Improving the Prediction of Cloud Ice in Operational NWP Models

Jason Milbrandt

Environment and Climate Change Canada (RPN-A)

In collaboration with:

Hugh Morrison, NCAR (Boulder, USA)

Zhipeng Qu, ECCC (Toronto)

Environment and Climate Change Canada

HAIC-HIWC Science Team Meeting

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RPN Service through science

Simplified organizational chart of ECCC

Environment and Climate Change Canada

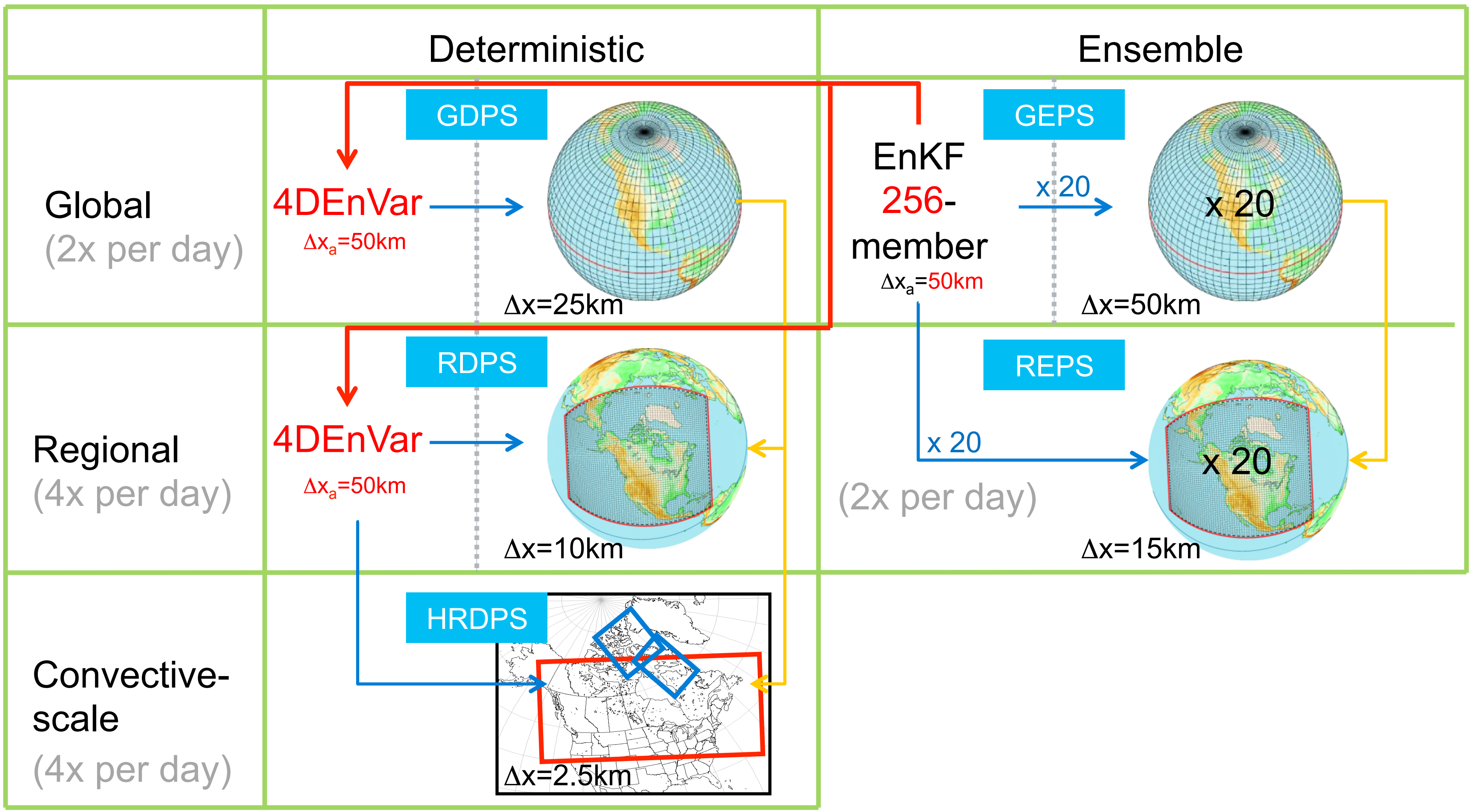
Science and Technology Branch

Cloud Physics and Severe Weather (Toronto)
- measurements, nowcasting techniques, etc.…

Numerical Weather Prediction Research (Montreal)
- development of NWP model and modeling systems

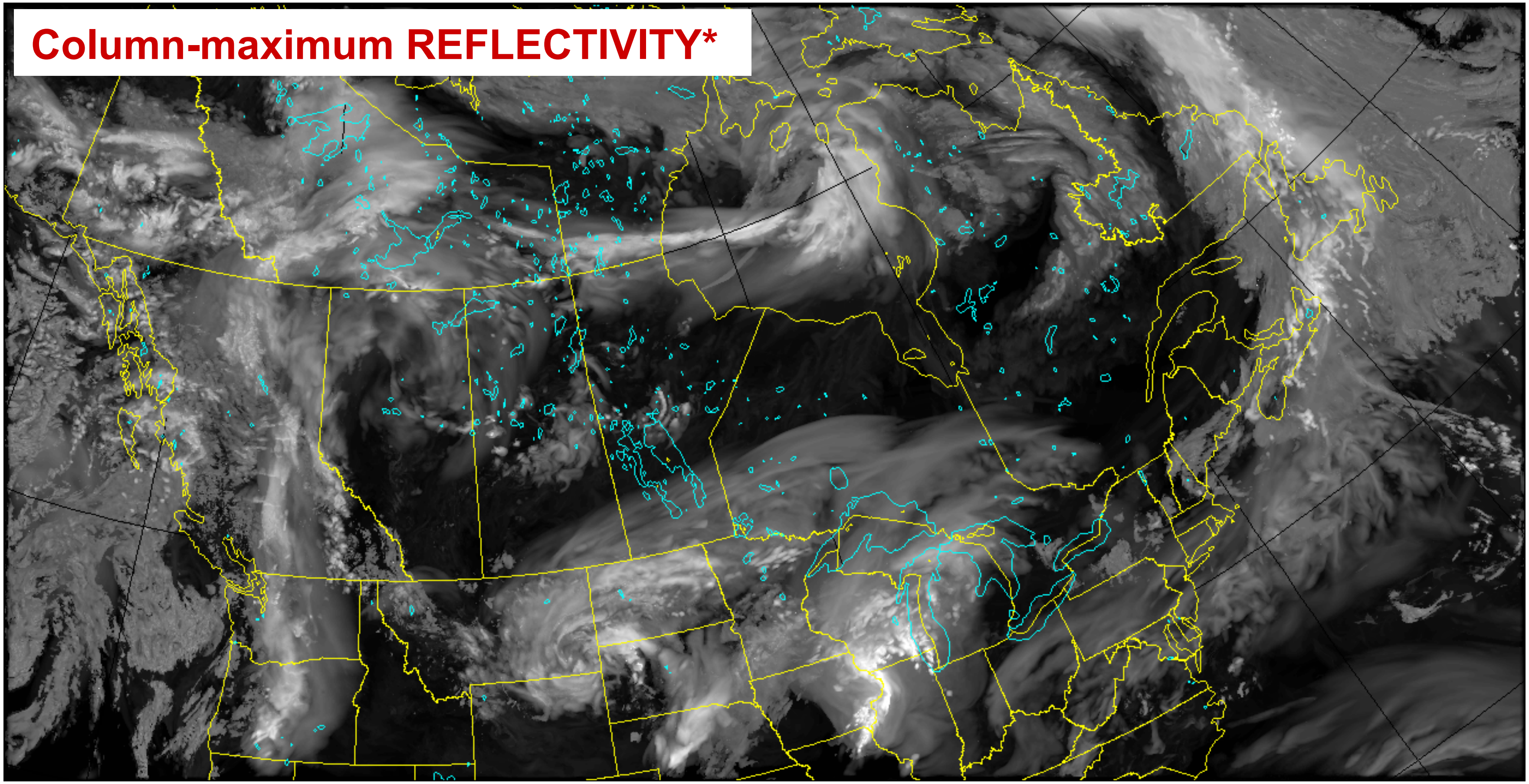
Meteorological Services of Canada
- operational NWP (modeling, forecasting, …)

ECCC’s current NWP systems



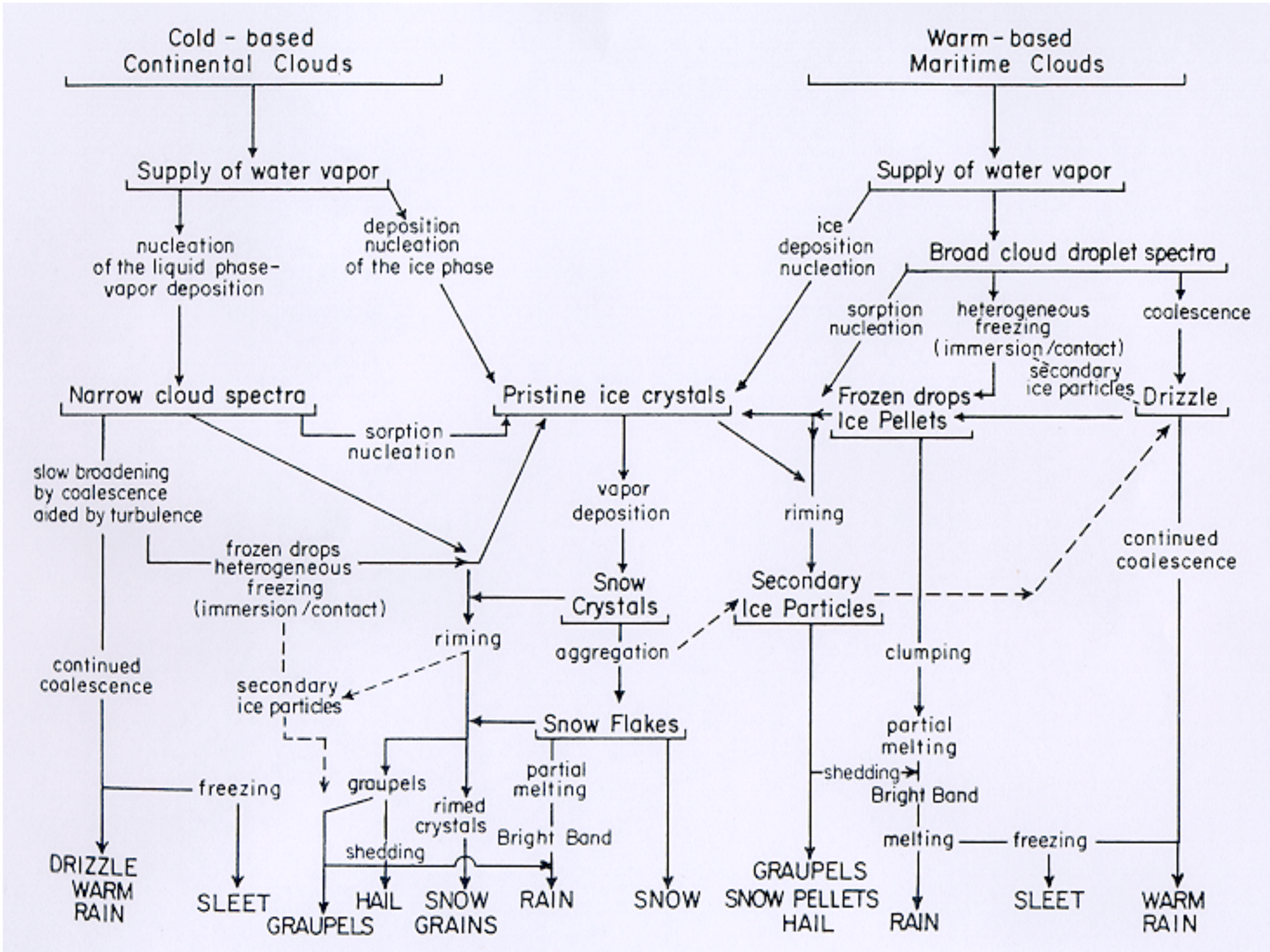
Simulation with 2.5-km HRDPS

(High Resolution Deterministic Prediction System)



*** Computed from microphysics**
(Milbrandt-Yau 2-moment)

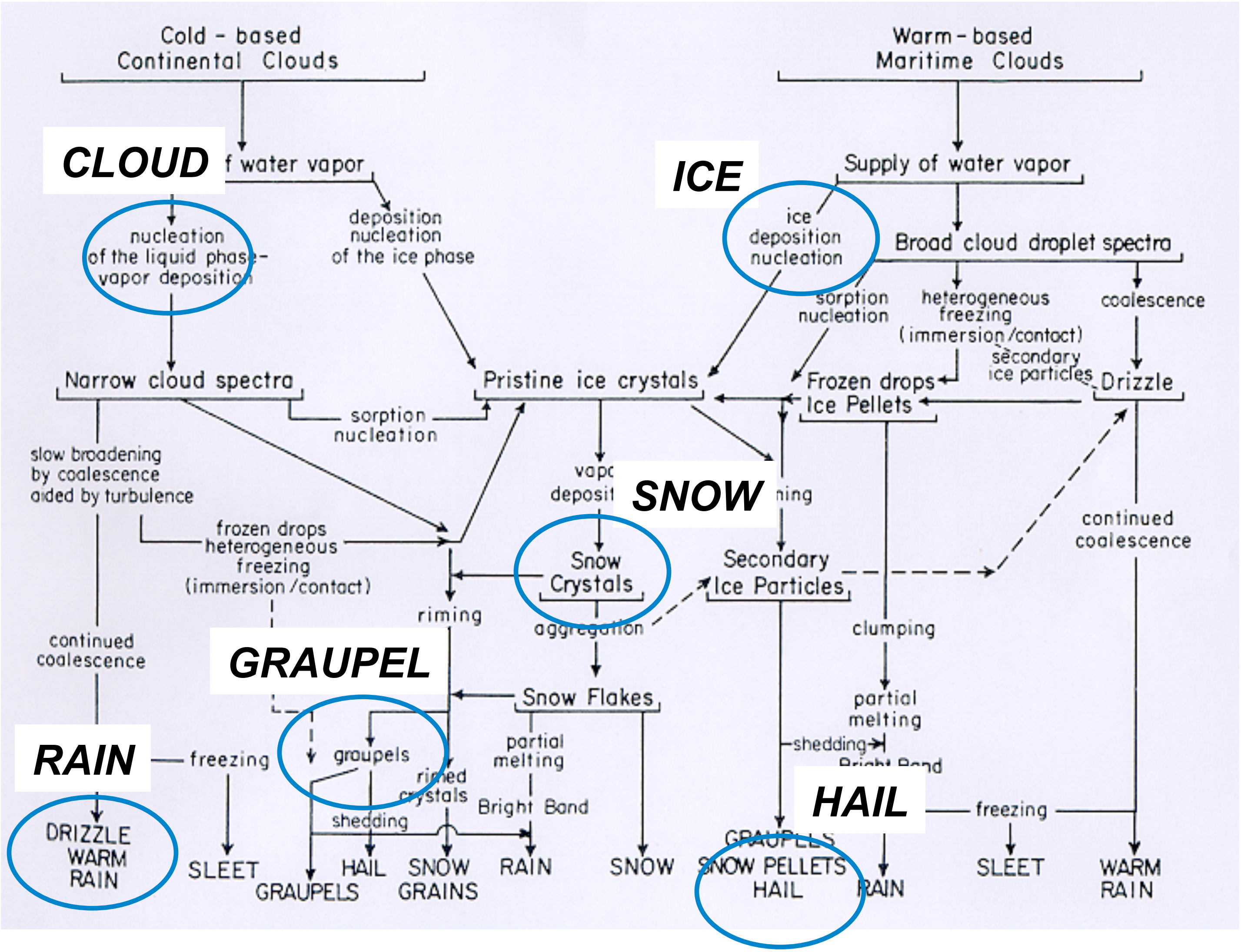
Cloud Microphysical Processes



***BAMS*, 1967**

Microphysics Parameterization Schemes

Hydrometeors are traditionally partitioned into categories

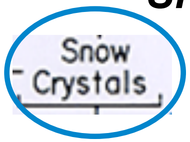


***BAMS*, 1967**

Microphysics Parameterization Schemes

The particle size distributions are modeled

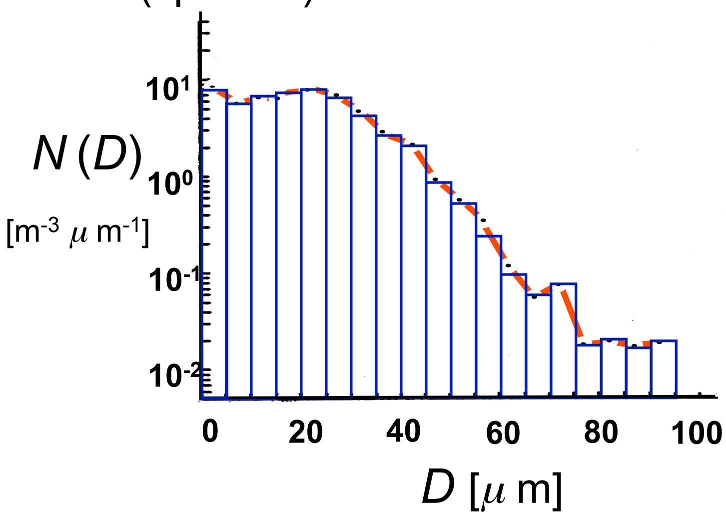
e.g. ***SNOW***



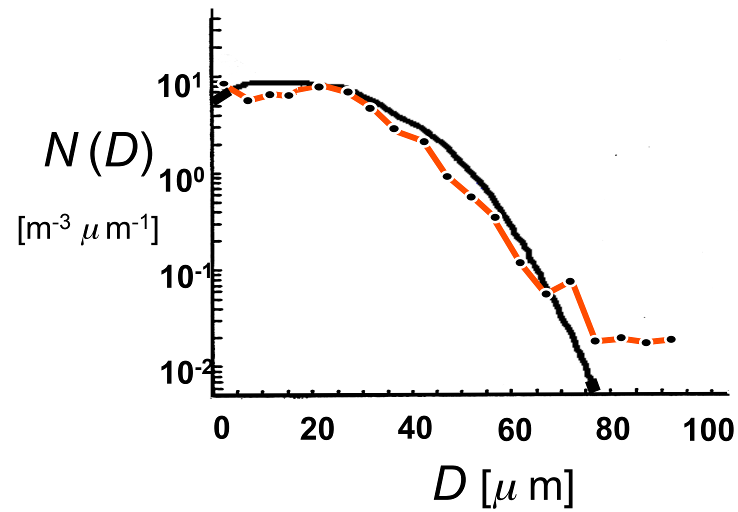
For each category, microphysical processes are parameterized to predict the evolution of the *particle size distribution, N(D)*

TYPES of SCHEMES:

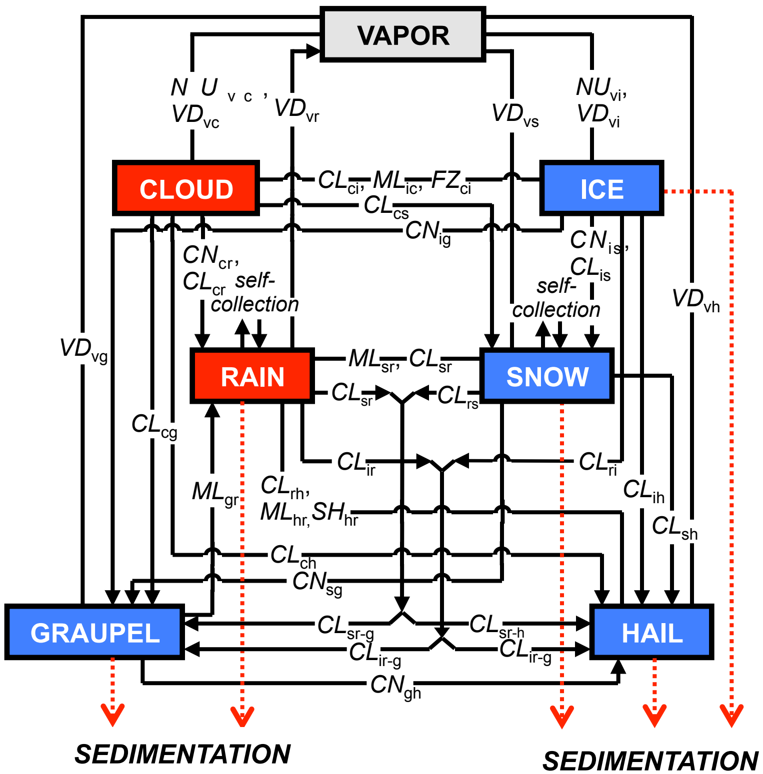
Bin-resolving: (spectral) $$N(D) = \sum_{i=1}^{I} N_i$$



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



Bulk Microphysics Scheme* in GEM (HRDPS)



Six hydrometeor categories:

2 liquid: ***cloud*, *rain***

4 frozen: ***ice*, *snow*, *graupel*, *hail***

For each category *x* = *c, r, i, s, g, h*:

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

$$V_x(D) = a_x D^{b_x}$$

$$m_x(D) = c_x D^{d_x}$$

(empirical)

Scheme version	Prognostic variables	
double-moment	q_x, N_x	(12)
triple-moment	q_x, N_x, Z_x	(17)

* Milbrandt and Yau (2005)

Traditional bulk approach for the ice phase

Problems with pre-defined categories:

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

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}
$m = (\pi/6\ \rho_h)D^3$
$V = a_h D^{bh}$

← abrupt / unphysical conversions

NOTE: *Bin microphysics schemes have the identical problem*

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

vs.

"fixed" category – traditional; prescribed properties, pre-determined type

Compared to traditional (ice-phase) schemes, P3:

- avoids <u>some</u> 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)
Milbrandt and Morrison (2016)

Overview of P3 Scheme

Prognostic Variables: (advected)

LIQUID PHASE: 2 categories, 2-moment:

$\boldsymbol{Q_c}$	– cloud mass mixing ratio	[kg kg^{-1}]
$\boldsymbol{Q_r}$	– rain mass mixing ratio	[kg kg^{-1}]
$\boldsymbol{N_c}$	– cloud number mixing ratio	[#kg^{-1}]
$\boldsymbol{N_r}$	– rain number mixing ratio	[#kg^{-1}]

ICE PHASE: *nCat* categories, 4 prognostic variables each:

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

* $Q_{tot} = Q_{dep} + Q_{rim}$, total ice mass mixing ratio (actual advected variable)

Overview of P3 Scheme

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)

GENERAL (all schemes)

$$Q^{+} = Q^{0} + \underbrace{\Delta Q\Big|_{PROC\_1}} + \Delta Q\Big|_{PROC\_2} + \ldots$$

$$\Delta Q\Big|_{PROC\_1} = \Delta t \cdot \frac{1}{\rho}\int_0^\infty \underbrace{\frac{dm(D)}{dt}\Big|_{PROC\_1} N(D)dD}$$

$\propto M^{(p)}$ (and other moments)

Computing the tendencies for the prognostic variables (i.e. process rates) essentially amounts to computing various moments of $N(D)$

Predicting process rates for V_x → computing various $M_x^{(p)}$

V = prognostic variable (Q, N, …)
x = category (rain, ice, …)

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

TRADITIONAL SCHEMES **(e.g. 2-moment)**

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

Fixed category ⇨ constant m-D parameters $\qquad m(D) = \alpha D^\beta$

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

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

- impose assumption about μ
- 2 equations, 2 unknowns → solve for λ, N_0

→ **Now, any $M^{(p)}$ can be computed analytically**

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

P3 SCHEME

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

Free category ⇨ variable m-D, A-D, and V-D parameters

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

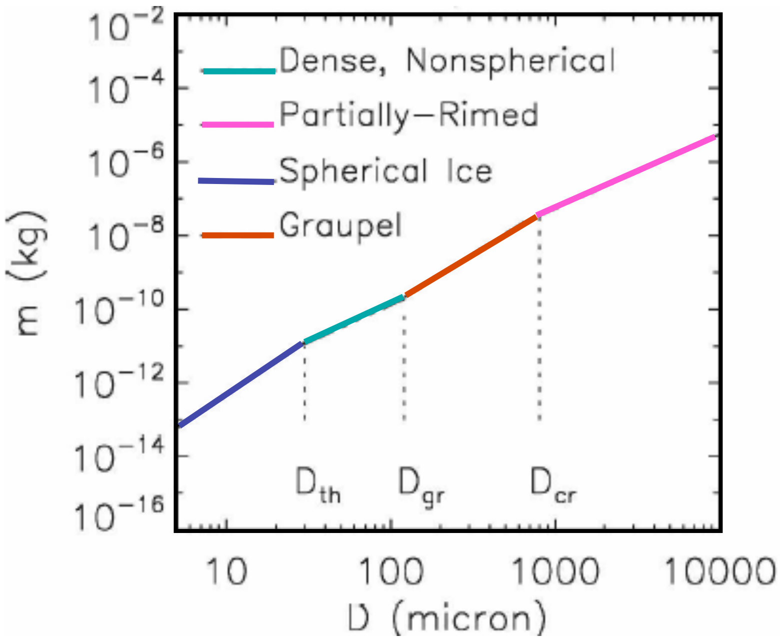
$$N = \int_0^\infty N_x(D)dD = M^{(0)} = N_{0x}\frac{\Gamma(1+\mu_x)}{\lambda_x^{1+\mu_x}}$$

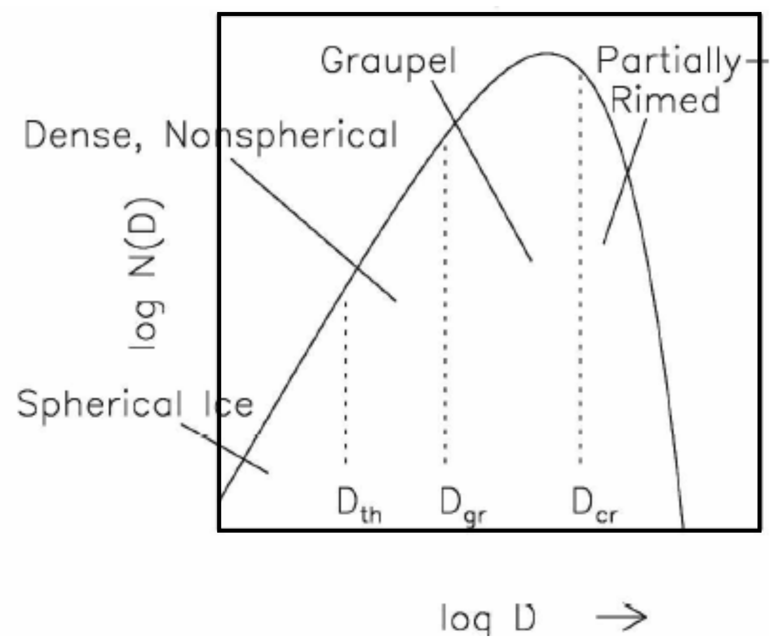
→ cannot compute Q (or any other $M^{(p)}$) analytically

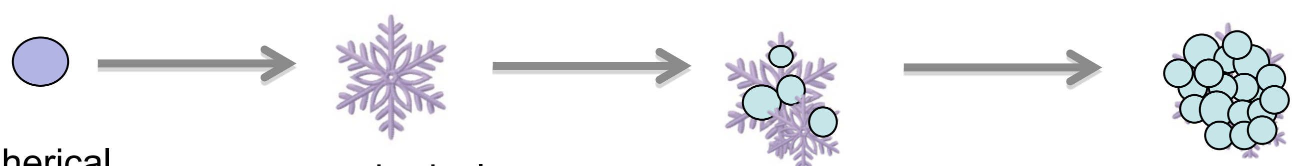
Predicting process rates ~ computing $M_x^{(p)}$

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

General: **1 > F_{rim} > 0; for a given ρ_{rim}**







spherical unrimed	non-spherical unrimed	non-spherical, partially rimed	spherical completely rimed
$m(D) = \alpha_1 D^{\beta 1}$	$m(D) = \alpha_2 D^{\beta 2}$	$m(D) = \alpha_3 D^{\beta 3}$	$m(D) = \alpha_4 D^{\beta 4}$

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

P3 SCHEME – Computing $N(D)$ parameters :

1. Compute properties $F_{rim} = Q_{rim}/(Q_{dep}+Q_{rim})$, $\rho_{rim} = Q_{rim} / B_{rim}$
2. Determine integral ranges, D_{th}, D_{gr}, D_{cr}
3. Determine PSD parameters (λ, N_0, μ)
   - solved numerically (iteratively; pre-computed and stored in look-up table)

$$Q = \frac{1}{\rho}\left[\int_0^{D_{th}} \alpha_1 D^{\beta_1+\mu} e^{-\lambda D} dD + \int_{D_{th}}^{D_{gr}} \alpha_2 D^{\beta_2+\mu} e^{-\lambda D} dD + \int_{D_{gr}}^{D_{cr}} \alpha_3 D^{\beta_3+\mu} e^{-\lambda D} dD + \int_{D_{cr}}^{\infty} \alpha_4 D^{\beta_4+\mu} e^{-\lambda D} dD\right]$$

$$N = N_{0x} \frac{\Gamma(1+\mu_x)}{\lambda_x^{1+\mu_x}}$$

$$\mu = f(\lambda)$$

4. Also, match A-D parameters to m-D parameters for the various regions of D
   - based on geometric + empirical relations
   - for V-D (process rates and sedimentation) and r_{i_eff} (optical properties)

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

***P3 SCHEME* – Computing the process rates:**

Now, have λ, N_0, μ, and integral ranges D_{th}, D_{gr}, D_{cr} (plus $\alpha_{(i)}$, $\beta_{(i)}$, …)

$$Q^{+} = Q^{0} + \underbrace{\Delta Q\big|_{PROC\_1}} + \Delta Q\big|_{PROC\_2} + \ldots$$

$$\Delta Q\big|_{PROC\_1} = \Delta t \cdot \frac{1}{\rho}\underbrace{\int_0^\infty \frac{dm(D)}{dt}\bigg|_{PROC\_1} N(D)dD}$$

$\propto X_1$ (and X_2, …)

$$X_1 = \int_0^{D_{th}} D^a N_0 e^{-\lambda D} f(\alpha_1, \beta_1, \ldots)dD + \int_{D_{th}}^{D_{gr}} D^b N_0 e^{-\lambda D} f(\alpha_2, \beta_2, \ldots)dD$$

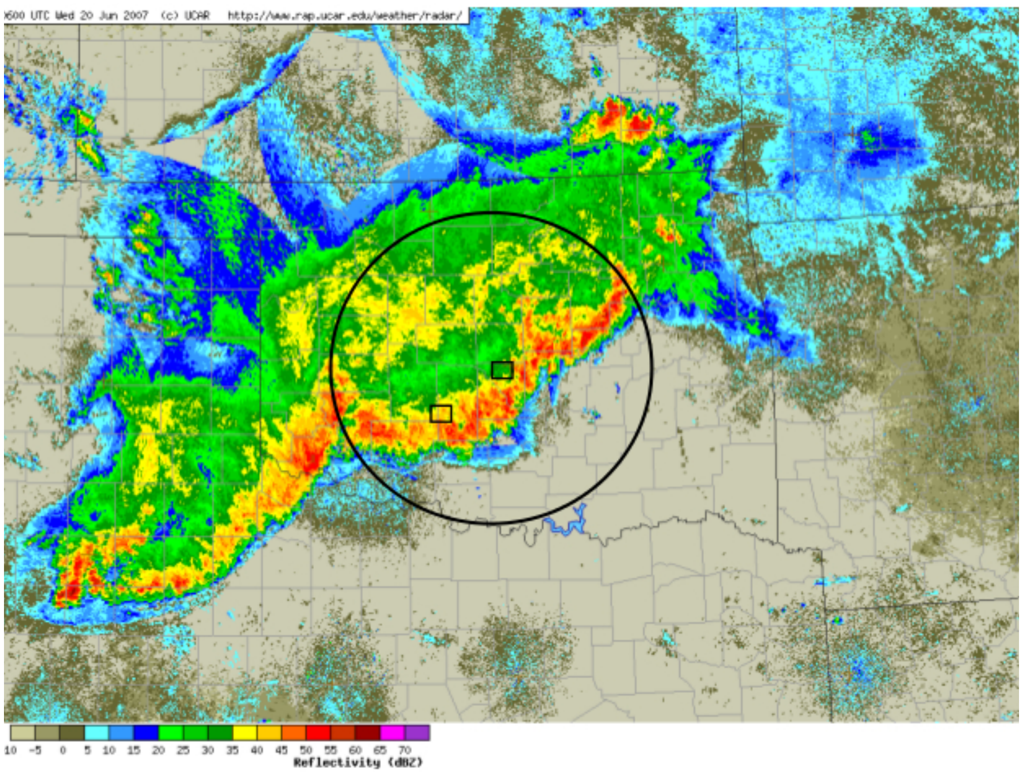
$$+ \int_{D_{gr}}^{D_{cr}} D^c N_0 e^{-\lambda D} f(\alpha_3, \beta_3, \ldots)dD + \int_{D_{cr}}^{\infty} D^d N_0 e^{-\lambda D} f(\alpha_4, \beta_4, \ldots)dD$$

Predicting process rates → computing sums (X_n) of partial moments

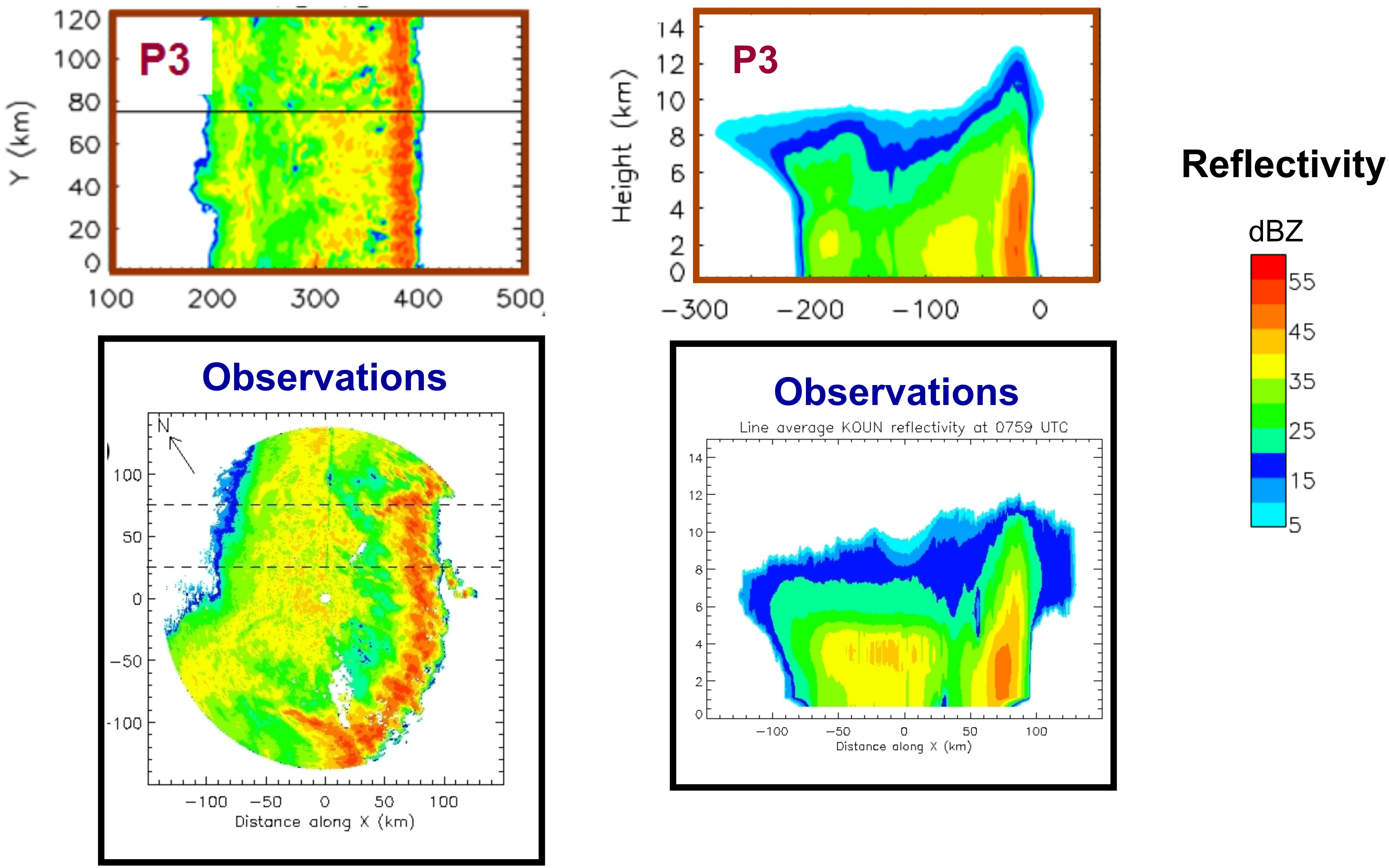
3D Squall Line case:

(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

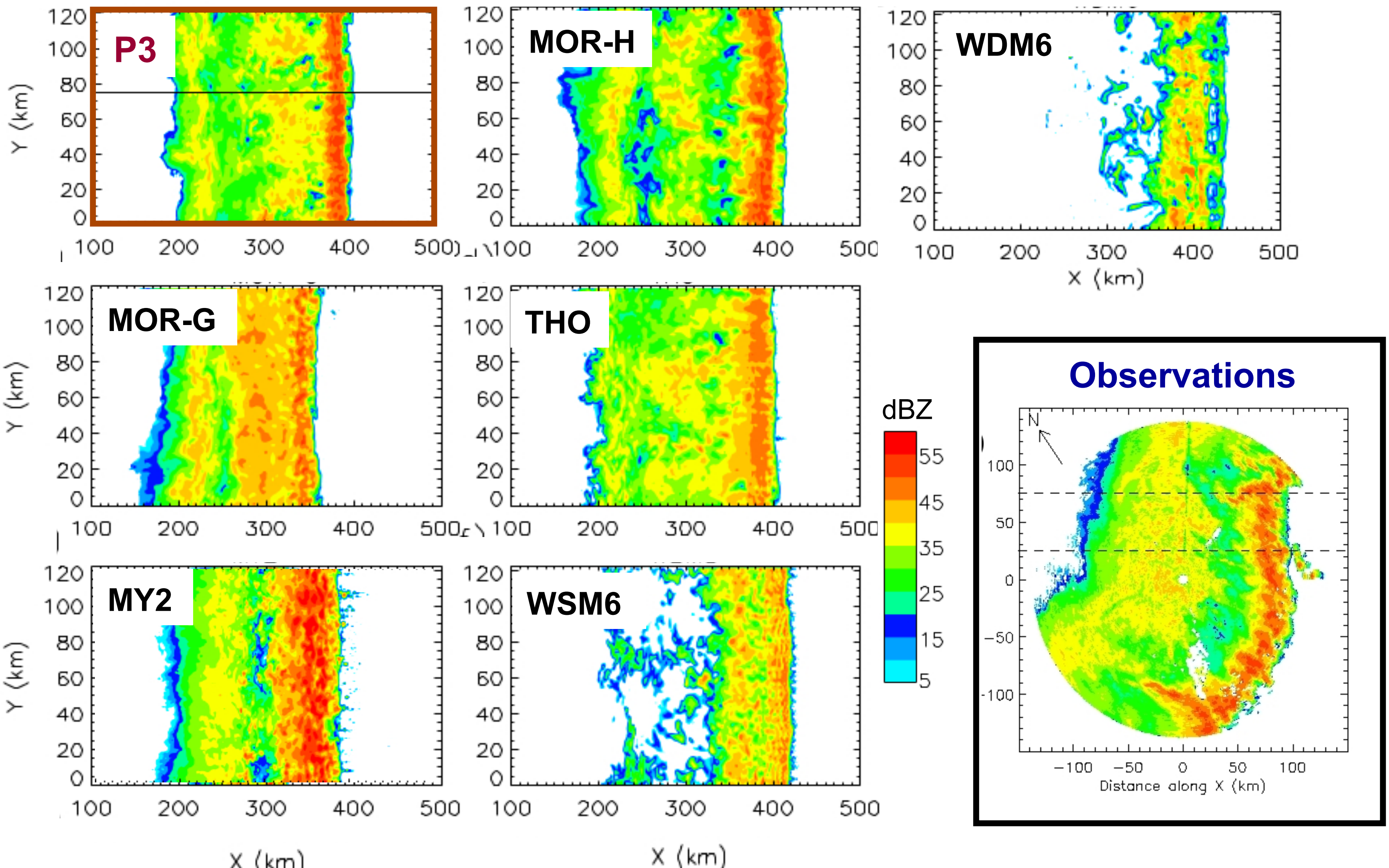


1-km WRF Simulations with P3 microphysics (1 category):



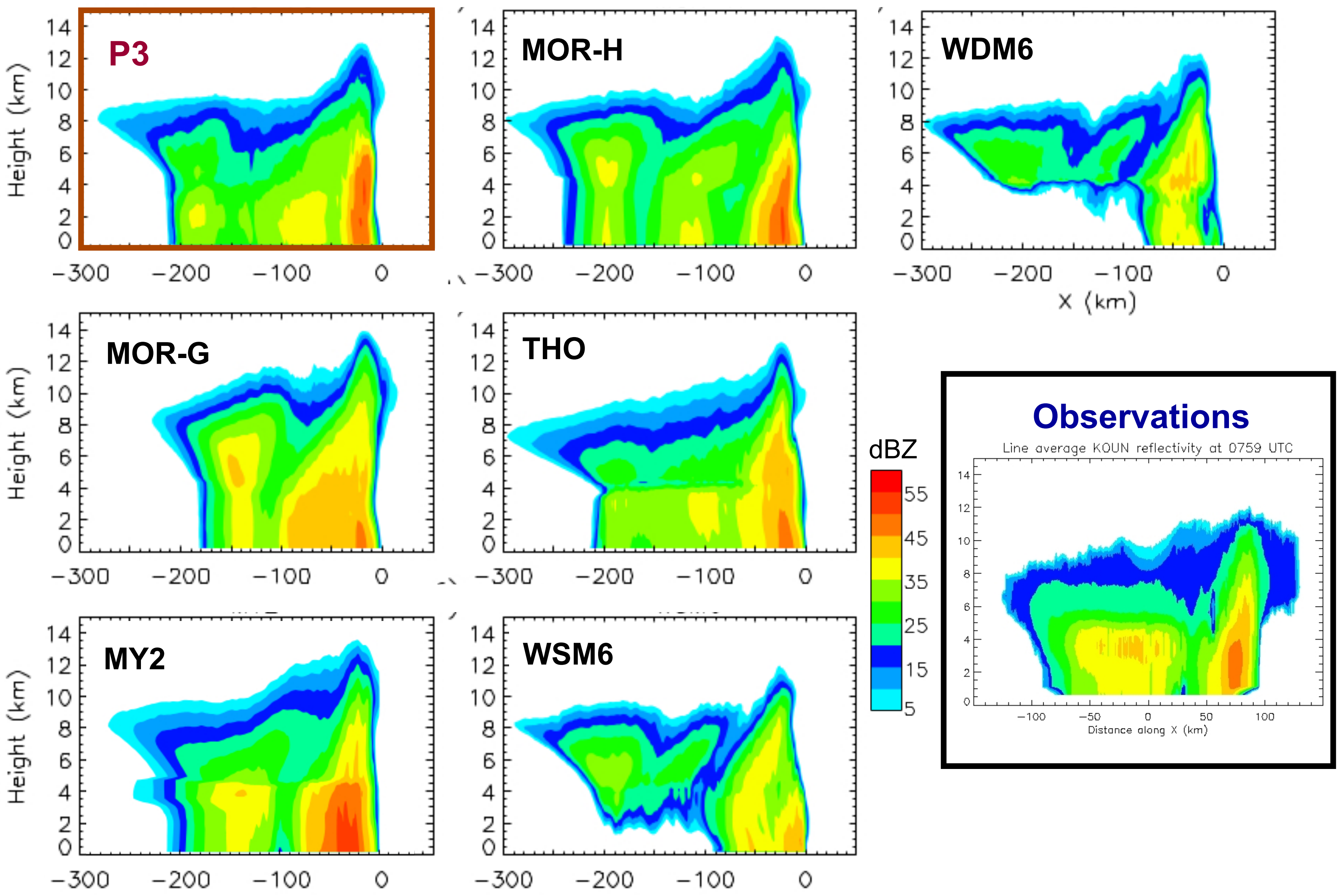
Morrison et al. (2015) [P3, part 2]

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 ~ 0-0.1
ρ ~ 900 kg m^{-3}
V ~ 0.3 m s^{-1}
D_m ~ 100 μm
→ ***small crystals***

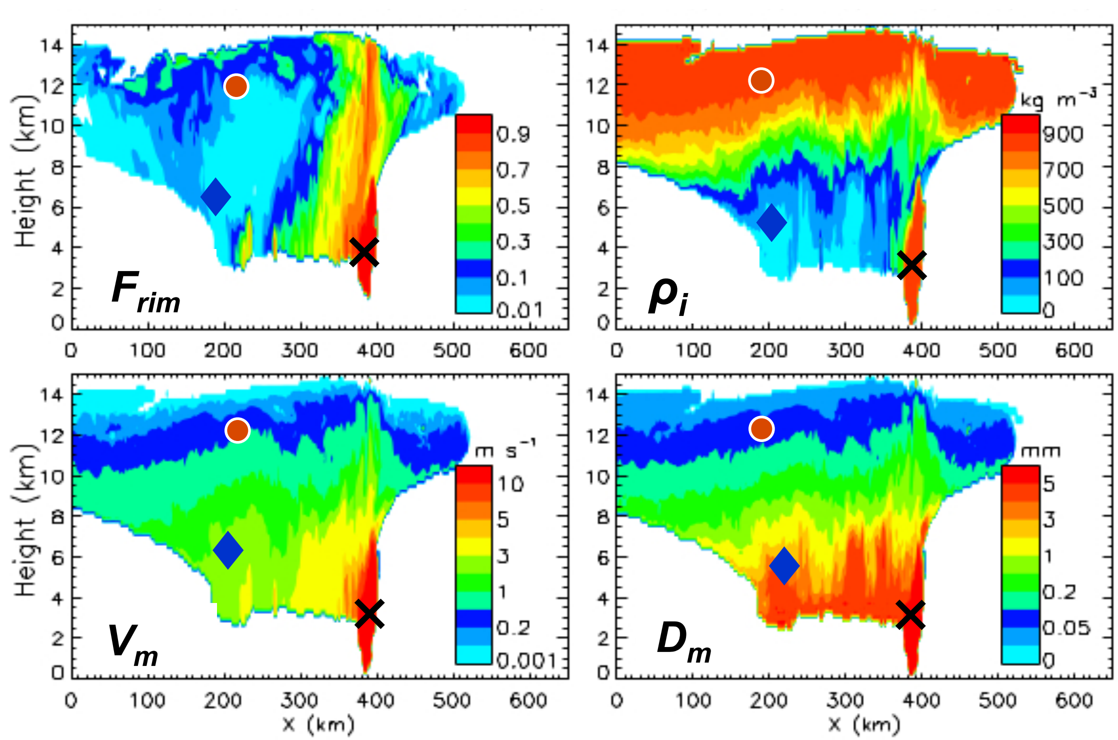
F_r ~ 0
ρ ~ 50 kg m-3
V ~ 1 m s^{-1}
D_m ~ 3 mm
→ ***aggregates***

F_r ~ 1
ρ ~ 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:



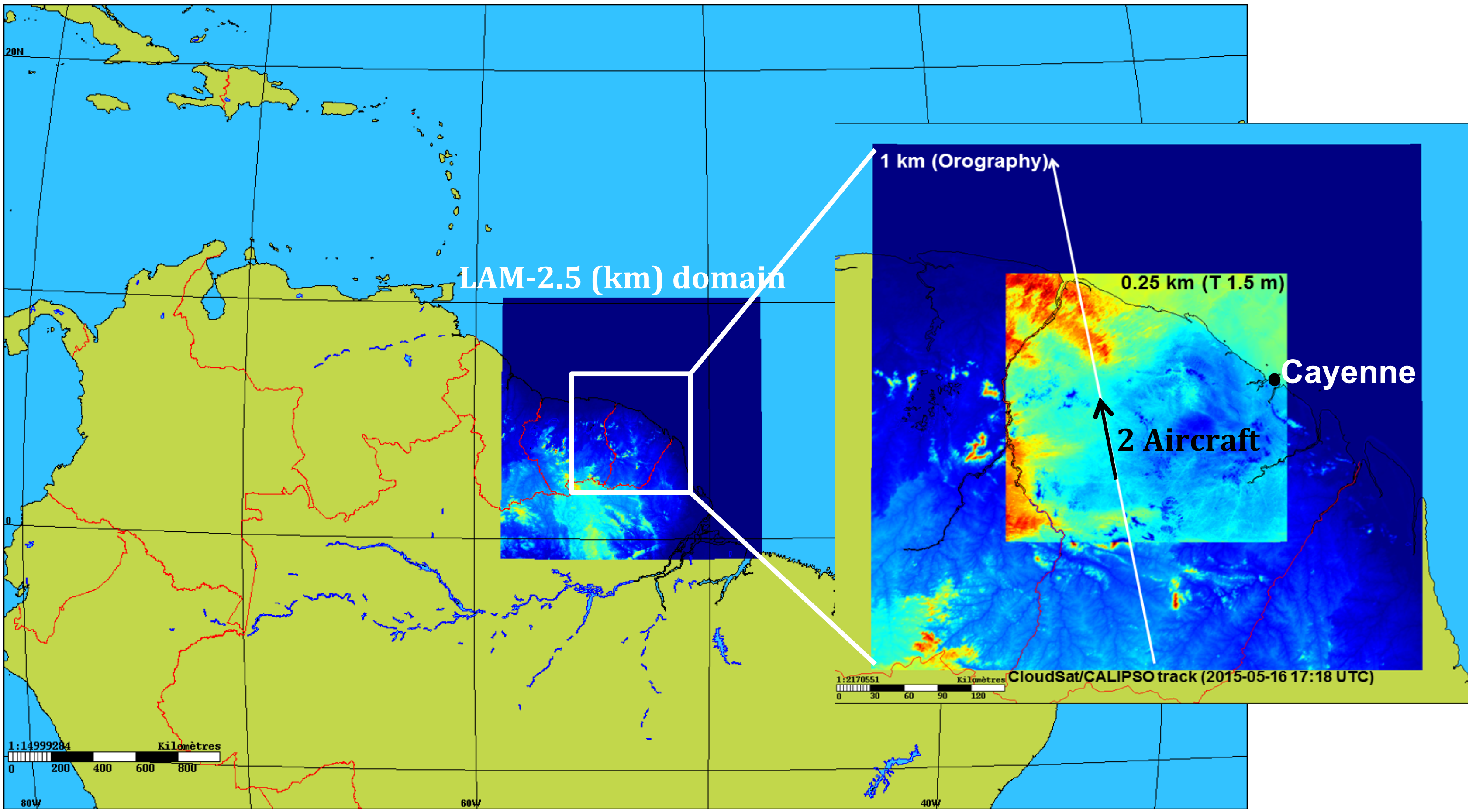
Note – *only <u>one</u> (free) category*

1. High Resolution NWP model at Environment Canada

Objective 2: Assessment of the hi-res NWP model.

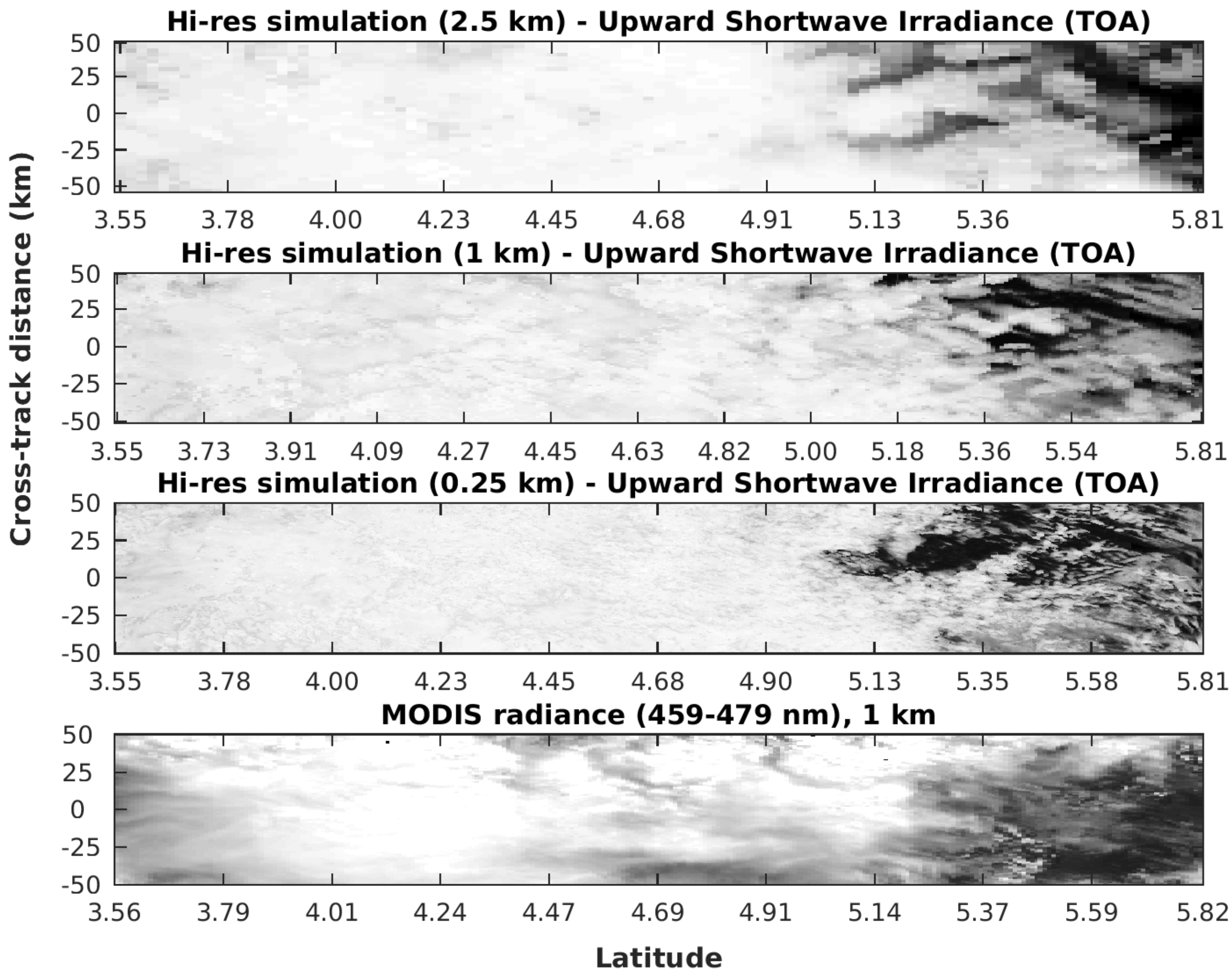
Case: Cayenne, French Guiana (May 16, 2015)

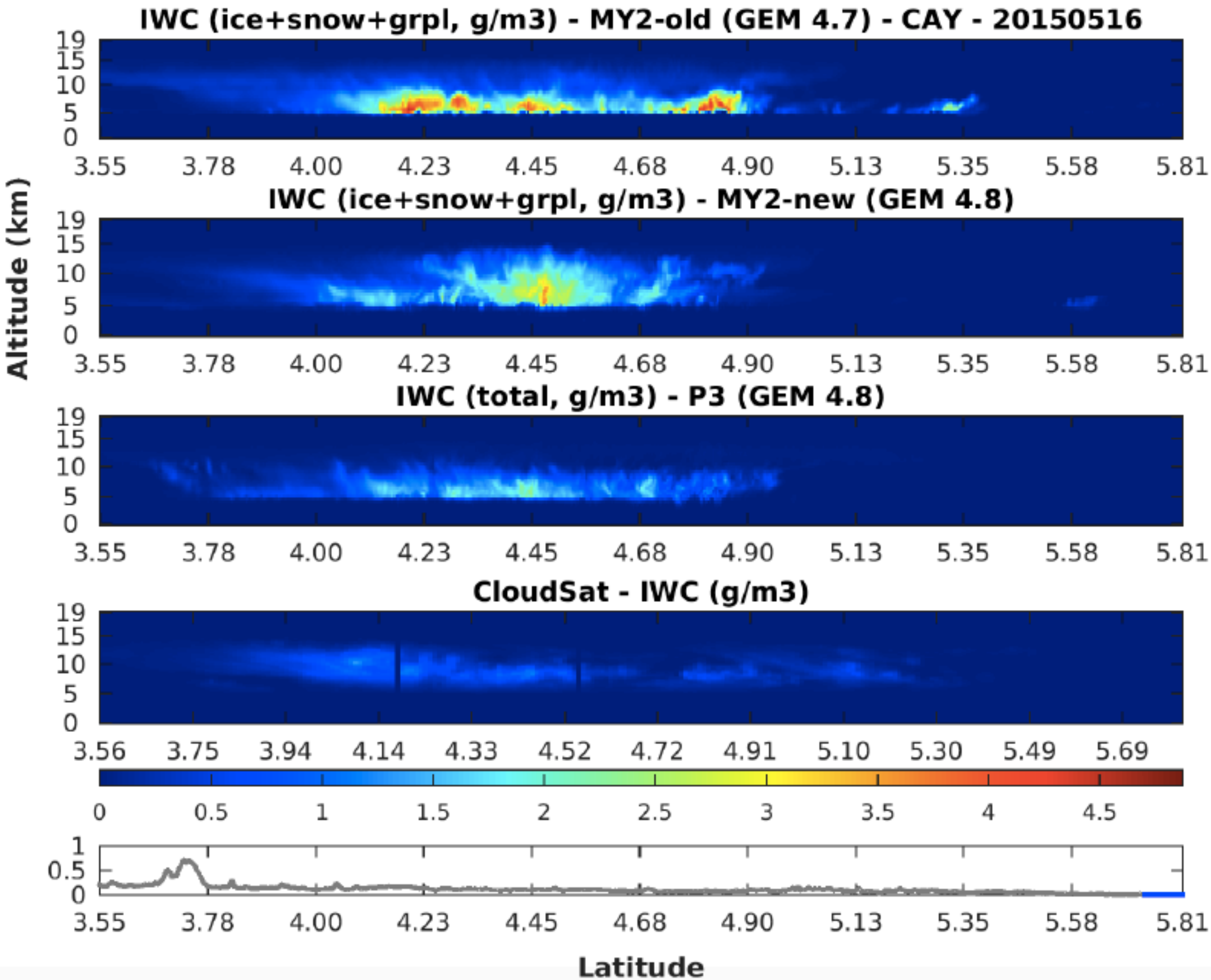
(Aircraft *in situ* measure, A-train overpasses, tropical deep convective cloud)

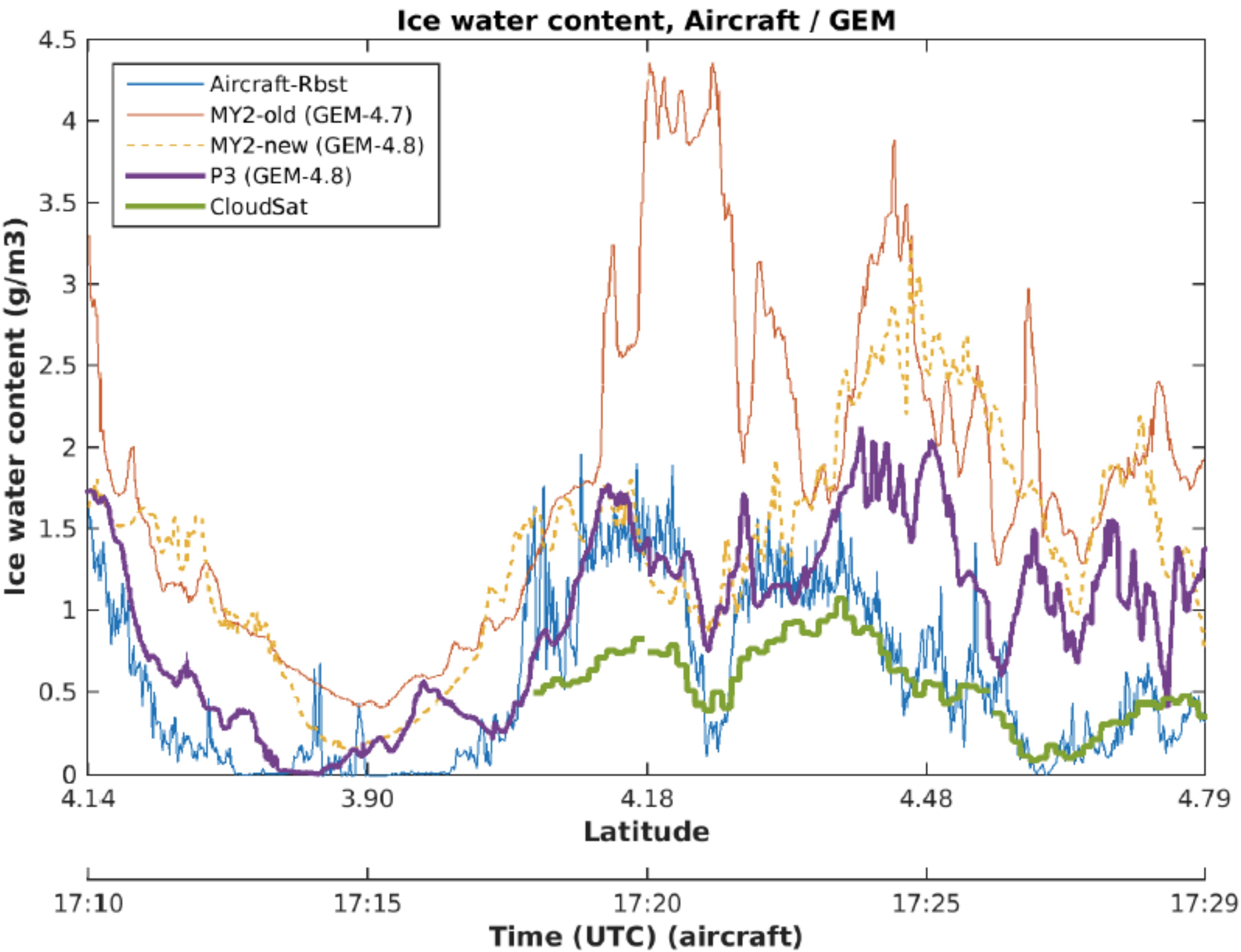


3. Case study

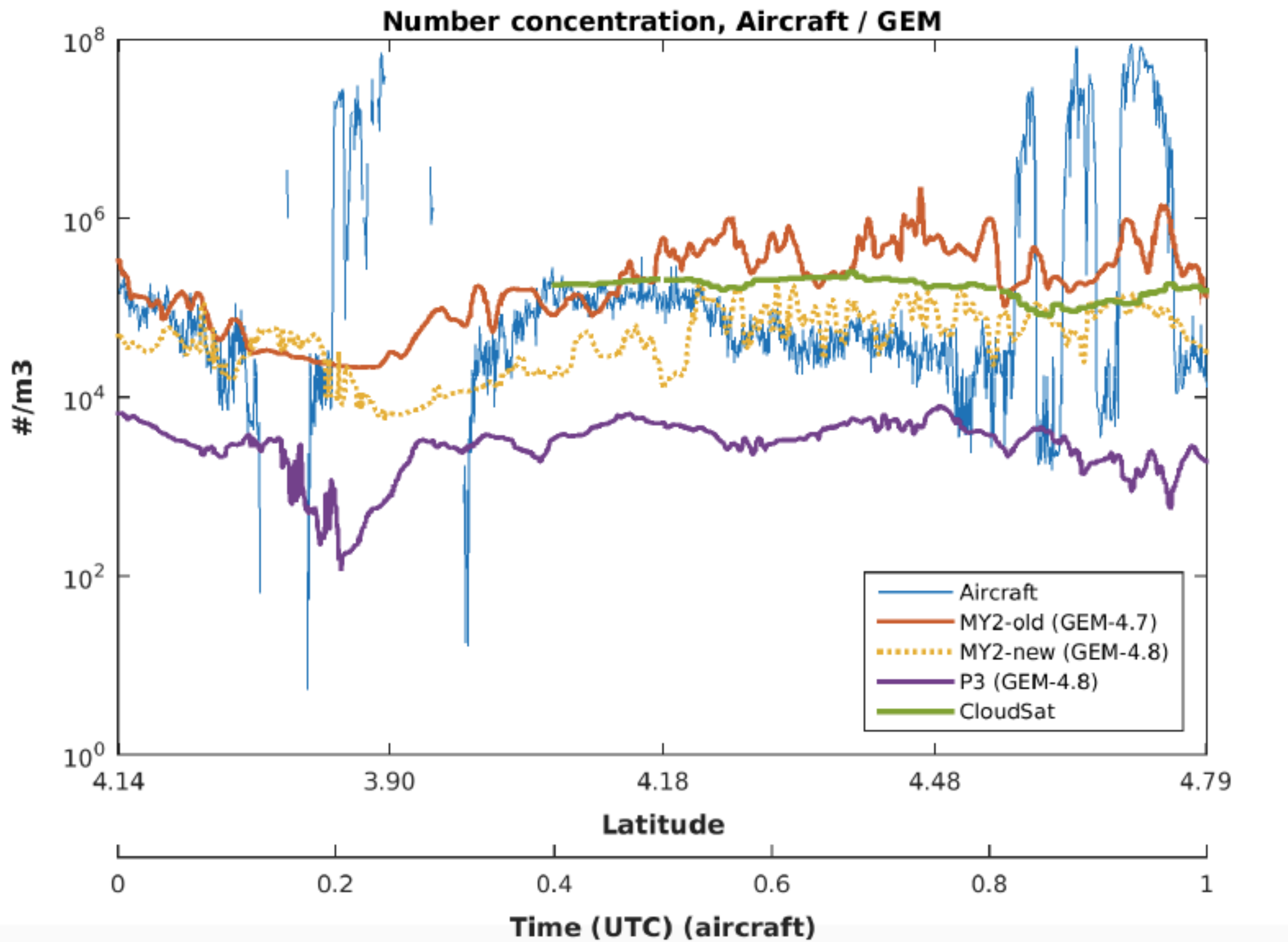
Model simulation for 17:20 UTC




IWC (ice+snow+grpl, g/m3) - MY2-old (GEM 4.7) - CAY - 20150516
IWC (ice+snow+grpl, g/m3) - MY2-new (GEM 4.8)
IWC (total, g/m3) - P3 (GEM 4.8)
CloudSat - IWC (g/m3)
Altitude (km)
Latitude
3.55 3.78 4.00 4.23 4.45 4.68 4.90 5.13 5.35 5.58 5.81
3.56 3.75 3.94 4.14 4.33 4.52 4.72 4.91 5.10 5.30 5.49 5.69
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5

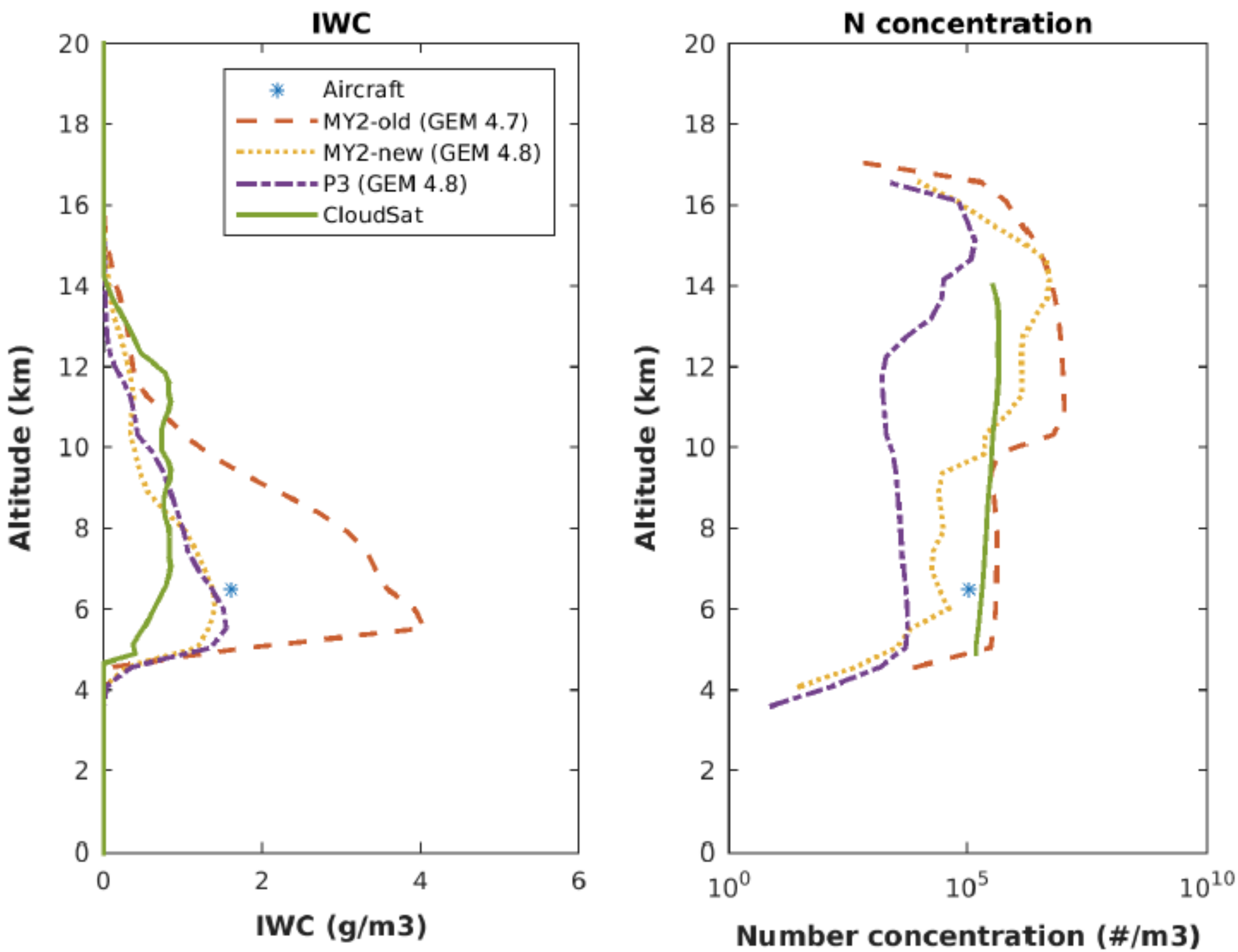


Ice water content, Aircraft / GEM
Aircraft-Rbst
MY2-old (GEM-4.7)
MY2-new (GEM-4.8)
P3 (GEM-4.8)
CloudSat
Ice water content (g/m3)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
4.14
3.90
4.18
4.48
4.79
Latitude
17:10
17:15
17:20
17:25
17:29
Time (UTC) (aircraft)



Number concentration, Aircraft / GEM
#/m3
10^8
10^6
10^4
10^2
10^0
4.14
3.90
4.18
4.48
4.79
Latitude
0
0.2
0.4
0.6
0.8
1
Time (UTC) (aircraft)
Aircraft
MY2-old (GEM-4.7)
MY2-new (GEM-4.8)
P3 (GEM-4.8)
CloudSat

Vertical profile at Lat: 4.17, Lon: -53.52



Concluding comments

Operational NWP models are now at the convective scale (dx = 1-3 km) which permits (requires) detailed bulk microphysics parameterizations (BMPs) and thus detailed treatment of cloud ice

New techniques in BMPs – such as the P3 approach to the representation of ice – show promise for the improvement in numerical guidance of fields related to ice-phase microphysics

For the development and improvement of BMPs – for research and operational NWP – field campaigns such as HAIC-HIWC and the related research are essential