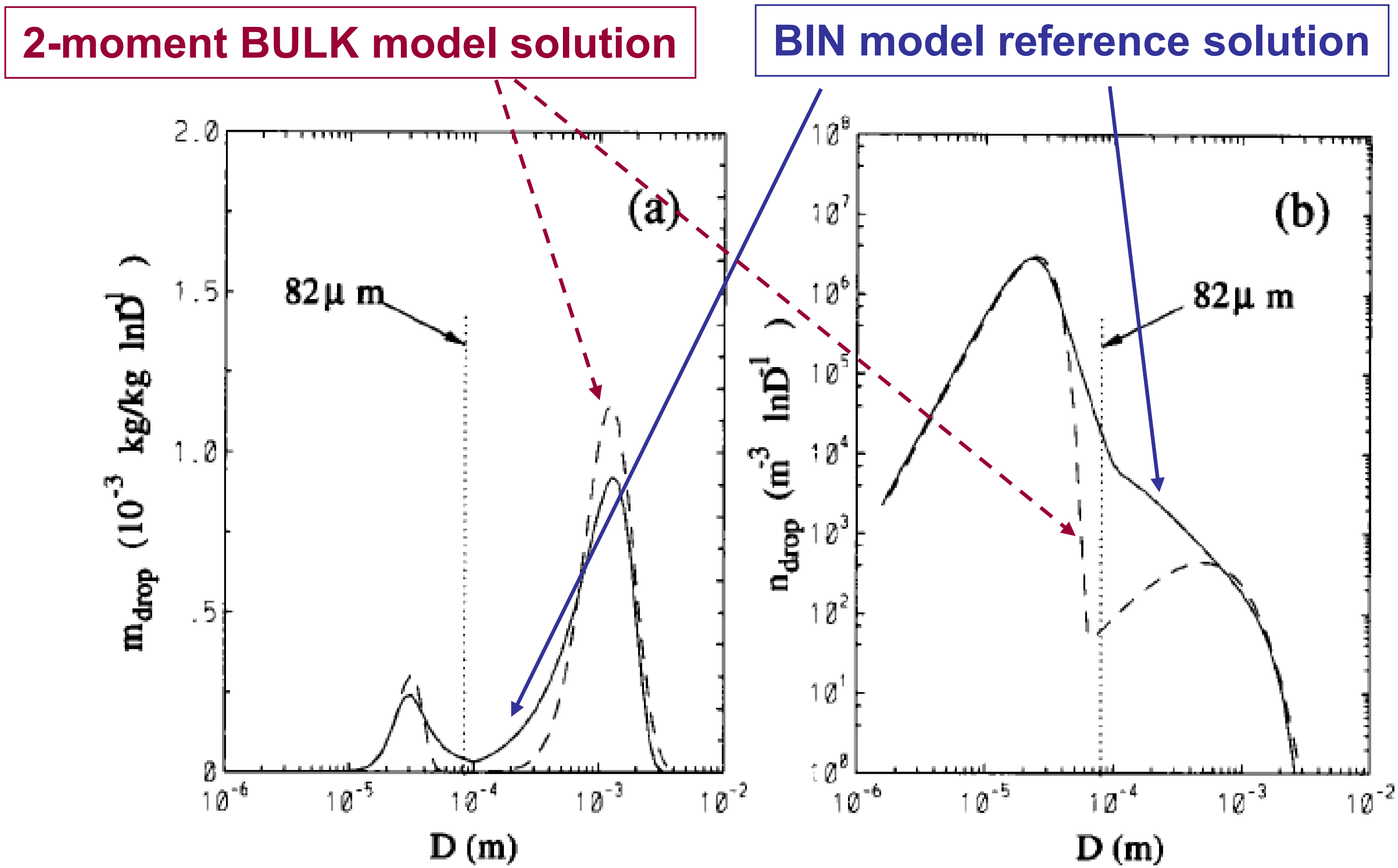


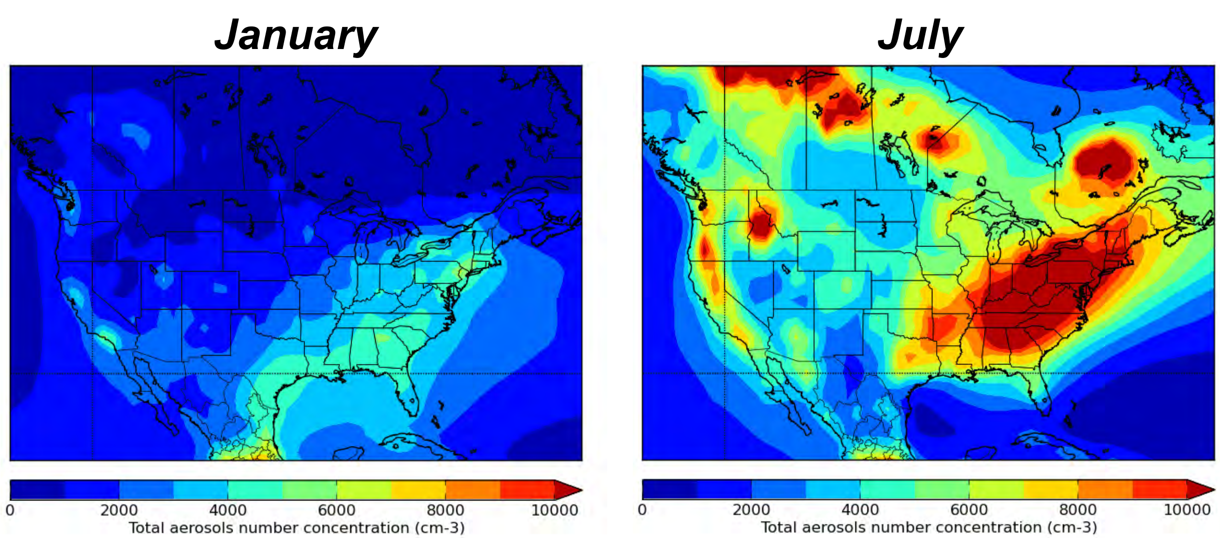
Figure 1. Representative distributions of (a) liquid-water mass and (b) number concentration, resulting from the discrete bin integration of Eq. (13) (solid lines) and resulting from the parametrization set out in section 3(c) with two generalized gamma functions (dashed lines). Initial experimental conditions: $r_c = 1.5 \times 10^{-3}$ kg kg^{-1}, $D_c = 24$ μm, $\nu_c = 1$ 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*



~ 1000 to 10 000 cm^{-3}

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

Aerosols monthly climatology at model level near the surface

Nucleation of Cloud Droplets (*NU_{vc}*)

- Implementation of *Abdul-Razzak & Ghan (2002)* activation scheme.

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

$$S_{\max}^2 = 1 \Big/ \sum_m \frac{1}{S_m^2}\left[f_m \left(\frac{\zeta}{\eta_m}\right)^{3/2} + g_m \left(\frac{S_m^2}{\eta_m + 3\zeta}\right)^{3/4} \right]$$

ζ and η 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: $N_{act} = \frac{1}{2}\sum_m N_{aero}\left[1 - erf(z_m)\right] \quad z_m \equiv 2\frac{\ln\left(S_m / S_{\max}\right)}{3\sqrt{2}\ln\sigma_m}$

Nucleation of Cloud Droplets (NU_{vc})

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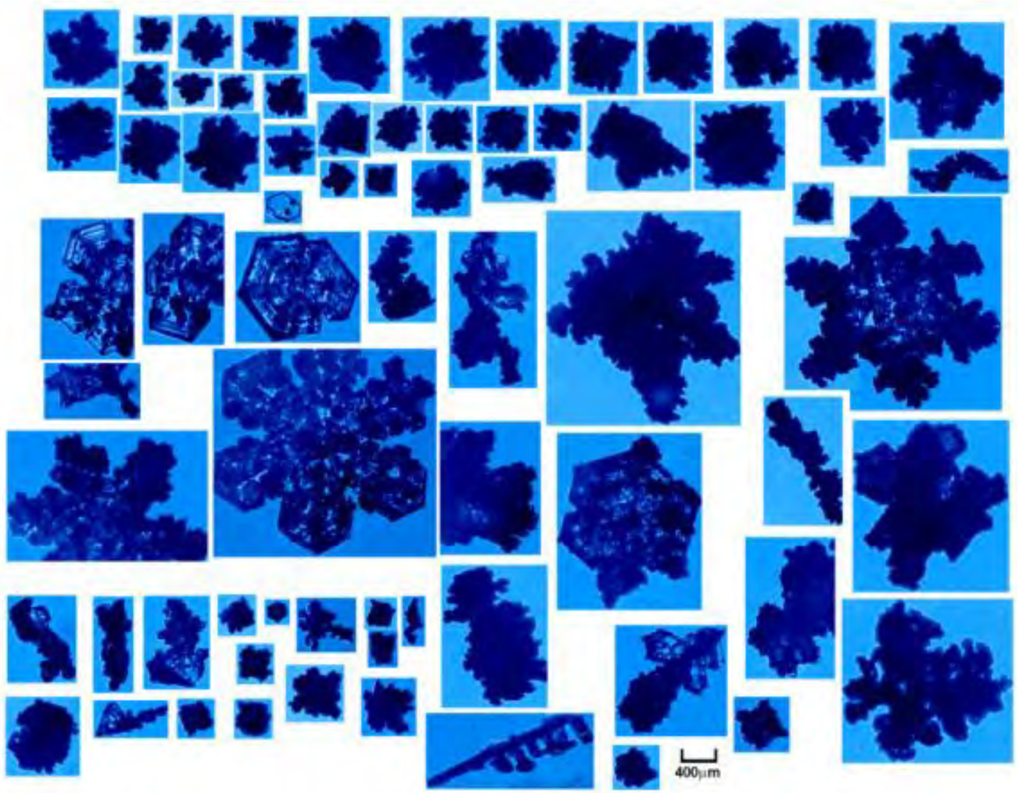
Activation depends on:	Implementation details:
▪ aerosol concentration, N_{aero} ▪ aerosols mean radius, r_{aero} ▪ aerosol hygroscopicity, *kappa* ▪ aerosol size distribution, σ ▪ updraft velocity, w ▪ temperature and pressure, T, p	▪ grid-scale vertical velocity ▪ one aerosol mode/type ▪ *kappa* = 0.4 ▪ σ = 1.8 ▪ r_{aero} = 0.04 μm ▪ N_{aero}: **3-D monthly climatology**

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 } mass-diameter (*m-D*) relations
- shape }
- fall speed-diameter *(V-D*) relations
- etc.

e.g.

CLOUD "ICE"

ρ_s = 500 kg m^{-3}

$m = (\pi/6\ \rho_s)D^3$

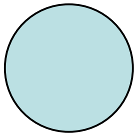
$V = a_i D^{bi}$

"SNOW"

ρ_s = 100 kg m^{-3}

$m = cD^2$

$V = a_s D^{bs}$

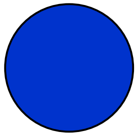


GRAUPEL

ρ_g = 400 kg m^{-3}

$m = (\pi/6\ \rho_g)D^3$

$V = a_g D^{bg}$



HAIL

ρ_h = 900 kg m^{-3}

$m = (\pi/6\ \rho_h)D^3$

$V = a_h D^{bh}$

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**

CLOUD "ICE"
ρ_s = 500 kg m^{-3}
$m = (\pi/6\ \rho_s)D^3$
$V = a_i D^{bi}$

"SNOW"
ρ_s = 100 kg m^{-3}
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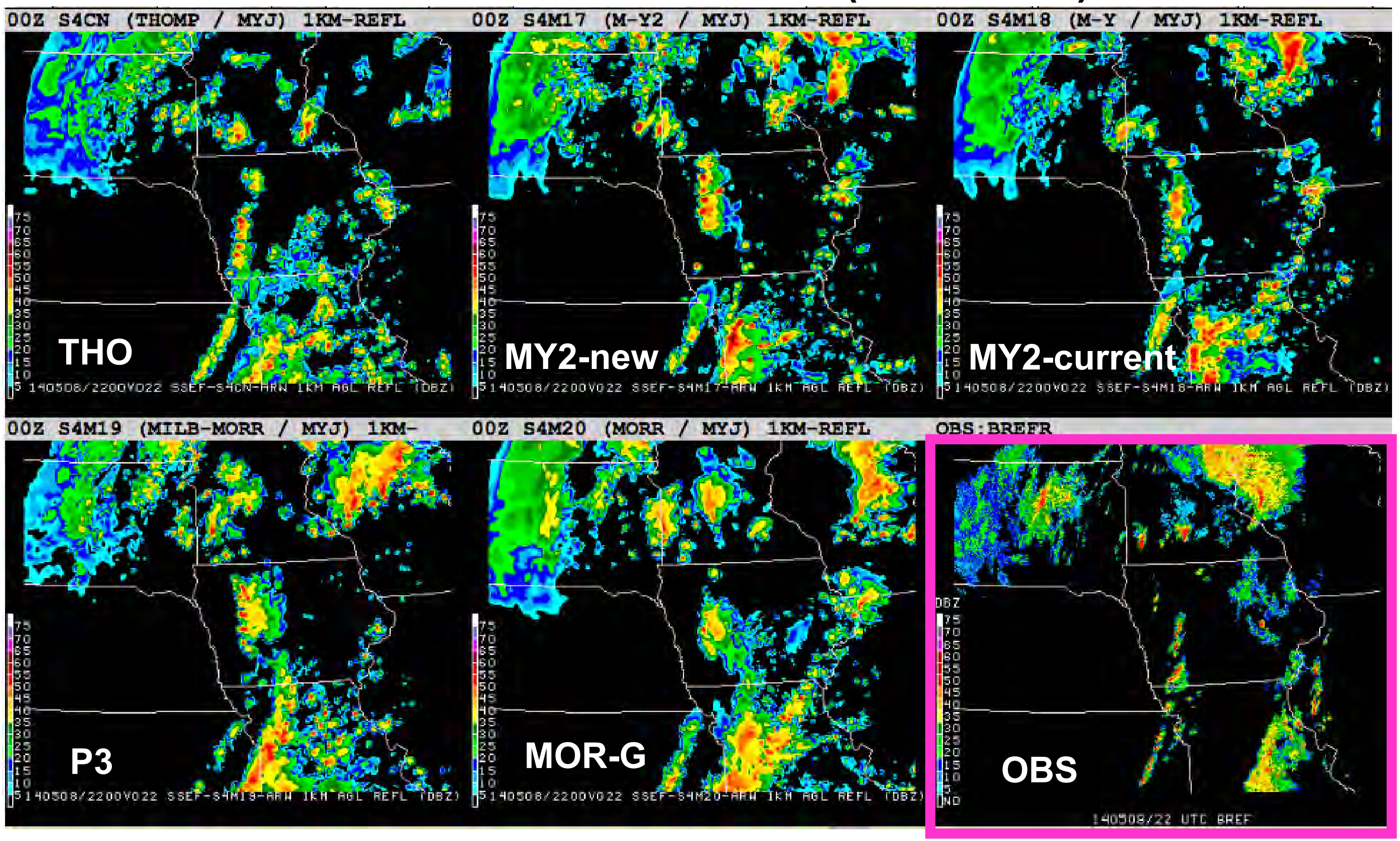
GRAUPEL
ρ_g = 400 kg m^{-3}
$m = (\pi/6\ \rho_g)D^3$
$V = a_g D^{bg}$

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

← abrupt / unphysical conversions

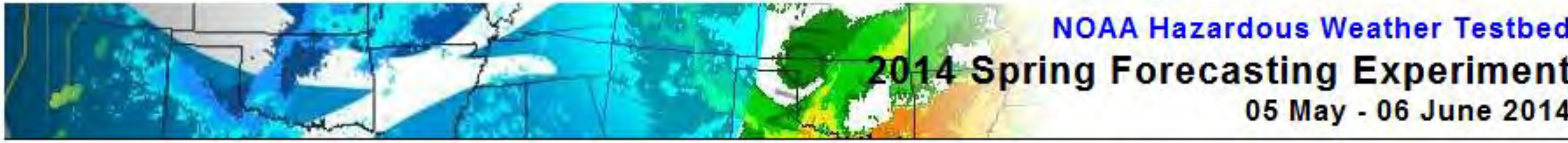
NOTE: *Bin microphysics schemes have the identical problem*

2014 OU CAPS Ensemble (4-km WRF)*

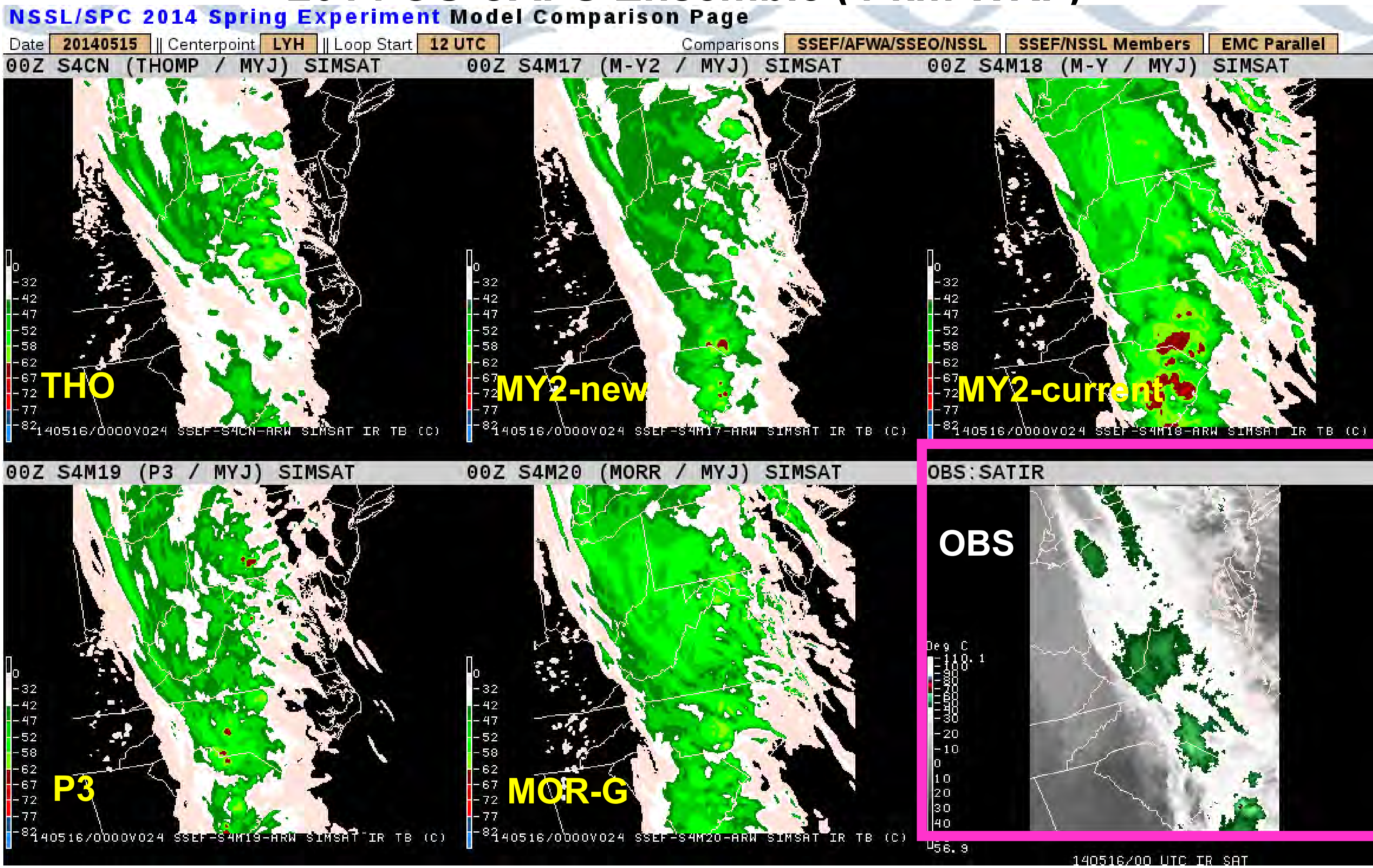


22-h FCST, 1-km Reflectivity, 22 UTC 8 May, 2014

* c/o Fanyou Kong



2014 OU CAPS Ensemble (4-km WRF)*

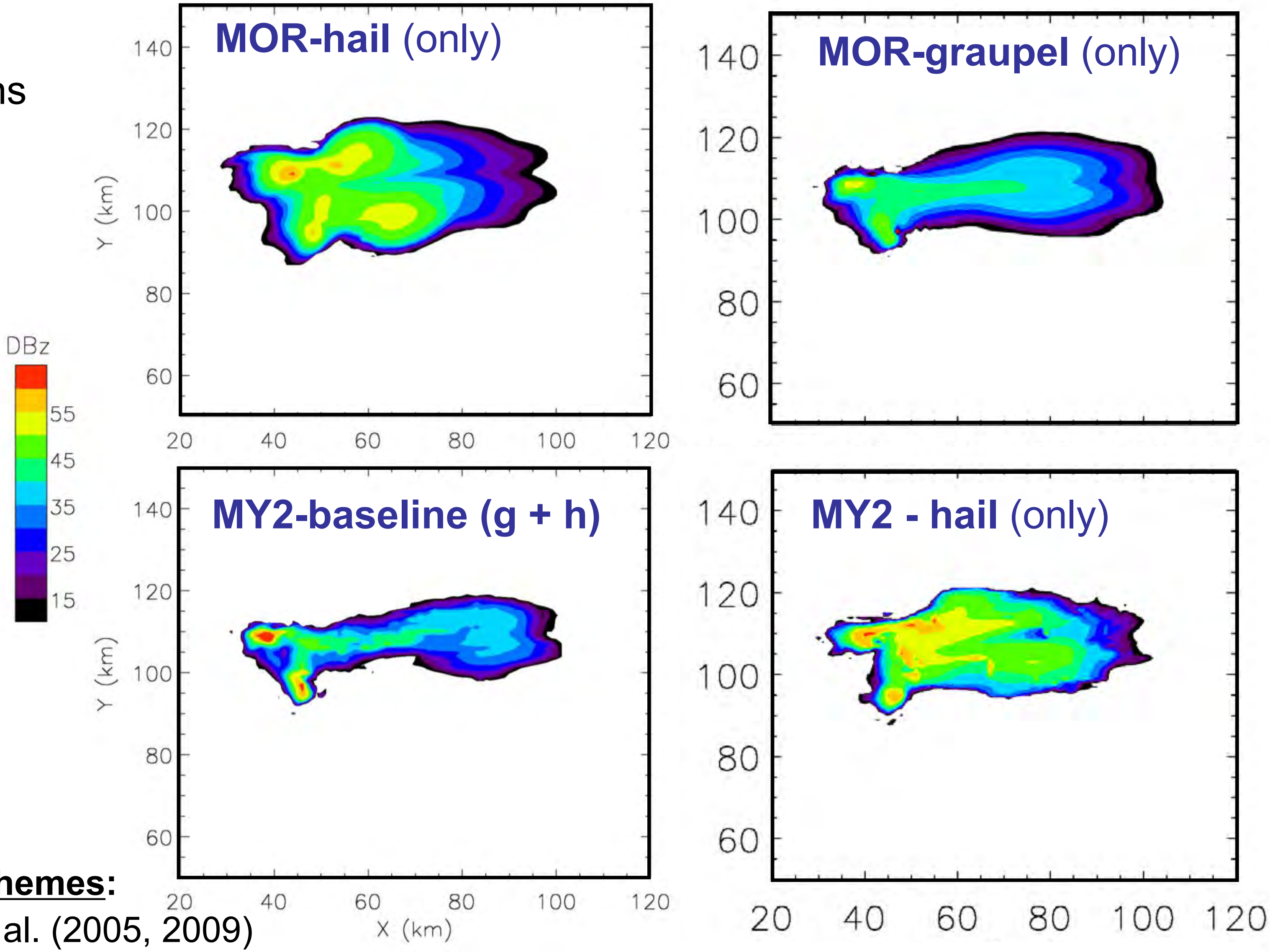


Simulated 10.7 MICRON Brightness Temperatures

* 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*

CURRENT TREND:

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
ρ_g = 400 kg m^{-3}
$V = a_g D^{bg}$

HAIL
ρ_h = 900 kg m^{-3}
$V = a_h D^{bh}$

← ***abrupt / unphysical conversions***

MODIFICATION:*

SNOW
$\rho_s = f(D_s)$
$V = a_s D^{bs}$

GRAUPEL
ρ_g *is predicted* *
$V = a_g(\rho_g) D^{bg(\rho_g)}$

HAIL
ρ_h = 900 kg m^{-3}
$V = a_h D^{bh}$

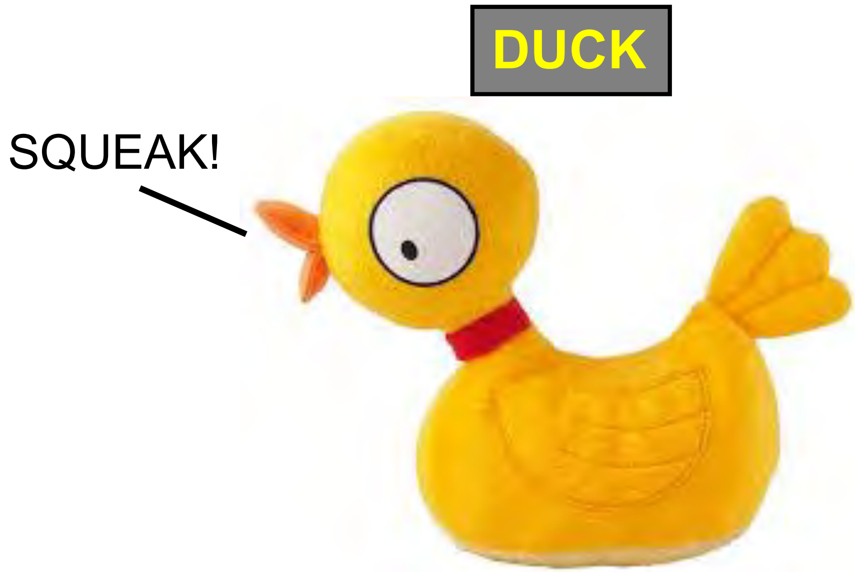
← ***smooth conversions***

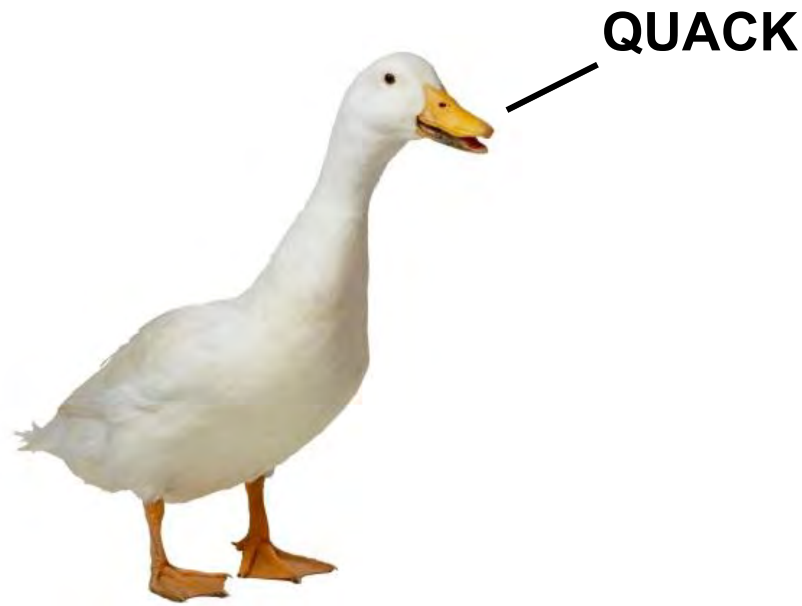
Qs, Ns ***Qg, Ng, Bg*** ***Qh, Nh***

<u>Partial</u> mitigation to the problems with pre-defined categories

* Milbrandt and Morrison (2013), *JAS*

Which of the following is more duck-like?





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

- **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)
[P3, part 1] *J. Atmos. Sci.*

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, $F_{rim} = Q_{rim} / (Q_{rim} + Q_{dep})$ [--]

ρ_{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

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

Fixed category ⇨ constant *m-D, A-D, V-D* parameters

Free category ⇨ <u>variable</u> *m-D, A-D, V-D* parameters

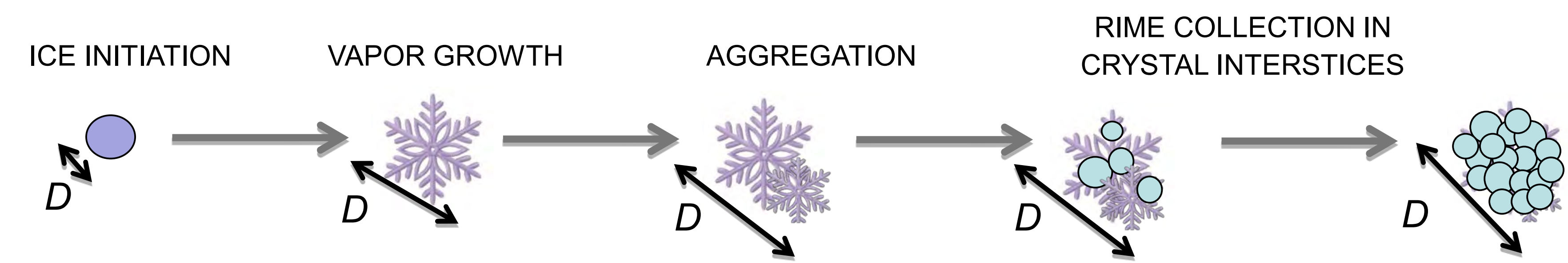
$$Q = \frac{1}{\rho}\int_0^\infty m(D)N(D)dD = \frac{1}{\rho}\int_0^\infty \alpha D^\beta N_x(D)dD = \frac{\alpha}{\rho}M^{(\beta)} = \frac{\alpha}{\rho}N_{0x}\frac{\Gamma(1+\mu_x+\beta)}{\lambda_x^{1+\mu_x+\beta}}$$

→ 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):



spherical ice
$\alpha = \pi/6\ \rho_{bulk\_ice}$
$\beta = 3$

unrimed crystals
α = const
$\beta \sim 2$

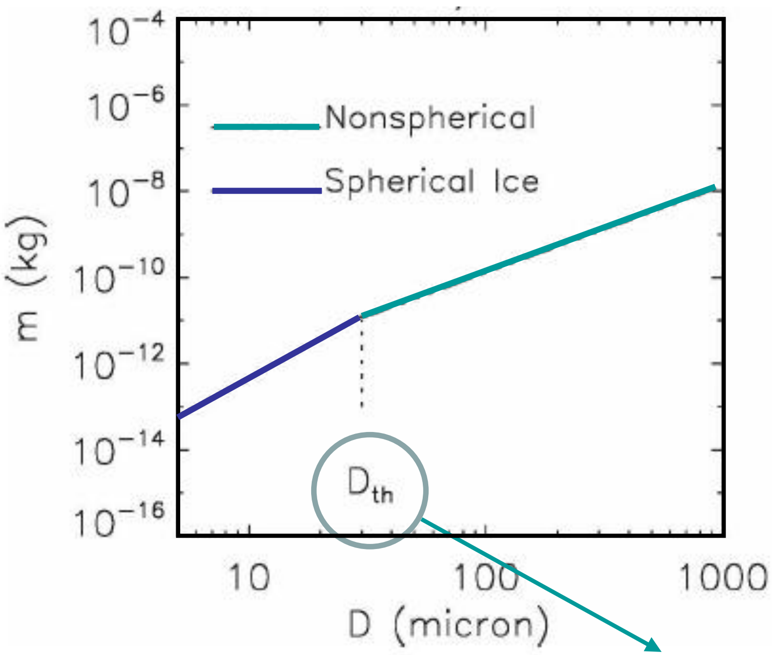
partially rimed crystal
$\alpha = f(F_{rim}, \rho_{rim})$
$\beta \sim 2$

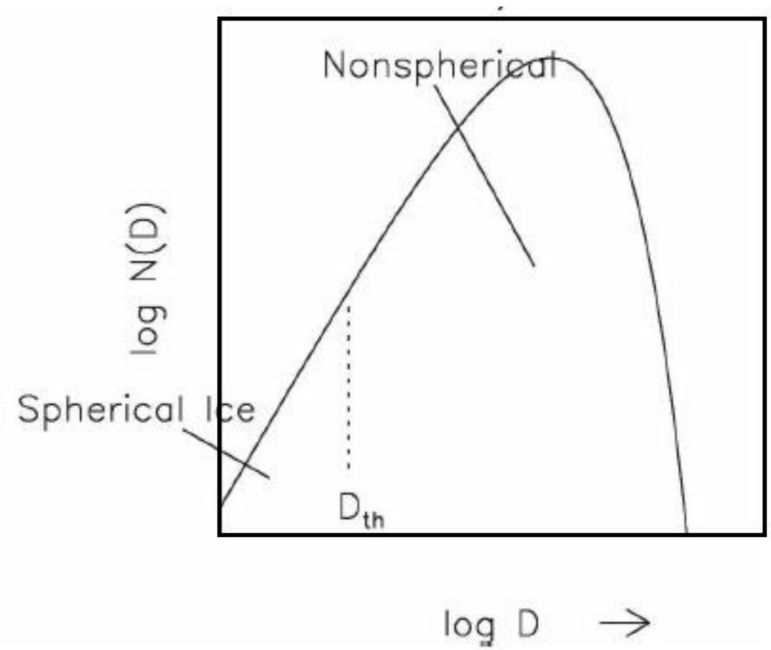
spherical graupel
$\alpha = f(F_{rim}, \rho_{rim})$
$\beta = 3$

Predicting process rates ~ computing $M_x^{(p)}$

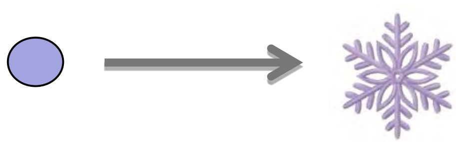
P3 SCHEME – **Determining $m(D) = \alpha D^{\beta}$ for regions of D:**

e.g. F_{rim} **= 0**





conceptual model + algebraic derivation



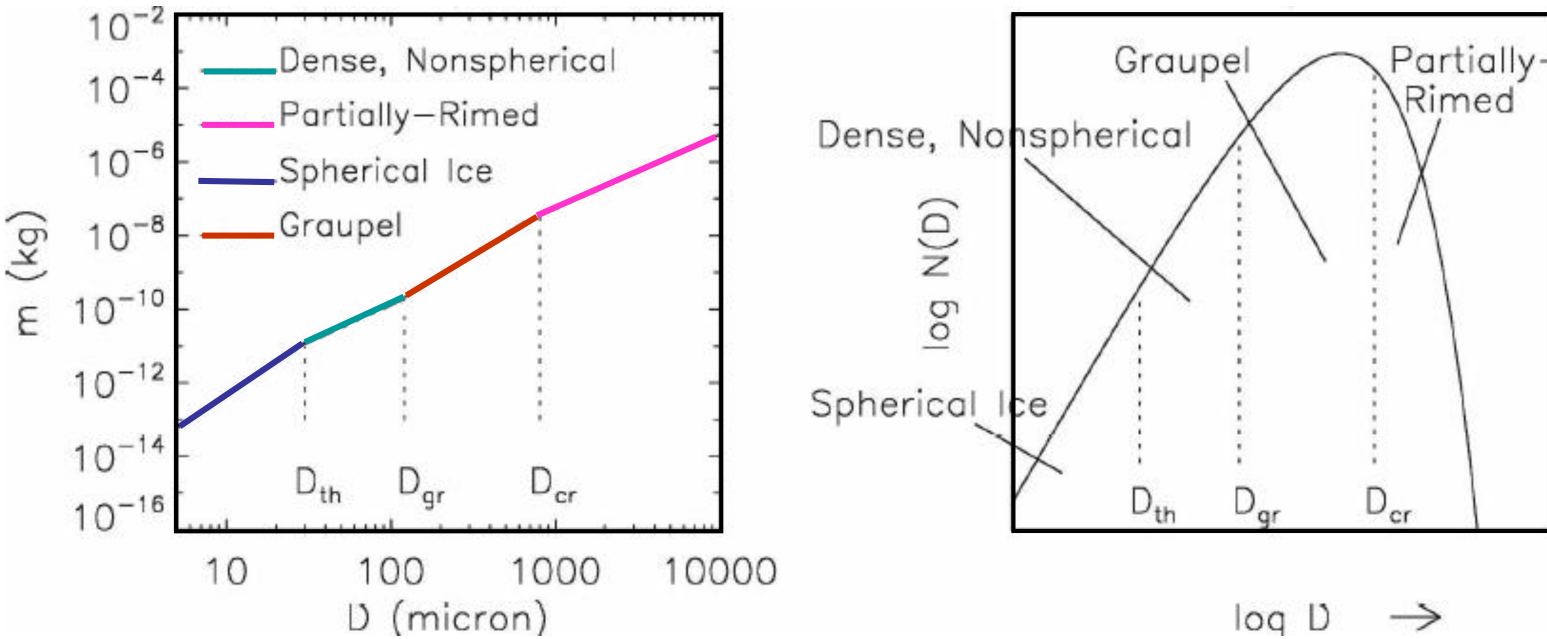
spherical ice
$\alpha_1 = \pi/6\ \rho_{bulk\_ice}$
$\beta_1 = 3$

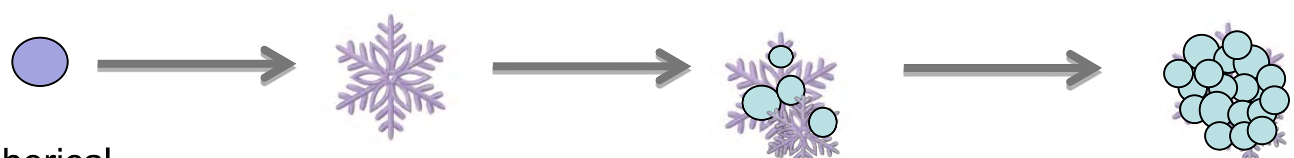
unrimed, non-spherical crystals
α_2 = const
$\beta_2 \sim 2$
} based on observed crystals

Predicting process rates ~ computing $M_x^{(p)}$

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

e.g. **$1 > F_{rim} > 0$; for a given ρ_{rim}**





spherical unrimed
$m(D) = \alpha_1 D^{\beta 1}$

non-spherical unrimed
$m(D) = \alpha_2 D^{\beta 2}$

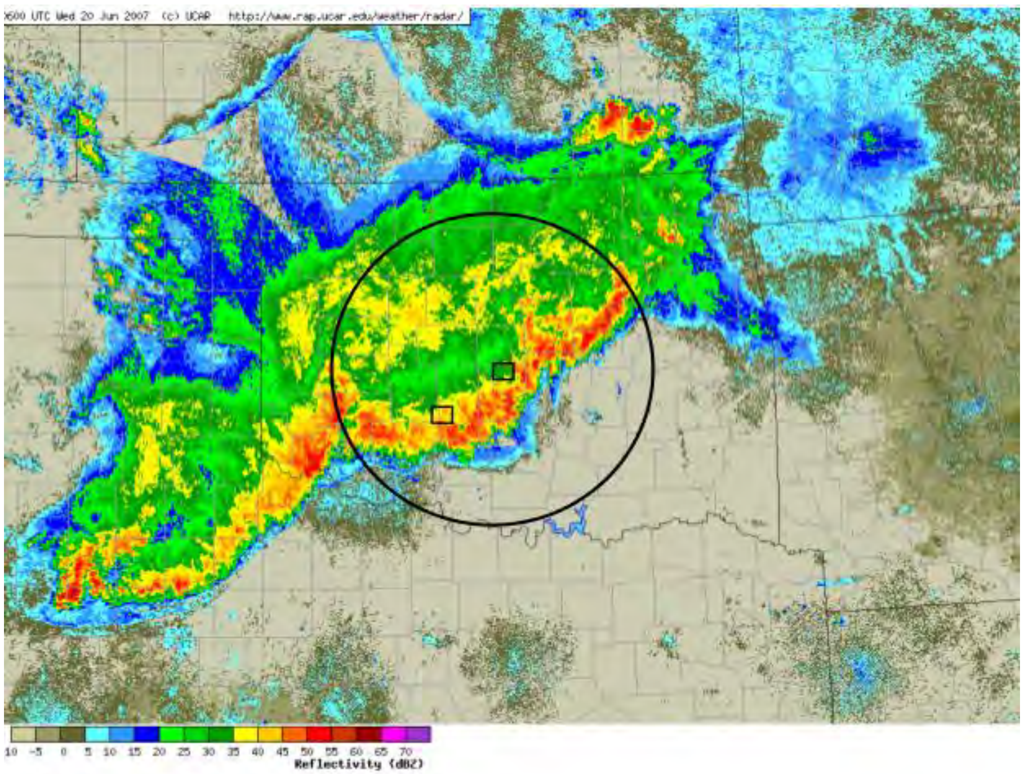
non-spherical, partially rimed
$m(D) = \alpha_3 D^{\beta 3}$

spherical completely rimed
$m(D) = \alpha_4 D^{\beta 4}$

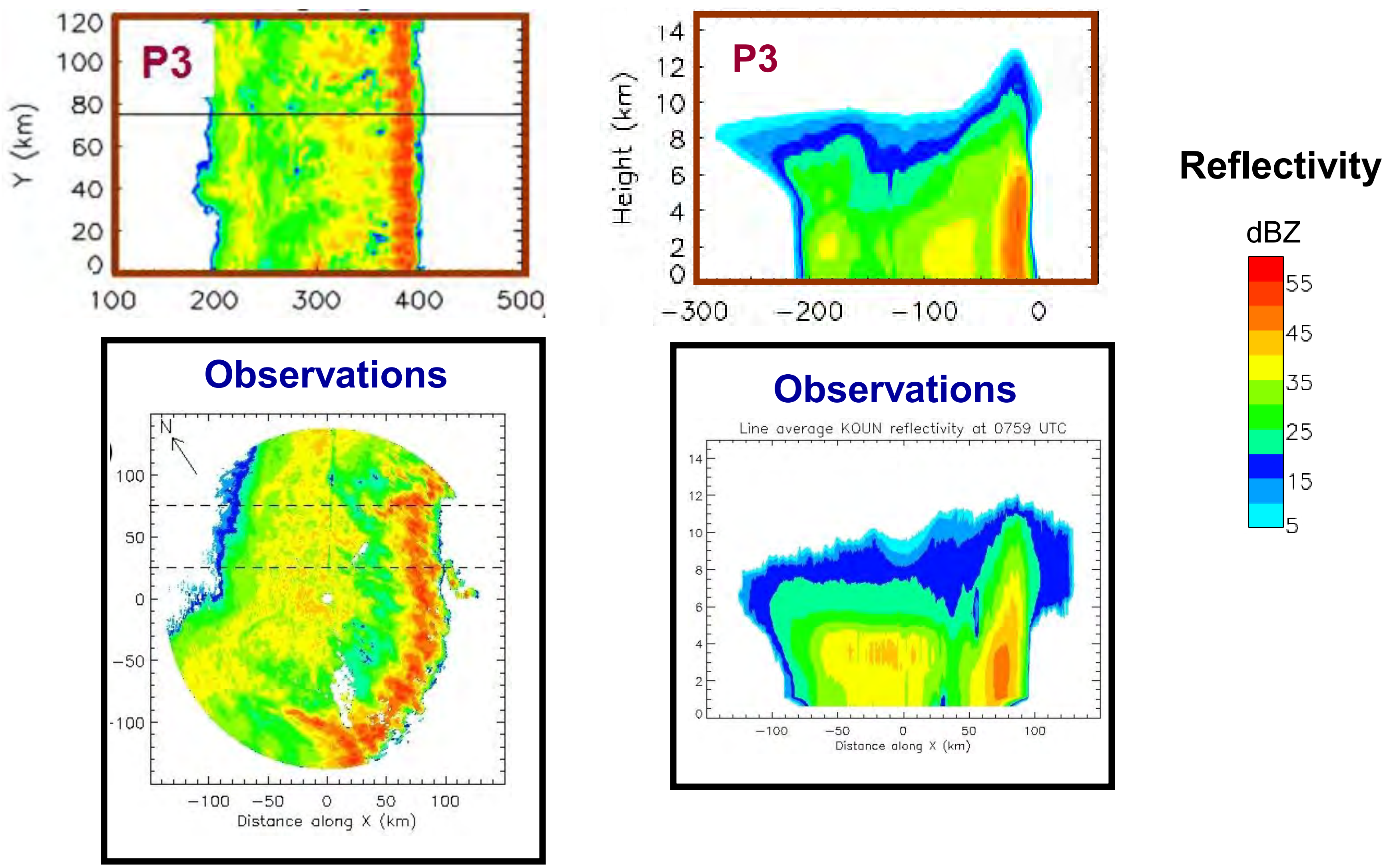
3D Squall Line case:

(June 20, 2007 central Oklahoma)

- WRF_v3.4.1, Δx = 1 km, Δz ~ 250-300 m, 112 x 612 x 24 km domain
- initial sounding from observations
- convection initiated by *u*-convergence
- no radiation, surface fluxes

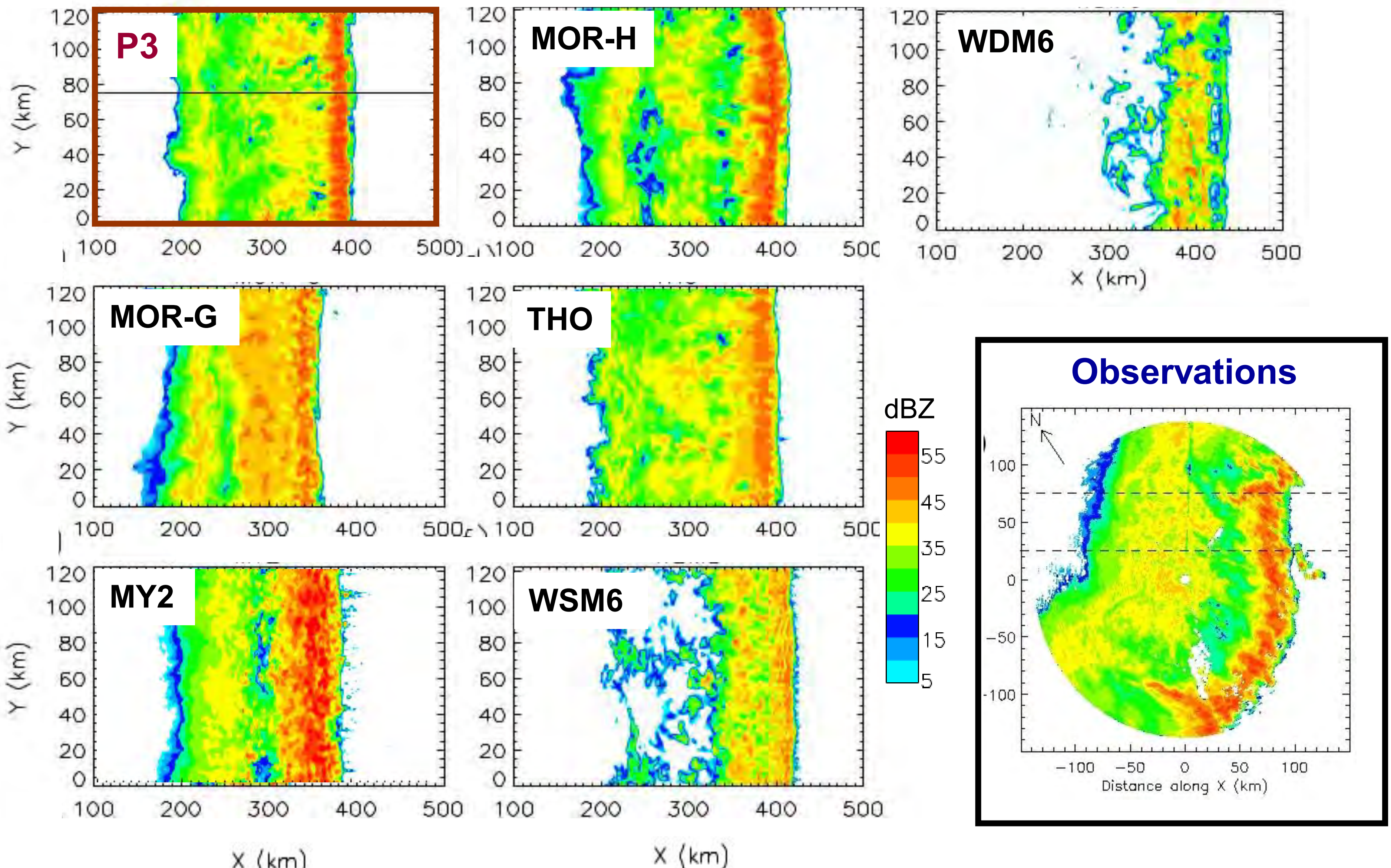


1-km WRF Simulations with P3 microphysics (1 category):



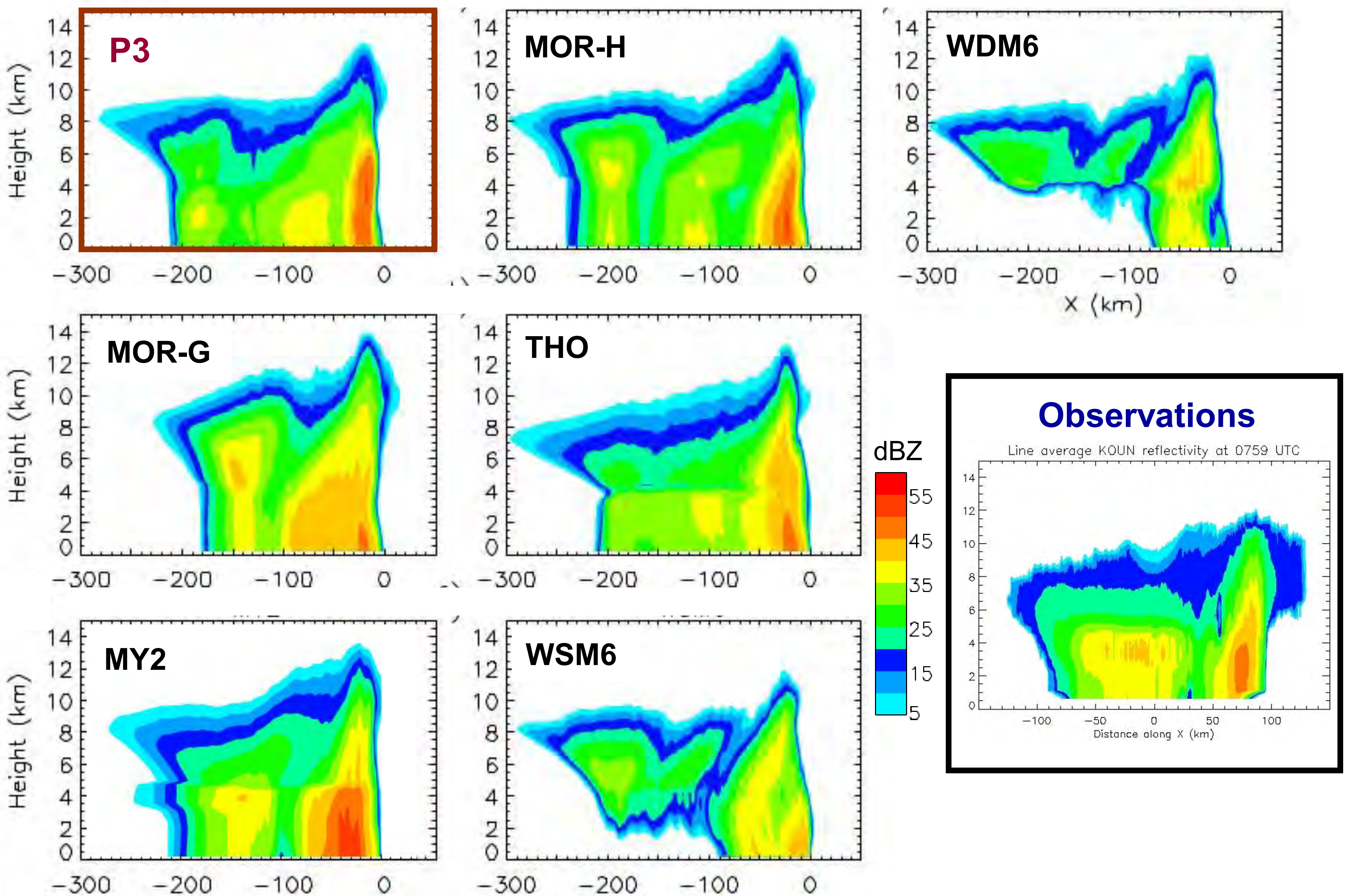
Morrison et al. (2015) [P3, part 2]

WRF Results: Base Reflectivity (1 km AGL, t = 6 h)



Morrison et al. (2015) [P3, part 2]

WRF Results: Line-averaged Reflectivity (t = 6 h)



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

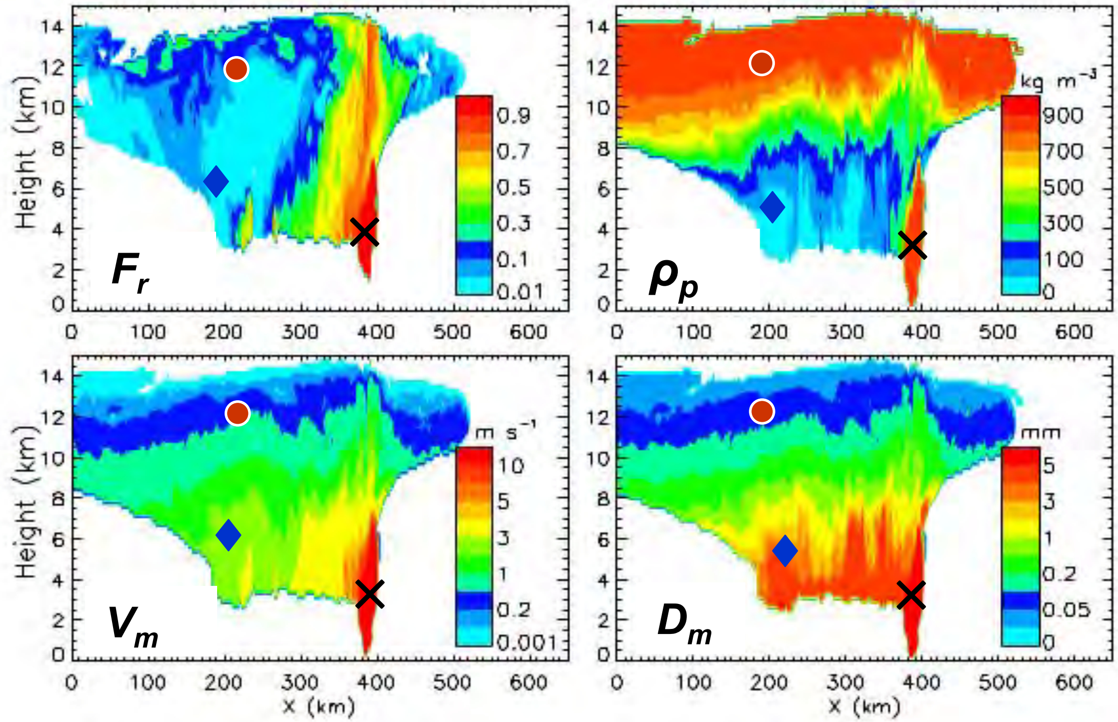
$F_r \sim 0$
$\rho \sim 50$ kg m-3
$V \sim 1$ m s^{-1}
$D_m \sim 3$ mm
→ ***aggregates***

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

etc.

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

Ice Particle Properties:



Note – *only <u>one</u> (free) category*

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

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

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

etc.

QUACK!

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

→ ***duck***

Timing Tests for 3D WRF Simulations

Scheme	Squall line case (Δx = 1 km)	Orographic case (Δx = 3 km)	# prognostic variables
P3	0.436 (**1.043**)	0.686 (**1.013**)	**7**
MY2	0.621 (1.485)	1.012 (1.495)	12
MOR-H	0.503 (1.203)	0.813 (1.200)	9
THO	0.477 (1.141)	0.795 (1.174)	7
WSM6	0.418 (**1.000**)	0.677 (**1.000**)	**5**
WDM6	0.489 (1.170)	0.777 (1.148)	8

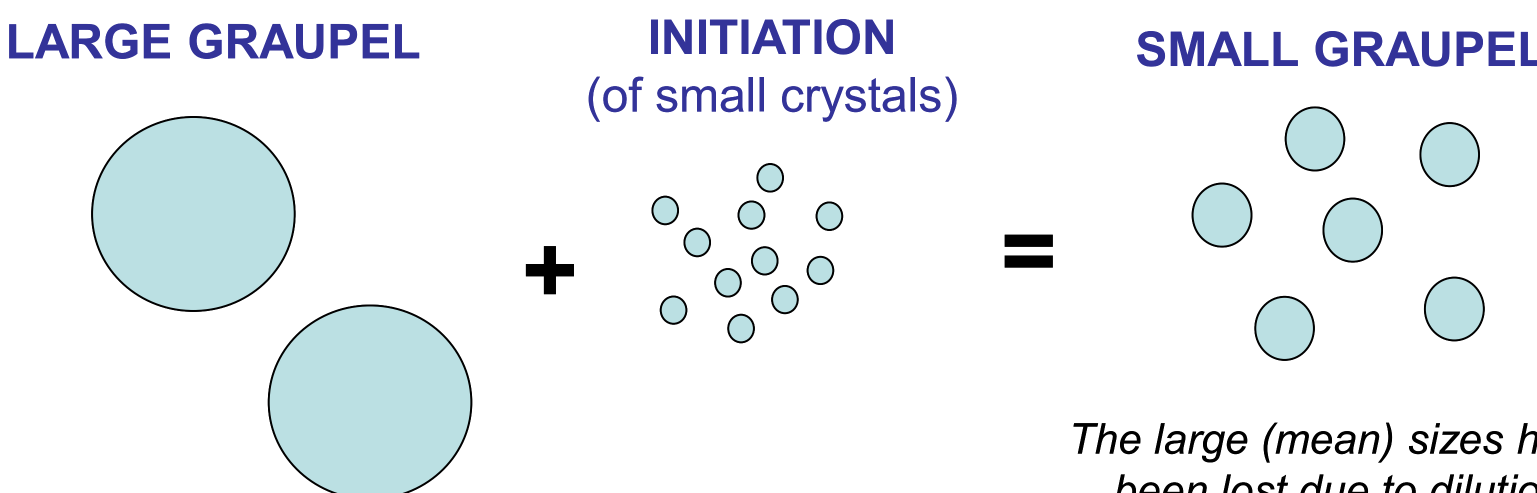
- Average wall clock time per model time step (units of seconds.)
- Times relative to those of WSM6 are indicated parenthetically.

→ 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



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

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:

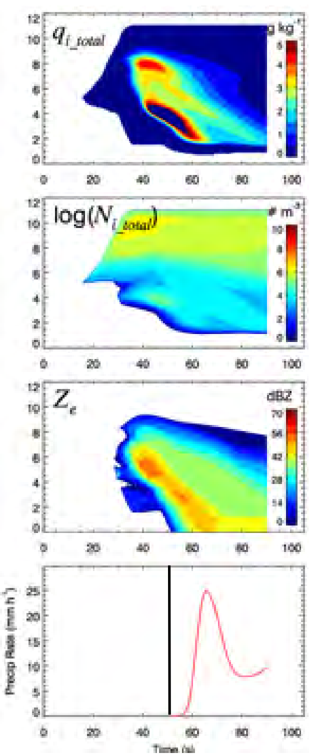
1. Initiation of new particles → **determine destination category**
2. Growth/decay processes
   - interactions with water vapor
   - interactions with liquid water
   - self-collection
   - **collection amongst other ice categories**
3. Sedimentation

Inclusion of Hallet-Mossop (rime splintering) process

with *nCat* = 1

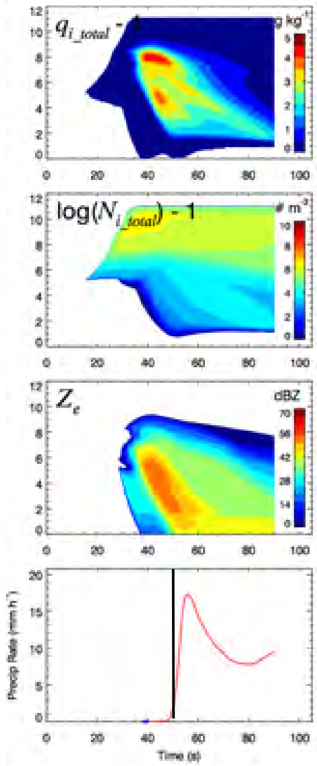
H-M *on*

***nCat* = 1**



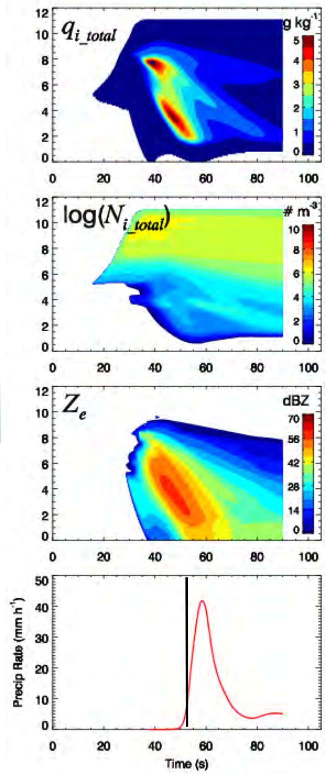
H-M *off*

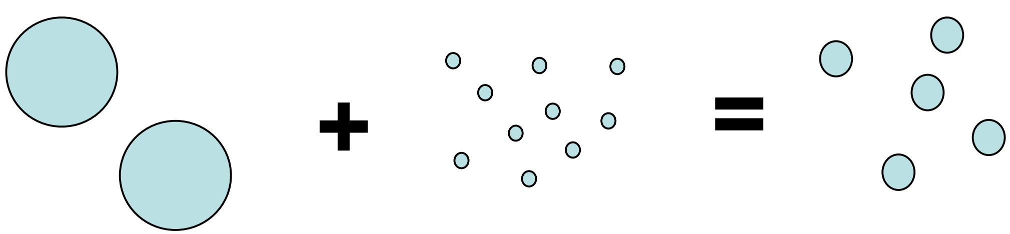
***nCat* = 1**



H-M *on*

***nCat* = 4**

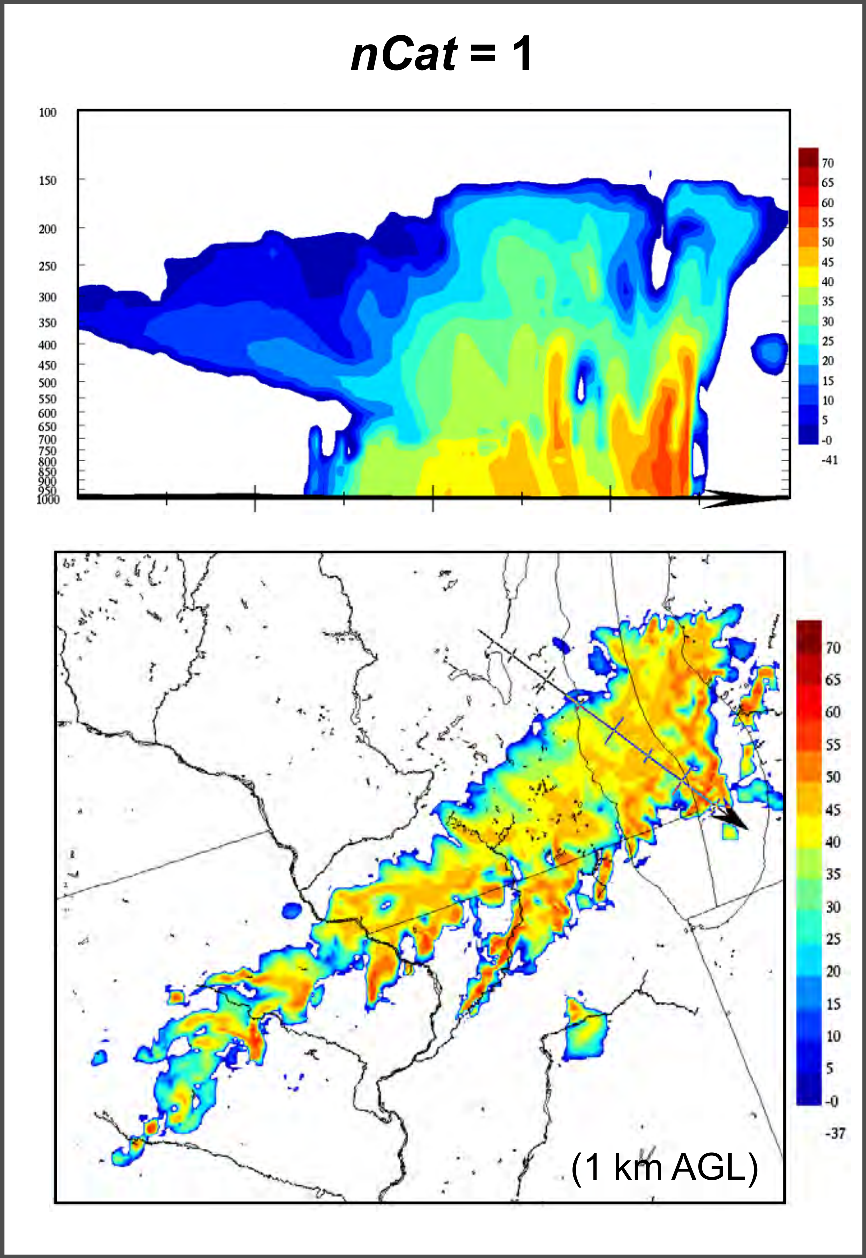


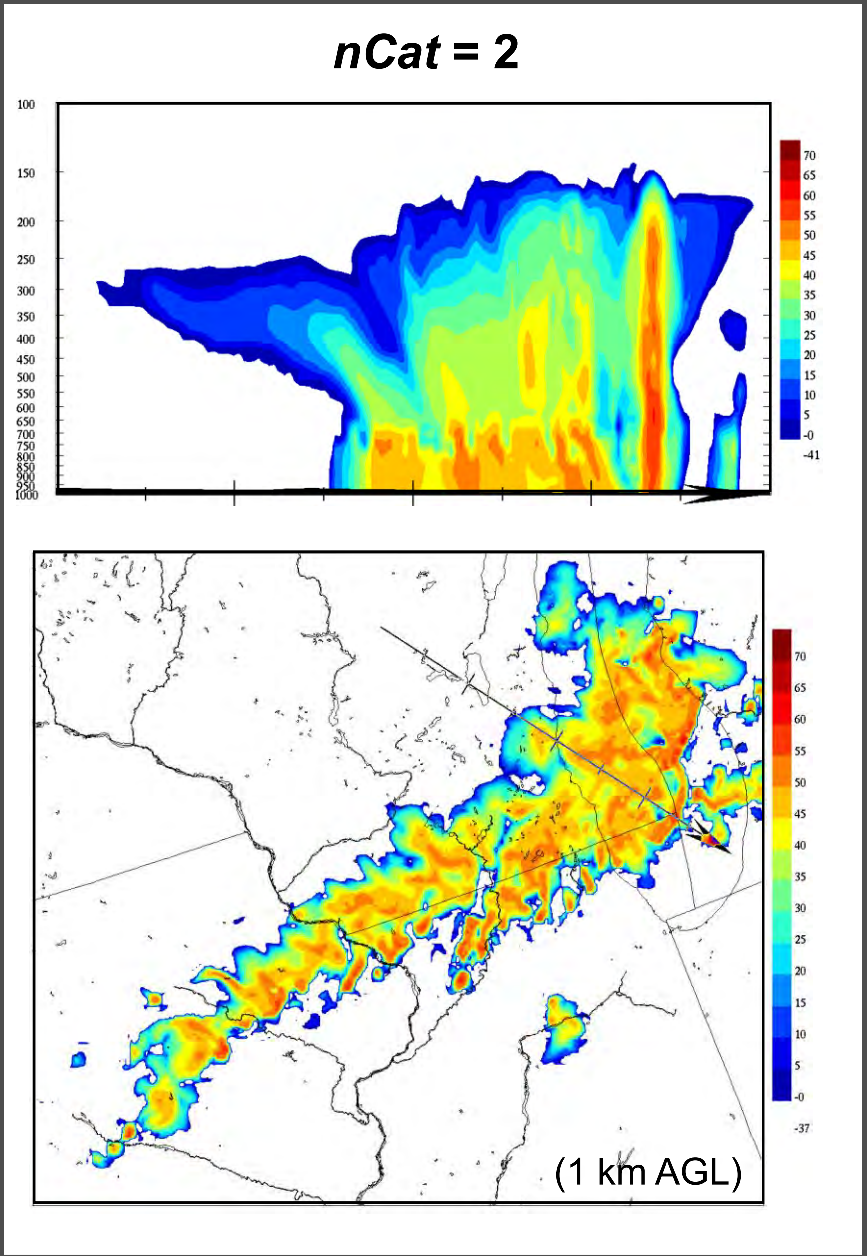


→ With *nCat* = 1, the Hallet-Mossop process results in excessive dilution

GEM (2.5 km), P3

Reflectivity





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 ~ 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!