REPRESENTING CLOUD AND PRECIPITATION

IN

NWP MODELS IN CANADA

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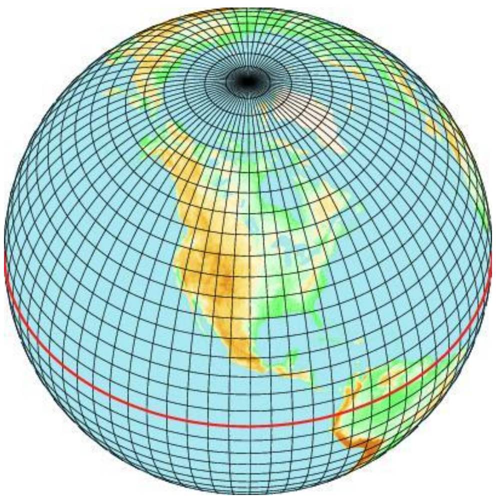
Environment Canada's forecast model

GEM (**G**lobal **E**nvironmental **M**ultiscale)

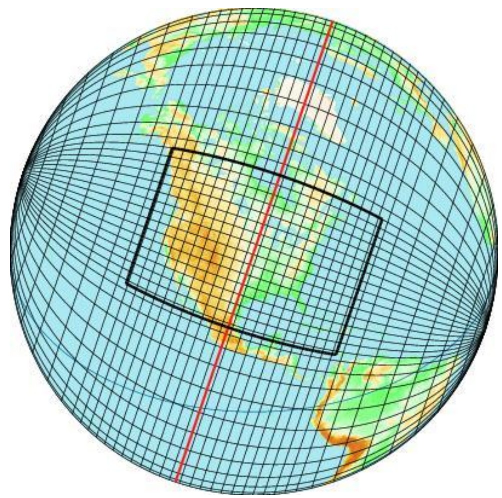
Grid configurations:

Global Uniform



- medium-range (10-d)
- Δx = 35 km → 25 km
- Δt = 15 min

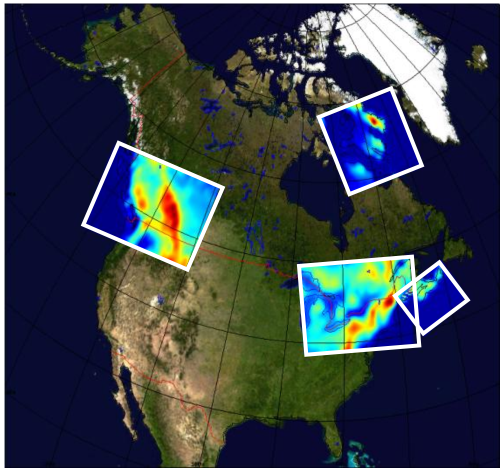
Global Variable



- short-range (48-h)
- Δx = 15 km → 10 km
- Δt = 7.5 min

Simple Cloud Scheme

Limited Area (LAM)

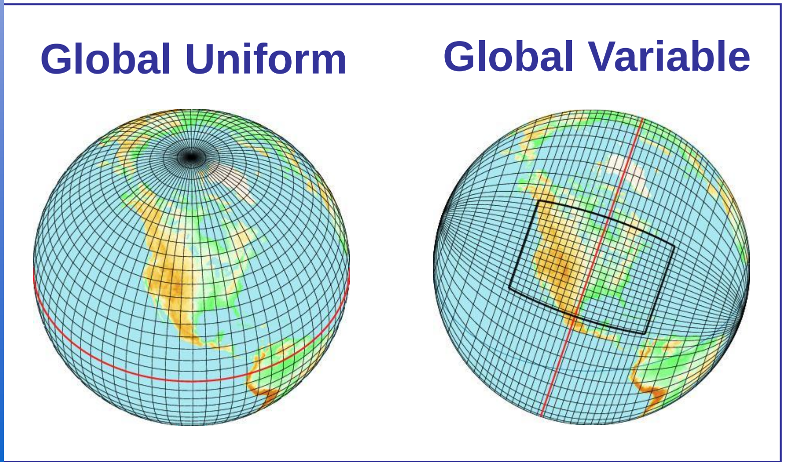


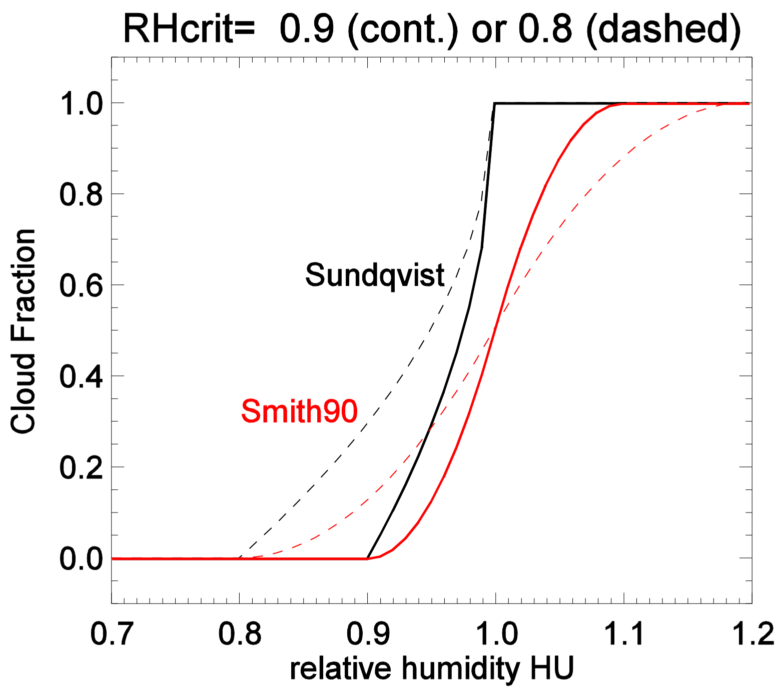
- experimental
- short-range (24-h)
- Δx = 2.5 km → 1 km
- Δt=1 min (Δt=30s)

Detailed Microphysics Scheme

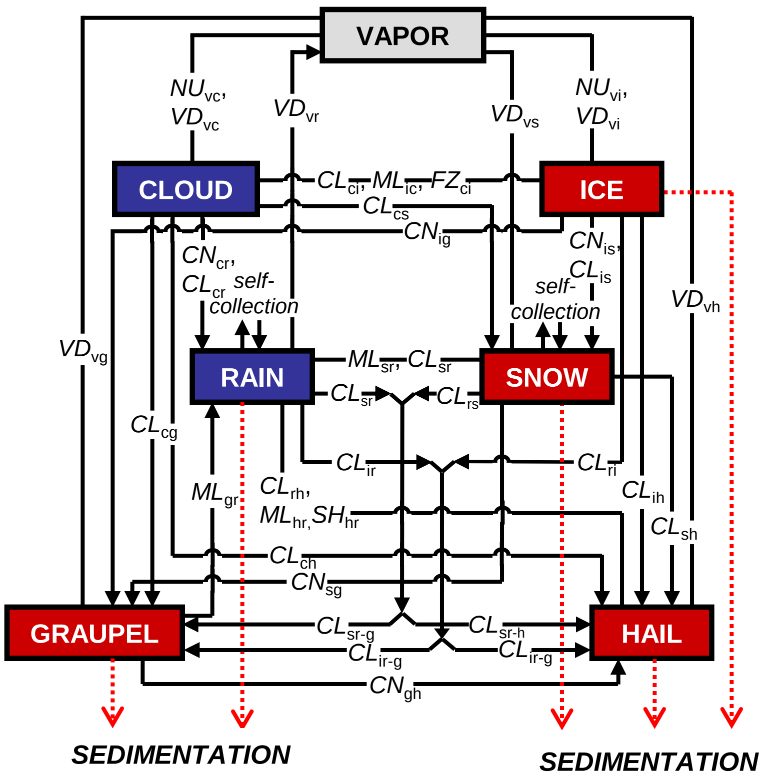
The simple cloud scheme (Sundqvist)

- Cloud-cover fraction is diagnosed (function of RH)
- Condensation occurs when RH exceeds a threshold (80% near surface)
- Total condensate (cloud water/ice) is prognostic (advected)
- Precipitation falls instantly to the ground – there is no advection of precipitation

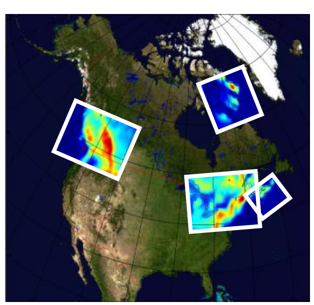




The detailed microphysics scheme



Limited Area Model



Six hydrometeor categories:

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

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

Multi-moment scheme

Milbrandt and Yau (JAS 2005 a,b)
Milbrandt and Yau (JAS, 2006 a,b)
Gultepe and Milbrandt (Pure App. Geoph.,2007)
Milbrandt et al. (MWR, 2008)
Milbrandt et al. (MWR, 2010)
Dawson et al. (MWR, 2010)

Scheme implemented in

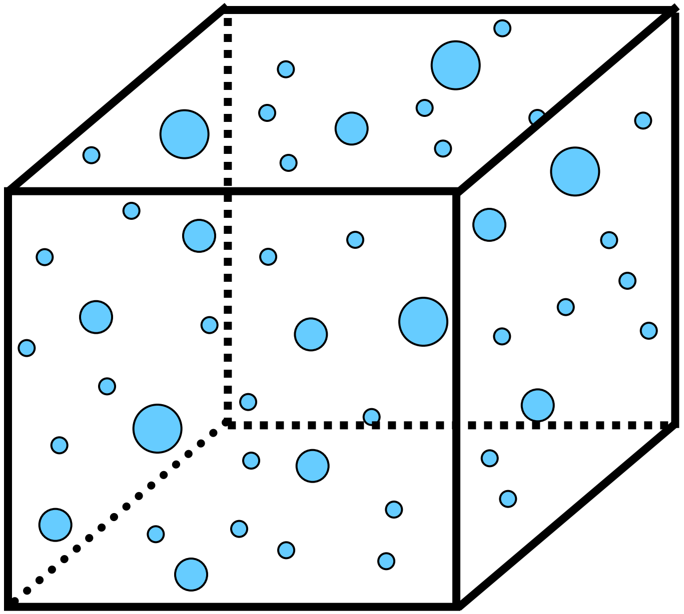
GEM-LAM, Global variable (Canada)

ARPS (U Oklahoma, US)

WRF 3.2 (US)

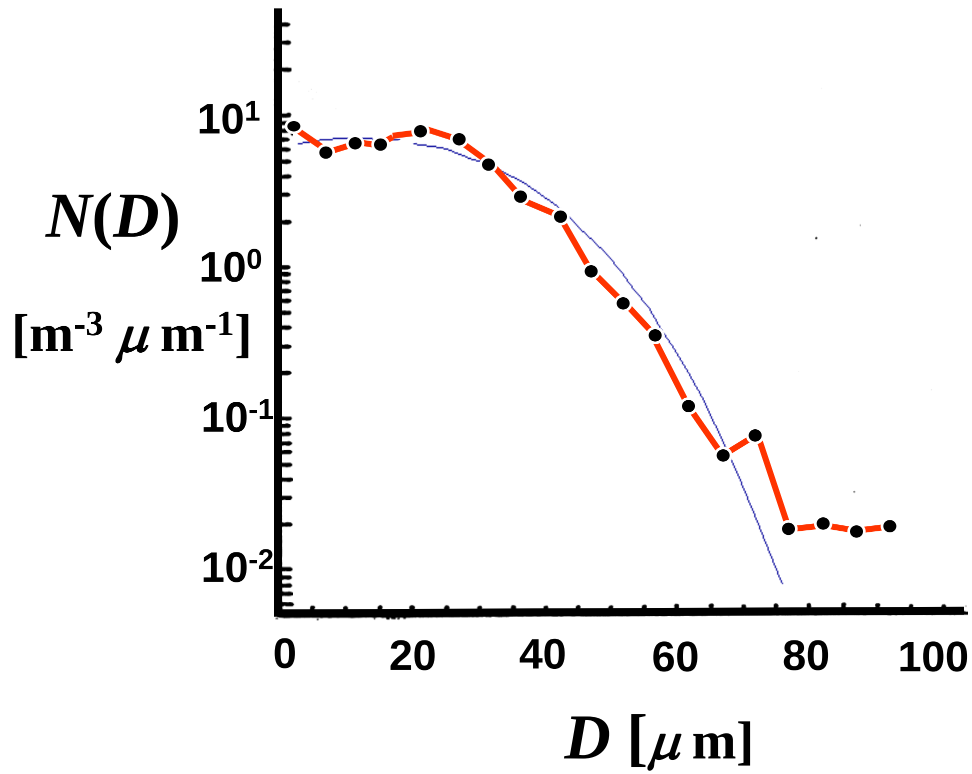
- Overview of the scheme
- Testing and improvement in IMPROVE-2 (GEM-LAM)
- Forecast in winter Olympics 2010 (GEM-LAM)
- Testing over Arctic (GEM-Global Variable)

Representing the size spectrum



1 m³

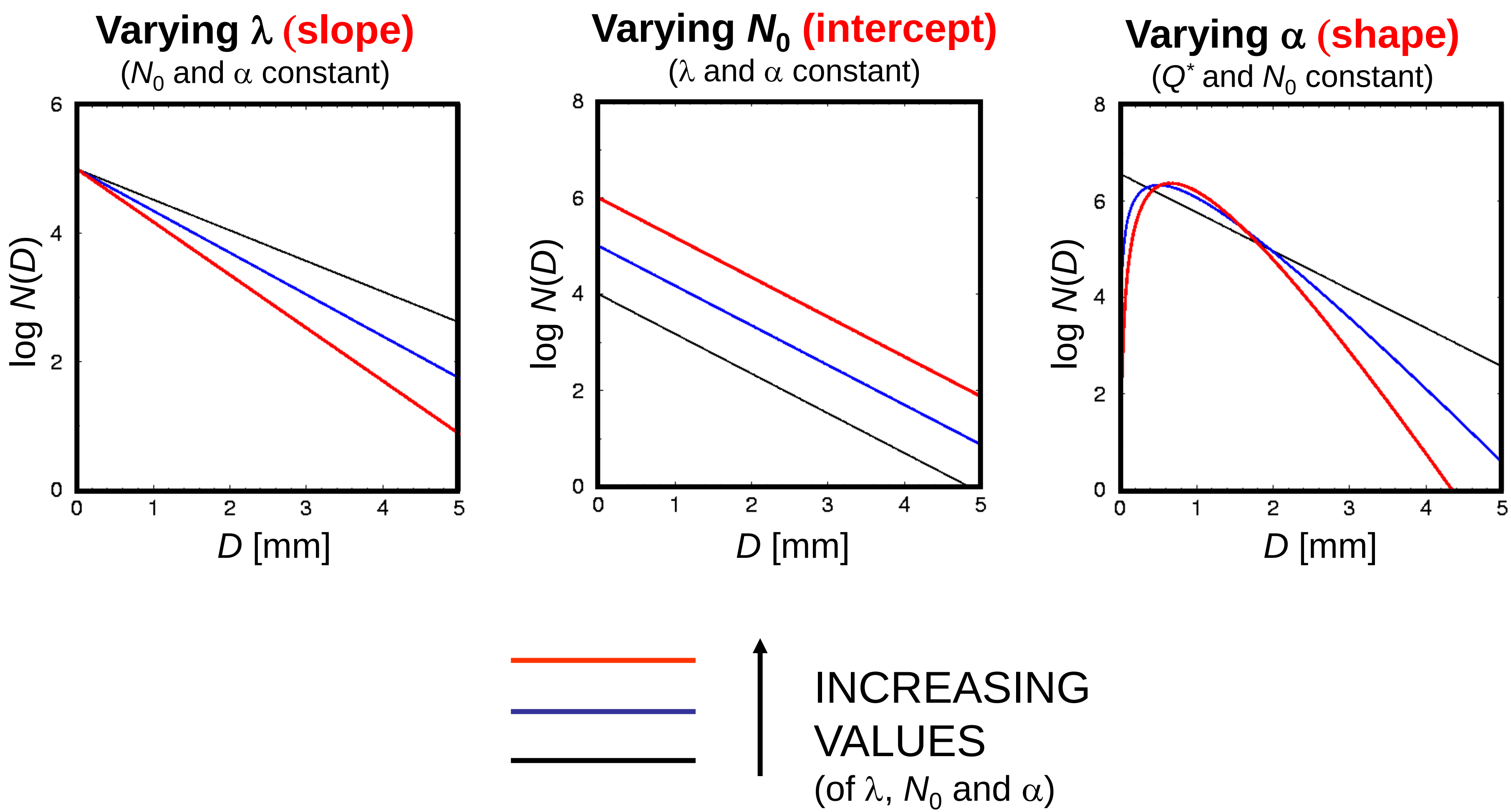
ANAYLTICAL FUNCTION



BULK METHOD

Gamma Distribution Function:

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



[*] $Q = \rho\, q$ (mass content)

BULK METHOD

Predict evolution of specific moment(s)

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

Implies prediction of evolution of parameters

i.e. N_{0x}, λ_x, ...

***Size Distribution Function*:**

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

~~Total number concentration~~, N_{Tx}

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

<u>Mass mixing ratio,</u> q_x

$$q_x \equiv \frac{c_x}{\rho} \int_0^\infty D^3 N_x(D)dD = \frac{c_x}{\rho} M_x(3),$$

$$\textit{where } m_x(D) = c_x D^3, \rho = \textit{air density}$$

<u>Radar reflectivity factor</u>, Z_x

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

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

For every predicted moment, there is one prognostic parameter.

The remaining parameters are prescribed or diagnosed.

Predict evolution of specific moment(s)

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

$\downarrow$

Implies prediction of evolution of parameters

i.e. N_{0x}, λ_x, ...

e.g.

One-moment scheme:

q_x is predicted;

$\rightarrow \lambda_x$ is prognosed

(N_{0x} and α_x are specified)

Two-moment scheme:

q_x and N_{Tx} are predicted;

$\rightarrow \lambda_x$ and N_{0x} are prognosed;

(α_x is specified)

Three-moment scheme:

q_x, N_{Tx} and Z_x are predicted;

$\rightarrow \lambda_x$, N_{0x} and α_x is prognosed

***Size Distribution Function*:**

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

***p*th moment:**

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

CLOSURE OF SYSTEM

Solve for shape parameter α from

$$\frac{c^2 N_T Z}{(\rho q)^2} = G(\alpha) = \frac{(\alpha+6)(\alpha+5)(\alpha+4)}{(\alpha+3)(\alpha+2)(\alpha+1)},$$

$$where\ m(D) = cD^3, and\ \rho = air\, density$$

Solve for slope parameter λ from

$$\lambda = \left(\frac{cN_T\Gamma(\alpha+4)}{\rho q\Gamma(\alpha+1)}\right)^{\frac{1}{3}}$$

Solve for intercept parameter N_0 from

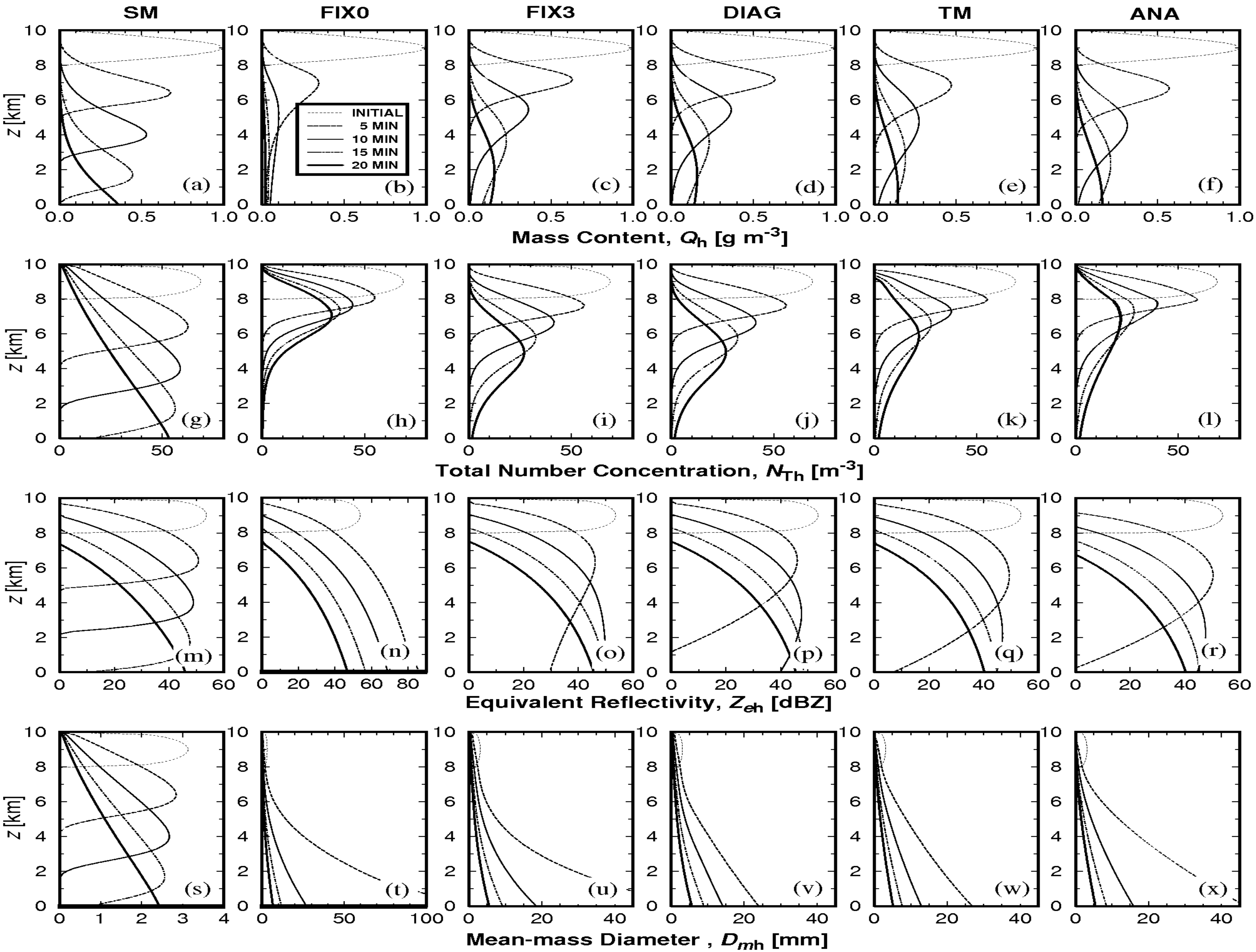
$$N_0 = \frac{N_T\lambda^{\alpha+1}}{\Gamma(\alpha+1)}$$

→ N_T and *q* vary monotonically in a 1-moment scheme

Diagnostic closure for α in 2-moment scheme

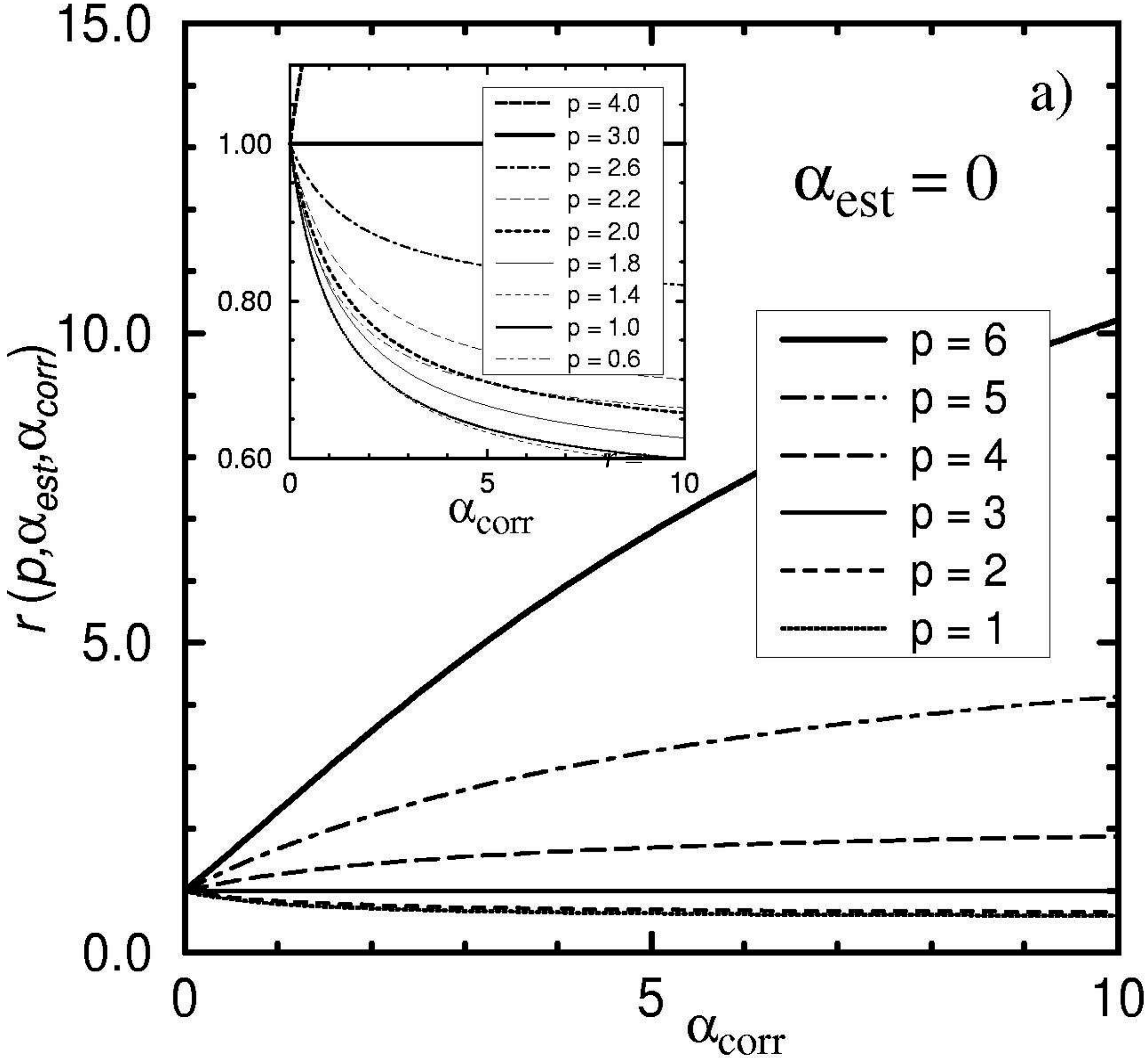
$$D_m = \left[\frac{\rho q}{c N_T} \right]^{\frac{1}{3}},$$

$$\alpha = f(D_m)$$



SM
FIX0
FIX3
DIAG
TM
ANA
INITIAL
5 MIN
10 MIN
15 MIN
20 MIN
z [km]
(a) (b) (c) (d) (e) (f)
Mass Content, Q_h [g m^{-3}]
(g) (h) (i) (j) (k) (l)
Total Number Concentration, N_{Th} [m^{-3}]
(m) (n) (o) (p) (q) (r)
Equivalent Reflectivity, Z_{eh} [dBZ]
(s) (t) (u) (v) (w) (x)
Mean-mass Diameter , D_{mh} [mm]

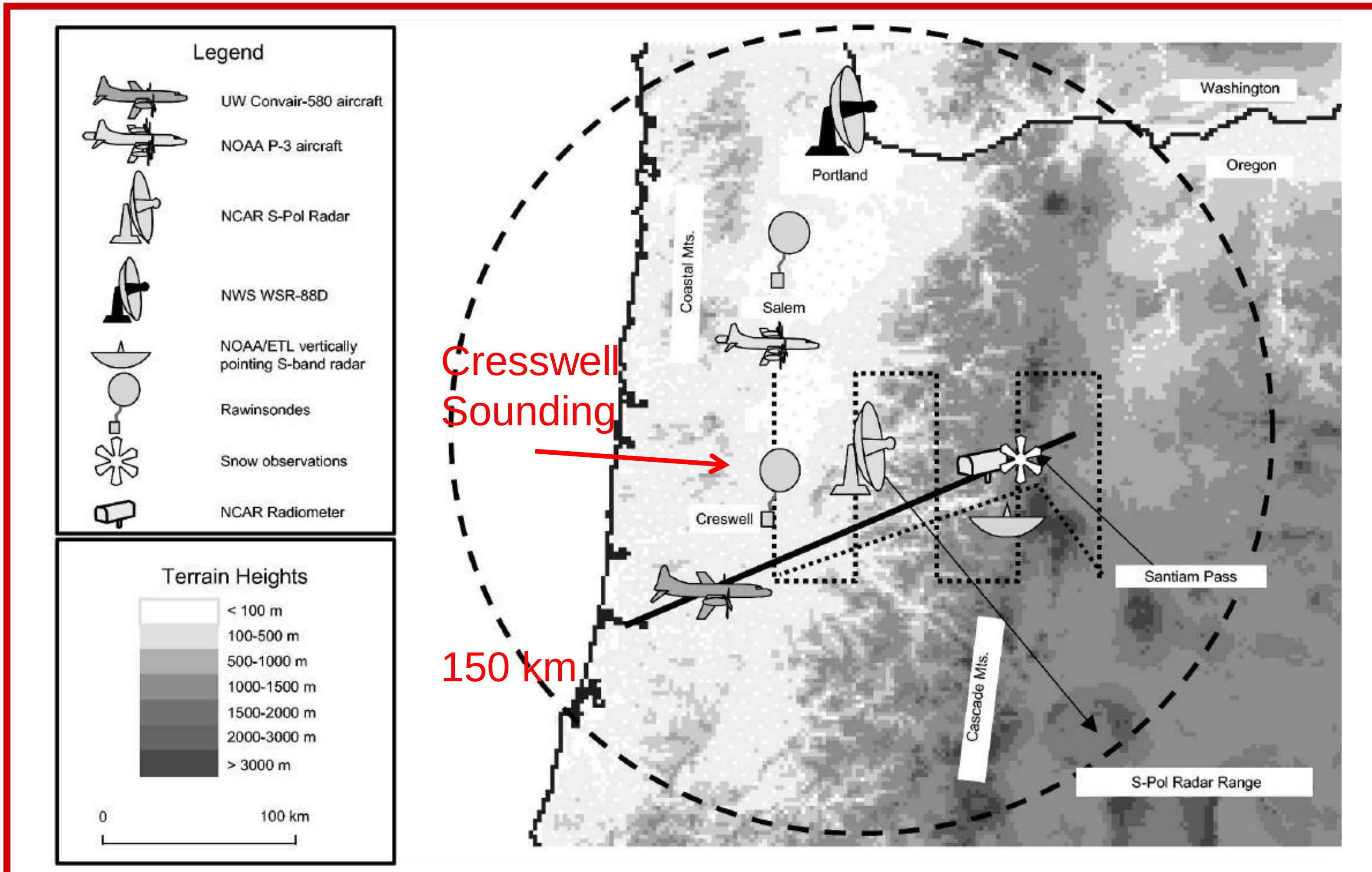
$r = M(p,\alpha_{est}) / M(p,\alpha_{corr})$



Verification and improvement of Multi-moment scheme in GEM-LAM (1 km) in IMPROVE-2

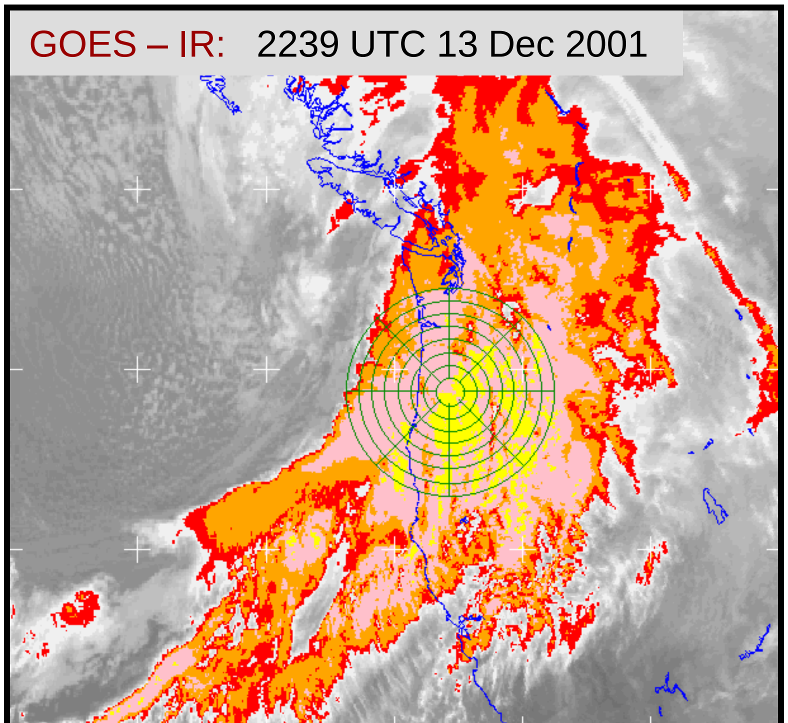
November-December 2001: IMPROVE-2 Observational Campaign

Improvement of Microphysical Parameterization through Observational Verification Experiment



13-14 Dec 2001 case:

- chosen for study at W.M.O. *International Cloud Modeling Workshop*, Hamburg (July 2004)
- special issue of *J. Atmos. Sci.* (October 2005) dedicated to IMPROVE-2



Characteristics:

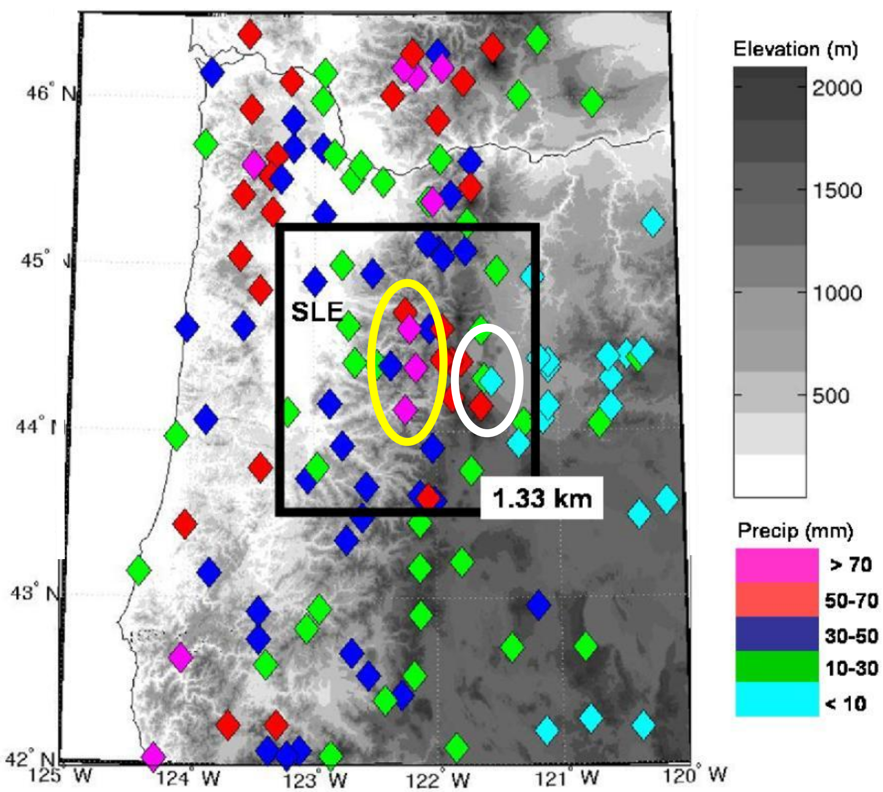
- large-scale baroclinic system
- strong low-level cross-barrier flow

Precipitation in IOP region:

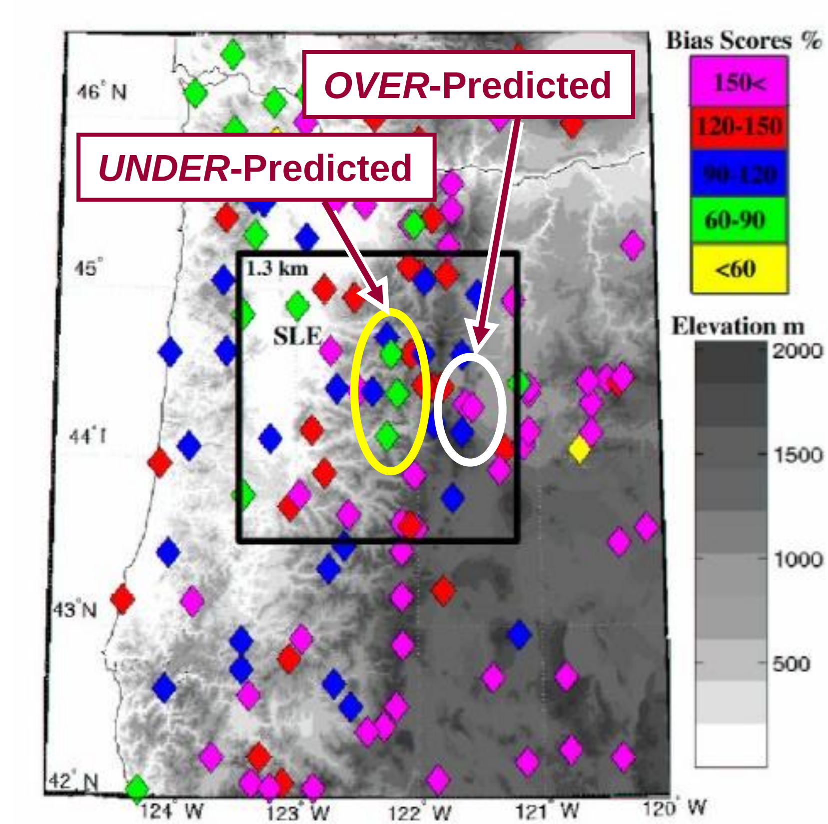
- prefrontal showers;
- moderate to heavy stratiform rain (associated with mid-level baroclinic zone);
- surface frontal rain-band;
- transition to sporadic showers

13-14 Dec 2001 case:

- **MM5 runs at 4-km and 1.3 km exhibited errors in surface precipitation attributed to problems associated with the microphysics (SM Reisner-2)**



OBSERVED PRECIPITATION
1600 UTC 13 Dec – 0800 UTC (18 h)



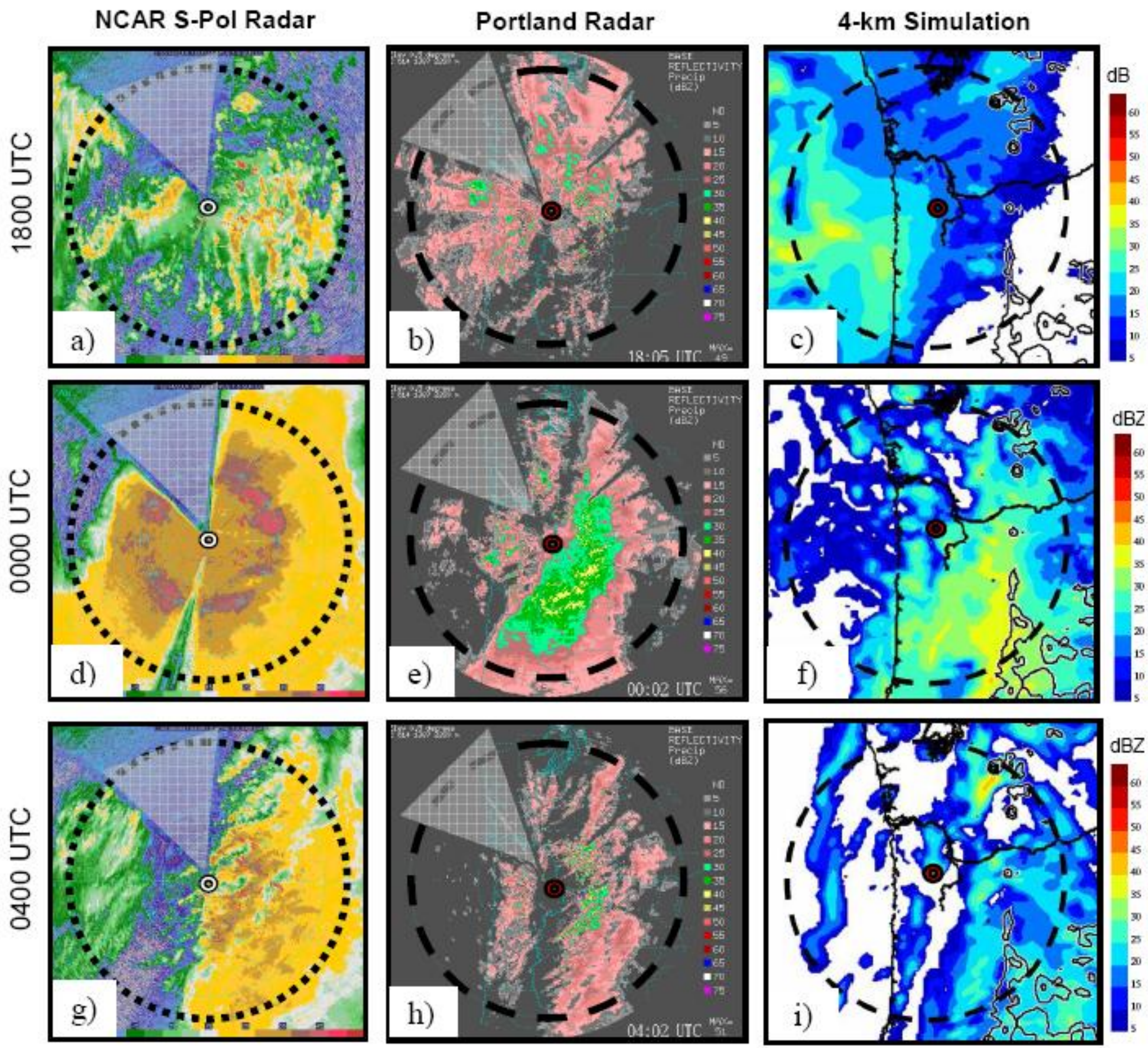
BIAS SCORES
4-km MM5 Simulation

Source: Garvert et al. (2005a) [*J. Atmos. Sci.*]

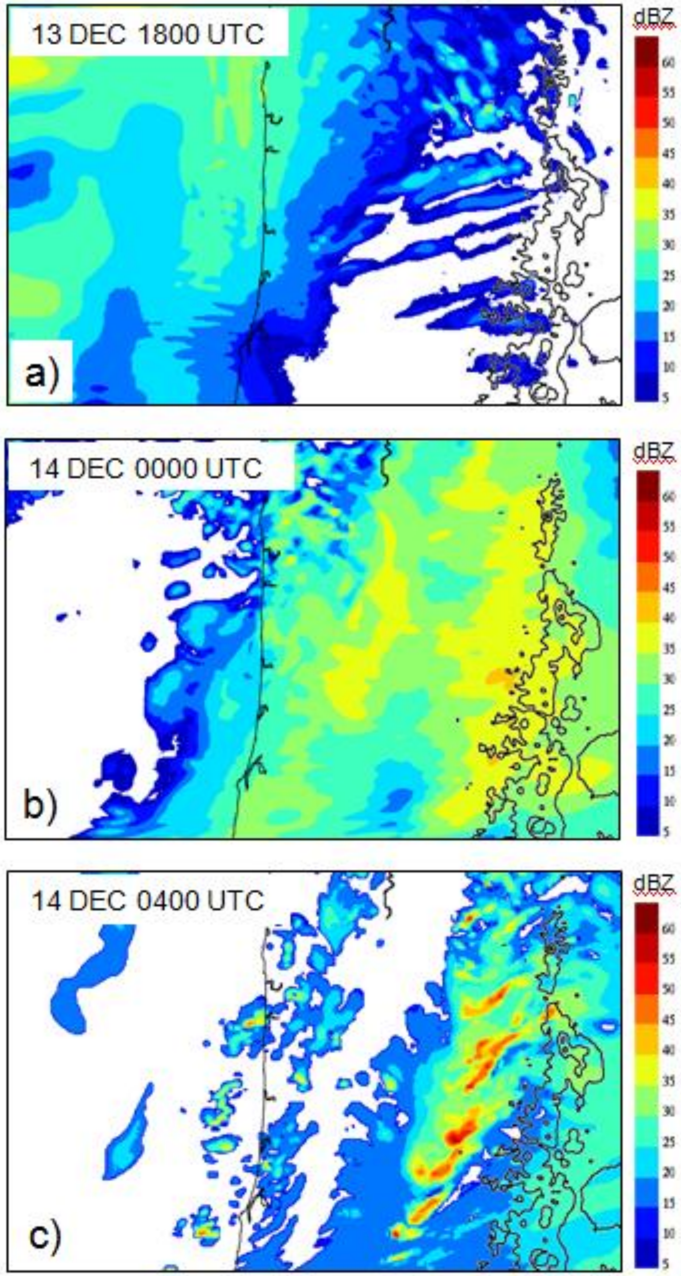
S-Pol
1.5 PPI
R 150 km

Portland
0.5 PPI
R 200 km

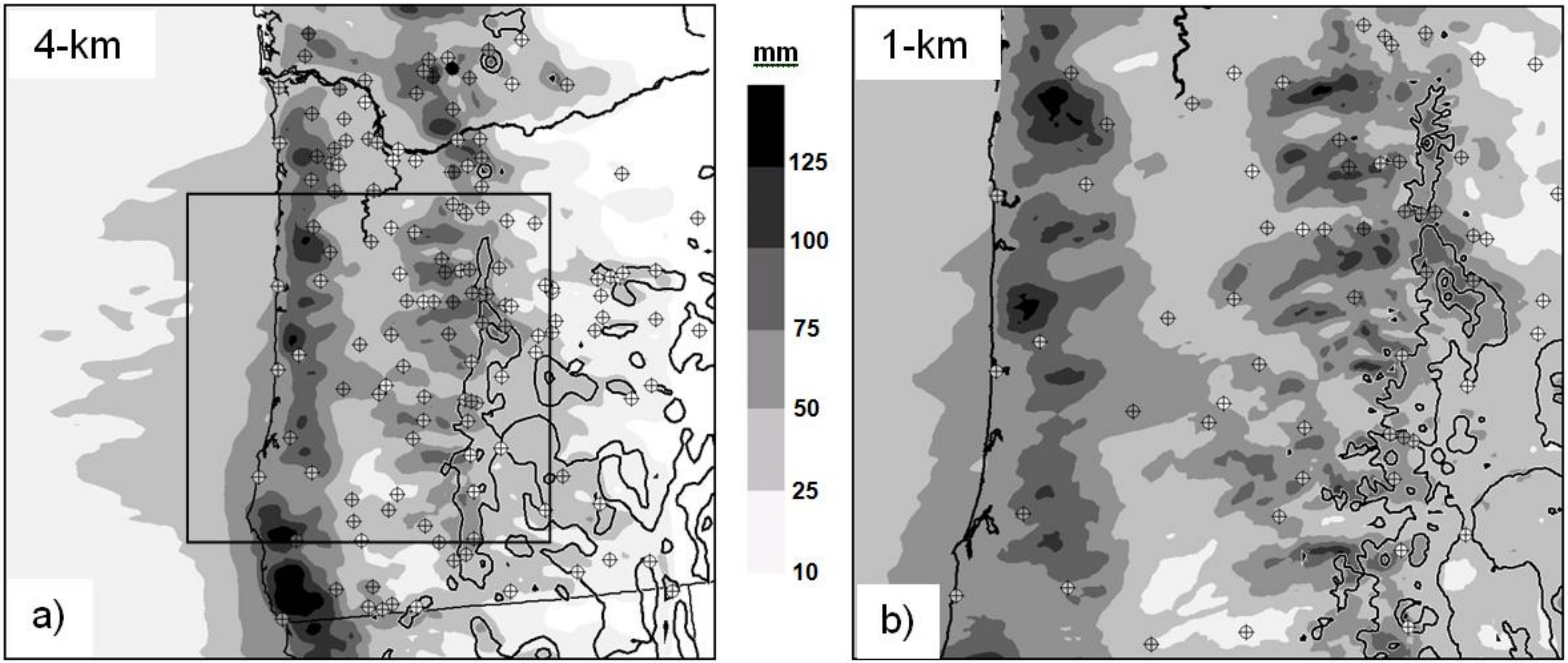
4km-GEM
700 hPa



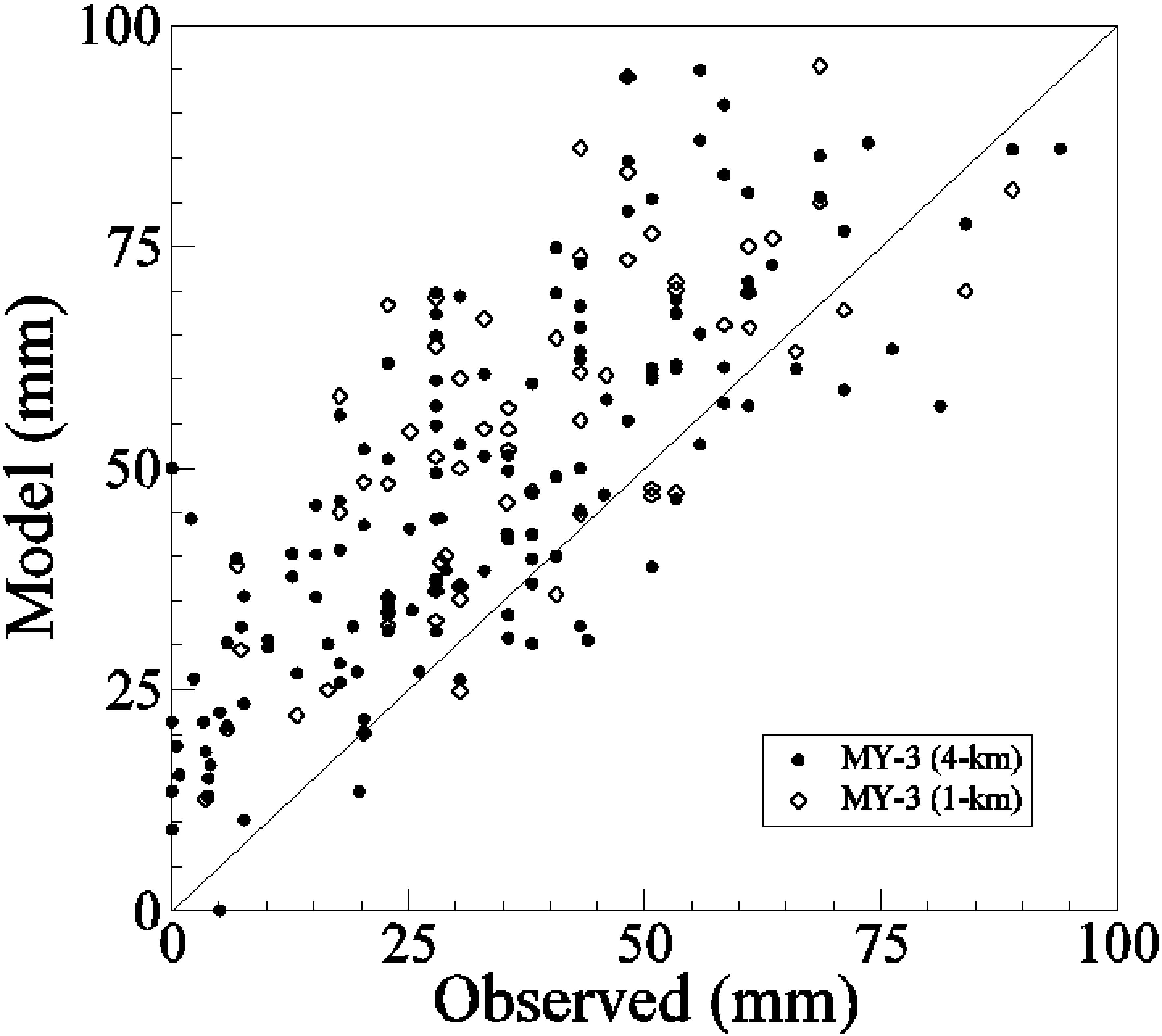
1-km GEM
E. Reflectivity



18-h Accumulated Precipitation
Observed vs. Simulated

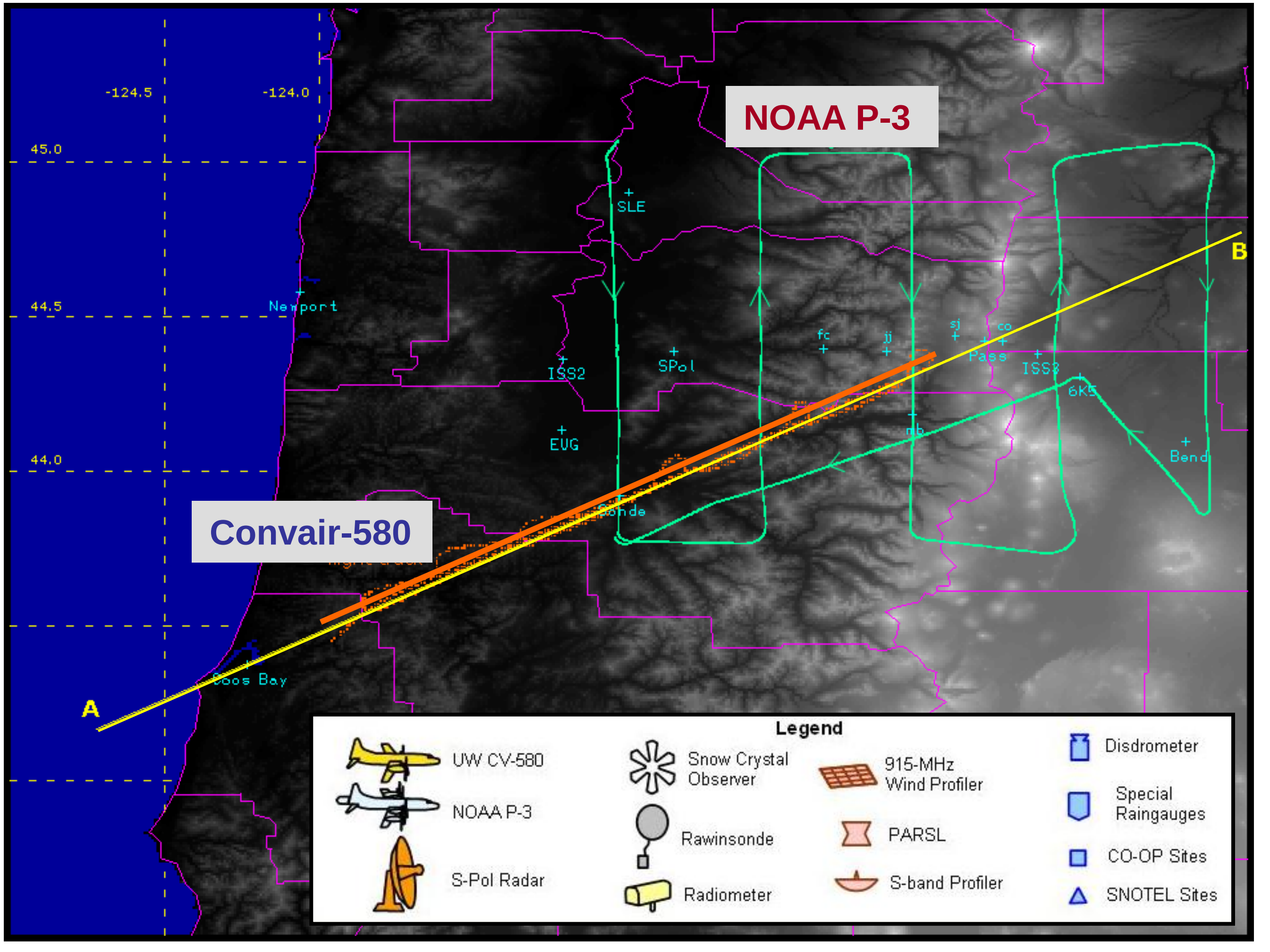


No pronounced over prediction along lee side of Cascade



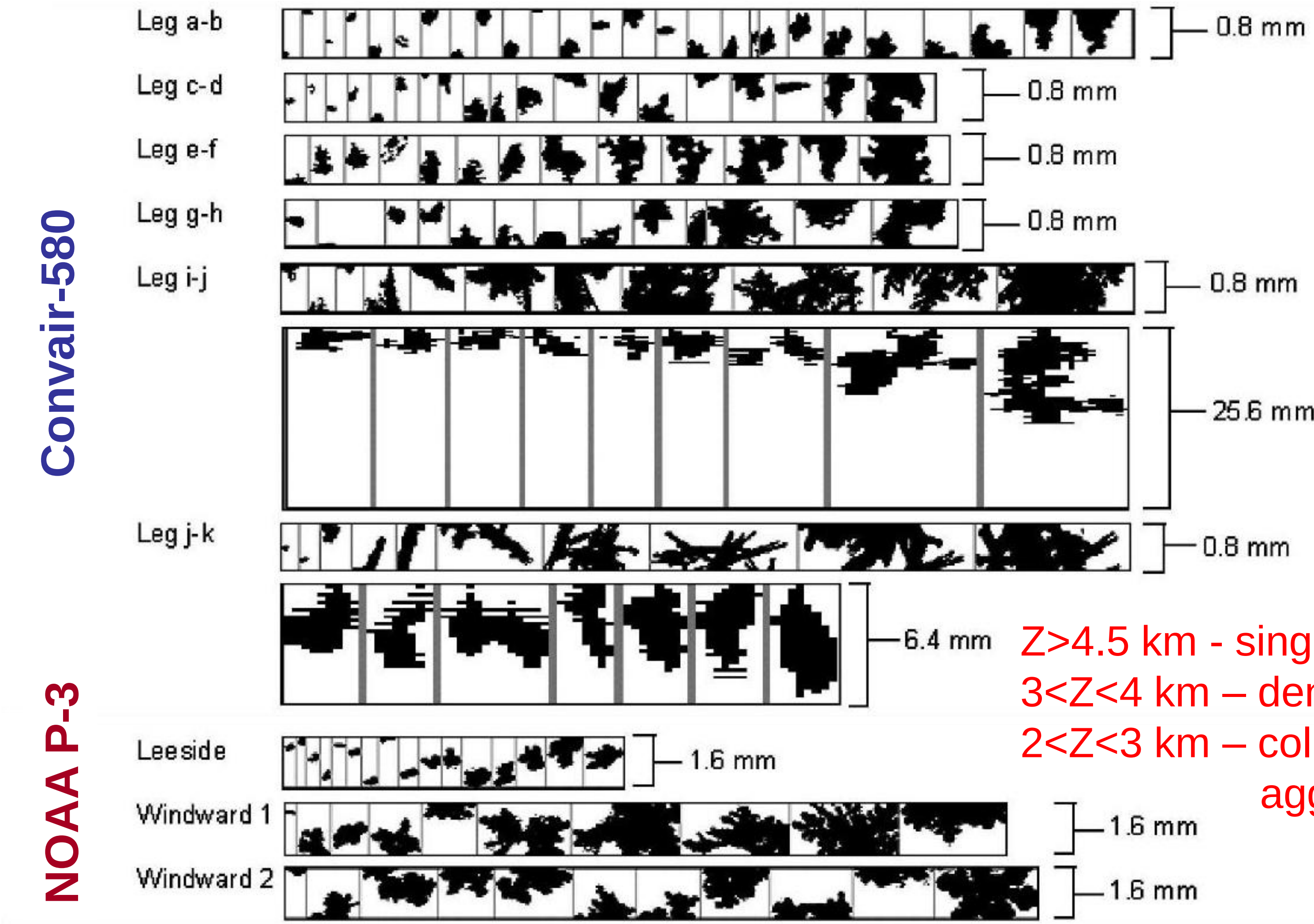
100
75
50
25
0
Model (mm)
0
25
50
75
100
Observed (mm)
MY-3 (4-km)
MY-3 (1-km)

Aircraft flight tracks (2200 – 0200 UTC)



Source: Stoelinga et al. (2003) [*Bull. Amer. Meteor. Soc.*]

MICROPHYSICS: **Observations**

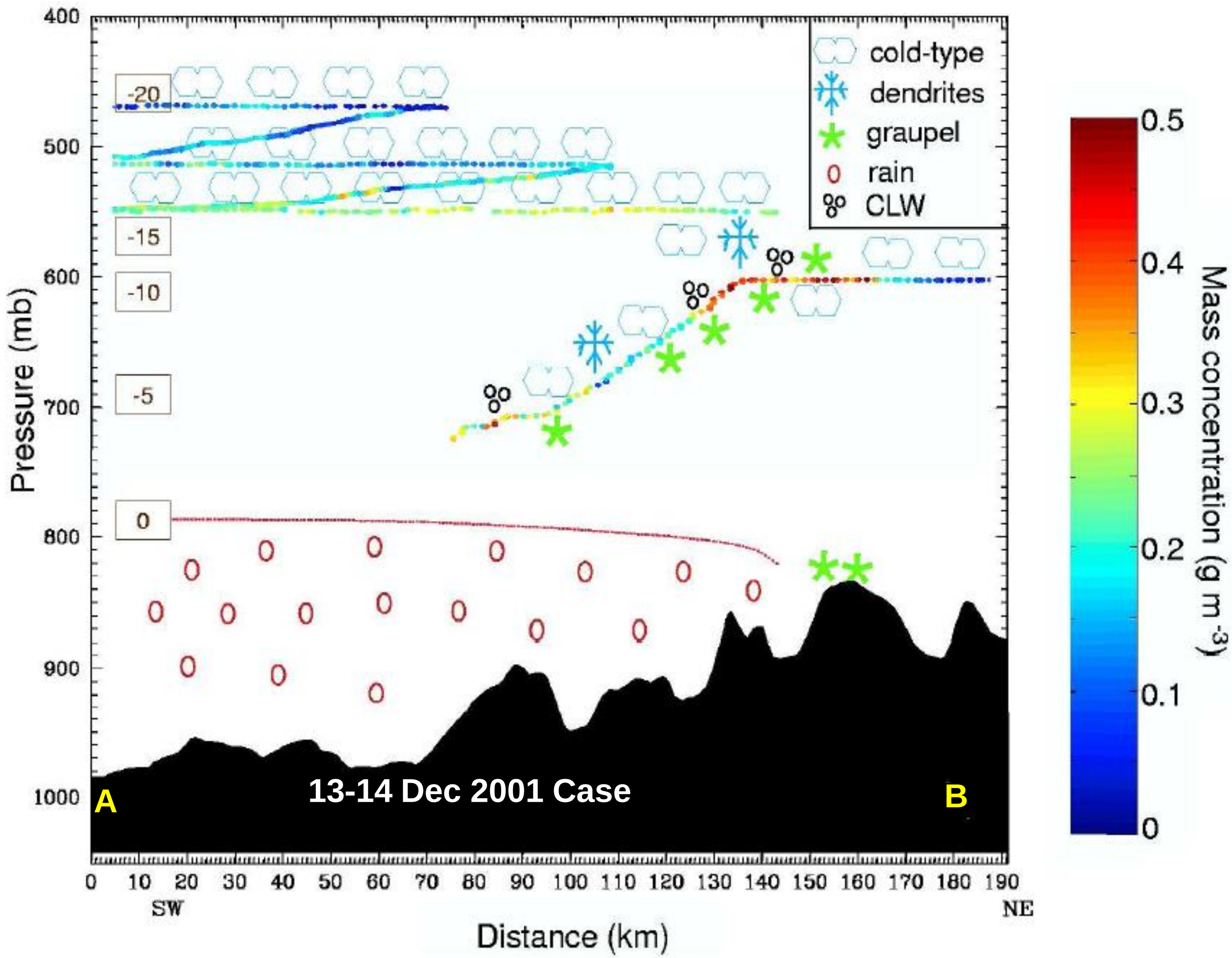


Z>4.5 km - single ice xtal
3<Z<4 km – dendrite
2<Z<3 km – column & aggregate

Mean size inc. with dec. height

Source: Wood et al. (2005) [*J. Atmos. Sci.*]

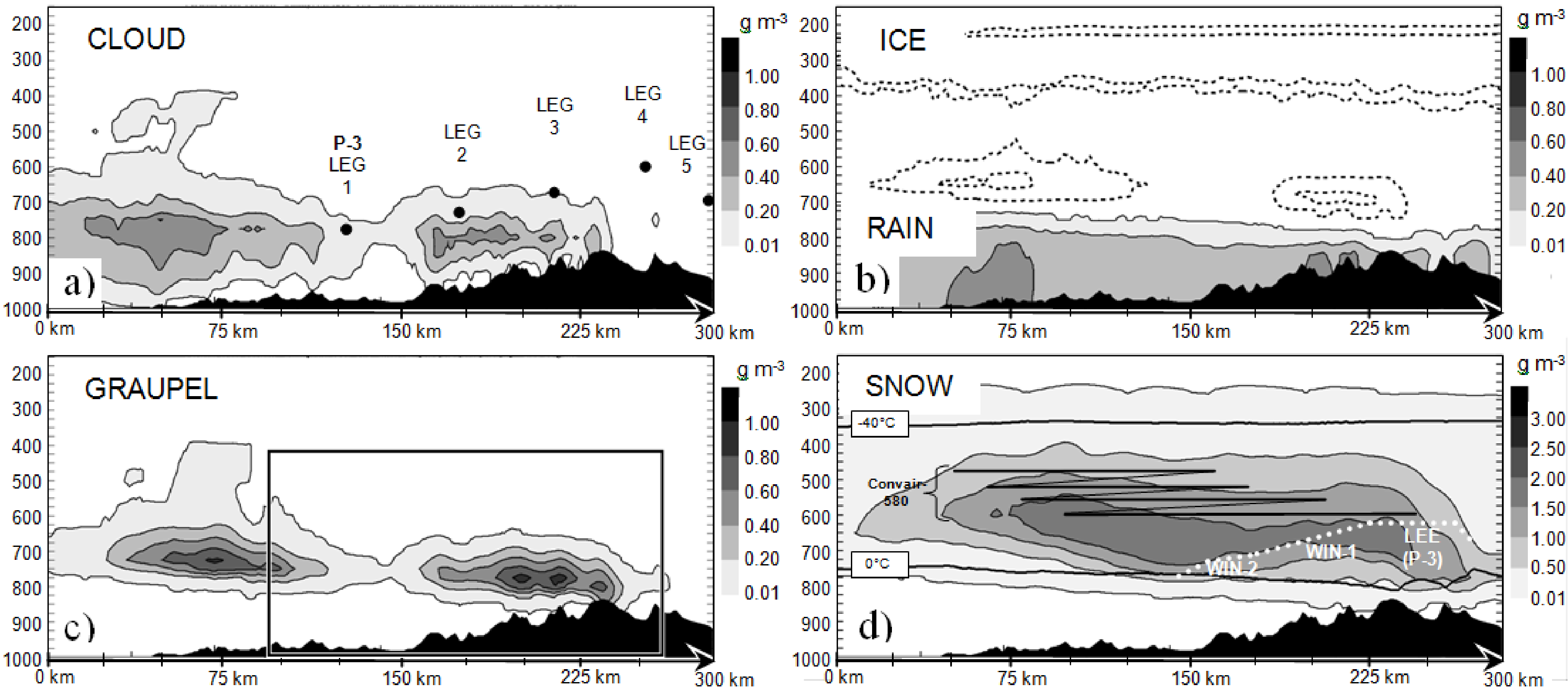
Combined Observations for 2200–0200 UTC



Source: Garvert et al. (2005b) [*J. Atmos. Sci.*]

Q_x [g m^{-3}] for 1-km (MY-3) Simulation

Time-Averaged, 2300-0100 UTC



Cloud liquid water along P-3 flight legs

	Valley	*Windward*		*Lee*	
Flight Leg	**Leg 1**	**Leg 2**	**Leg 3**	**Leg 4**	**Leg 5**
Elevation [m] (Pressure level [hPa])	2000 (775)	2500 (725)	3450 (650)	4000 (600)	3100 (675)
Observation (g m^{-3}) Ave. [Peak]	0.14 [0.40]	0.26 [0.50]	0.20 [0.25]	0.12 [0.15]	0.04 [0.10]
Model (1-km) (g m^{-3}) Ave. [Peak]	0.22 [0.27]	0.08 [0.34]	0.00 [0.09]	0.00 [0.00]	0.01 [0.02]

Under prediction of vertical extent of cloud water

Ice/snow content along Corvair flight legs

Flight Leg	Leg a-b	Leg c-d	Leg e-f	Leg g-h
Elevation [m] (Pressure level [hPa])	6000 (450)	5300 (500)	4900 (525)	4300 (625)
Observed Ave. (g m^{-3})	0.12	0.17	0.25	0.27
Model (1-km) (g m^{-3}) Ave. [Peak]	0.85 [1.34]	0.93 [1.33]	1.15 [1.67]	1.67 [1.94]

Over prediction of concentration of snow mass

→ too large deposition and/or riming

IMPROVEMENTS OF SNOW CATEGORY

- Diffusional growth
- Growth by riming

Electrostatic Analogy for Diffusional Growth of Ice Crystals

$$\frac{dm}{dt} = \frac{4\pi C(S_i - 1)}{AB_i}$$

"The electrostatic analogy of the capacitance theory of ice crystal growth is highly flawed and does not produce the observed growth rates of ice crystals.

It severely overpredicts the growth rates in almost all cases [by a factor of 3 to 8+ for plates and 2 to 4 for columns] involving even simple hexagonal shapes."

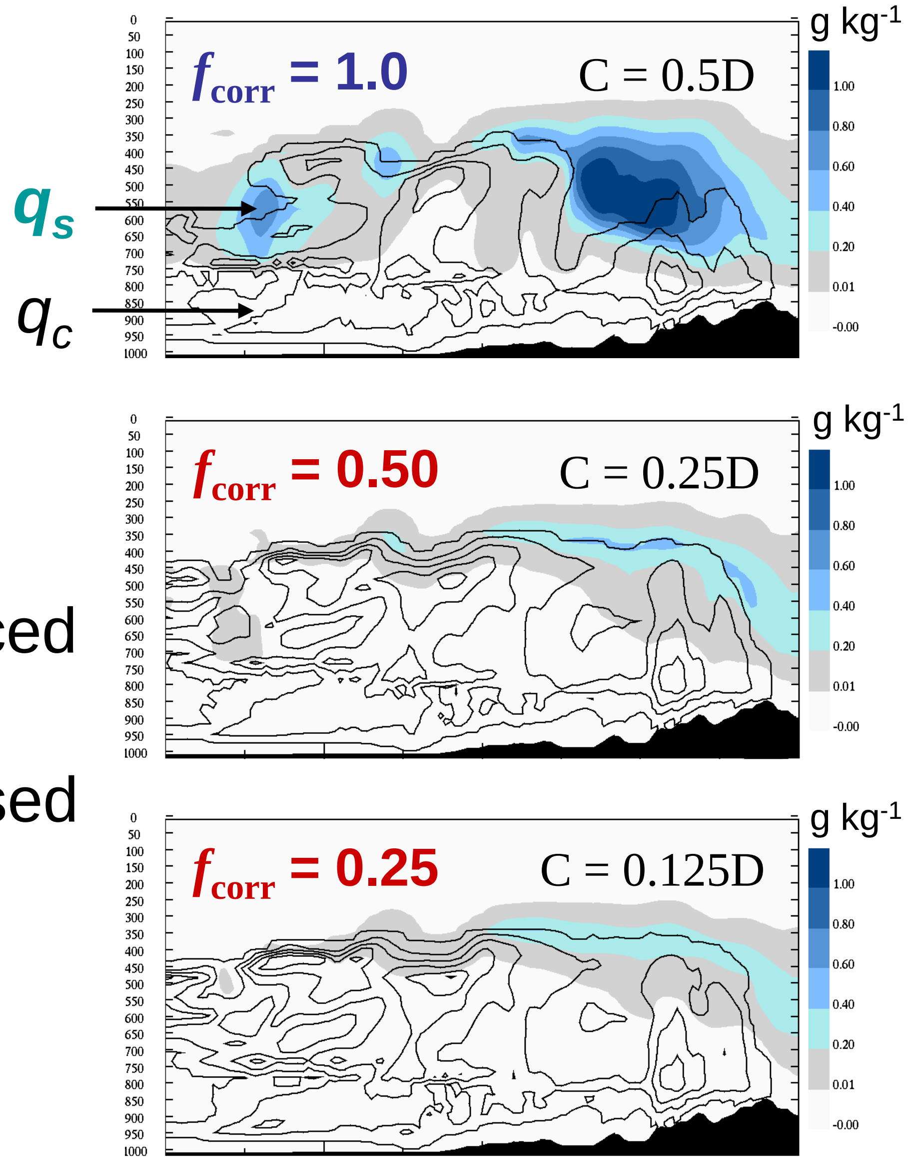
Bailey and Hallet (2006)

Add **CORRECTION FACTOR** to DIFFUSIONAL GROWTH EQUATION

$$\frac{dm}{dt} = \frac{4\pi\, C(S_i - 1)}{AB_i} \longrightarrow \frac{dm}{dt} = \frac{4\pi\, C \cdot f_{corr} \cdot (S_i - 1)}{AB_i}$$

where f_{corr} must be < 1, with value justified by results

Sensitivity Tests for IMPROVE-2:



With decreasing f_{corr},

SNOW content (q_s) is reduced

and

CLOUD LWC (q_c) is increased

Other evidence:

Field et al. (2008)
Westbrook et al. (2008)

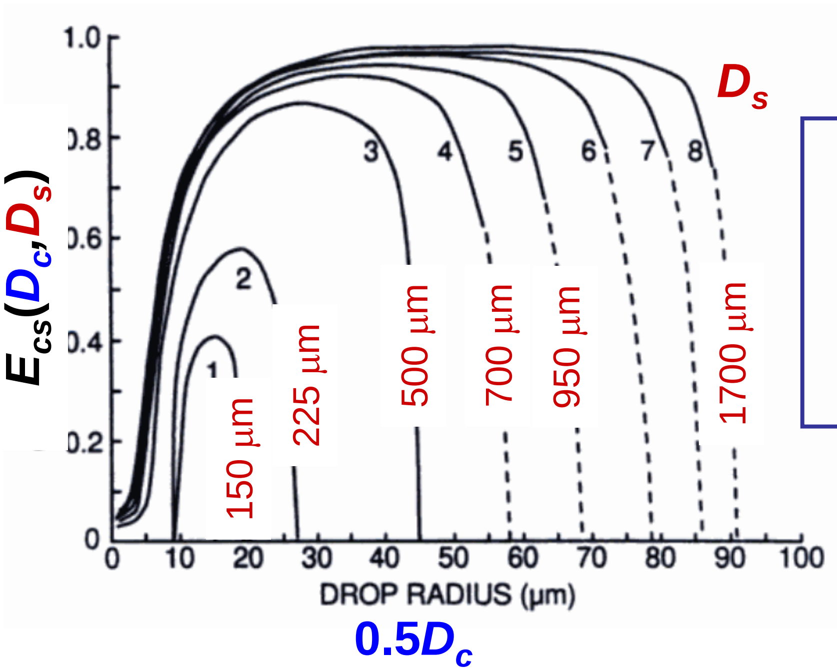
RIMING of *SNOW*

Stochastic collection equation: (for category ***x*** collecting category ***y***)

$$CL_{yx} = \frac{1}{\rho}\frac{\pi}{4}\int_0^\infty\int_0^\infty \left|V_x(D_x) - V_y(D_y)\right|\left(D_x + D_y\right)^2 m_y(D_y)\underbrace{E_{xy}(D_x, D_y)}_{\text{COLLECTION EFFICIENCY}} N_y(D_y) N_x(D_x)\, dD_y\, dD_x$$

- For the collection efficiency, $E_{cs} = 1$ is often assumed (for collection of *cloud* by *snow*)
- If $E_{cs} < 1$, the snow riming rate will be <u>overestimated</u>

RIMING of *SNOW*



*Wang and Ji, 1992

Approximation:

$$E_{cs}(D_c,D_s) = \frac{\min(D_c, 30\,\mu m)}{30\,\mu m} \cdot \left[\frac{\min(D_s, 1000\,\mu m)}{1000\,\mu m}\right]^{0.5}$$

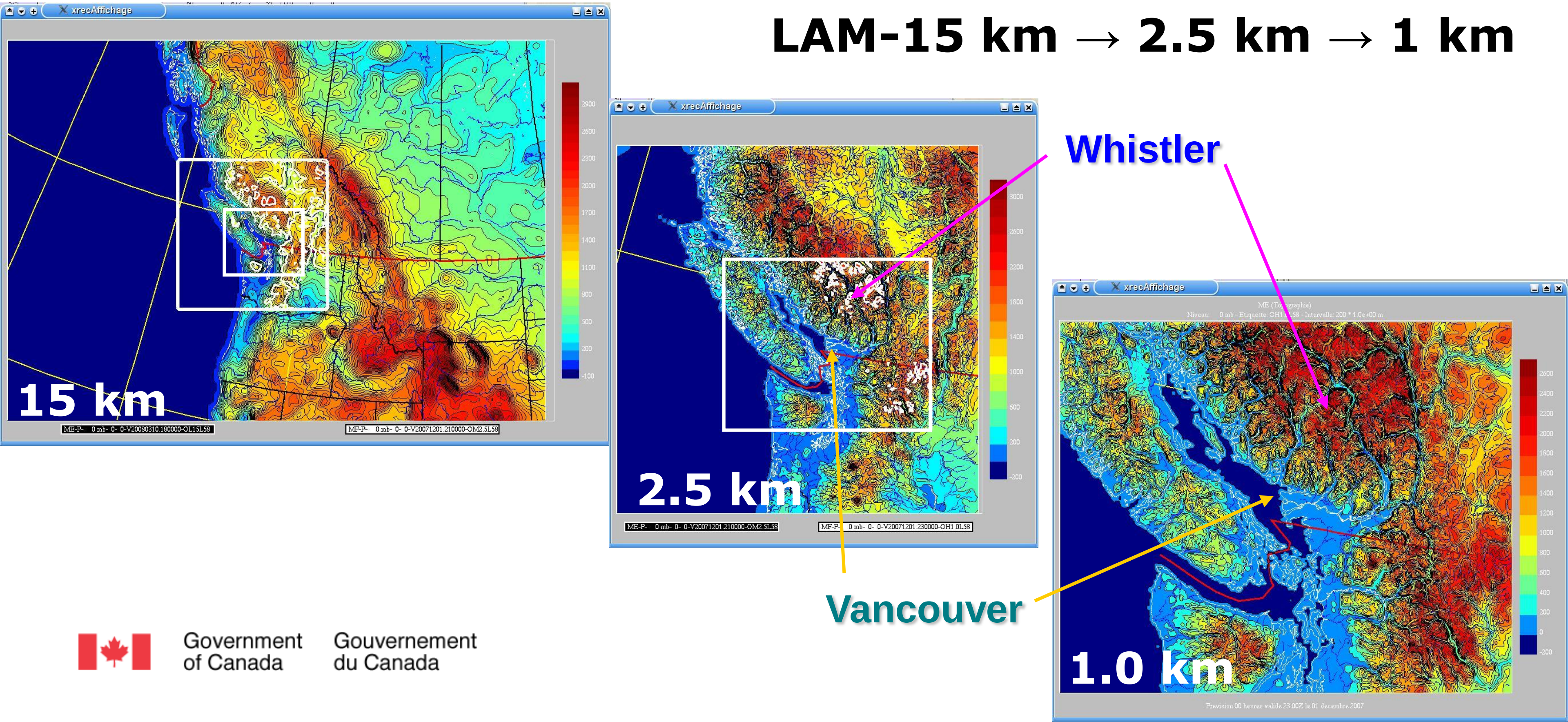
- Works for D_c ~ 15-30 µm, and D_s ~ 150-1500 µm
- Reduces riming rate 10-80% (vs. $E_{cs} = 1$)

Test of 2-moment microphysics in Vancouver Olympics 2010 in 1 km GEM-LAM

Nesting strategy for LAM-V10 system

- **3 nested LAM integrations twice daily from 0000 and 1200 UTC GEM-Regional forecasts:**

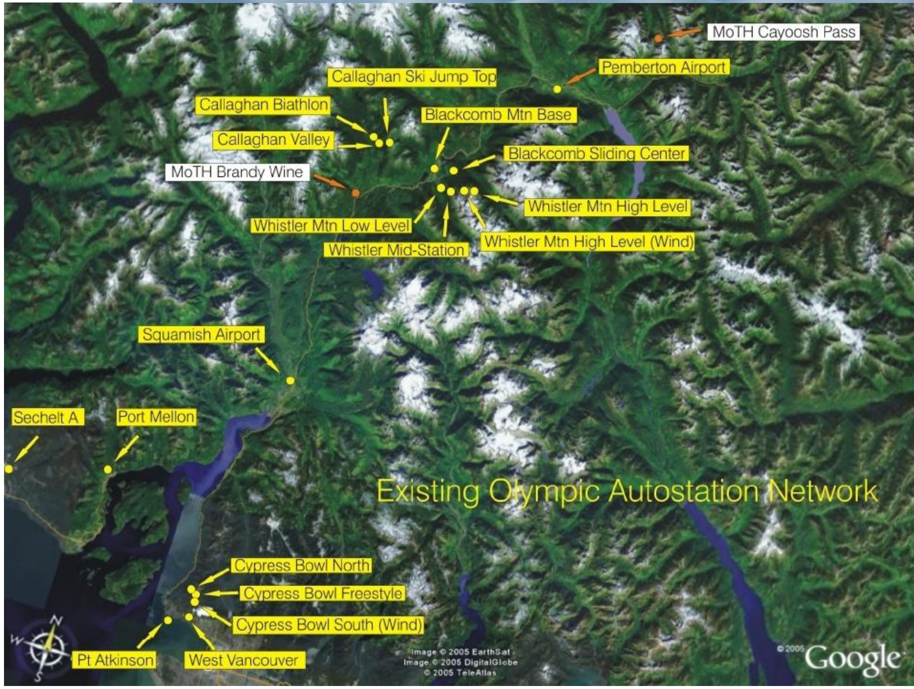
LAM-15 km → 2.5 km → 1 km



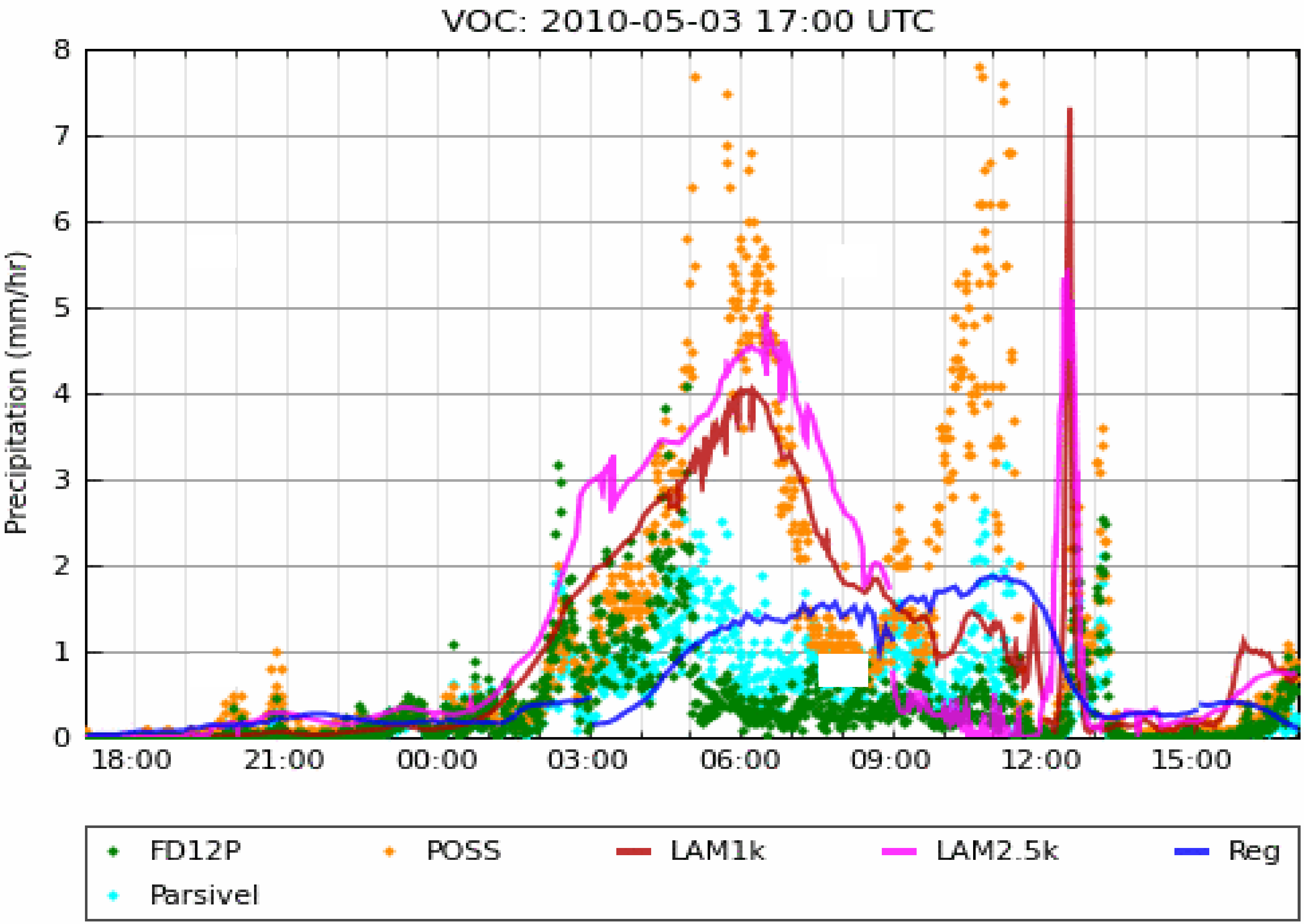
Verification for LAM-V10

Olympic Autostation Network (OAN):

- approx. 40 standard and special surface observing sites (hourly or synop available on GTS)
- large number (relatively) of surface stations
- concentrated in small region



Verification Examples



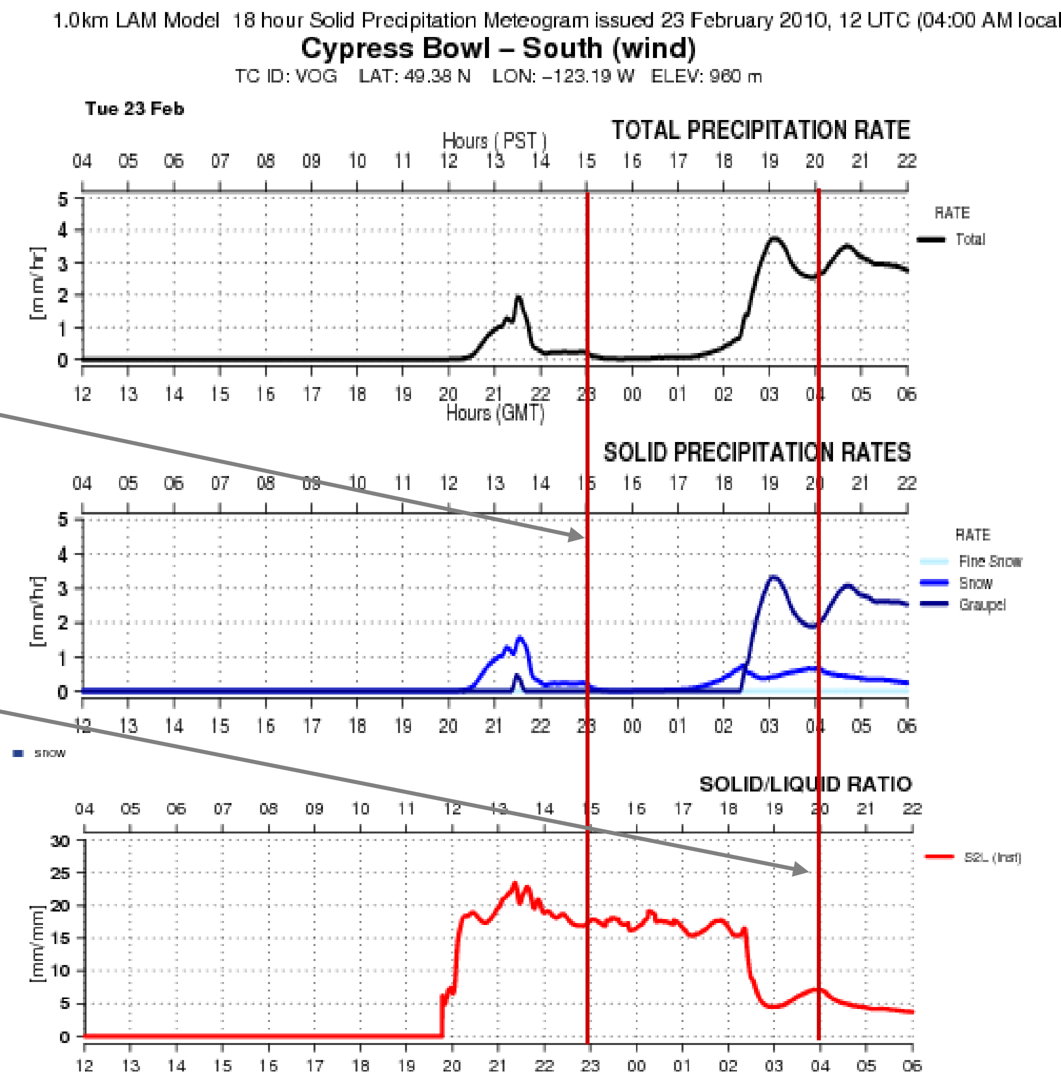
Observations courtesy of George Isaac

Experimental field: *Solid-to-Liquid ratio*

Observed:*

FLUFFY SNOWFLAKES

SNOW PELLETS



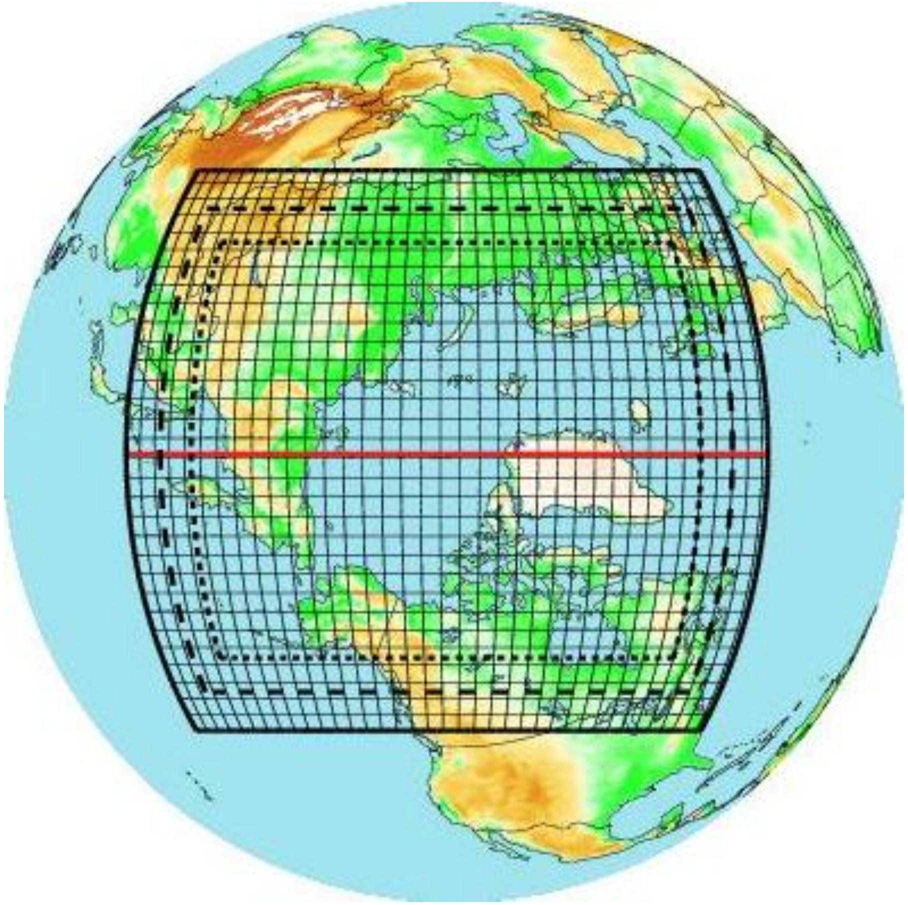
*Forecaster:
Michael Gélinas

Government of Canada Gouvernement du Canada

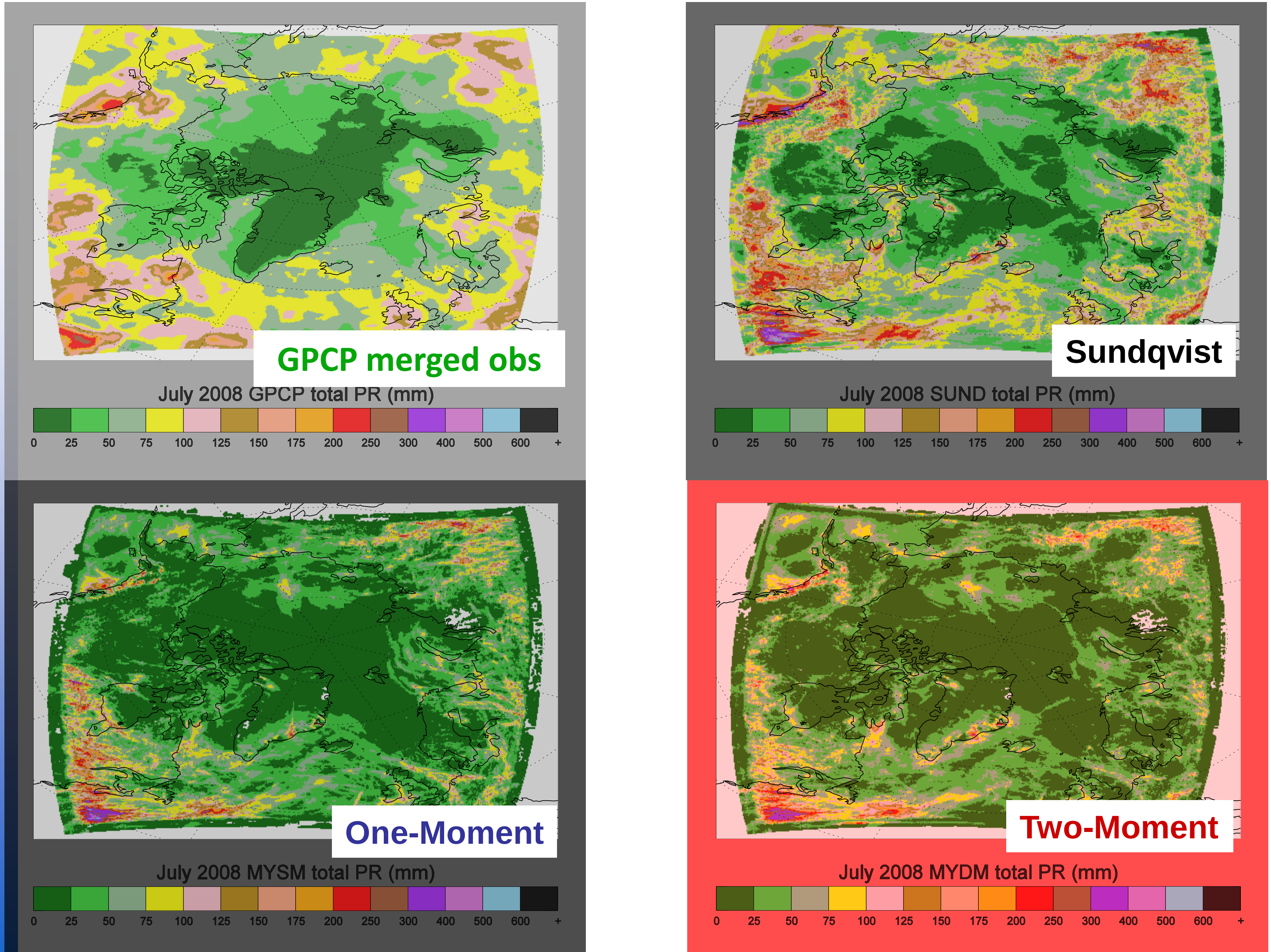
Testing of 2-moment microphysics in Global GEM variable 15 km over the Arctic

30 day simulation – July 2008 over Arctic

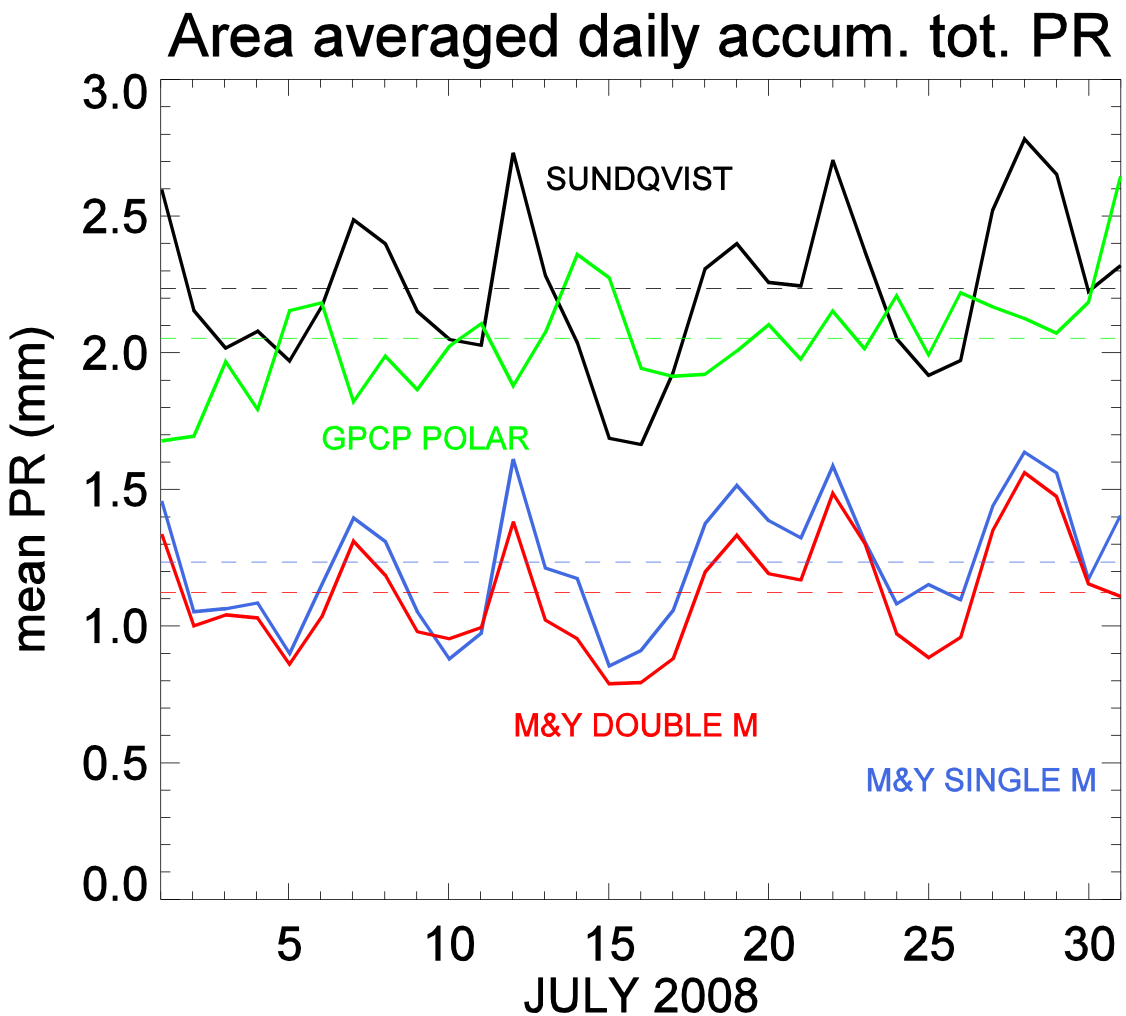
Polar-GEM:



•Δx = 15 km


GPCP merged obs
July 2008 GPCP total PR (mm)
0 25 50 75 100 125 150 175 200 250 300 400 500 600 +
Sundqvist
July 2008 SUND total PR (mm)
0 25 50 75 100 125 150 175 200 250 300 400 500 600 +
One-Moment
July 2008 MYSM total PR (mm)
0 25 50 75 100 125 150 175 200 250 300 400 500 600 +
Two-Moment
July 2008 MYDM total PR (mm)
0 25 50 75 100 125 150 175 200 250 300 400 500 600 +

PRECIPITATION



GPCP merged obs

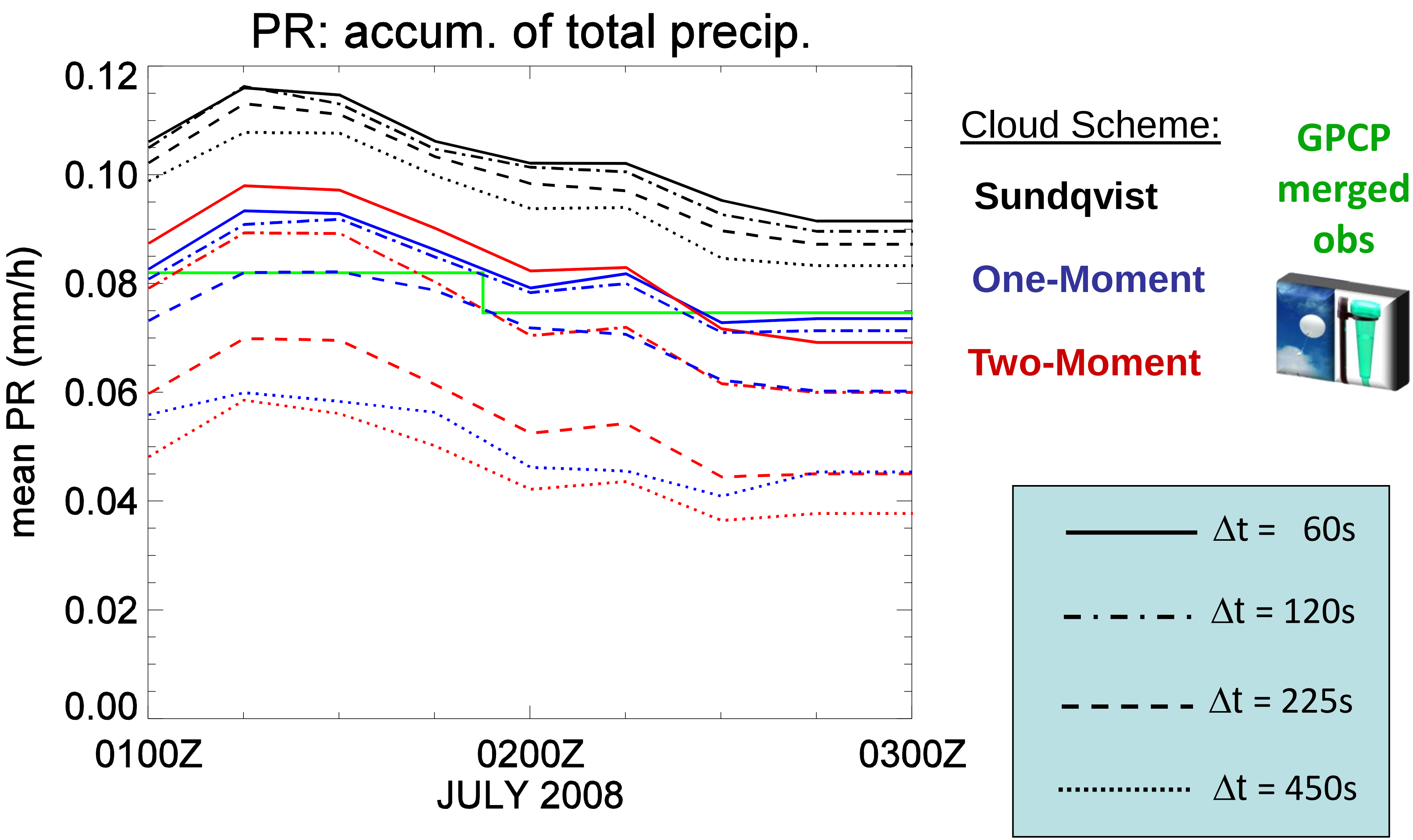
Cloud Scheme:

Sundqvist

One-Moment

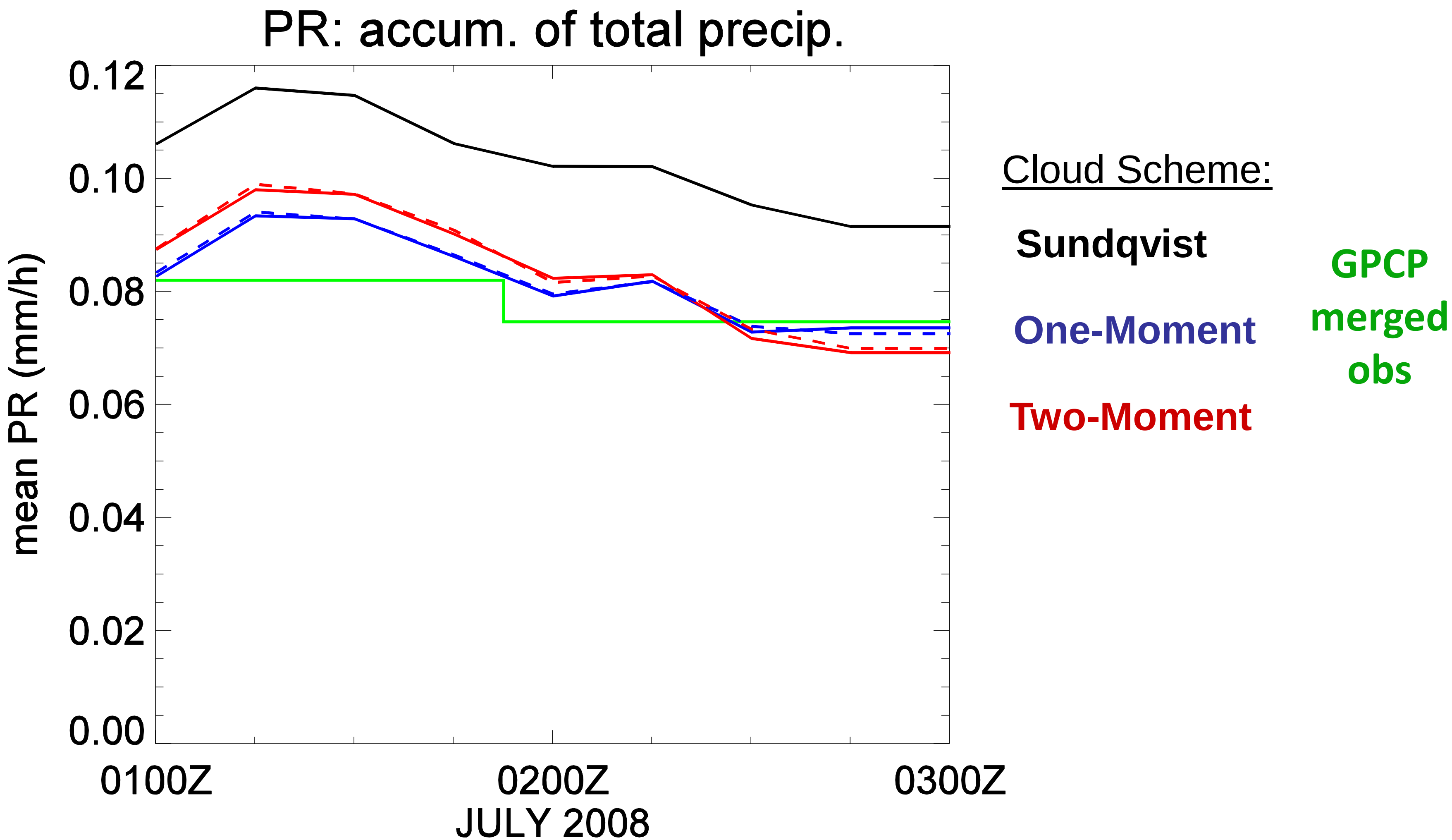
Two-Moment

SENSITIVITY TO TIME STEP



60-h Simulation

SENSITIVITY TO TIME STEP



60-h Simulation (Δt = 60 s)

SUMMARY

1) Multi-moment mixed phase bulk cloud microphysical schemes have been developed and implemented in GEM-LAM and GEM-Global Variable

2) Comparison with in-situ field measurements allows improvements in the scheme

3) Implementation in GEM-Global Uniform is planned but still needs work to address

a) time splitting for microphysics
b) subgrid scale cloud fraction
c) simplification to allow for a mixture of higher and lower moment hydrometeor categories

SEDIMENTATION: Bulk scheme

$$\left.\frac{\partial \rho q_x}{\partial t}\right|_{SEDI} = \frac{\partial\left(\rho q_x \overline{V}_{xq}\right)}{\partial z}$$

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

SM

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

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

DM

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

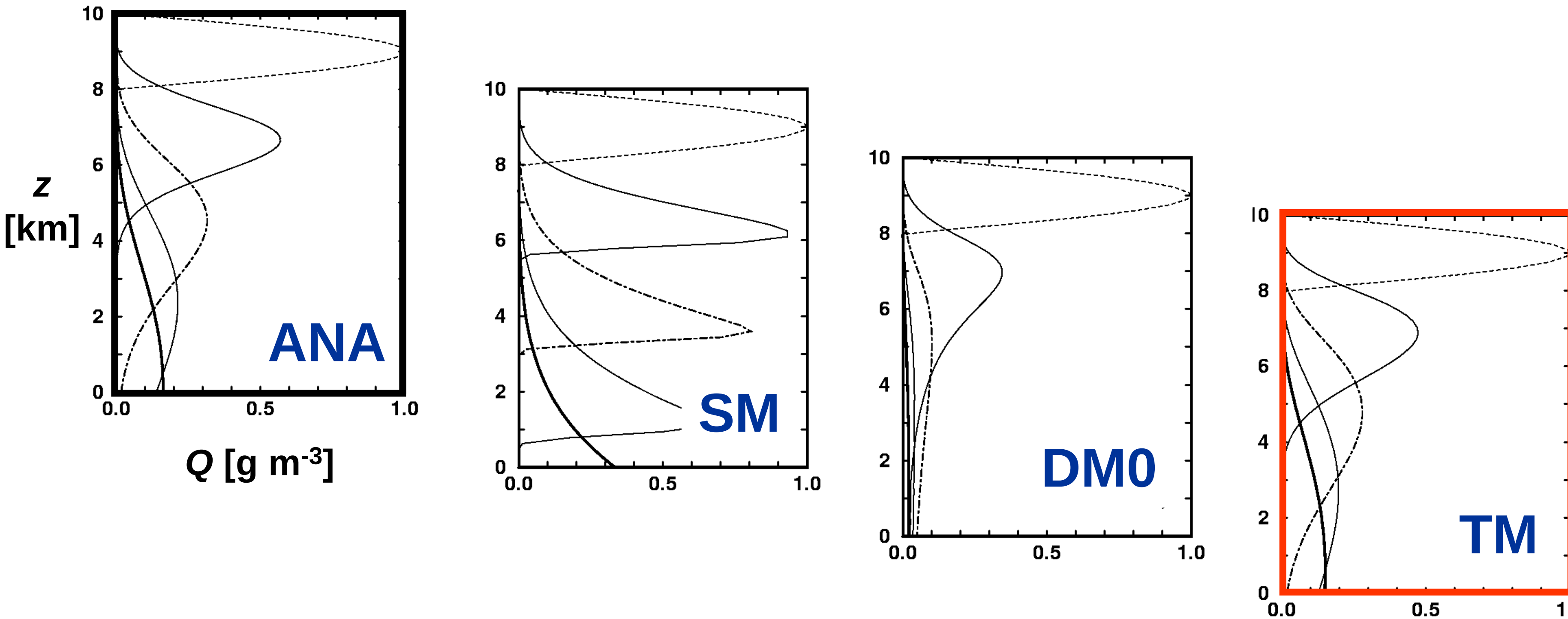
$\overline{V}_{xZ}$ = reflectivity-weighted fall velocity

TM

For a given size distribution, $\overline{V}_{xZ} > \overline{V}_{xq} > \overline{V}_{xN}$

Effects on sedimentation terms

$(Q = \rho\, q)$



TM better than DM0 better than SM

DIFFERENCE RELATED TO SIZE SORTING

Disadvantages of 1-moment scheme

a) Inconsistency in modeling physical processes

From closure relation, N_T and q vary monotonically → N_T increases or decreases with q, but

in breakup, N_T increases but q = constant, and
in diffusional growth, q increases but N_T = constant.

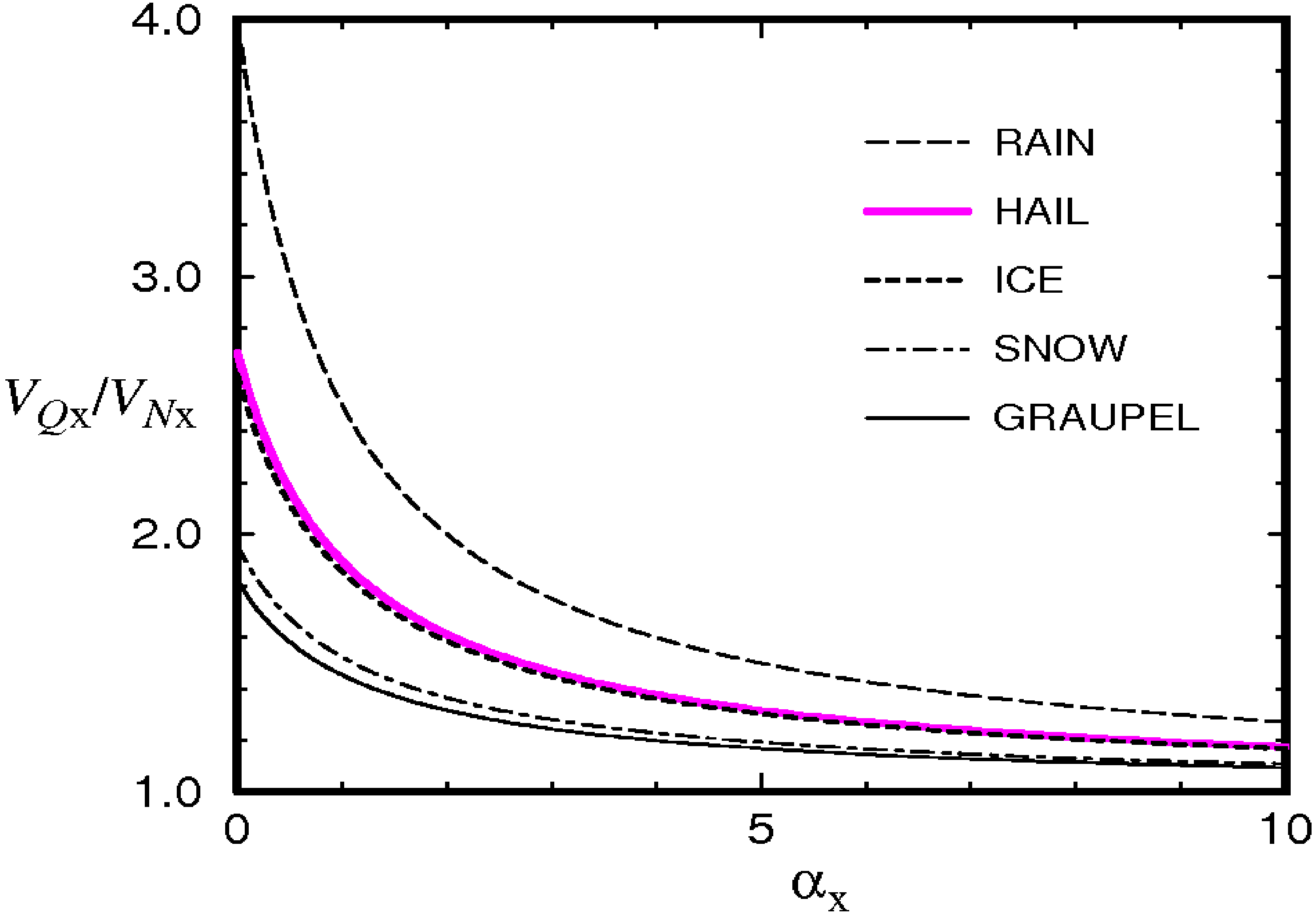
c) Inconsistency in modeling size sorting in sedimentation

→ mean size increases with decreasing height, but not necessarily true in 1-moment as mean diameter is

$$D_m = \left[\frac{\rho q}{c N_T}\right]^{\frac{1}{3}}$$

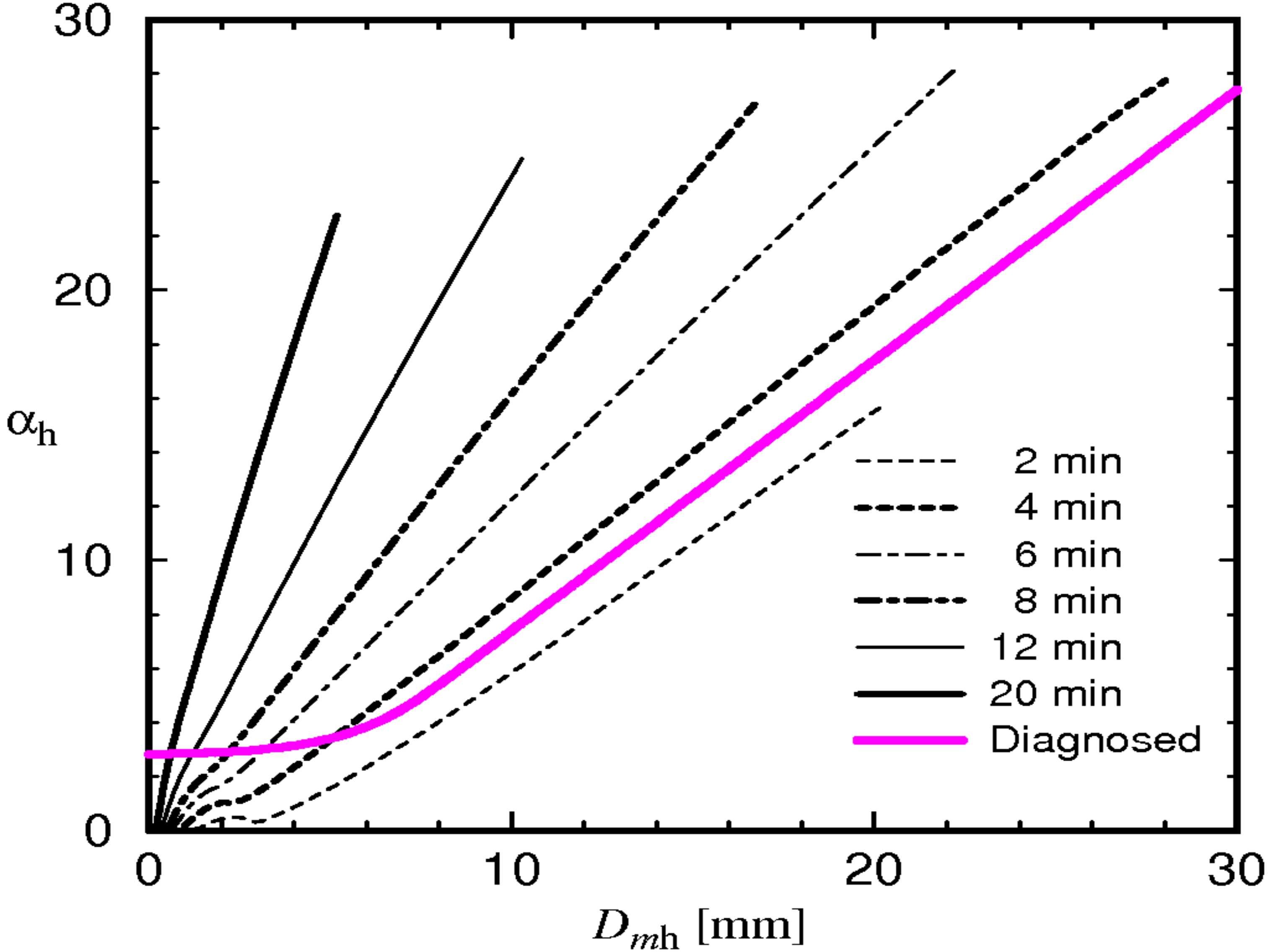
Disadvantages of 2-moment fixed α scheme in sedimentation

Rate of change of D_{mx} (size sorting) proportional to fallspeed ratio

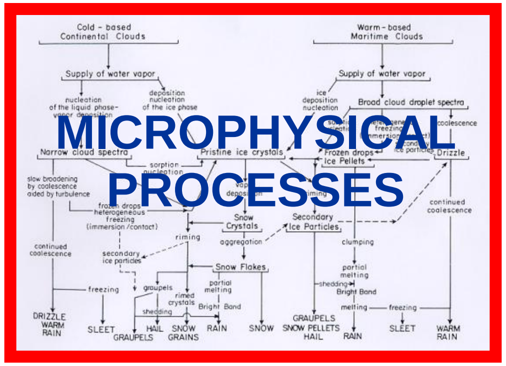


Diagnosed α → sedimentation results in larger mean size (larger D_m) but narrower spectrum (larger α)

From TRIPLE- MOMENT sedimentation profiles:



How well do the various bulk scheme predict <u>sources/sinks</u>?



$$\left.\frac{dq_x}{dt}\right|_S = \left.\frac{dq_x}{dt}\right|_{proc1} + \left.\frac{dq_x}{dt}\right|_{proc2} + \ldots$$

e.g.

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

CONTINUOUS COLLECTION OF CLOUD WATER

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

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

$$\boxed{\left.\frac{dq_x}{dt}\right|_{CL} \propto M_x(2+b_x)}$$

p^{th} moment:

$$M_x(p) \equiv \int_0^\infty D^p N_x(D)dD$$

$$V_x(D) = \gamma\, a_x D^{b_x}$$

How well do the various bulk scheme predict sedimentation and sources/sinks?

TM and DIAG DM schemes

better than

SM AND FIXED DM schemes