# Parameterization of Cloud Microphysics

# – Update on Current Research –

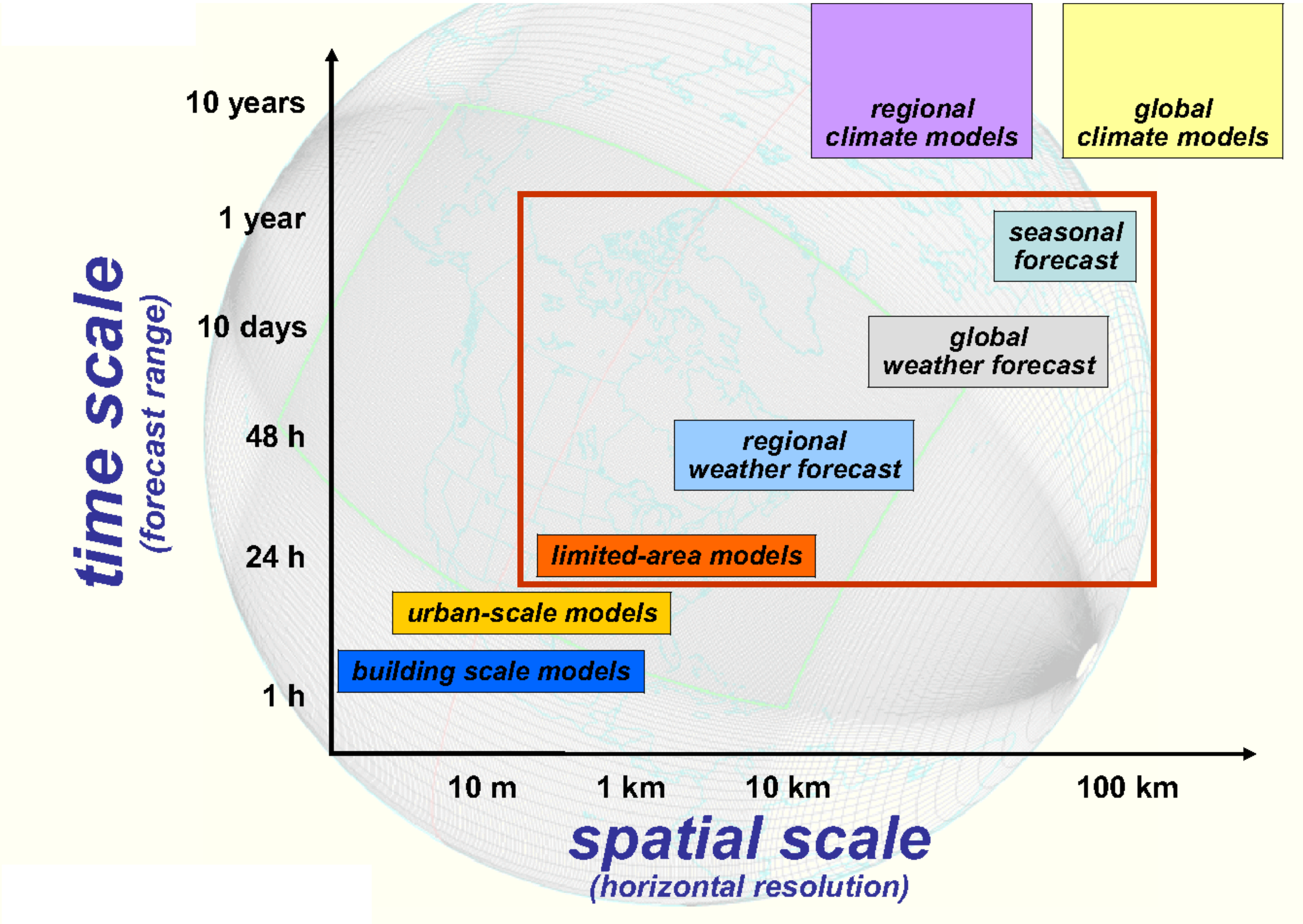
**Jason Milbrandt**

**Atmospheric Numerical Prediction Research Section (RPN-A)**
Environment Canada

# OUTLINE of PRESENTATION

- **Background**
- **Current research** on *bulk microphysics schemes* (BMS)
  1. Prognostic snow density
  2. Sedimentation-induced errors (in BMS)
  3. Comparison of 2-moment schemes

# Modelling Systems and Applications at RPN/CMC



# Physical Processes and Systems (PPS) Group

https://wiki.cmc.ec.gc.ca/wiki/PPS

**ERPS**
Extended Range Prediction System

(GEM-CLIM)

**GDPS**
Global Deterministic Prediction System

(GEM-Global)

**RDPS**
Regional Deterministic Prediction System

(GEM-REG)

**HRDPS**
High Resolution Deterministic Prediction System

(GEM-LAM 2.5)

# Physical Processes and Systems (PPS) Group

https://wiki.cmc.ec.gc.ca/wiki/PPS

**ERPS**
Extended Range Prediction System

(GEM-CLIM)

$\Delta x$ = 2 deg (220 km)
**STCOND:*  Sundqvist**

**GDPS**
Global Deterministic Prediction System

(GEM-Global)

$\Delta x$ = 33 km
**STCOND:  Sundqvist**

**RDPS**
Regional Deterministic Prediction System

(GEM-REG)

$\Delta x$ = 15 km
**STCOND:  Sundqvist**

**HRDPS**
High Resolution Deterministic Prediction System

(GEM-LAM 2.5)

$\Delta x$ = 2.5 km
**STCOND: Milbrandt-Yau (1-moment)**

***STCOND** = grid-scale condensation/precipitation scheme

# Physical Processes and Systems (PPS) Group

https://wiki.cmc.ec.gc.ca/wiki/PPS

**NEAR FUTURE**

**ERPS**
Extended Range Prediction System

$\Delta x$ = 2 deg (220 km)
STCOND: Sundqvist

**GDPS**
Global Deterministic Prediction System

$\Delta x$ = 33 km → $\Delta x$ = 25 km (possibly)
STCOND: Sundqvist → **simplified 2-moment (M-Y)**

**RDPS**
Regional Deterministic Prediction System

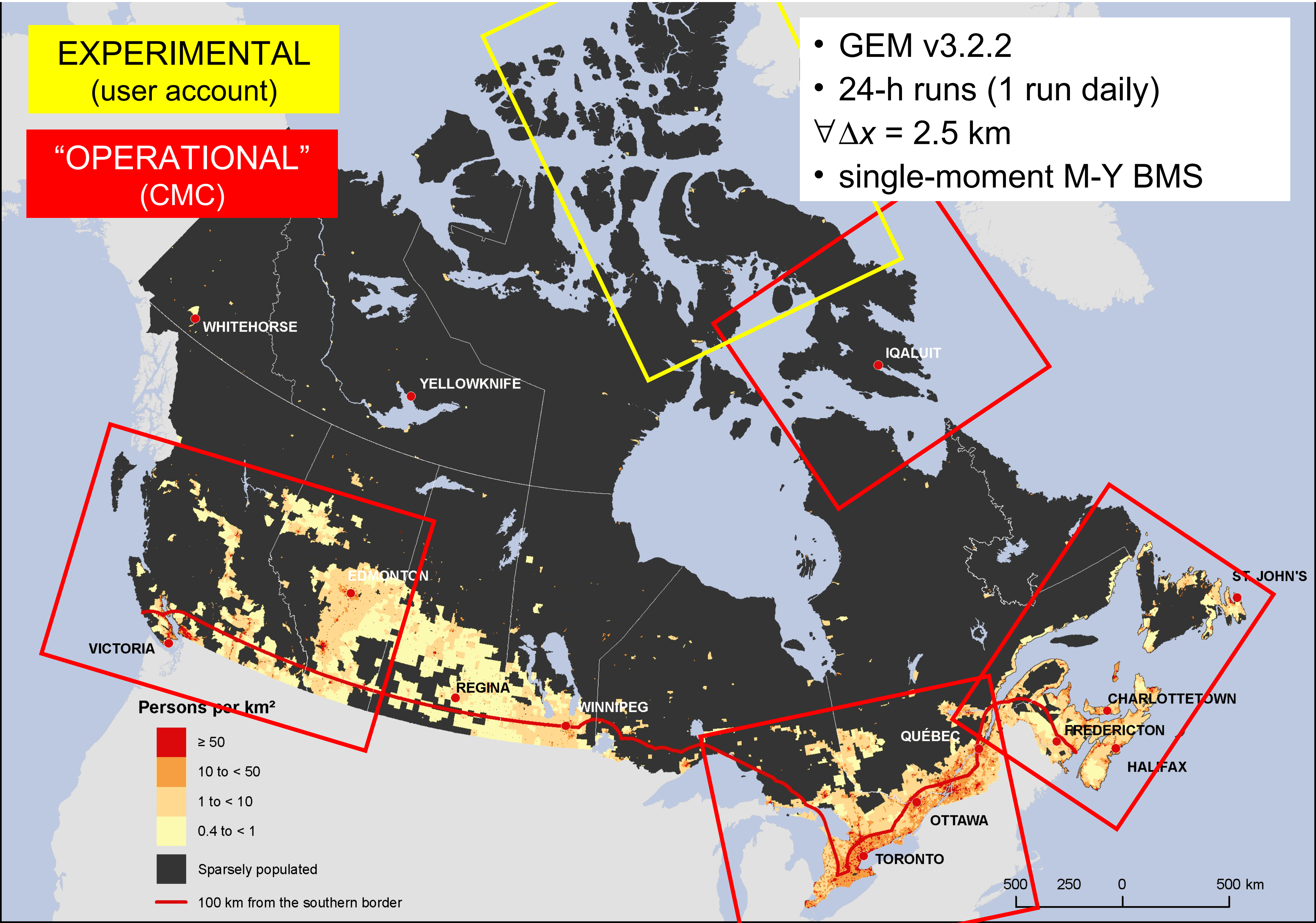
$\Delta x$ = 15 km → $\Delta x$ = 10 km
STCOND: Sundqvist → **simplified 2-moment (M-Y)**

**HRDPS**
High Resolution Deterministic Prediction System

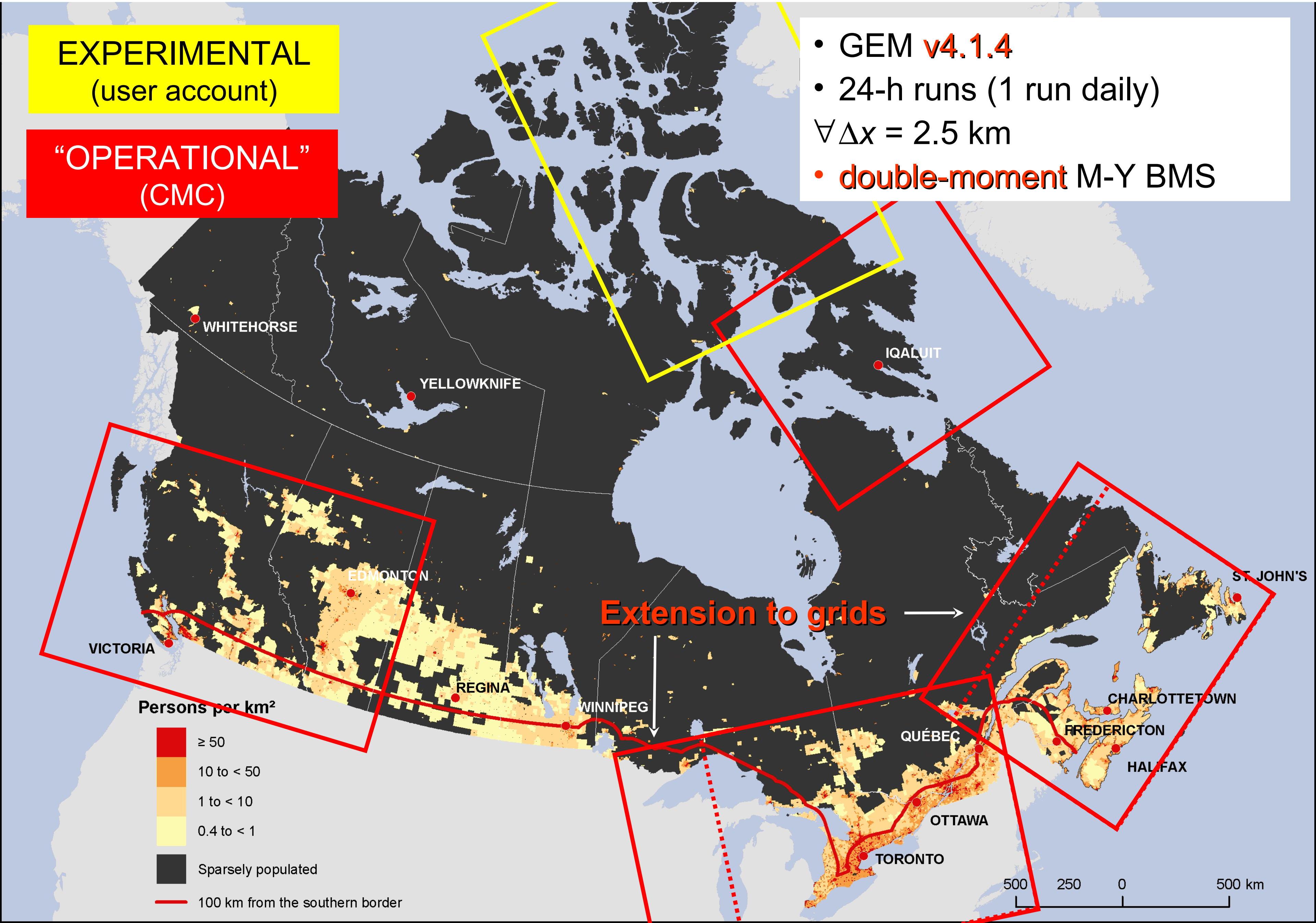
$\Delta x$ = 2.5 km
STCOND: Milbrandt-Yau (1-moment) → **2-moment (M-Y)**

**Role of BMS is increasing in EC modelling systems**

# HRDPS: Current Configuration



# HRDPS: Next upgrade (January 2011)



# Current Research in Microphysics Parameterization

1. Prognostic Snow Density
2. Sedimentation-Induced Errors
3. Comparison of 2-Moment Schemes

# Current Research in Microphysics Parameterization

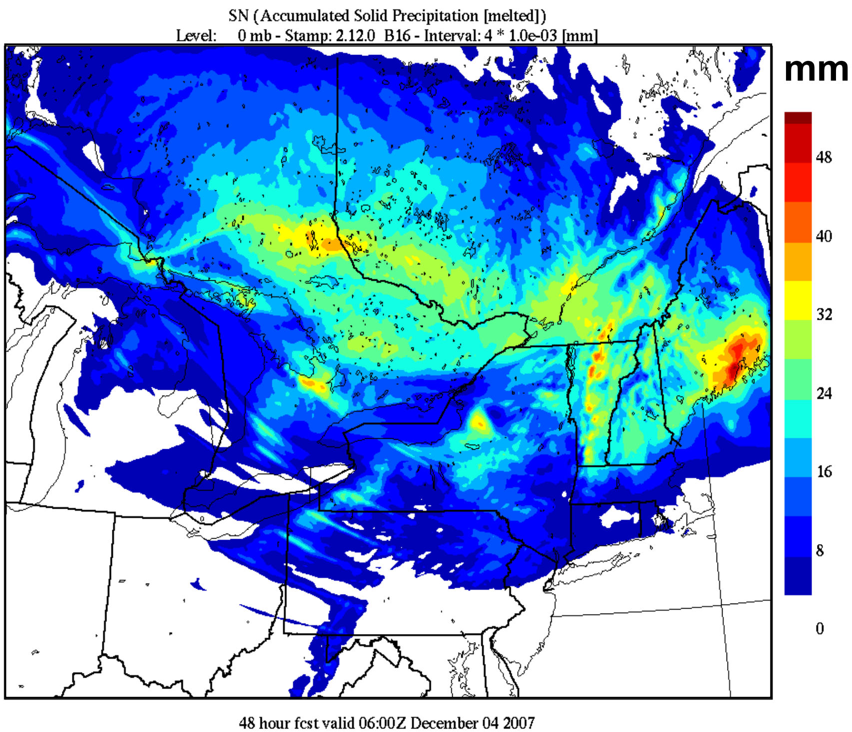
1. **Prognostic Snow Density**
2. Sedimentation-Induced Errors
3. Comparison of 2-Moment Schemes

# MOTIVATION:

# How much snow will fall?

Standard forecast parameter:

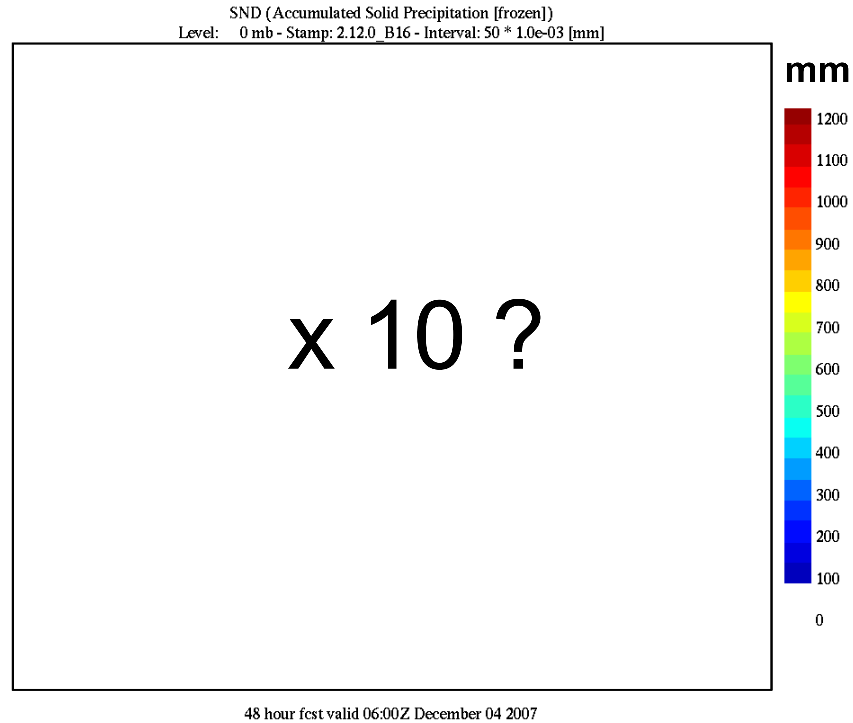
(directly from model QPF)




**Accumulated Precipitation**

**(Liquid-Equivalent)**

Desired forecast parameter:

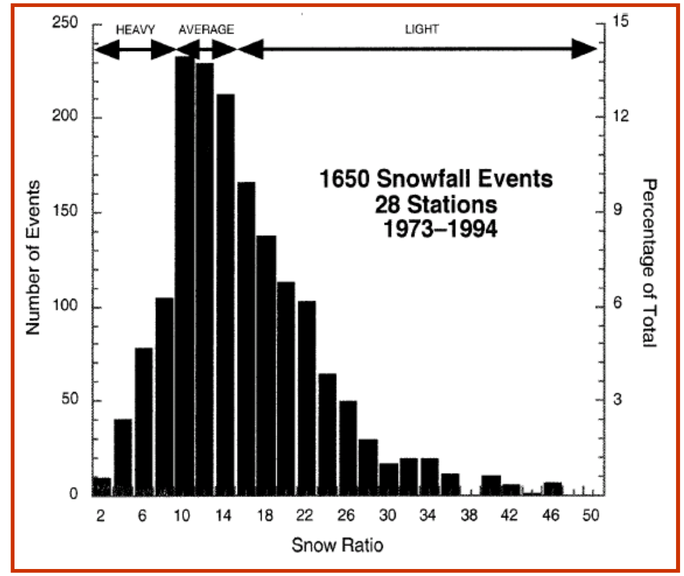


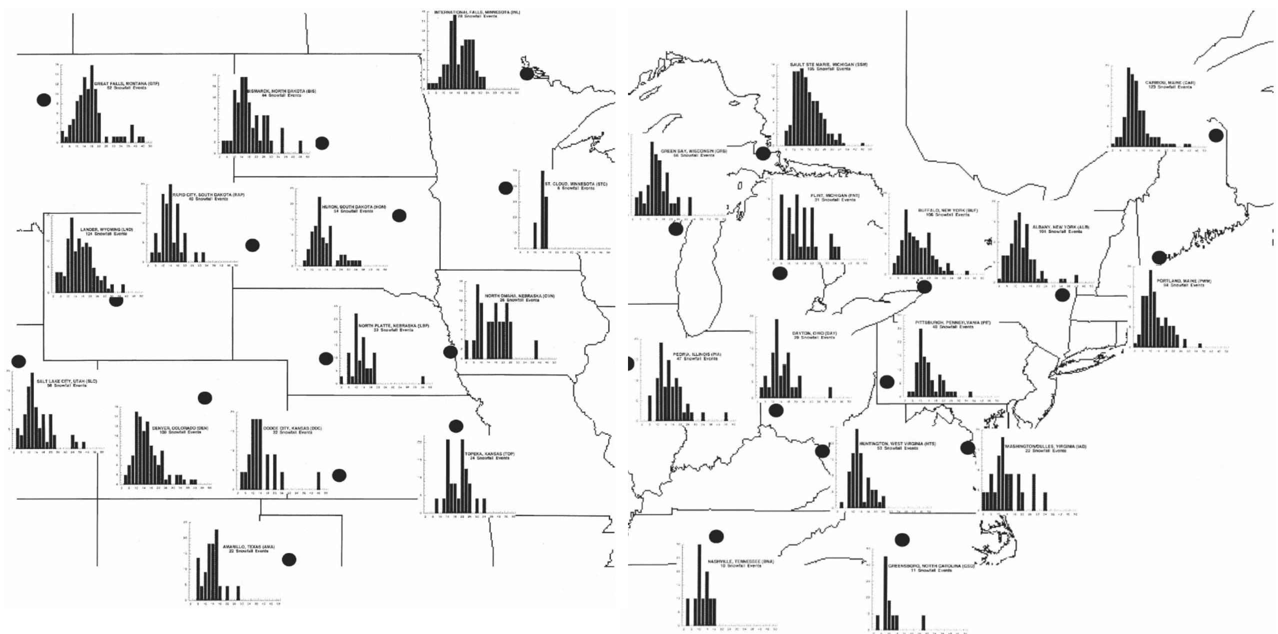

**Accumulated Precipitation**

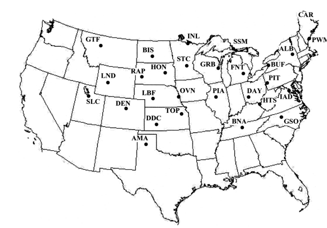
**(Unmelted - i.e. Snowfall Amount)**

# Observed SOLID-LIQUID ratios:

- average value approximately 10:1
- can range from 3:1 to 100:1
- varies geographically





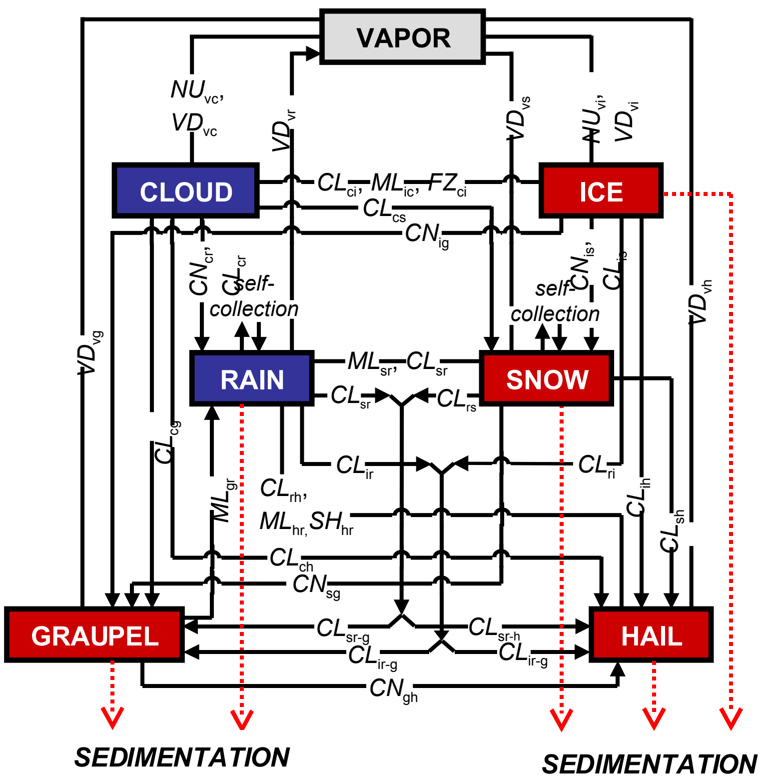
Source: Ware et al. (2006), *Wea and Forecasting*

# APPROACHES TO PREDICTION:

- 10:1 rule
- Climatology
- Neural network diagnostic (statistics of environmental conditions)
  e.g. Roebber et al. (2003)
- Decision tree algorithm (based on physical principles and environment)
  e.g. Dubé (2006)
- **Prognostic from the microphysics of a NWP model**

# Cloud Microphysics Scheme:*

## 6 hydrometeor categories




## Size distribution of each category *x*:

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

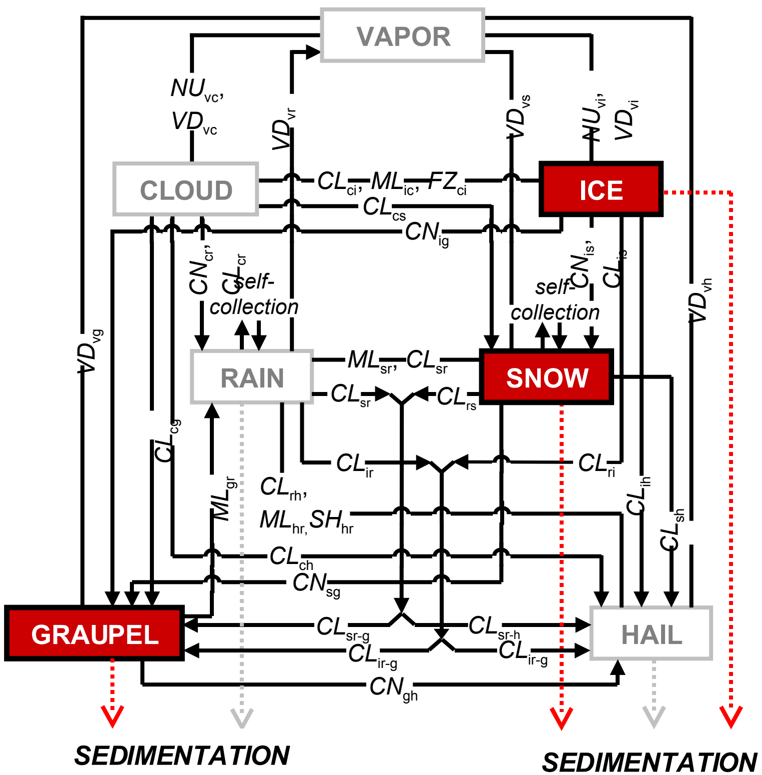
## Prognostic quantities:

- mass mixing ratio ($q_x$)
- total number concentration ($N_x$)

* Milbrandt and Yau, 2005a,b (*J. Atmos. Sci.*)

# Cloud Microphysics Scheme:

Representation of "snow": (i.e. solid, white precipitation at ground)




## Size distribution of each category $x$:

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

## Prognostic quantities:

- mass mixing ratio ($\boldsymbol{q_x}$)
- total number concentration ($\boldsymbol{N_x}$)

**"Snow" is represented by 3 categories:**

ICE (pristine crystals)

SNOW (large crystals / aggregates)

GRAUPEL (heavily rimed crystals)

**“Snow” is represented by 3 categories:**

***ICE*** (pristine crystals), $\rho_i = 500$ kg m$^{-3}$

***GRAUPEL*** (rimed crystals) $\rho_g = 400$ kg m$^{-3}$

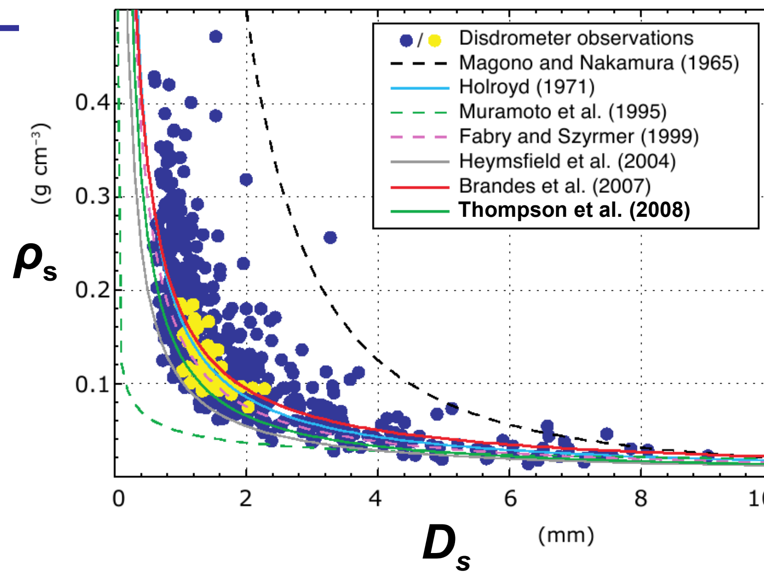
***SNOW*** (large crystals / aggregates) * $\rho_s = f(D_s)$

* For ***SNOW*** :

Use of $m_s(D) = cD_s^{\,d}$

$\Rightarrow \rho_s(D) = eD_s^{\,f}$

(for the bulk density of an equivalent-mass sphere)




Brandes et al. (2007) *J. Appl. Meteor. and Clim.*

# Approach:

For each category $x$ ($x = i, g, s$):

Compute solid (unmelted) volume fluxes, $F_{v\_x}$

$$\frac{F_{v_x}}{F_{m_x}} = \frac{\int_0^\infty V(D)\cdot vol(D)\cdot N(D)\,dD}{\int_0^\infty V(D)m(D)N(D)\,dD} = \frac{\int_0^\infty V(D)\cdot\frac{m(D)}{\rho(D)}\cdot N(D)\,dD}{\int_0^\infty V(D)m(D)N(D)\,dD} = \frac{\frac{1}{\rho_x}\int_0^\infty V(D)m(D)N(D)\,dD}{\int_0^\infty V(D)m(D)N(D)\,dD} = \frac{1}{\rho_x}$$

$$F_{v_x} = \frac{F_{m_x}}{\rho_x}$$

**BUT** – only true for constant $\rho_x$

(OK for *ICE* and *GRAUPEL*)

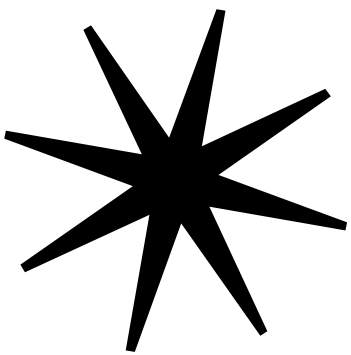
For *SNOW*, $\rho = \rho(D)$ - must compute $F_v$ directly (from integral)

$$\longrightarrow \quad F_{v_s} = \int_0^\infty V(D)\cdot vol(D)\cdot N(D)\,dD$$

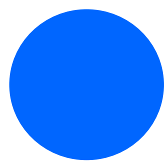
# Estimation of liquid fraction (during melting):

**Actual model representation:**

$\rho_S = f(D_s)$  $\rho_L = 1000 \text{ kg m}^{-3}$



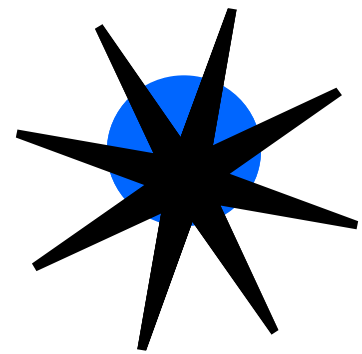
$q_s$



$q_r$

**Conceptual view of melting snow:**

$\rho_{s\_melting}$



$$\frac{q_r}{q_r + q_s}$$

→ liquid fraction of melting snow

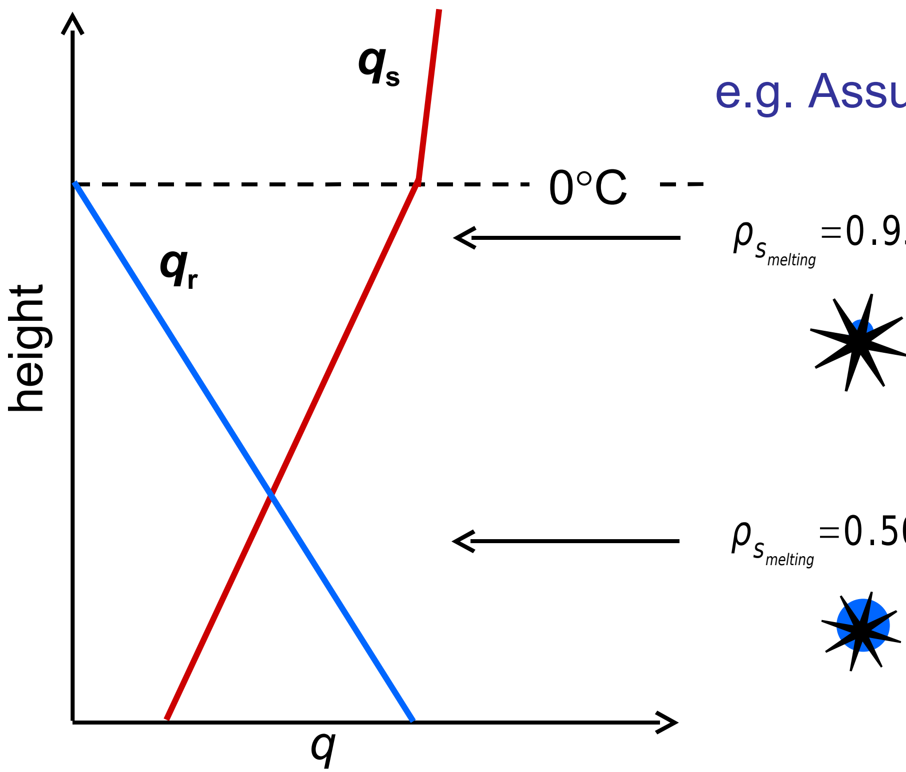
# Adjustments:

if $T < 0°C$:

$$f_{liq} = \frac{q_r}{q_r + (q_i + q_g + q_s)}$$

$$F_v = (1 - f_{liq}) \cdot F_{v'} + f_{liq} \cdot F_{v_{liq}}$$

e.g. Assume $D_s$ = 5 mm → $\rho_s(D_s)$ = 26 kg m$^{-3}$:




$$\rho_{s_{melting}} = 0.95(26 \text{ kg m}^{-3}) + 0.05(1000 \text{ kg m}^{-3}) = 75 \text{ kg m}^{-3}$$

$$\rho_{s_{melting}} = 0.50(26 \text{ kg m}^{-3}) + 0.50(1000 \text{ kg m}^{-3}) = 513 \text{ kg m}^{-3}$$

**Thus,** **instantaneous precipitation rates are given by:**

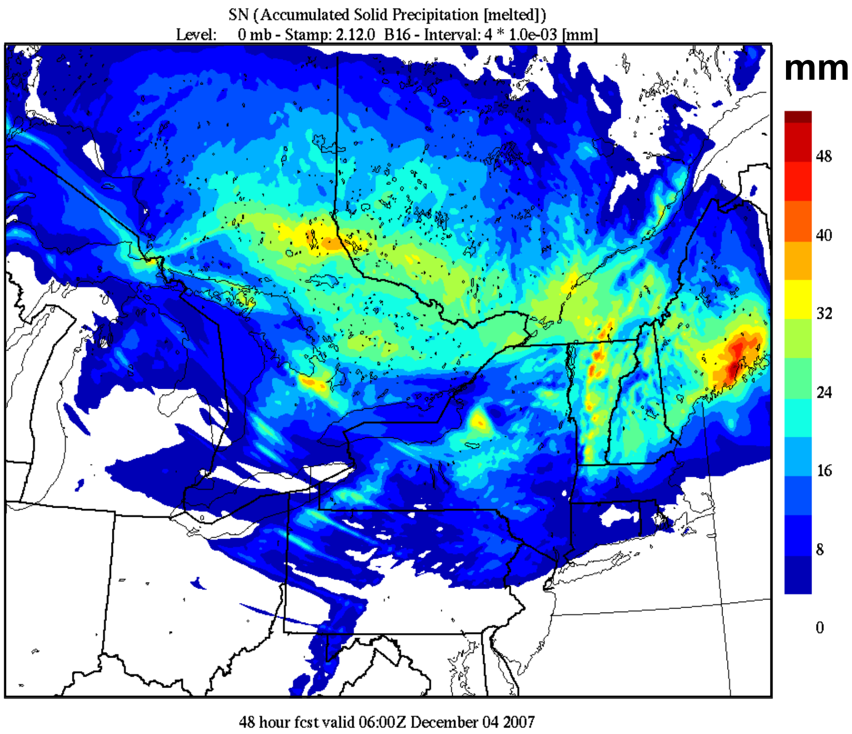
$$F_{v_{liq}} = \frac{F_{m_i}}{\rho_L} + \frac{F_{m_g}}{\rho_L} + \frac{F_{m_s}}{\rho_L}$$

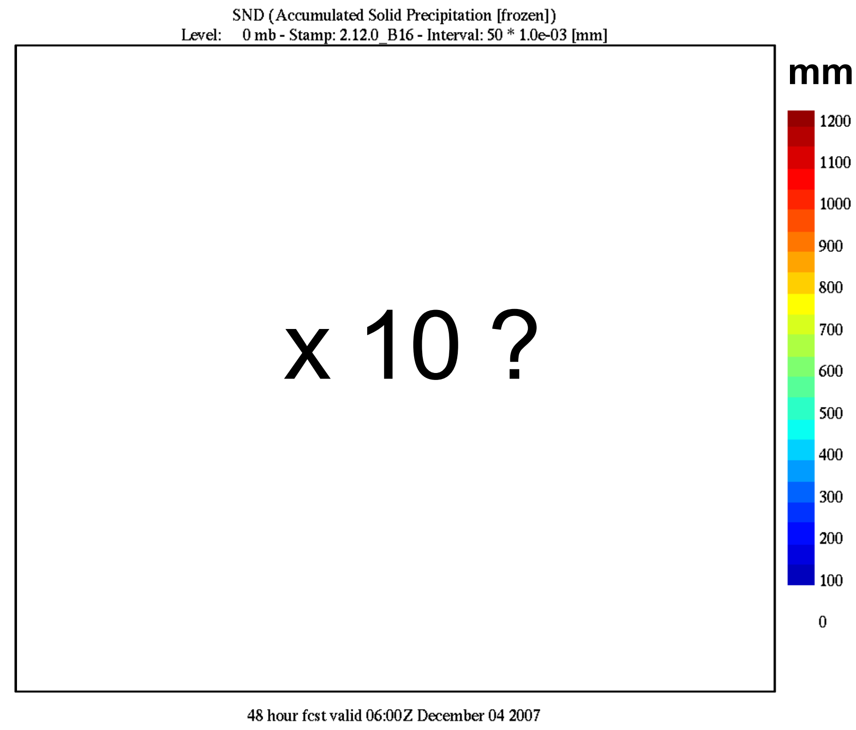
→ total solid (liquid-equivalent) precipitation rate

$$F_{v'} = \frac{F_{m_i}}{\rho_i} + \frac{F_{m_g}}{\rho_g} + \int_0^\infty V_s(D) \cdot vol_s(D) \cdot N_s(D)\, dD$$

$$F_v = (1 - f_{liq}) \cdot F_{v'} + f_{liq} \cdot F_{v_{liq}} \qquad \text{(if } T < 0°\text{C)}$$

→ $$SOLID-to-LIQUID_{inst} = \frac{F_v}{F_{v_{liq}}}$$

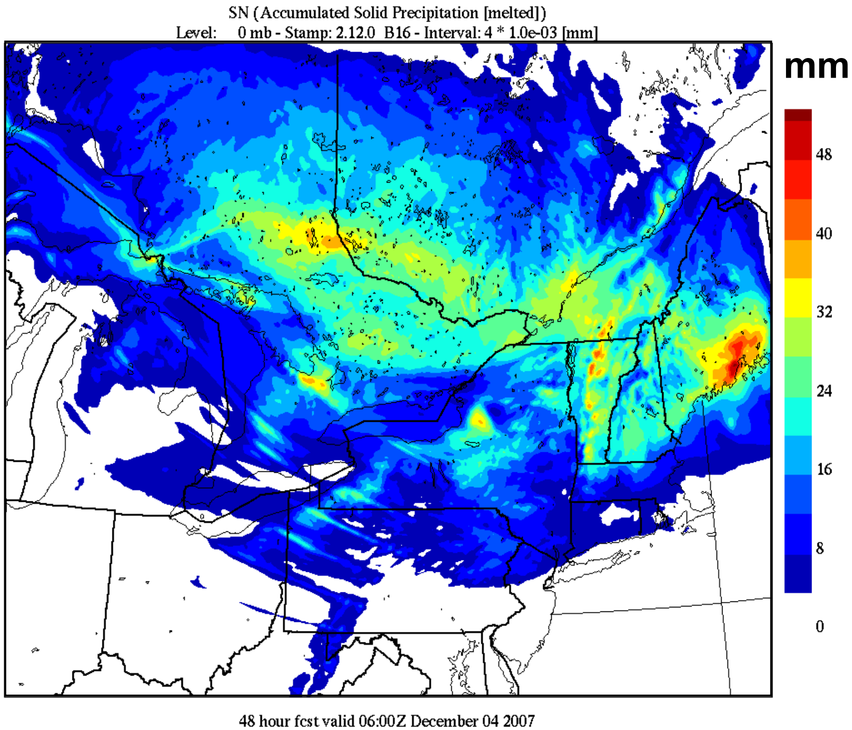


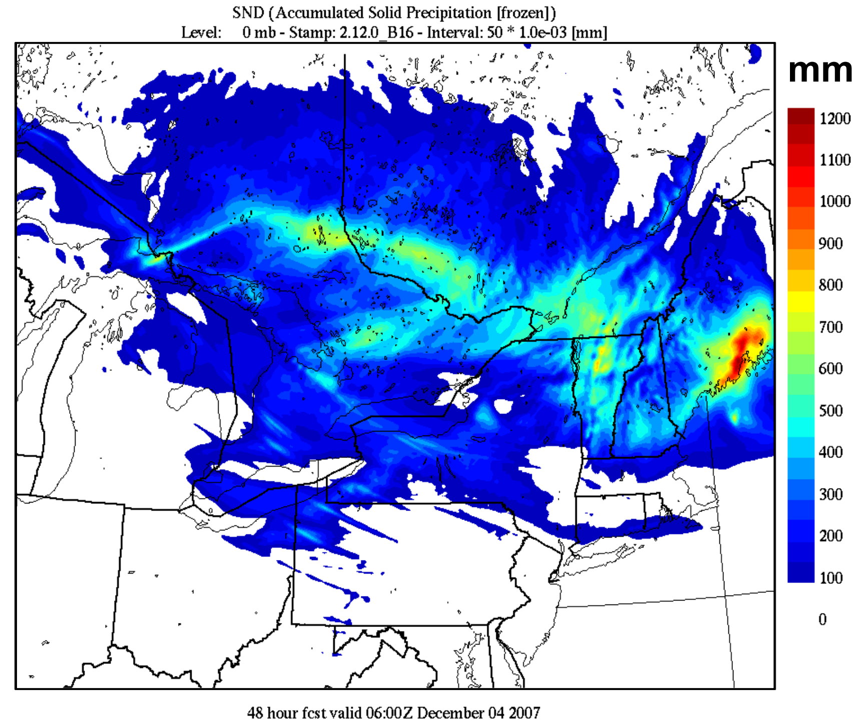




**Accumulated Precipitation**
(liquid-equivalent)

**Accumulated Precipitation**
(unmelted)

- snowfall amount -




**Accumulated Precipitation**

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**Accumulated Precipitation**

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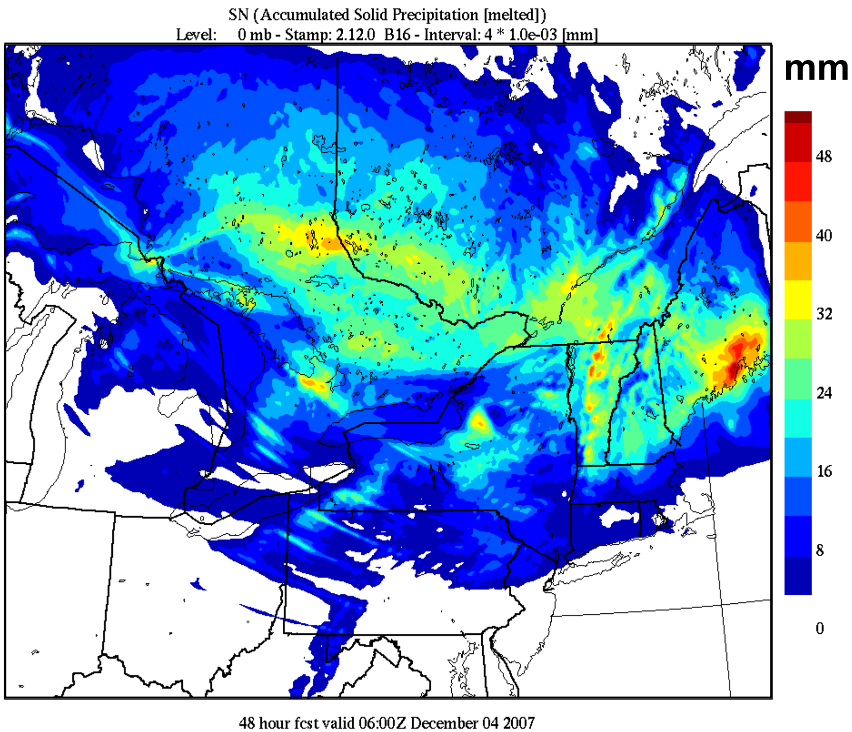
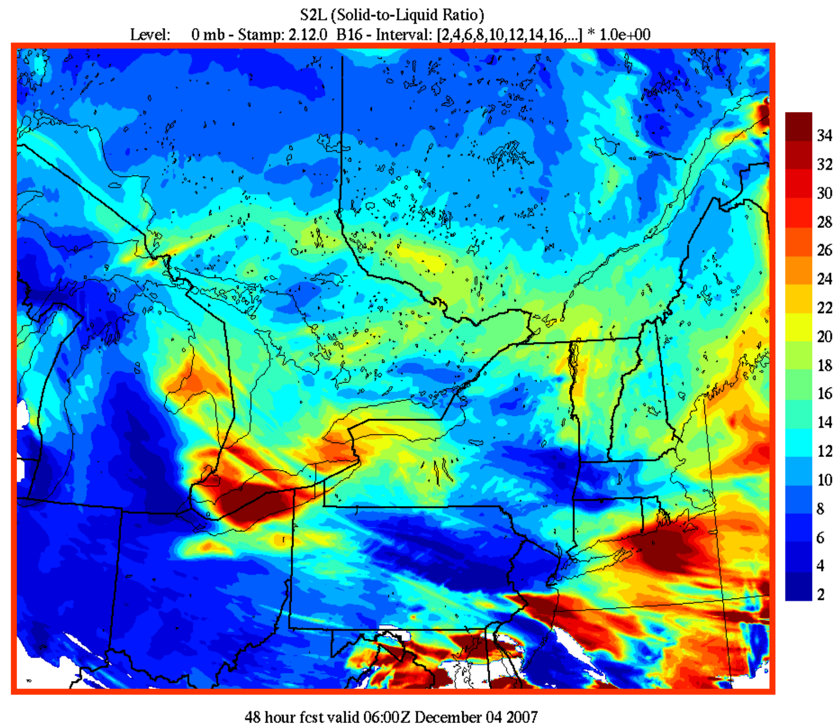


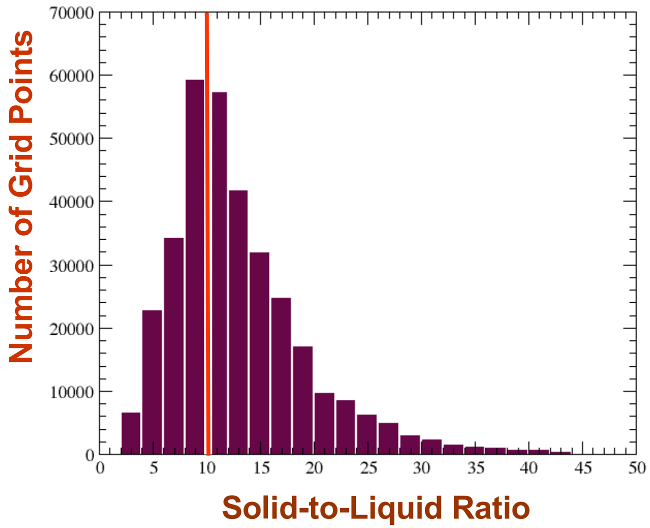




**Accumulated Precipitation**

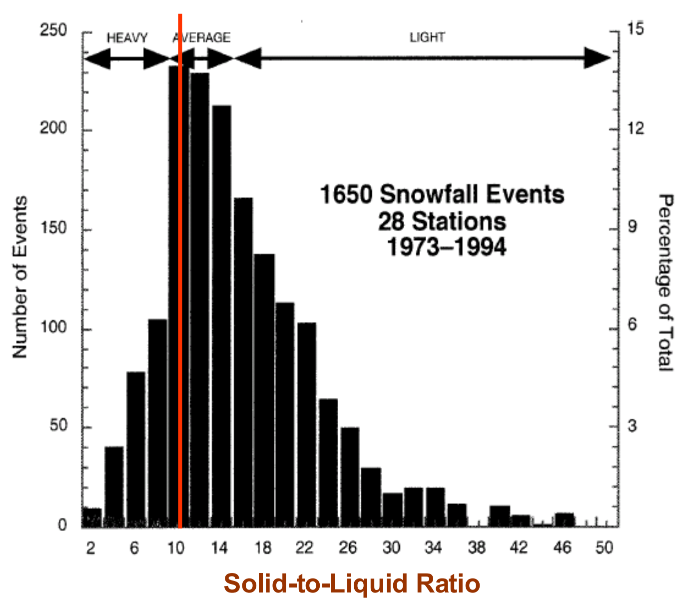
(liquid-equivalent)

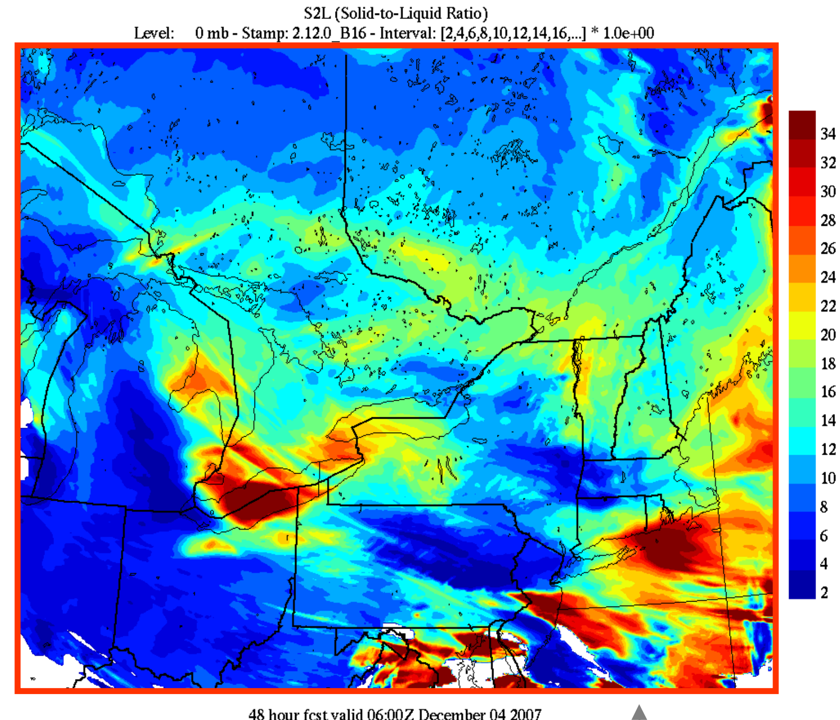
**Solid-to-Liquid Ratio**

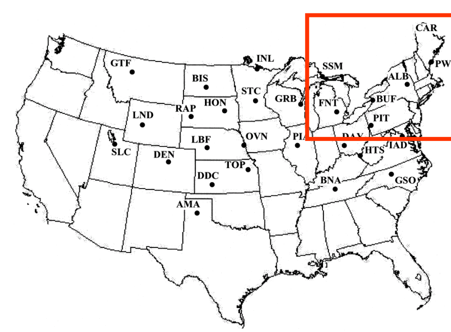
10:1




10:1



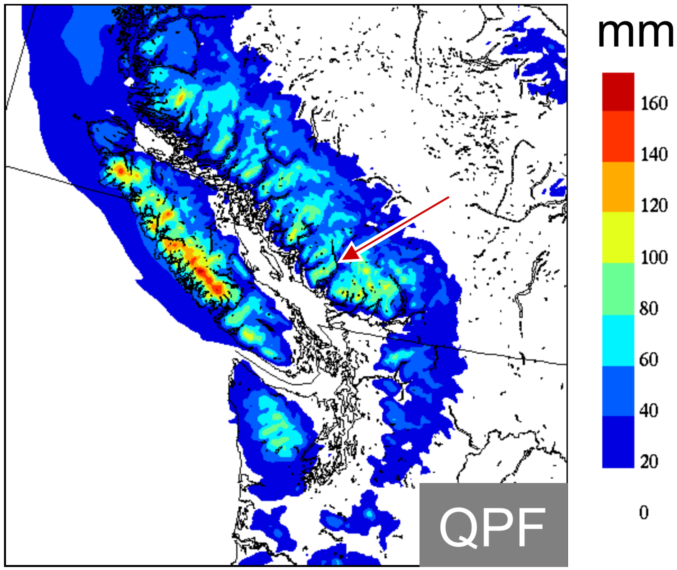



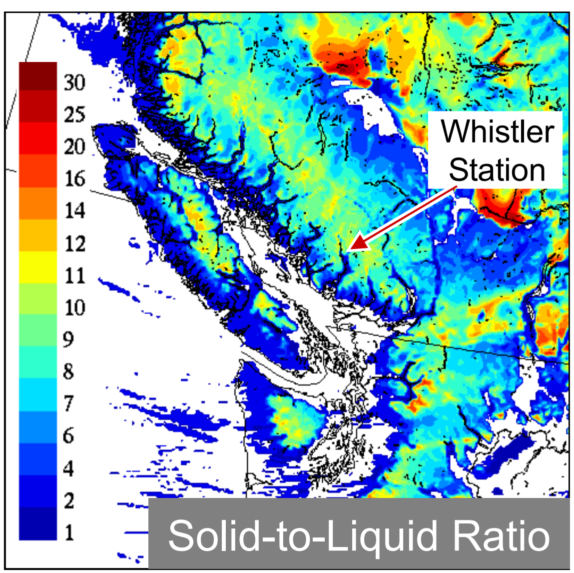

grid area

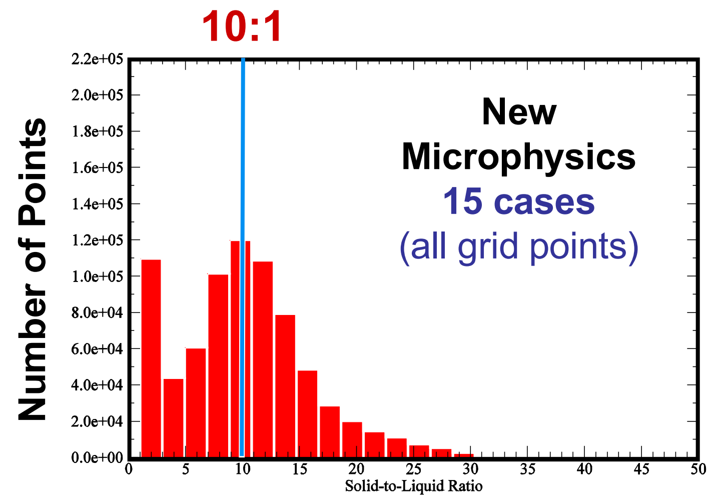
Source: Roebber et al. (2003), *Weather and Forecasting*

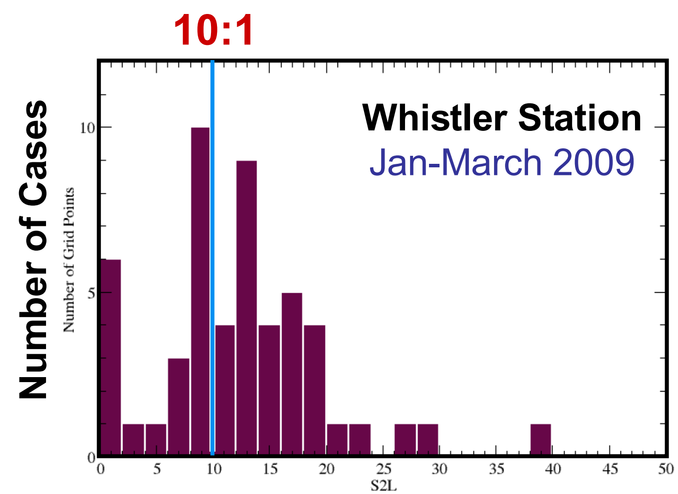
## Solid-to-Liquid Ratio




Case: 12 March 2009 (00 z)

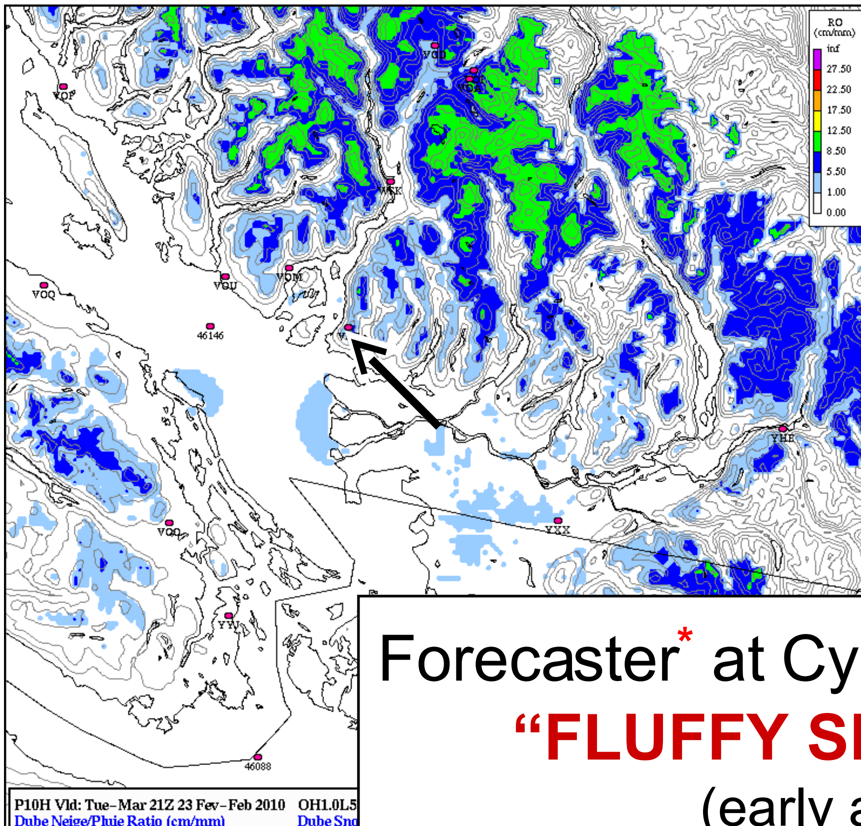


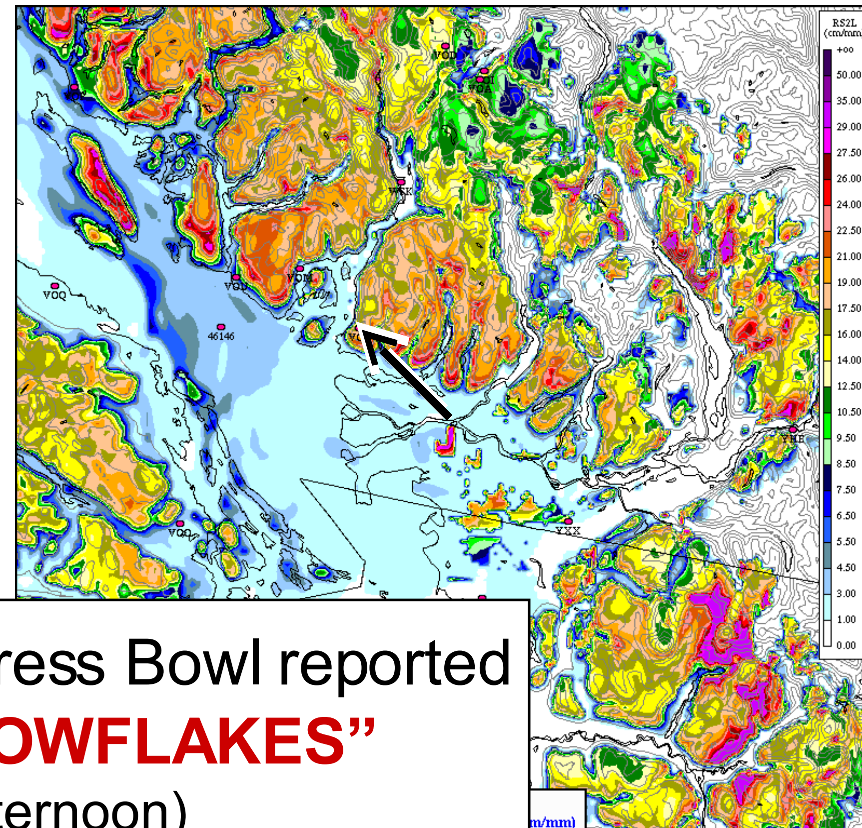



# Solid-to-Liquid Ratio

**Diagnostic**
(Dubé algoritm)




**Explicit**
(Milbrandt-Yau)



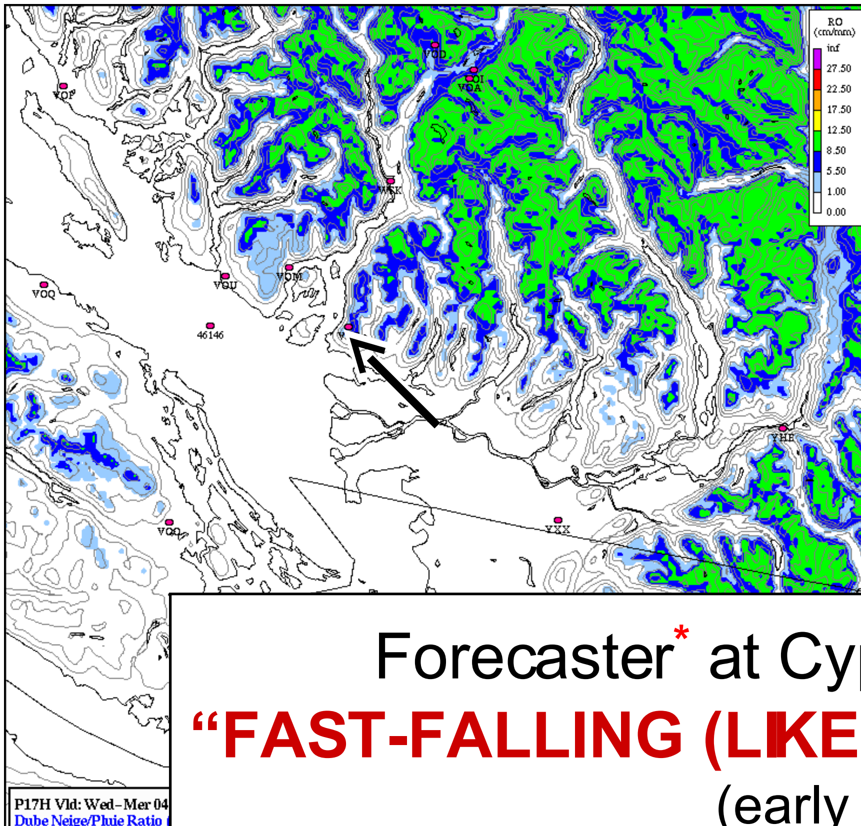

Forecaster* at Cypress Bowl reported
**"FLUFFY SNOWFLAKES"**
(early afternoon)

*Michael Gélinas
2010 Olympics forecaster

**2100 UTC (3:00 pm)**
23 Feb 2010

# Solid-to-Liquid Ratio

**Diagnostic**
(Dubé algoritm)

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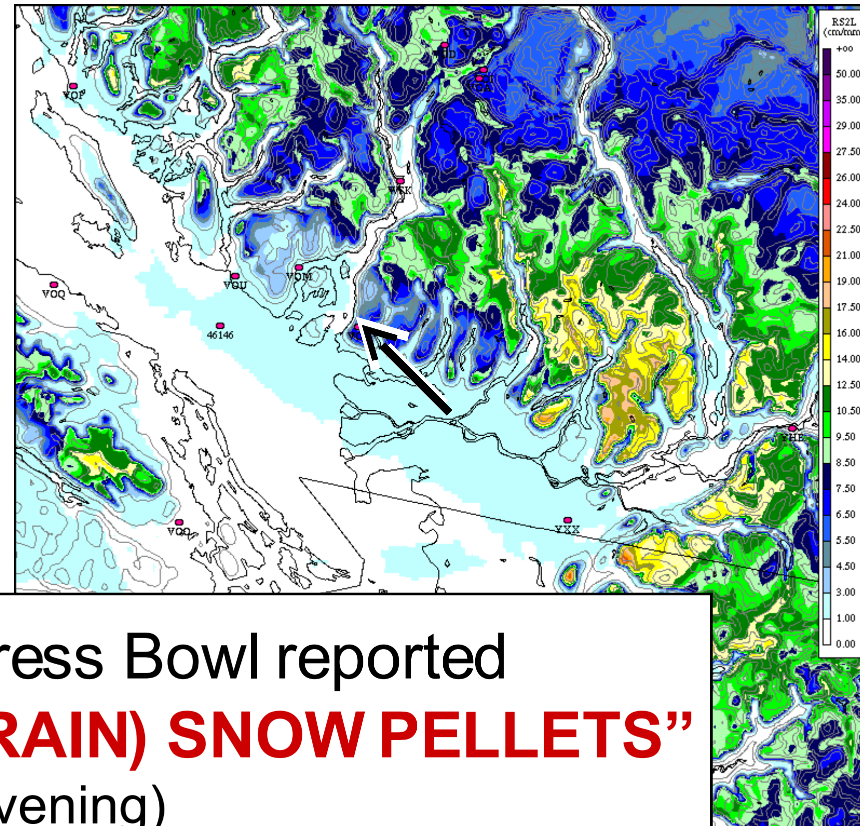
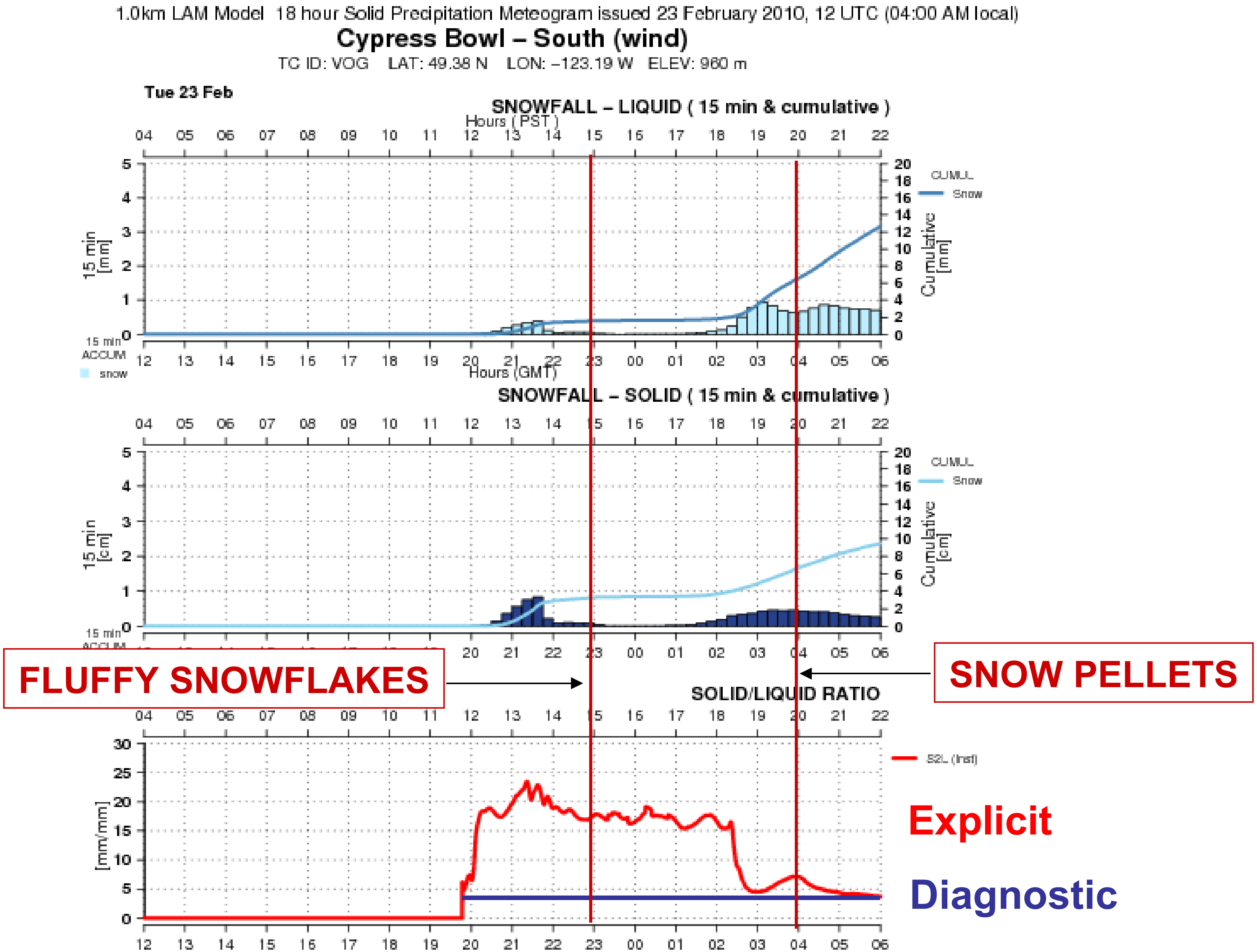


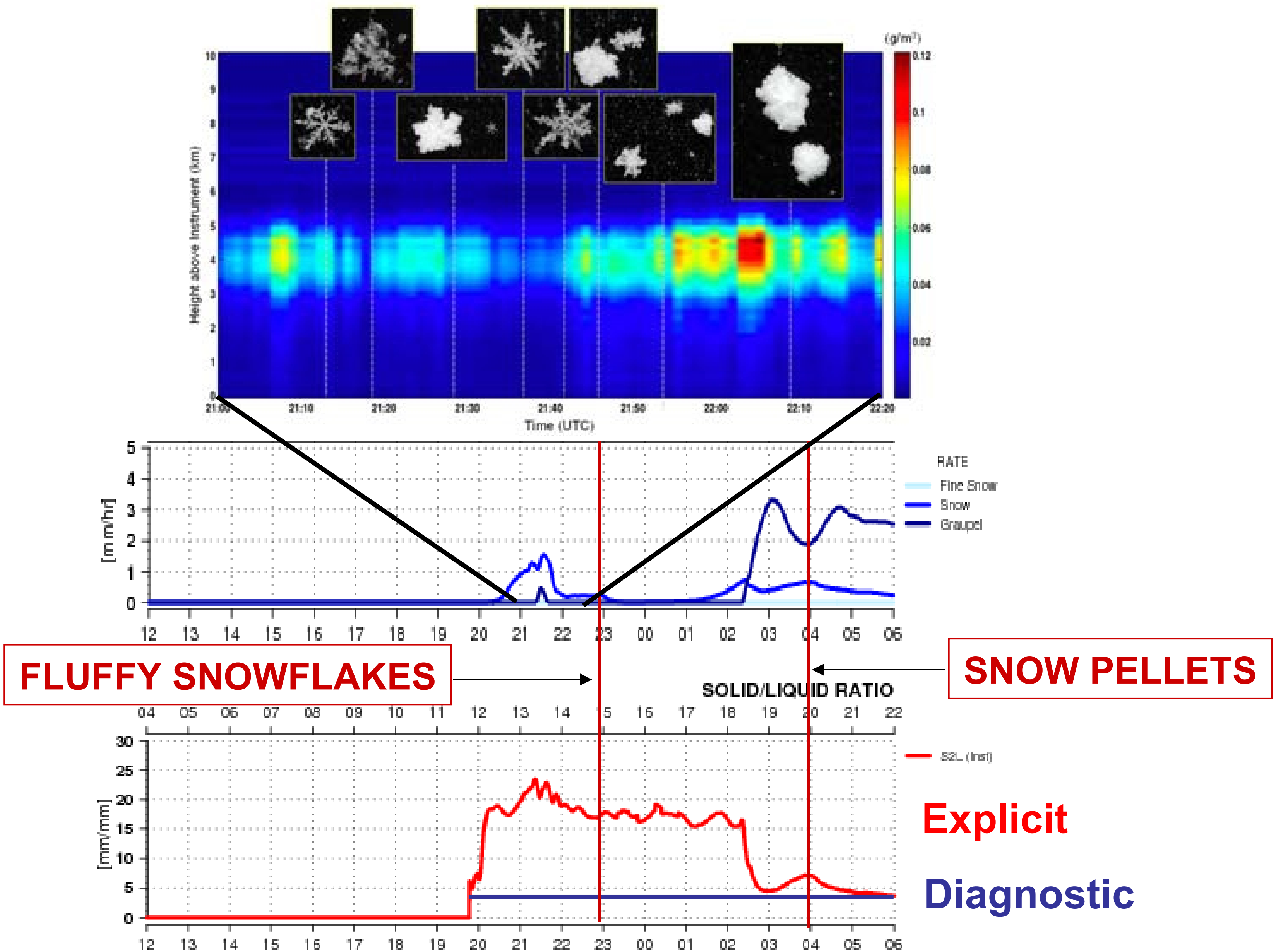

Forecaster* at Cypress Bowl reported
**"FAST-FALLING (LIKE RAIN) SNOW PELLETS"**
(early evening)

*Michael Gélinas
2010 Olympics forecaster

**0400 UTC (8:00 pm)**
23 Feb 2010



1.0km LAM Model 18 hour Solid Precipitation Meteogram issued 23 February 2010, 12 UTC (04:00 AM local)
Cypress Bowl – South (wind)
TC ID: VOG LAT: 49.38 N LON: –123.19 W ELEV: 960 m
Tue 23 Feb
SNOWFALL – LIQUID ( 15 min & cumulative )
Hours ( PST )
Hours (GMT)
15 min [mm]
Cumulative [mm]
CUMUL
Snow
15 min ACCUM
snow
SNOWFALL – SOLID ( 15 min & cumulative )
15 min [cm]
Cumulative [cm]
SOLID/LIQUID RATIO
[mm/mm]
S2L (Inst)
FLUFFY SNOWFLAKES
SNOW PELLETS
Explicit
Diagnostic



(g/m³)
Height above Instrument (km)
Time (UTC)
21:10
21:20
21:30
21:40
21:50
22:00
22:10
22:20
[mm/hr]
RATE
Fine Snow
Snow
Graupel
FLUFFY SNOWFLAKES
SNOW PELLETS
SOLID/LIQUID RATIO
[mm/mm]
Explicit
Diagnostic

# CONCLUSION – Part 1

- The cloud microphysics scheme predicts the individual quantities and size distributions of pristine crystals, aggregates, graupel

- This information can be exploited to compute the **instantaneous solid** (unmelted) **precipitation rate** → it need not be simply inferred (or diagnosed)

- Real-time simulations (during 2010 Olympics) indicate that this method produces a realistic results

# Current Research in Microphysics Parameterization

1. Prognostic Snow Density
2. **Sedimentation-Induced Errors**
3. Comparison of 2-Moment Schemes

# MODEL PREDICTION OF A PROGNOSTIC MOMENT

e.g. the mass mixing ratio, $q_x$, of category x (where $x = c, r, i, \ldots$)

$$\frac{\partial q_x}{\partial t} = -\frac{1}{\rho}\vec{\nabla}\cdot\left(\rho q_x \vec{U}\right) + TURB(q_x) + \left.\frac{dq_x}{dt}\right|_S + \frac{1}{\rho}\frac{\partial}{\partial z}\left(\rho q_x \bar{V}_{xq}\right)$$

ADVECTION / COMPRESSION

TURBULENT MIXING

SOURCES / SINKS

SEDIMENTATION

**MODEL DYNAMICS**

**MICROPHYSICS SCHEME**

# MOTIVATION

1. To propose a method to quantify the **sedimentation-induced errors** in bulk microphysics schemes

2. To examine alternatives to the "standard" two-moment approach

# BULK MICROPHYSICS SCHEMES

## COMPUTATION OF SEDIMENTATION

$$\frac{\partial q_x}{\partial t}\Big|_{SEDI} = \frac{\partial\left(\rho q_x \bar{V}_{xq}\right)}{\partial z} \; *$$

* $\bar{V}_{xq}$ = mass-weighted fall velocity

**1-moment**

$$* \quad \bar{V}_{xq} = \frac{\int_0^\infty V_x(D_x) m_x(D_x) N_x(D_x) dD_x}{\int_0^\infty m_x(D_x) N_x(D_x) dD_x}$$

$$\frac{\partial N_x}{\partial t}\Big|_{SEDI} = \frac{\partial\left(N_x \bar{V}_{xN}\right)}{\partial z}$$

$\bar{V}_{xN}$ = number-weighted fall velocity

**2-moment**

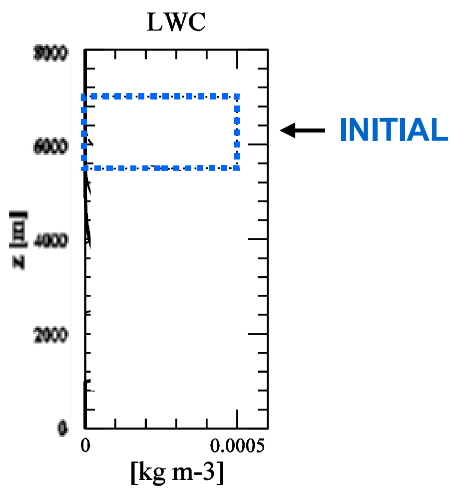
$$\frac{\partial Z_x}{\partial t}\Big|_{SEDI} = \frac{\partial\left(Z_x \bar{V}_{xZ}\right)}{\partial z}$$

$\bar{V}_{xZ}$ = reflectivity-weighted fall velocity

**3-moment**

# BULK MICROPHYSICS SCHEMES

## Sedimentation: 1-MOMENT scheme




$M_3$
$(\rho q_r)$

*

**Initial Conditions**:

$\rho q$ = 0.5 g m$^{-3}$

$N_0$ = 8×10$^6$ m$^{-4}$

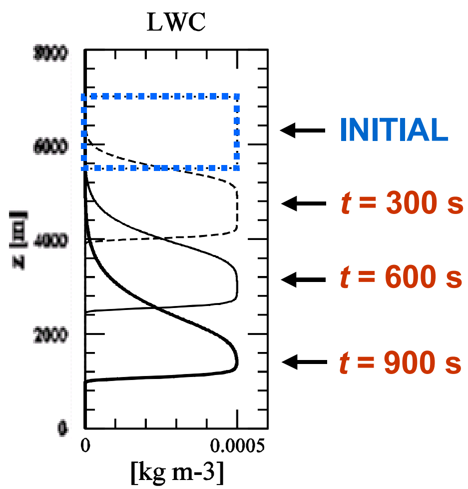
$\mu$ = 0

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

* Wacker and Lüpkes (2009)

# BULK MICROPHYSICS SCHEMES

## Sedimentation: 1-MOMENT scheme




$M_3$
$(\rho q_r)$

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$\rho q$ = 0.5 g m$^{-3}$

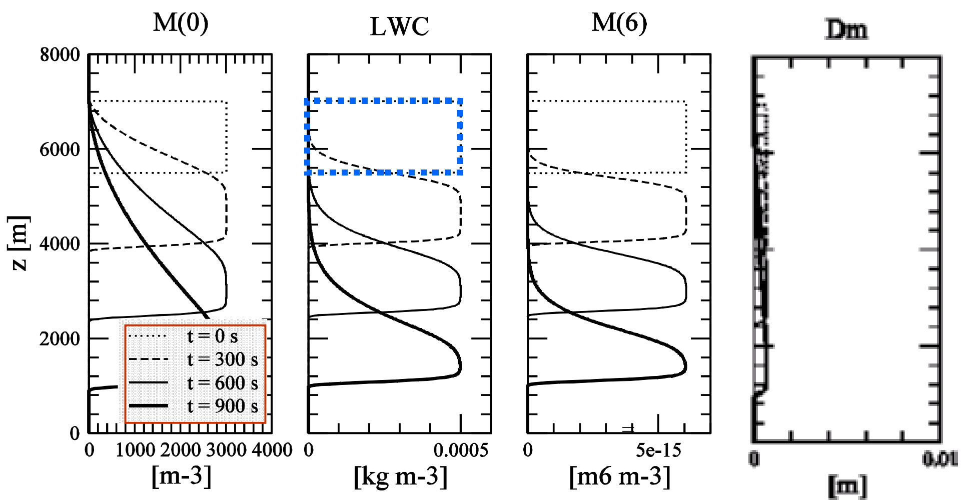
$N_0 = 8\times10^6$ m$^{-4}$

$\mu = 0$

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

# BULK MICROPHYSICS SCHEMES

## Sedimentation: 1-MOMENT scheme




$M_0$ ($N_{Tr}$)

$M_3$ ($\rho q_r$)

$M_6$ ($Z_r$)

$D_m = \left[\frac{M_3}{M_0}\right]^{\frac{1}{3}}$

**Initial Conditions**:

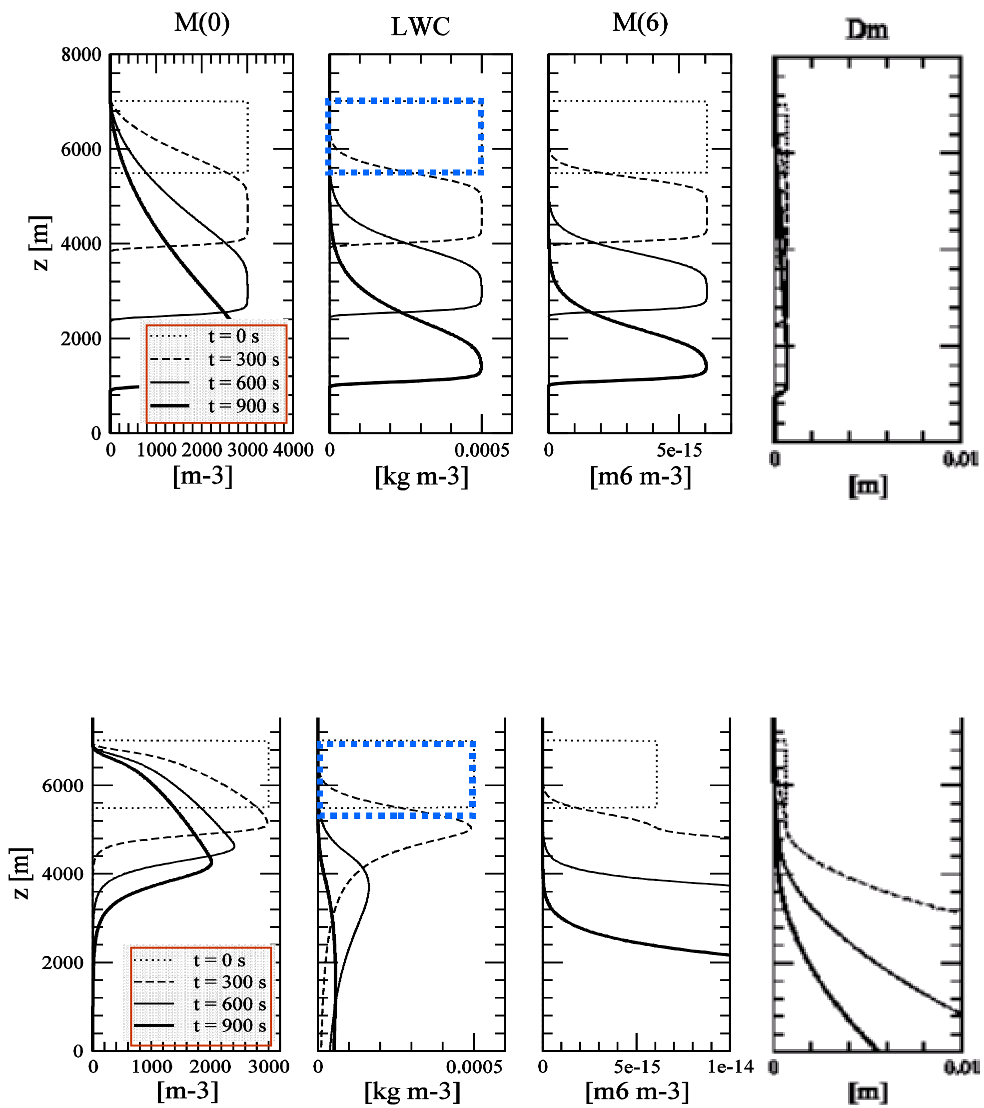
$\rho q$ = 0.5 g m$^{-3}$

$N_0 = 8\times10^6$ m$^{-4}$

$\mu = 0$

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

# BULK MICROPHYSICS SCHEMES




**Initial Conditions**:

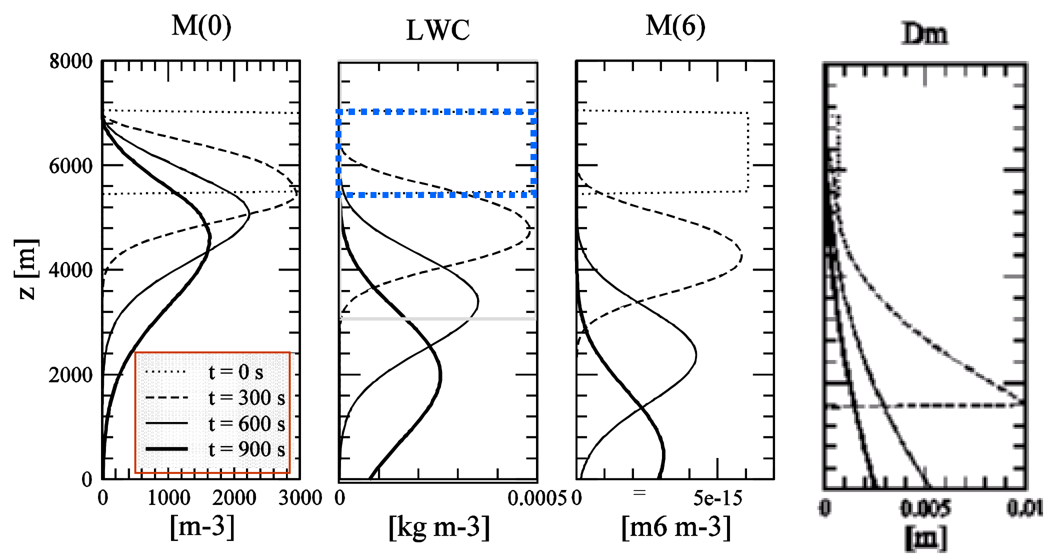
$\rho q$ = 0.5 g m$^{-3}$

$N_0$ = 8×10$^6$ m$^{-4}$

$\mu$ = 0

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

# Analytic bin model calculation: (1D column)




$M_0$ ($N_{Tr}$)

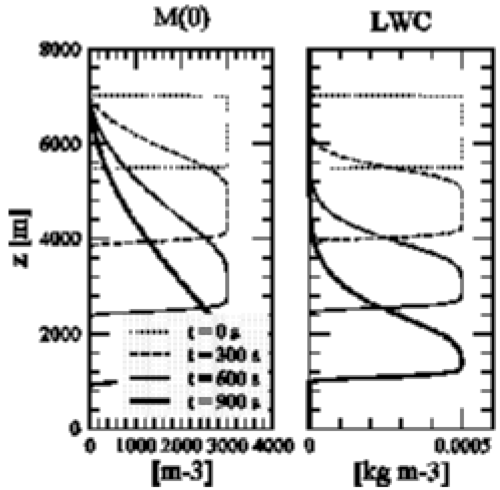
$M_3$ ($\rho q_r$)

$M_6$ ($Z_r$)

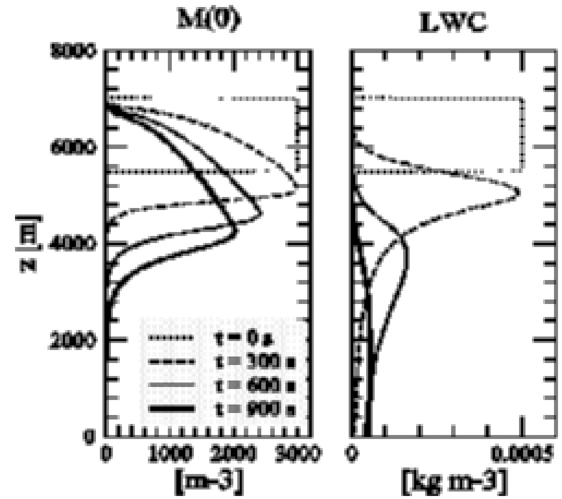
$$D_m = \left[\frac{M_3}{M_0}\right]^{\frac{1}{3}}$$

## Evaluation approach: <u>COMPARE PROFILES</u> of prognostic moments

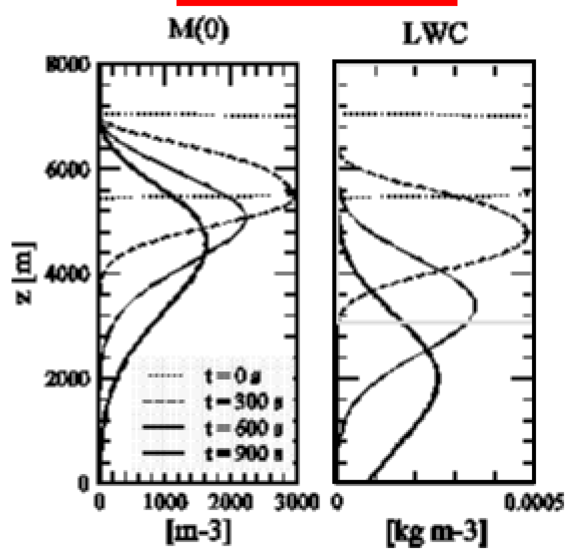
**1-MOMENT**




**2-MOMENT**




**ANALYTIC**




**Useful information,**
**BUT …**

## … other moments are important for microphysical growth rates

**e.g. continuous collection of cloud water ($CL_{cx}$):**

$$\frac{dq_x}{dt}\Big|_{CL} = \int_0^\infty \frac{dm(D)}{dt}\Big|_{CL} N(D)\,dD$$

$$\frac{dm(D)}{dt}\Big|_{CL} = \frac{\pi D^2}{4} V(D) E_{xc} \rho\, q_c = \left(\frac{\pi}{4} E_{xc} \rho q_c\right) D^{2+b_x}$$

$$\frac{dq_x}{dt}\Big|_{CL} = \left(\frac{\pi}{4} E_{xc} \rho q_c\right) \int_0^\infty D^{2+b_x} N(D)\,dD$$

$$\rightarrow \quad \boxed{\frac{dq_x}{dt}\Big|_{CL} \propto M_{2+b_x}}$$

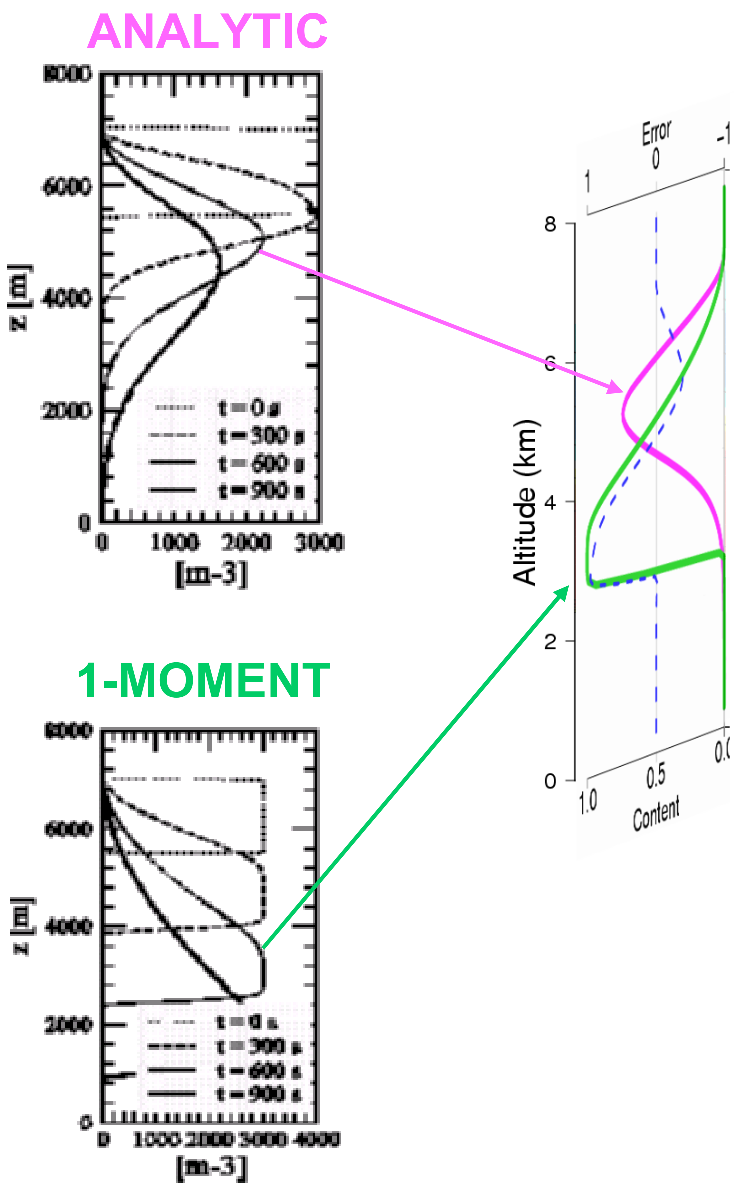
$$\left[\, M_x(p) \equiv \int_0^\infty D^p N_x(D)\,dD \,\right]$$

The $p^{th}$ moment of $N_x(D)$

**… etc. for other processes.**

**Most processes depend on moments between $M_0$ and $M_{3+b}$**

## Comparisons of profiles of a given moment: $M_0$




**For a given time:**

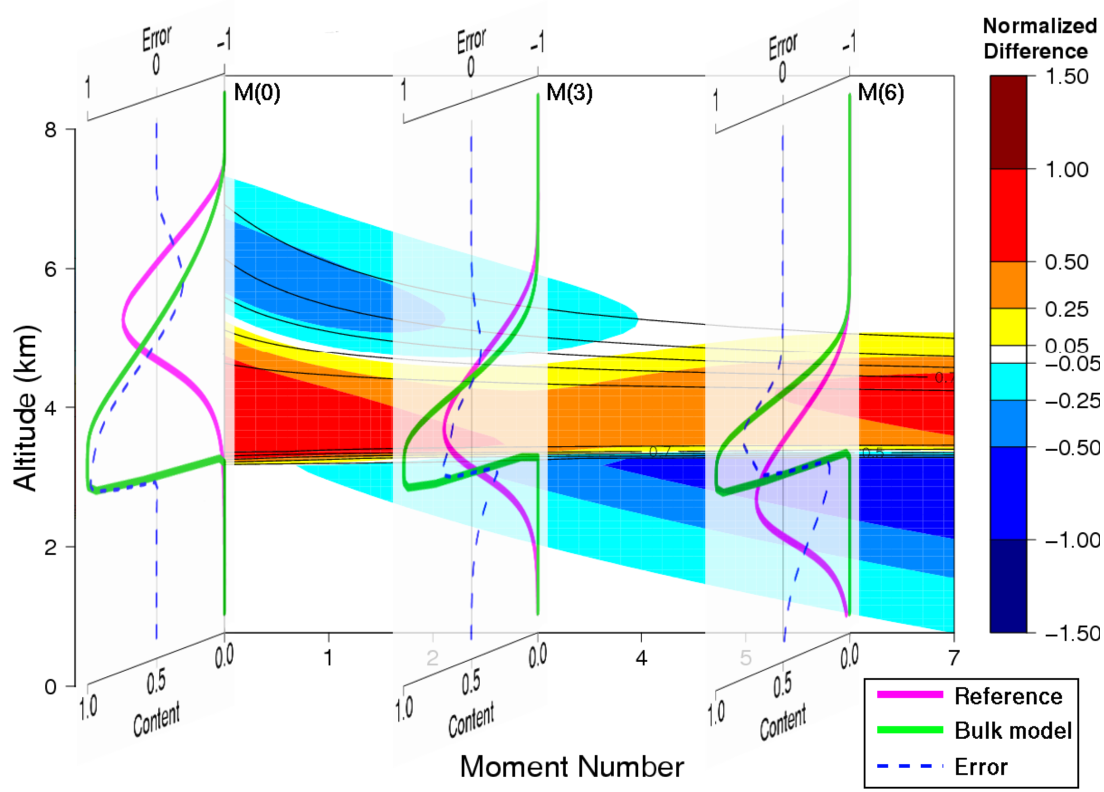
- sedimentation profiles are plotted (for both analytic and bulk models)
- errors (differences, normalized against the initial value) are computed

# <u>Error plots</u> for a range of computed moments: $M_0 - M_7$

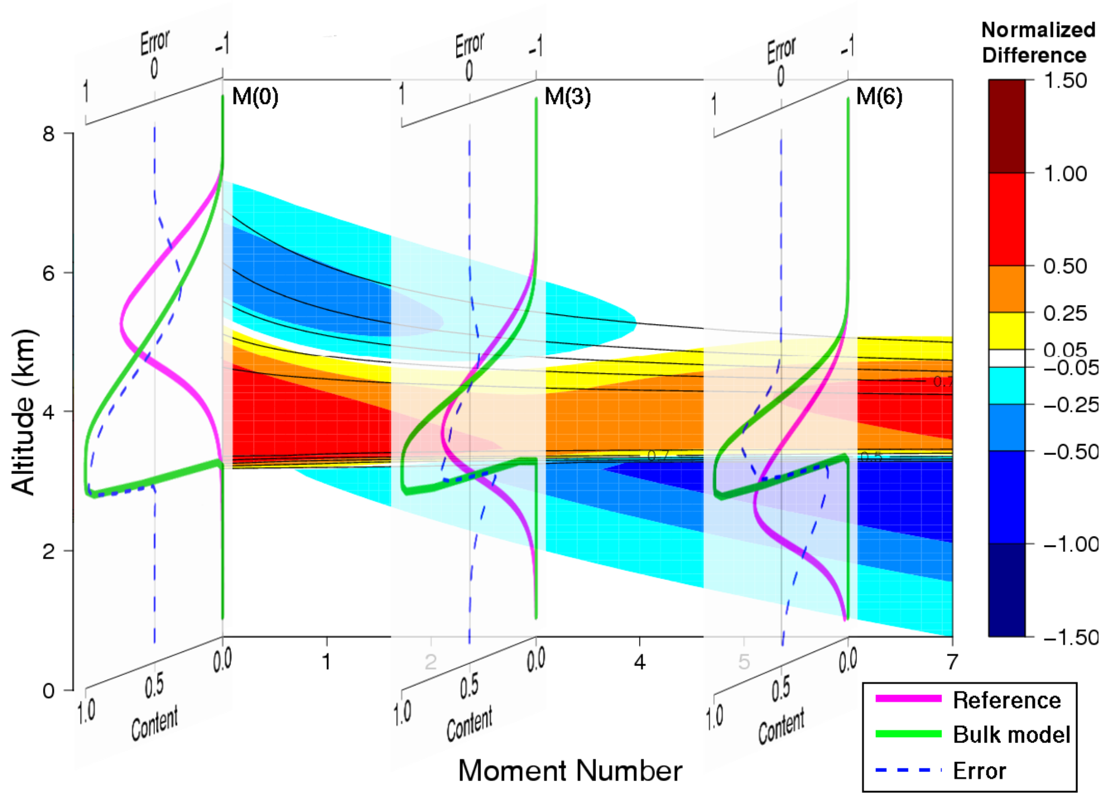
(for a given time)

**Normalized Errors** are

**POSITIVE** / **NEGATIVE**



# “Standard”* 1-MOMENT Scheme:




*

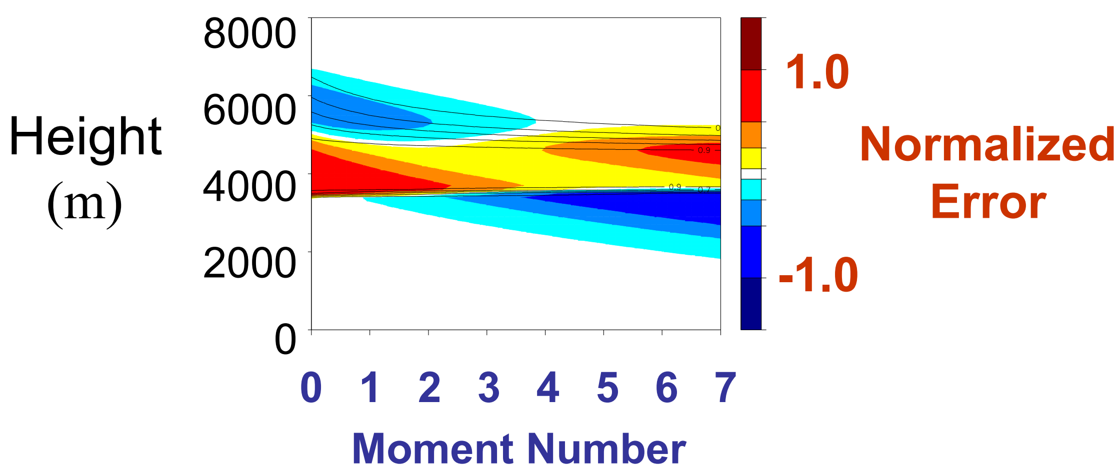
$$N_x(D) = N_{0x} D^{\mu_x} e^{-\lambda_x D}$$

**Prognostic $M_3$ (*q*)**

**Fixed $N_0$**

**Fixed $\mu = 0$**

## "Standard"* 1-MOMENT Scheme:




*

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

**Prognostic $M_3$ ($q$)**

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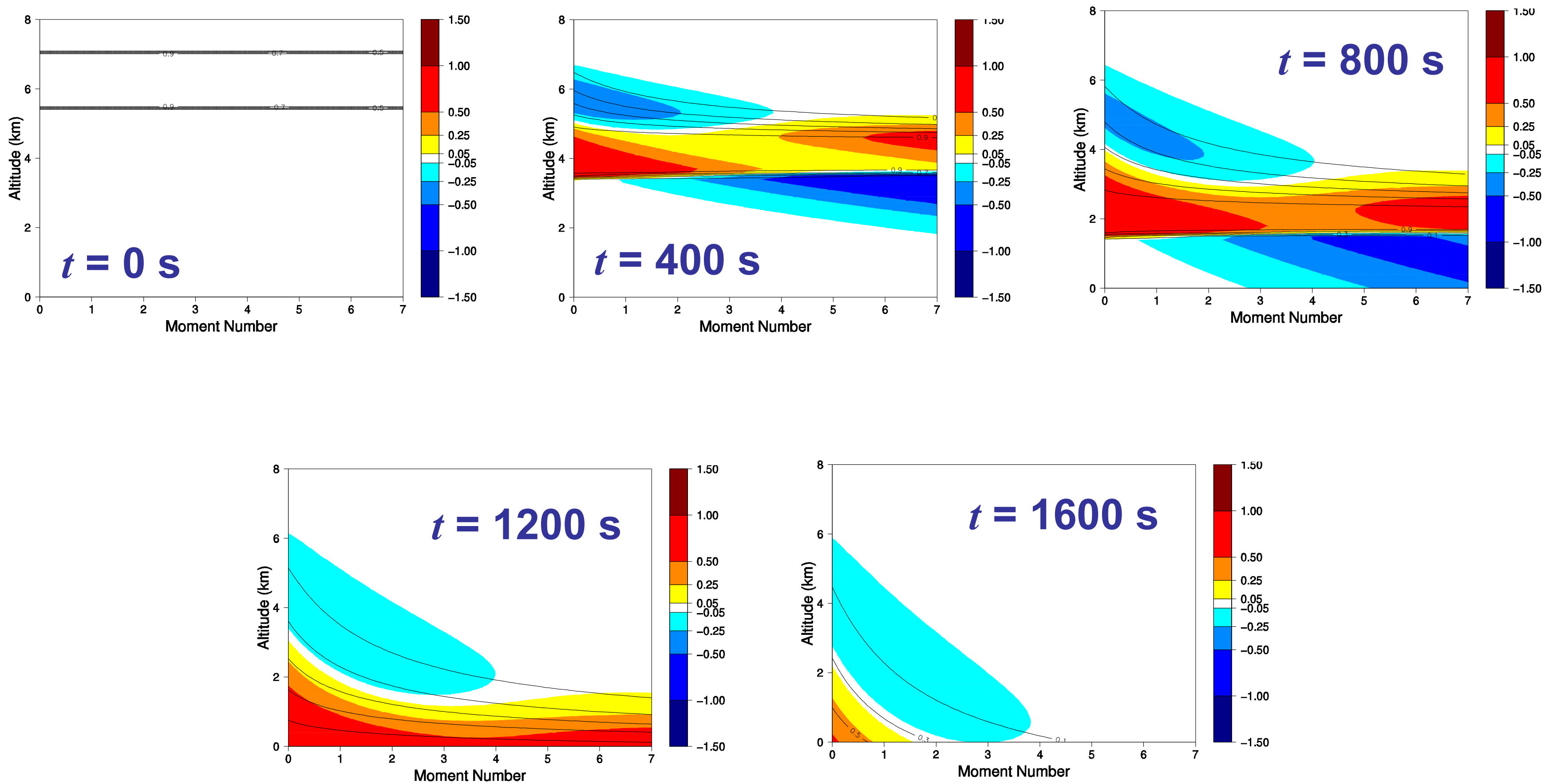
**Fixed $\mu = 0$**

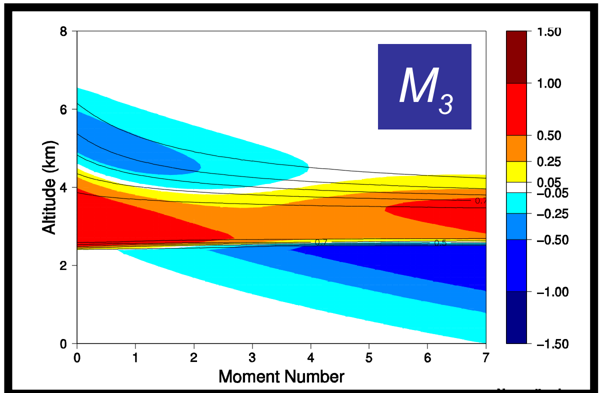
# “Standard” 1-MOMENT Scheme:



# "Standard" Bulk Schemes

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

**1-moment:**

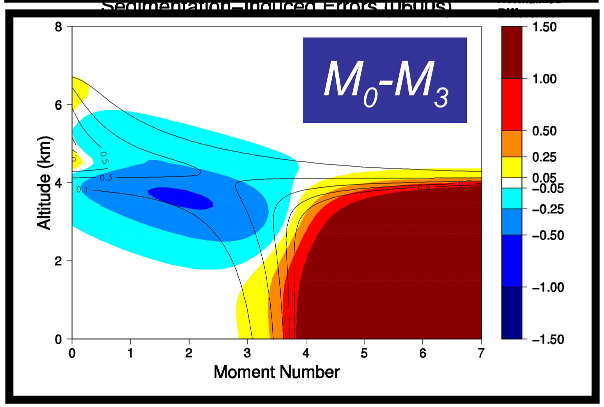



**Prognostic $M_3$ ($q$)**

**Fixed $N_0$**

**Fixed $\mu = 0$**

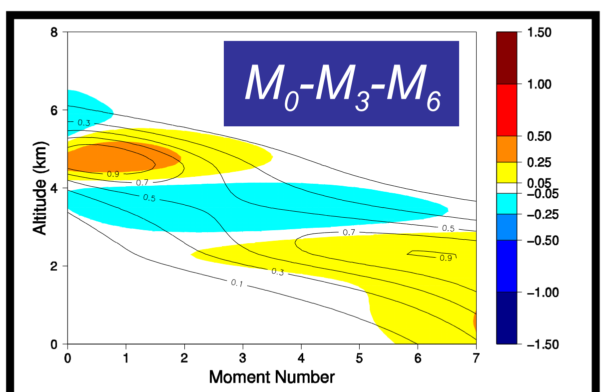
**2-moment:**




**Prognostic $M_0$ ($N_T$), $M_3$ ($q$)**

**Fixed $\mu = 0$**

**3-moment:**




**Prognostic**

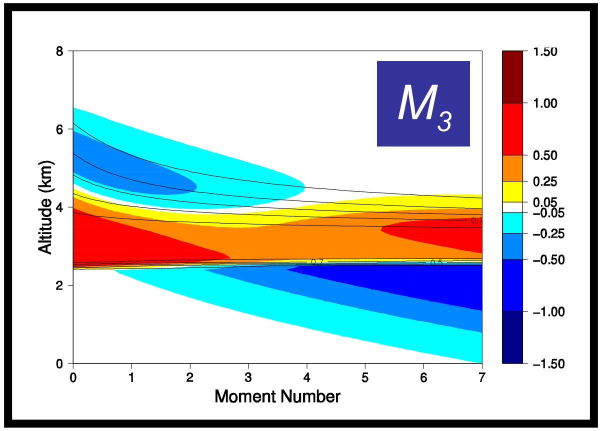
**$M_0$ ($N_T$), $M_3$ ($q$), $M_6$ ($Z$)**

$t$ = 600 s

**Prognostic Moment(s)**

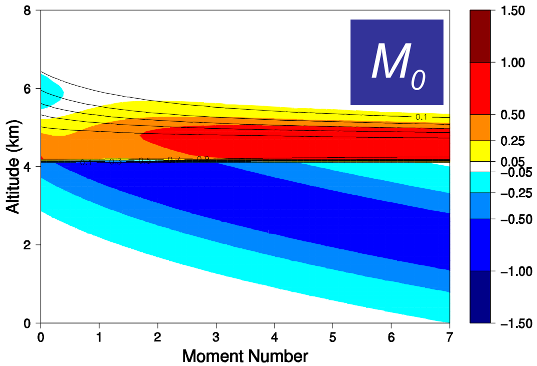
## Alternative Choices of Prognostic Moments:

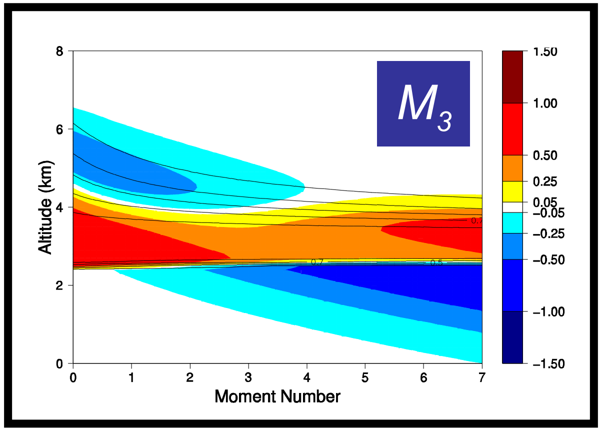
**1-MOMENT schemes**

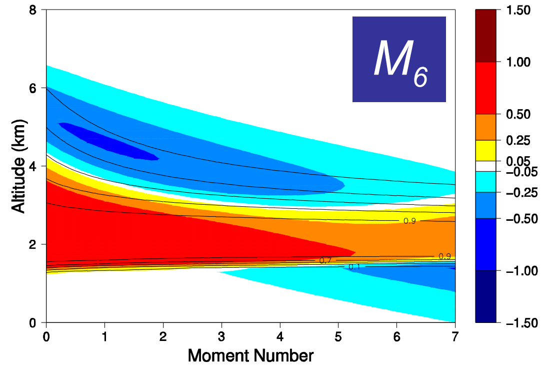


# Alternative Choices of Prognostic Moments:

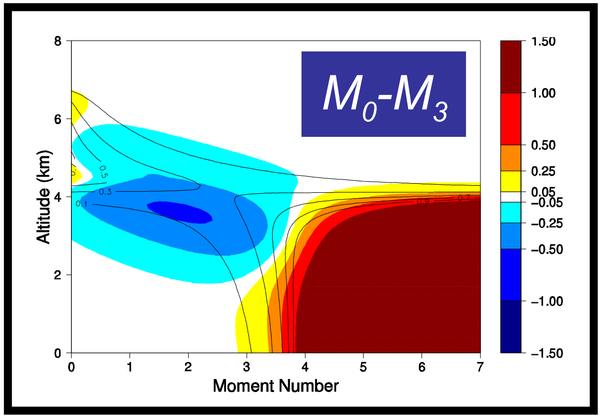
1-MOMENT schemes



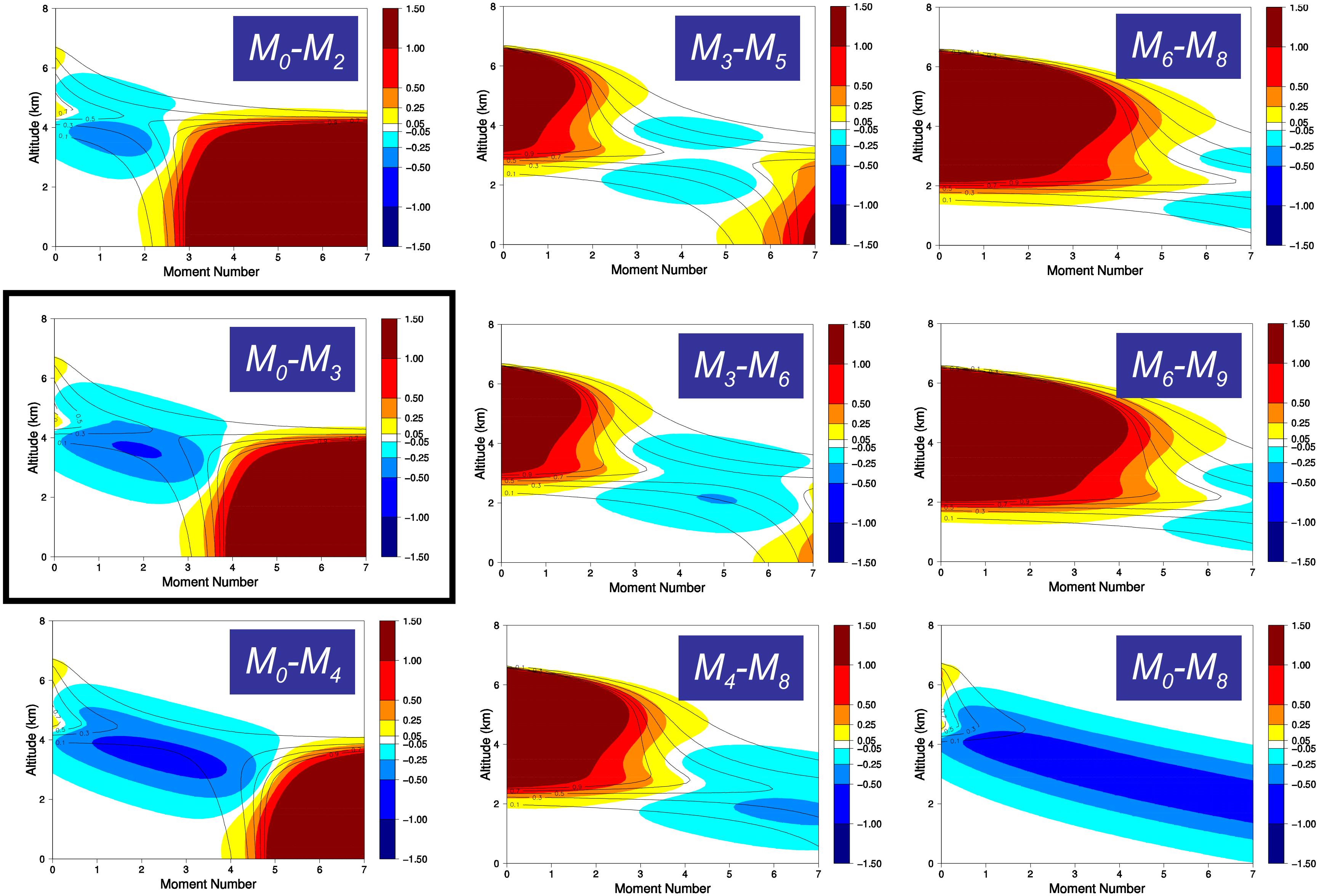



## Alternative Choices of Prognostic Moments: **2-MOMENT schemes**



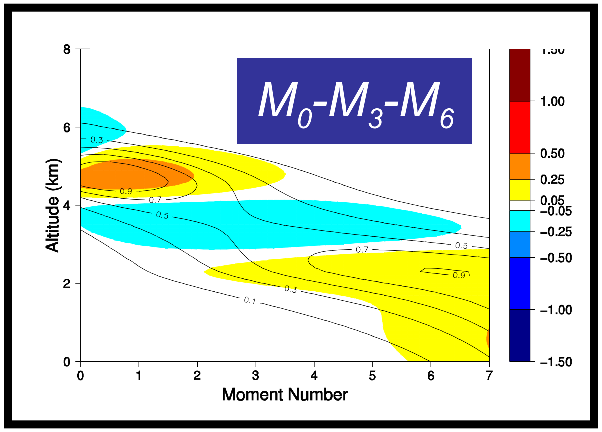
# Alternative Choices of Prognostic Moments:

**2-MOMENT schemes**

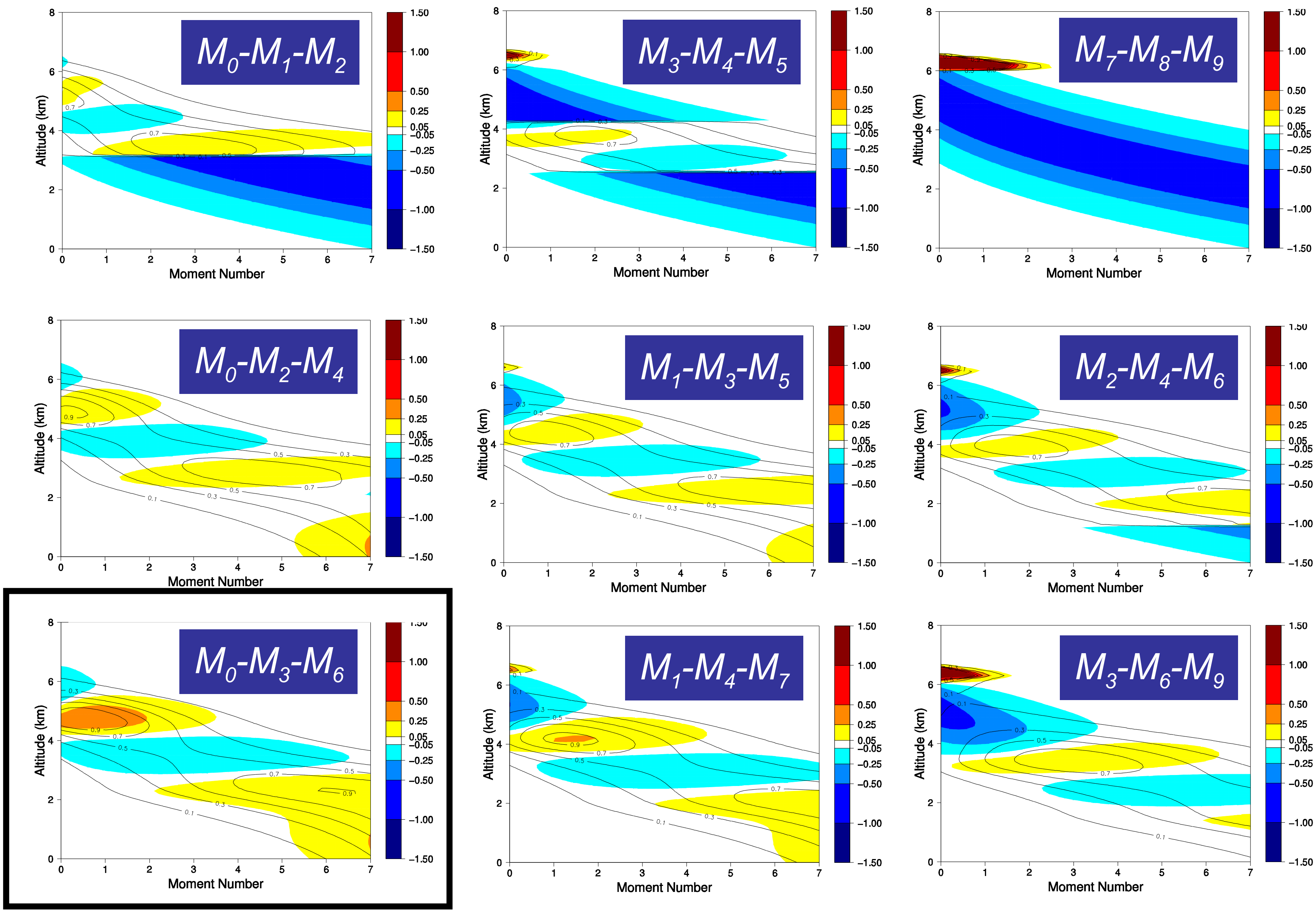


**Alternative Choices of Prognostic Moments:**

**3-MOMENT schemes**



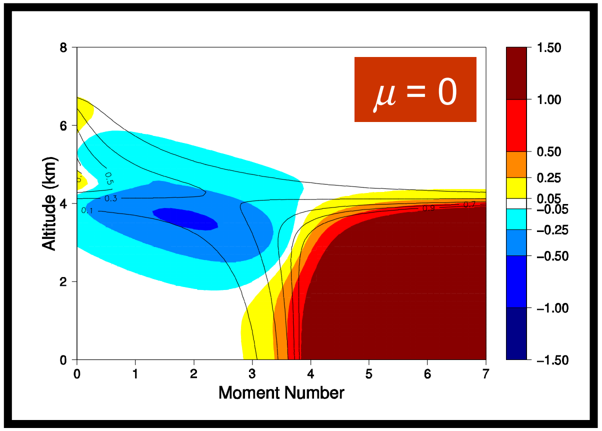
# Alternative Choices of Prognostic Moments: 3-MOMENT schemes



## Alternative treatment of the shape parameter:

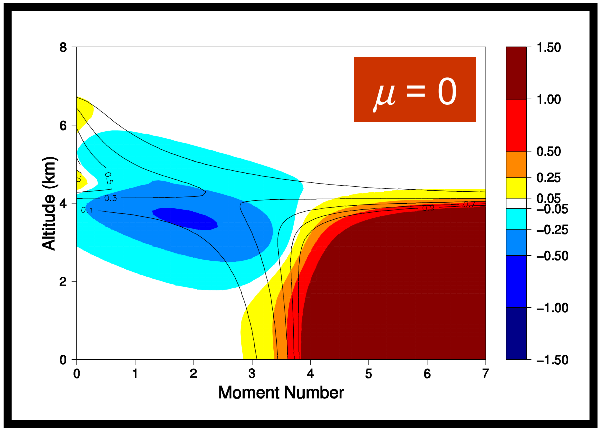
**2-MOM schemes**

$M_0$- $M_3$



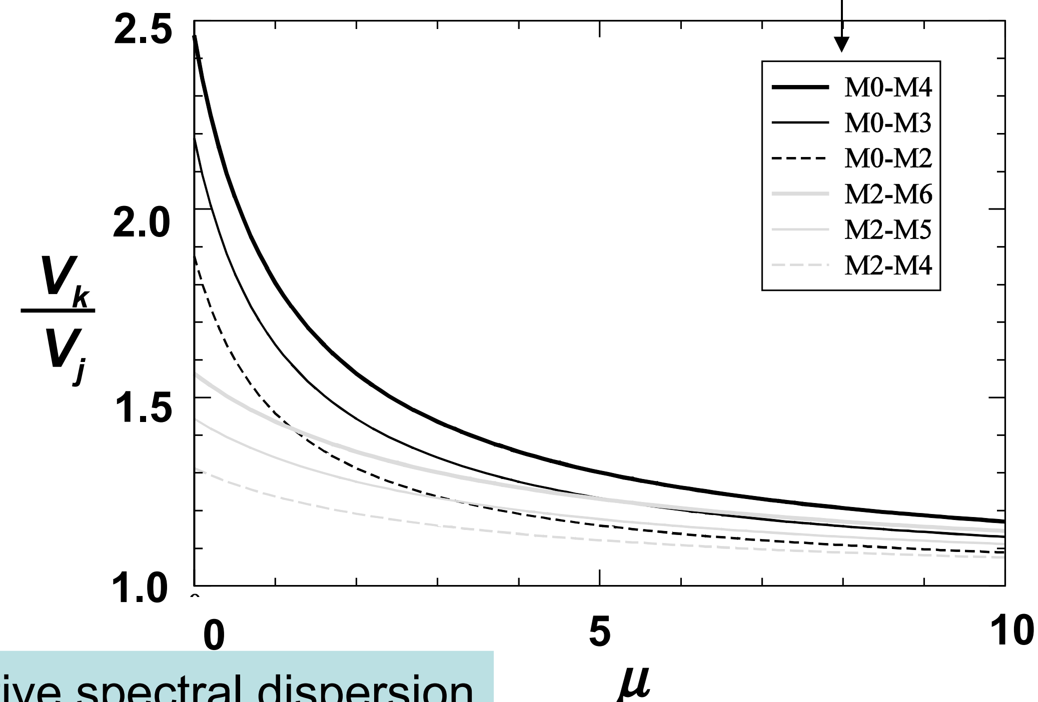
## Alternative treatment of the shape parameter:

**2-MOM schemes** **$M_0$- $M_3$**




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

Different pairs of moments, *k* and *j*




Rate of size-sorting is proportional to ratio $V_k/V_j$.

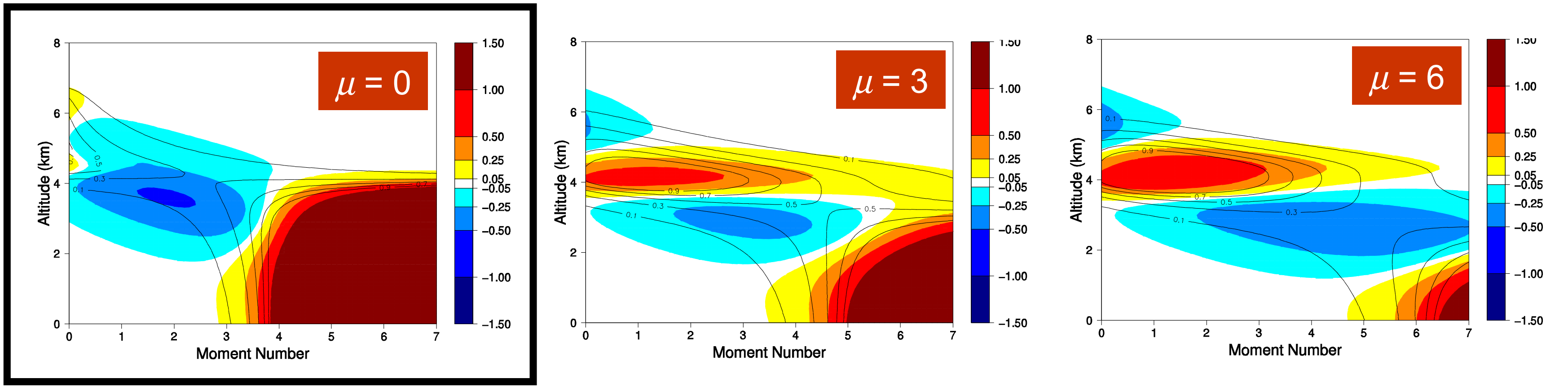
This ratio is a function of $\mu$ ; therefore, the value of $\mu$ controls the rate of size-sorting

NOTE: $\mu$ is a measure of the relative spectral dispersion

## Alternative treatment of the shape parameter:

2-MOM schemes

$M_0$- $M_3$

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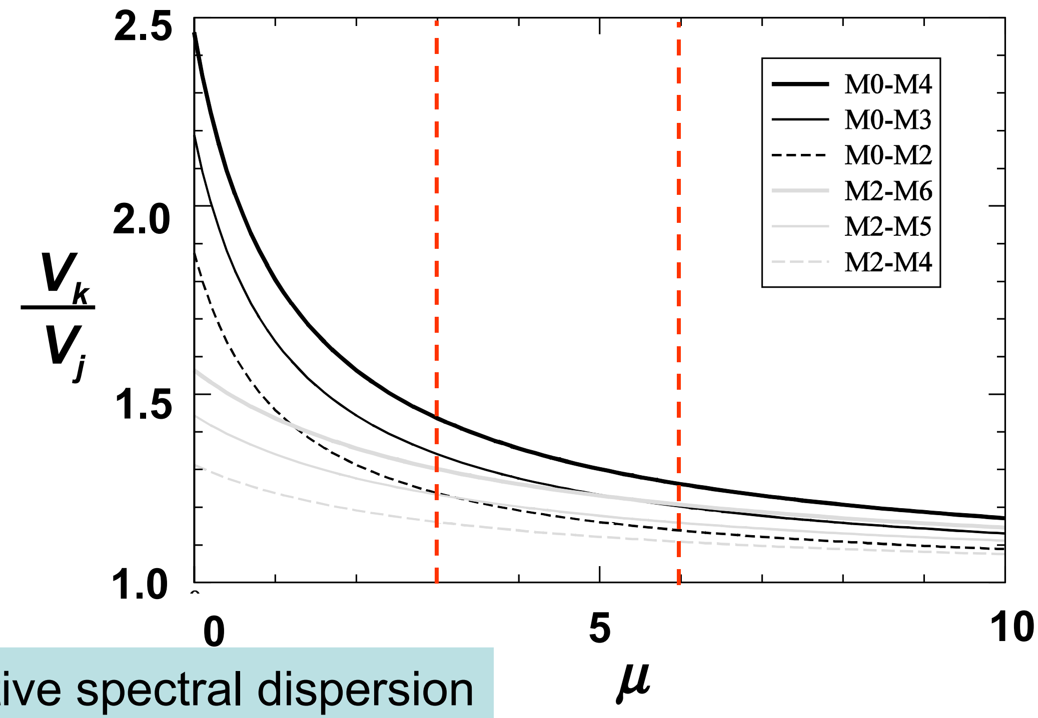
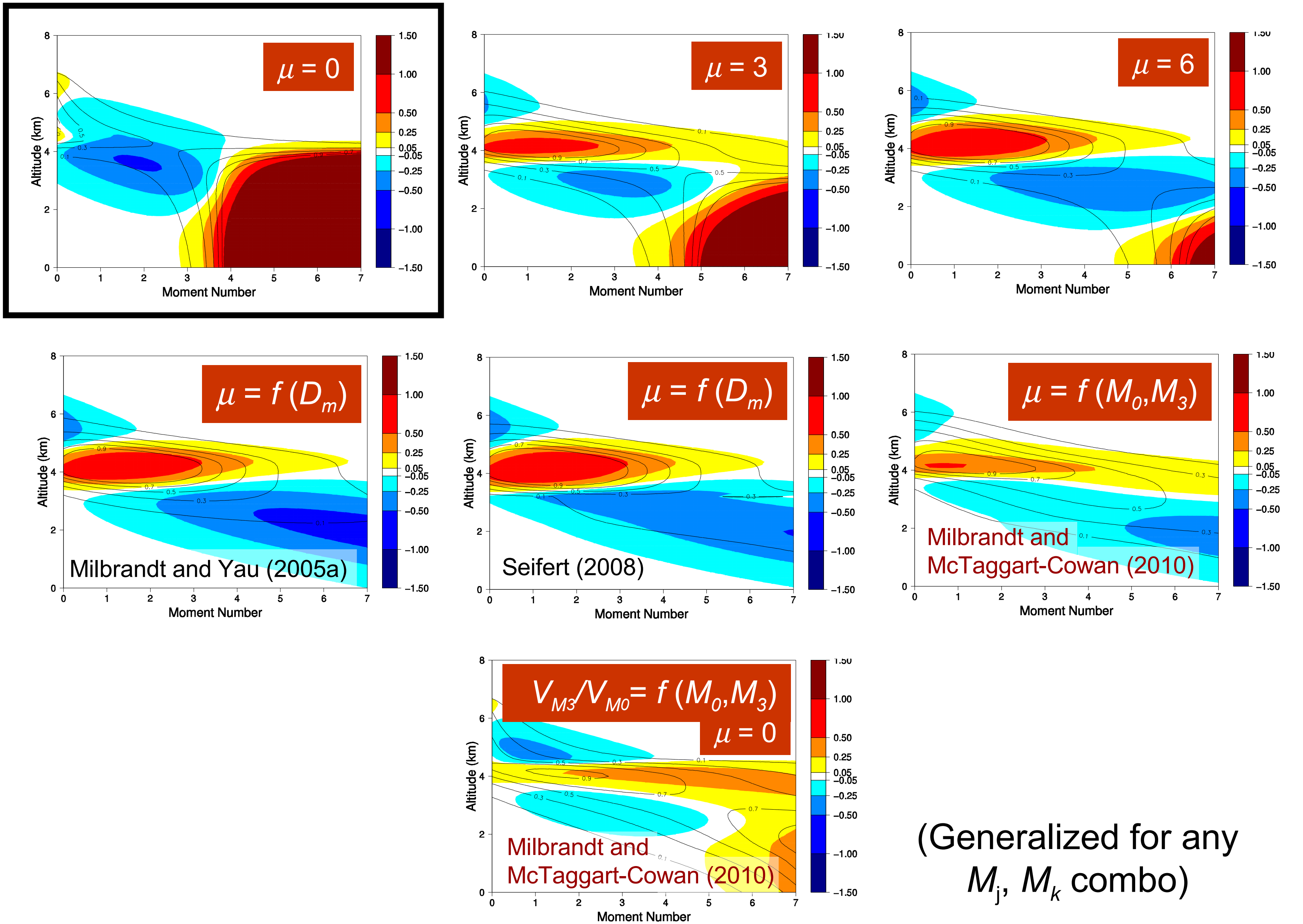



NOTE: $\mu$ is a measure of the relative spectral dispersion

## Alternative treatment of the shape parameter:

**2-MOM schemes** **$M_0$- $M_3$**




(Generalized for any $M_j$, $M_k$ combo)

# CONCLUSION – Part 2

1. Minimizing the sedimentation-induced errors in "computed" moments is important

2. Errors can be shifted to different ranges of moments by choosing different prognostic moment(s)

3. 3-moment schemes are generally superior to 2-moment schemes in terms of reducing sedimentation-induced errors

4. **Existing 2-moment schemes can be dramatically improved by controlling excessive size sorting that results with a fixed DSD dispersion (shape parameter, $\mu$)**

For more details: Milbrandt and McTaggart-Cowan (2010)
*J. Atmos. Sci.* (in press)

# Current Research in Microphysics Parameterization

1. Prognostic Snow Density
2. Sedimentation-Induced Errors
3. **Comparison of 2-Moment Schemes**

# PREMISE:

- 1-moment BMSs suffer from the need to specify DSD parameters; 2-moment BMSs predict DSD more feely
- 2-moment BMSs can better represent certain processes (e.g. sedimentation, self-collection, drop breakup)
- **Implication**: Increasing complexity of a BMS tends towards truth

# MOTIVATING QUESTIONS:

- **Do similar 2-moment schemes produce similar results?**
- **What are the major sensitivities in 2-moment BMSs?**

## METHODOLGY:

- Use similar 2-moment BMSs in a common modeling framework
- Conduct simulations (with each scheme) and compare results
- Identify, through sensitivity tests, the reasons for any major differences

# METHODOLGY:

- BMSs: Morrison* (MOR) and Milbrandt-Yau** (MY)
- Model: WRF (v3.1)
- Case: Idealized supercell (1-km, initial warm/moist bubble)

| MOR | MY |
| --- | --- |
| + 2-moment (all categories*) | + 2-moment (all categories*) |
| + cloud, rain, ice, snow, graupel | + cloud, rain, ice, snow, graupel, **hail** |
| + fixed shape parameters (0) | + fixed shape parameters (0) |
| + *$N_c$ = 250 $cm^{-3}$ | + *$N_c$ = 250 $cm^{-3}$ |

- similar fall velocity parameters
- similar warm rain coalescence parameterizations
- similar ice initiation
- different raindrop breakup parameterizations

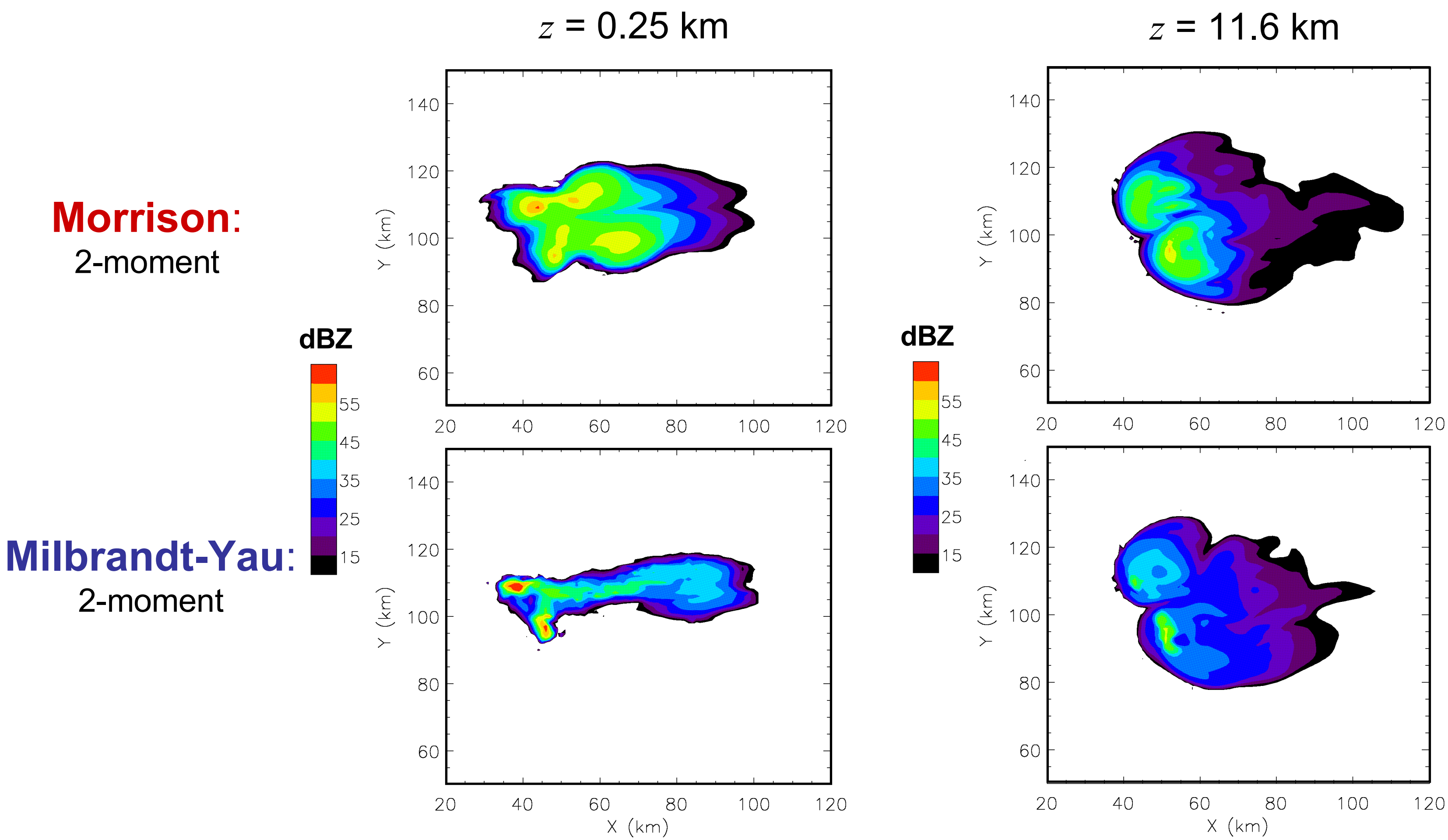
*** As tested in this study ***

* Morrison et al. (2009), *Mon. Wea. Rev.*

** Milbrandt and Yau (2005), *J. Atmos. Sci.*

# BASELINE (CONTROL) SIMULATIONS

**Radar Reflectivity**




t = 60 min

# BASELINE (CONTROL) SIMULATIONS

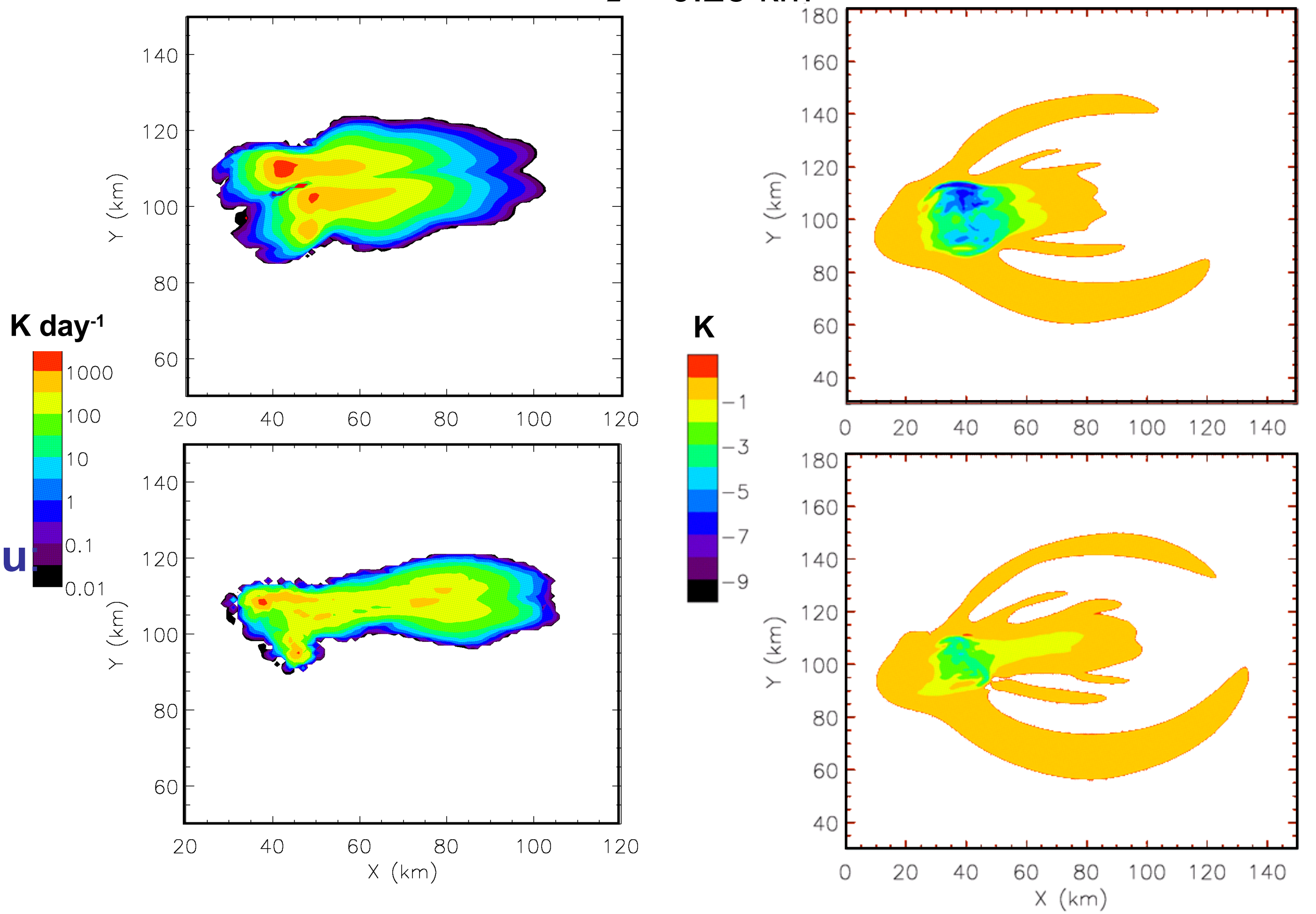
## Evaporative cooling rates

## Cold Pool Strength* ($\theta'$)

$z$ = 0.25 km

**Morrison:**
2-moment

**Milbrandt-Yau:**
2-moment



# BASELINE (CONTROL) SIMULATIONS

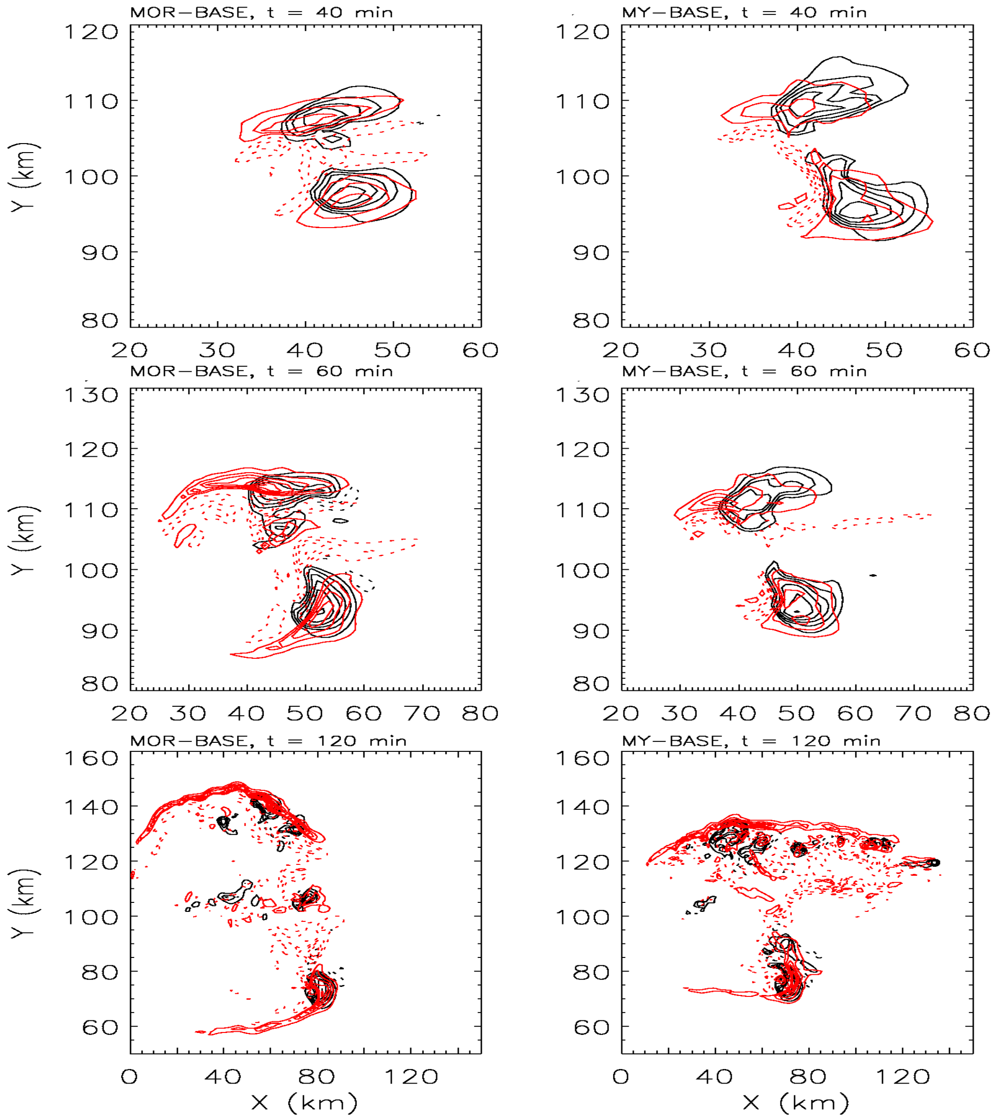
**Vertical Velocity**
$z$ = 0.8 km
$z$ = 4.7 km

**Morrison:** **Milbrandt-Yau:**

$t$ = 40 min

$t$ = 60 min

$t$ = 120 min



# SENSITIVITY EXPERIMENTS:
# 1. GRAUPEL vs. HAIL

**Morrison**:

category $x$ = *graupel* → $\rho_g$ = 400 kg m$^{-3}$
$V_g \sim$ 1 - 3 m s$^{-1}$
} medium-density **GRAUPEL**

***OR***

category $x$ = *hail* → $\rho_g$ = 900 kg m$^{-3}$
$V_g \sim$ 10 - 40 m s$^{-1}$
} high-density **HAIL**

→ **with a switch to toggle between types**

**Milbrandt-Yau**:

category $x$ = *graupel* → $\rho_g$ = 400 kg m$^{-3}$
$V_g \sim$ 1 - 3 m s$^{-1}$
} medium-density **GRAUPEL**

***AND***

category $x$ = *hail* → $\rho_h$ = 900 kg m$^{-3}$
$V_h \sim$ 10 - 40 m s$^{-1}$
} high-density **HAIL**

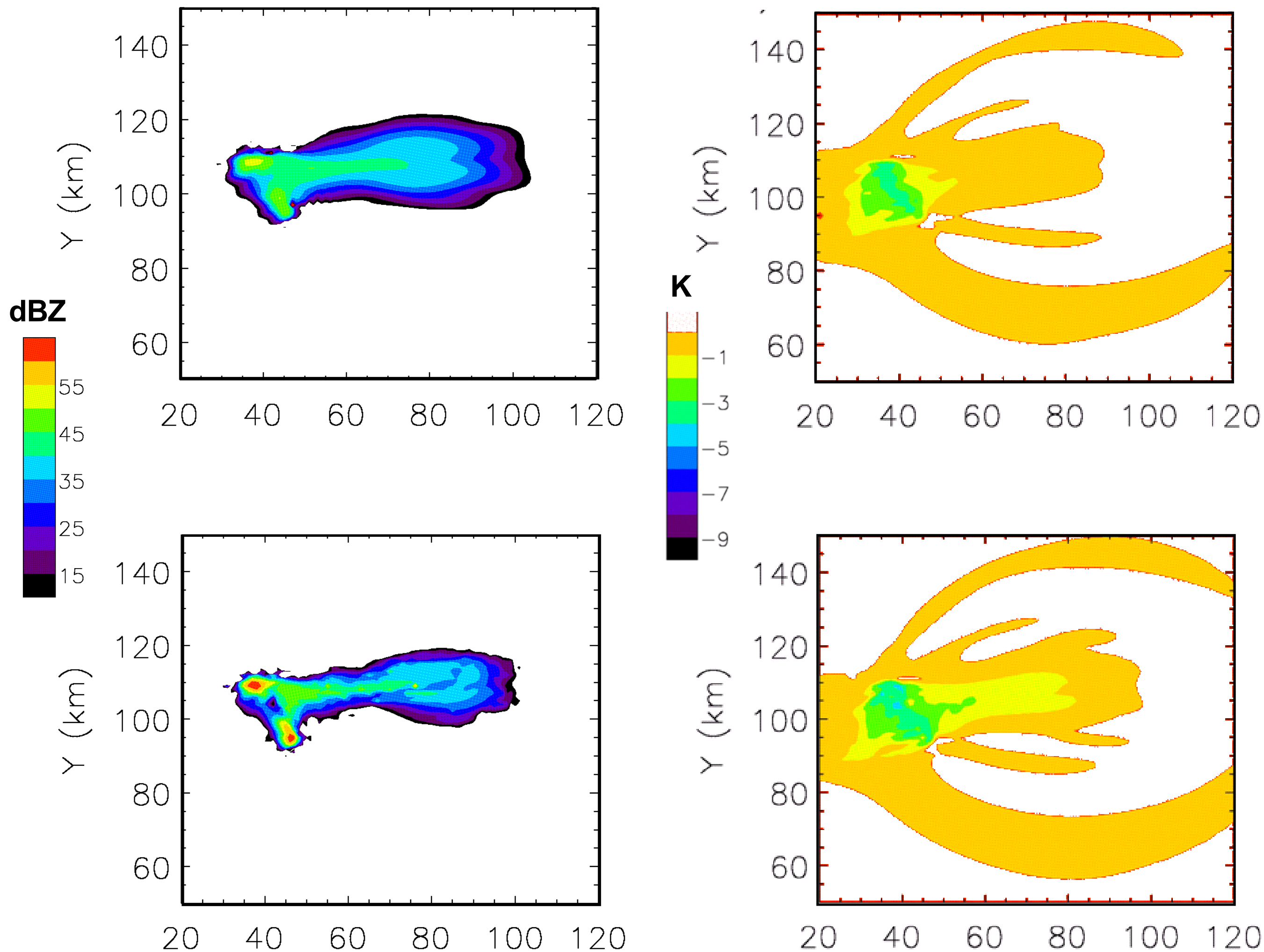
→ **with switches to shut OFF either category**

# SENSITIVITY EXPERIMENTS:
# 1. GRAUPEL vs. HAIL

**Radar Reflectivity** | **Cold Pool Strength* ($\theta'$)**

**Morrison:**
**GRAUPEL - only**

**Milbrandt-Yau:**
**GRAUPEL - only**



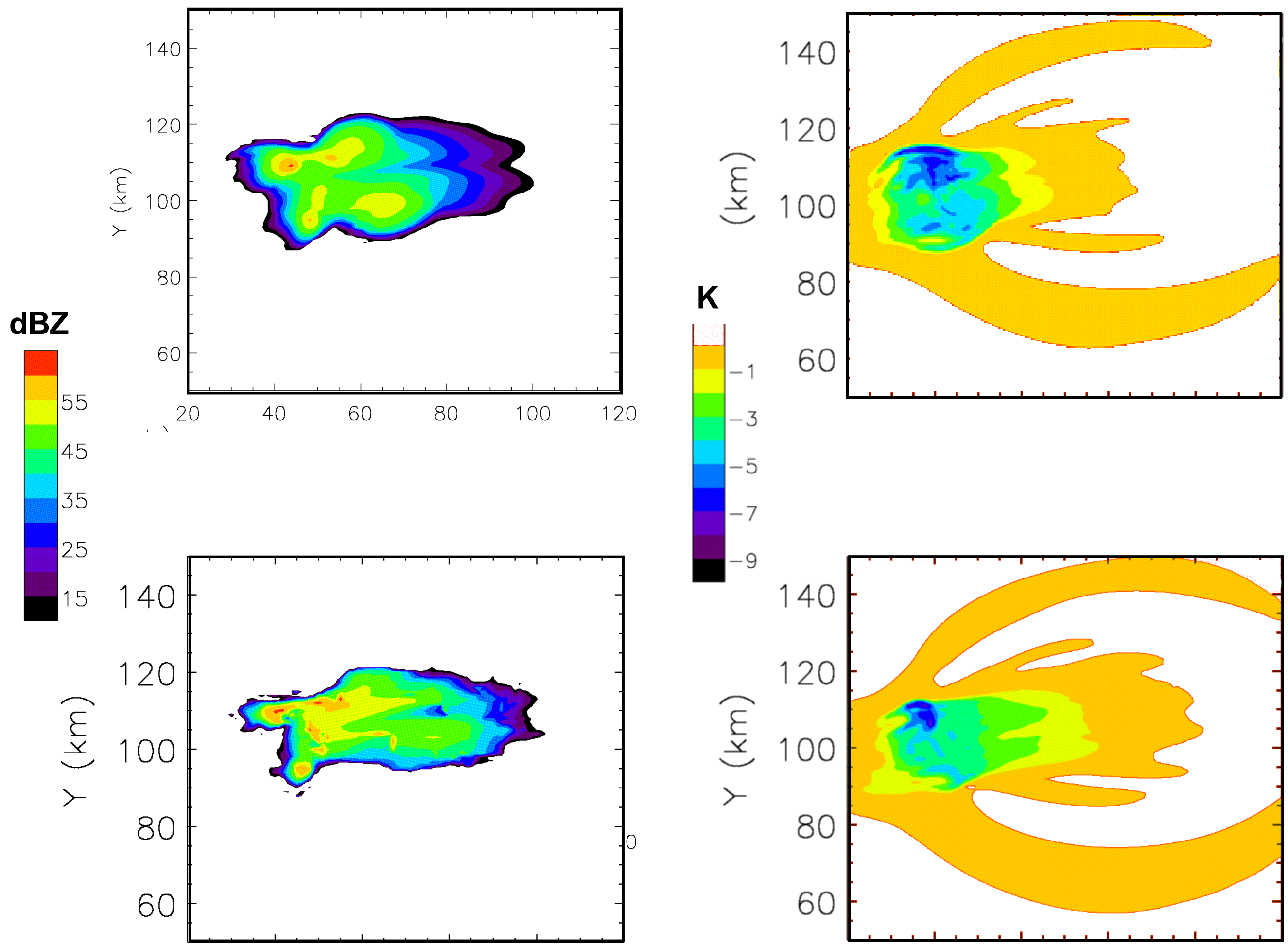

$z$ = 0.25 km

# SENSITIVITY EXPERIMENTS:
# 1. GRAUPEL vs. HAIL

**Radar Reflectivity** | **Cold Pool Strength* ($\theta'$)**

**Morrison:**
**HAIL – only**
(BASELINE)

**Milbrandt-Yau:**
**HAIL - only**

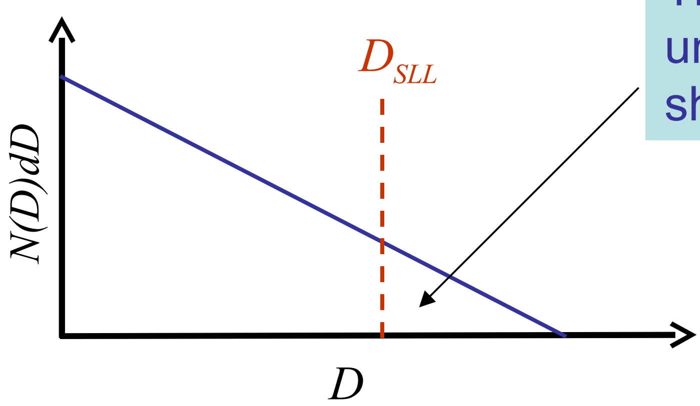



$z$ = 0.25 km

# CONVERSION of *GRAUPEL* to *HAIL*

- When a frozen particle growing by accretion first reaches the Shumann-Ludlam limit (*SLL*), it is termed a hailstone (Young, 1993)
- The size of a particle at the *SLL* is a function of the ambient *T*, *LWC*, and *IWC*:

$$D_{SLL} = 0.01 \exp\left( \frac{-T_c}{1\times10^4 \rho (q_c + q_r) - 1.3\times10^3 \rho q_i + 10^{-3}} \right)$$




**GRAUPEL size distribution**

This portion of *GRAUPEL* is undergoing **wet growth** and should therefore convert to *HAIL*

Strictly, the incomplete gamma distribution ($D_{SLL} \rightarrow \infty$) should be evaluated

Currently in Milbrandt-Yau scheme:

$$\rightarrow \quad CN_{gh} = \frac{D_{mg}}{2D_{SLL}} (CL_{cg} + CL_{rg} + CL_{ig})$$

# SENSITIVITY EXPERIMENTS:
# 2. PARAMETERIZATION OF DROP BREAKUP

## Raindrop breakup is parameterized by:

1. Imposing a drop size-limiter (maximum $D_{r\_mean}$)

**MORRISON**: $D_{r\_max}$ **= 0.9 mm**

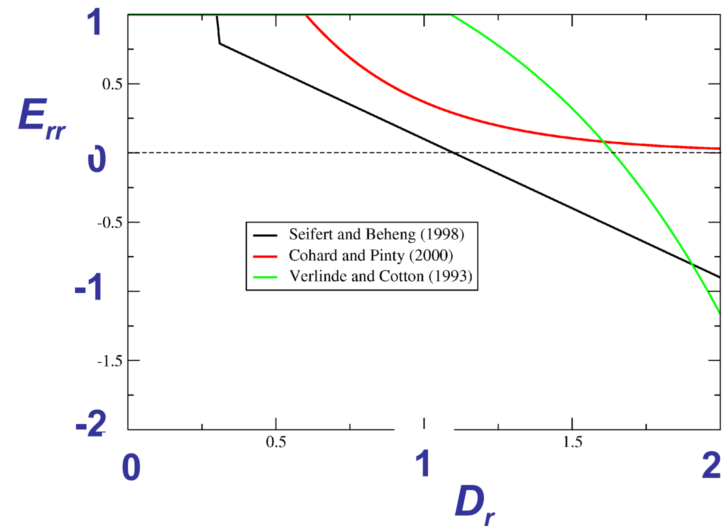
**MILBRANDT-YAU**: $D_{r\_max}$ **= 5.0 mm**

2. Reduction of collection efficiency in rain self-collection equation

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

**MORRISON**: **none**

**MILBRANDT-YAU**: **Ziegler (1985)**

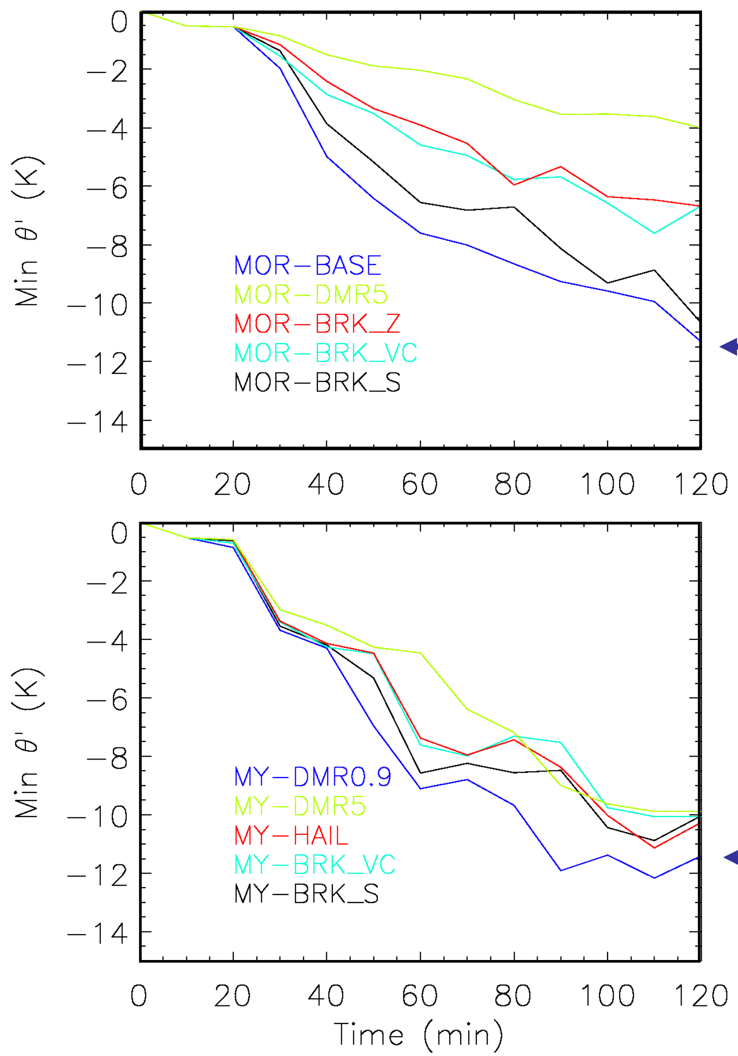


# SENSITIVITY EXPERIMENTS:
# 2. PARAMETERIZATION OF DROP BREAKUP

**Cold Pool Strength* (min. $\theta'$)**

**Morrison:**
2-moment

**Milbrandt-Yau:**
2-moment




**MOR-Baseline**

**MY-$D_{max}$= 0.9 mm**

All runs with **HAIL**-only

# CONCLUSION – Part 3

1. The simulation of deep convection can be sensitive to the parameterization of graupel/hail in a 2-moment BMS

2. The simulation of deep convection can be very sensitive to the parameterization of raindrop breakup (depending on how the ice-phase results in big/little drops)

3. **Increasing complexity in a BMS does <u>not</u> necessarily lead to convergence**

For more details: Morrison and Milbrandt (2010) *Mon. Wea. Rev.* (accepted)

# CONCLUSION – Part 3

1. The simulation of deep convection can be sensitive to the parameterization of graupel/hail in a 2-moment BMS

2. The simulation of deep convection can be very sensitive to the parameterization of raindrop breakup (depending on how the ice-phase results in big/little drops)

3. **Increasing complexity in a BMS does <u>not</u> necessarily lead to convergence**

Continued research: (collaboration with NCAR)

→ To examine the sensitivity of the parameterization of specific processes in 2-moment schemes – though sensitivity studies and comparison to observation – towards understanding the behavior of these schemes and of the microphysics of storm systems

# Current Research and Development

## 1. Upgrade of 2-moment (M-Y) scheme for HRDPS

- diagnostic $\mu_r$ and $\mu_h$
- new parameterization for hail initiation

## 2. Development of simplified version for RDPS

- reduction to essential categories and processes
- time-splitting for microphysics

## 3. Development* of version for GDPS

- cloud (and precipitation) fraction

  * current research of Frederick Chosson (McGill University)

# THANK YOU

**Acknowledgments**

LAM-V10 Development Team (RPN and CMDN)

Ron McTaggart-Cowan (RPN)

Hugh Morrison (NCAR)

# Milbrandt-Yau* Multi-Moment Scheme

- Six hydrometeor categories:
  - 2 liquid: ***cloud*** and ***rain***
  - 4 frozen: ***ice***, ***snow***, ***graupel*** and ***hail***
  - Each size spectrum described by a 3-parameter gamma distribution function
    → **Full version has 17 prognostic variables**

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

- ~ 50 distinct microphysical processes

- **Diagnostic-$\alpha_x$** relations added for 2-moment version

- **Predictive equations for $Z_x$** added for 3-moment version

* Milbrandt and Yau (2005a,b) *J. Atmos. Sci.*

# Milbrandt-Yau* Multi-Moment Scheme

## Applications of Scheme: (since 2005)

- Implementation of 1-moment version for **GEM-LAM-2.5** system
- Implementation of 3-moment version into **ARPS** (U of Oklahoma)
- 2-moment version used for 2010 Vancouver Olympics (**1-km LAM**)
- 2-moment version implemented into official **WRF_v3.2**
- 2-moment version to be implemented into **HRDPS**

* Milbrandt and Yau (2005a,b) *J. Atmos. Sci.*