Recent Developments to the Milbrandt-Yau Cloud Microphysics Scheme

The Proposed Double-Moment Version for the VO2010 High-Resolution NWP System

Jason Milbrandt [1]
Ron McTaggart-Cowan [1]
Jocelyn Mailhot [1]
Amin Erfani [2]
Andre Giguere [2]
Bertrand Denis [2]
Denis Jacob [3]

[1] RPN
[2] CMDN
[3] Severe Weather National Laboratory

Environment Canada Environnement Canada

January 7, 2009

RPN Service through science

OUTLINE OF PRESENTATION

1. **Background of the M-Y scheme**
2. **Recent developments**
   - changes to snow category
   - new prognostic/diagnostic fields
3. **Evaluation of VO2010 tests**
4. **Current and upcoming research**

1. Background

The Milbrandt-Yau multi-moment scheme:

- **Six hydrometeor categories**

LIQUID
- ***cloud*** (small droplets)
- ***rain*** (drizzle-sized and larger drops)

ICE-PHASE
- ***ice*** (pristine crystal)
- ***snow*** (large crystals and aggregates)
- ***graupel*** (rimed crystals)
- ***hail*** (frozen drops and high-density ice)

- **Versions:**
  - Single-Moment
    - *mass:* QC, QR, QI, QN, QG, QH
  - Double-Moment
    - *mass:* QC, QR, QI, QN, QG, QH
    - *concentration:* NC, NR, NI, NN, NG, NH
  - Triple-Moment
    - *mass:* QC, QR, QI, QN, QG, QH
    - *concentration:* NC, NR, NI, NN, NG, NH
    - *reflectivity:* ZR, ZI, ZN, ZG, ZH

} prognostic variables (advected)

History of M-Y scheme

2004:	full multi-moment scheme (v1) developed at McGill University
2007 (Jan.):	single-moment and double-moment versions (v2) implemented into RPN-CMC physics library (v4.4)
2007 (June-Dec.):	single-moment (v2, v3) used for MAP D-PHASE
2007-08 (winter):	single-moment (v3) used in VO2010 practicum 1
2008 (April):	single-moment (v4) implemented into GEM-LAM-2.5
2008 (summer):	double-moment (v4) used in real-time 1-km GEM-LAM in support of UNSTABLE project
2008 (Dec.):	single-moment (v4) and **new double-moment (v5)** tested in recent high-resolution LAM system for VO2010
2008 (Jan. 8):	To be proposed (CPOP): implementation of **double-moment (v5)** into VO2010 system for 2009 practicum 2

2. Recent Developments

Developments to Double-Moment Version (v5):

- further optimization of sedimentation
- fine-tuning of *hail* initiation conditions
    - freezing of *rain*
    - conversion of *graupel* to *hail*
- other minor modifications
- modernization of *snow* category

The SNOW Category (in most bulk schemes, including original M-Y)

- Represents large ice crystals and/or aggregates
- Represented by equivalent spheres
  - Prescribed bulk density (ρ_s = 100 kg m^{-3})
  - $m(D) = (\pi/6)\rho_s D^3$
  - $V(D) = aD^b$

$$\frac{dq_s}{dt} = \frac{1}{\rho}\int_0^\infty \frac{dm(D)}{dt} N(D)dD$$

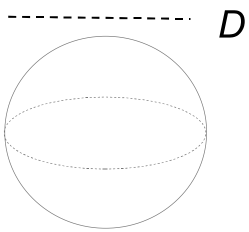
- Growth rates
  - Diffusion: electrostatic capacitance analogy
  - Accretion: continuous or stochastic collection equation
- Precipitation
  - Mass flux computed from bulk sedimentation velocities

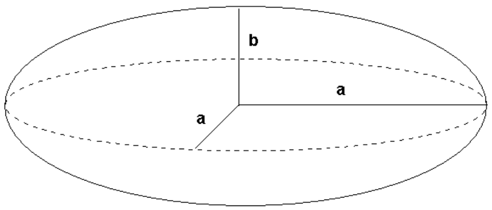
Electrostatic Analogy for Diffusional Growth of Ice Crystals

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

where $AB_i = \frac{L_s^2}{K_a R_v T^2} + \frac{1}{\rho q_{is} \psi}$

SHAPE	CAPACITANCE
Sphere	$C = \frac{D}{2}$
Prolate spheroid	$C = \frac{\sqrt{a^2 + b^2}}{\ln[(a + \sqrt{a^2 + b^2})/b]}$
Oblate spheroid	$C = a\varepsilon / \arcsin(\varepsilon)$ where ellipticity $\varepsilon = \sqrt{1 - b^2/a^2}$





Electrostatic Analogy for Diffusional Growth of Ice Crystals

"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)

Capacitances of Hexagonal Plates

Theoretical

Measured

Oblate Spheroid Plate Capacitances

Diameter	thickness	t/D	Capacitance	C/D
2.0	0.225	0.112	0.730	0.365
2.0	0.177	0.089	0.698	0.349
2.0	0.126	0.063	0.664	0.332
2.0	0.103	0.052	0.648	0.324
2.0	0.086	0.043	0.637	0.319
2.0	0.072	0.036	0.628	0.314
2.0	0.064	0.032	0.622	0.311
2.0	0.058	0.029	0.618	0.310

Measured Capacitances

-20 °C t/D	550 mb C/D	-30 °C t/D	400 mb C/D	-40 °C t/D	300 mb C/D
0.84	0.27	0.83	0.11-.23	0.82	0.07-.29
0.63	0.15	0.73	0.36-.62	0.72	0.11-.18
0.20	0.10	0.61	0.16-.28	0.59	0.10-.36
0.13	0.02	0.40	0.07-.17	0.45	0.09-.26
0.12	0.08	0.32	0.09-.29	0.32	0.08-.15
0.08	0.07	0.20	0.02-.13	0.20	0.02-.13
0.06	0.03-.13	0.10	0.01-.12	0.08	0.04-.08
0.04	0.02-.04	0.06	0.02-.19	0.04	0.01-.11

Sphere:
C/D = 0.5

THEORETICAL
0.310

↔

MEASURED
0.01 - 0.19

Bailey and Hallet (2006)

Correction factor: 0.03 – 0.38

Changes to SNOW Category

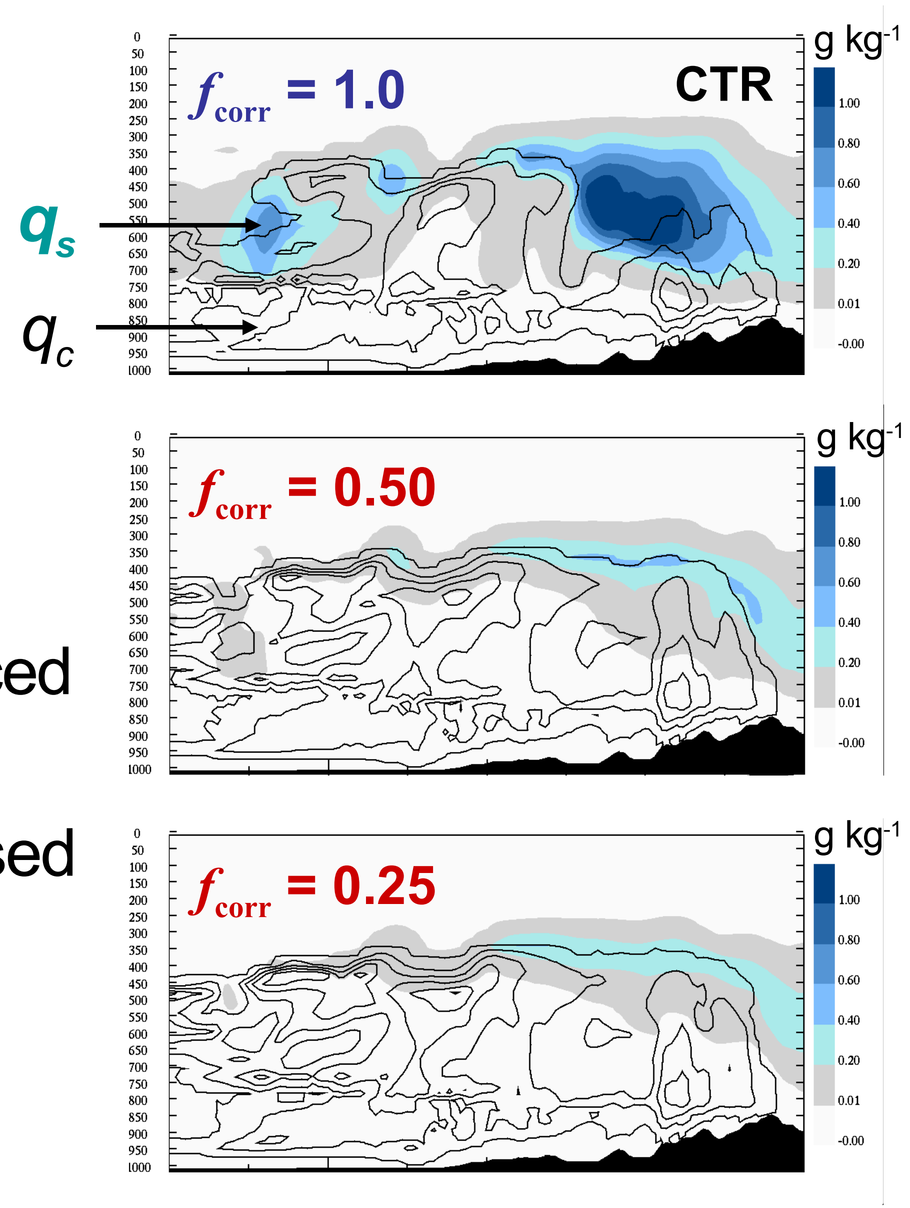
2. Modification to diffusional growth

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:



With decreasing f_{corr},

SNOW content (q_s) is reduced

and

CLOUD LWC (q_c) is increased

Riming (growth by collection of cloud water)

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

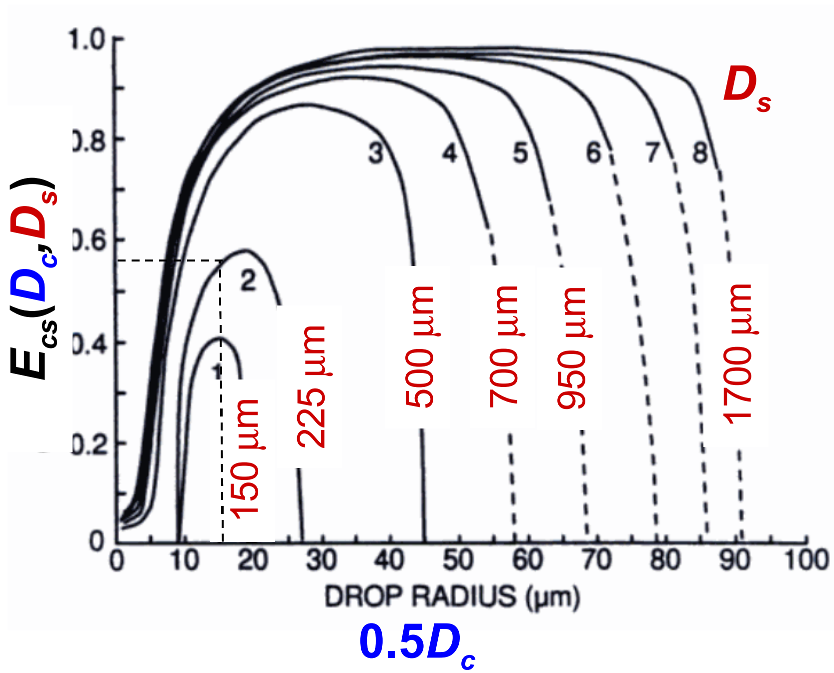
$$CL_{yx} = \frac{1}{\rho}\frac{\pi}{4}\int_0^\infty\int_0^\infty \left|V_x(D_x)-V_y(D_y)\right|\left(D_x+D_y\right)^2 m_y(D_y)\underbrace{E_{xy}(D_x,D_y)}_{\text{COLLECTION EFFICIENCY}} N_y(D_y)N_x(D_x)\,dD_y\,dD_x$$

COLLECTION EFFICIENCY

- Assumptions are made to solve analytically
- For the collection efficiency, $E_{cs} = 1$ is often assumed (for collection of *cloud* water by *snow*)
- If $E_{cs} < 1$, the snow riming rate will be overestimated

Riming (growth by collection of cloud water)

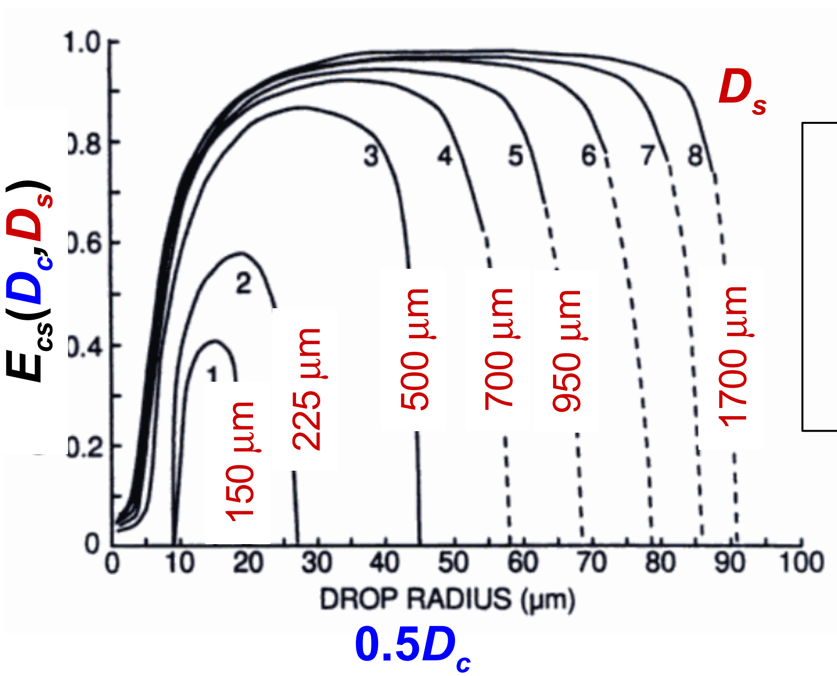
Computed from 3-D simulations* of Navier-Stokes equations:



e.g.
E_{cs}(30 µm, 225 µm) = 0.55

*Wang and Ji, 1992

Riming (growth by collection of cloud water)



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)

Note: For *graupel* and *hail*, E_{cg} = 1 is a reasonable approximation (Macklin and Bailey, 1966)

Mass-"Diameter" Relation for Snow Particles

Traditional approach:

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

- Based on spheres with constant bulk density, ρ_s

New approach:*

$m(D) = cD^d$ ($c = 0.062$, $d = 2$)

- Based on obs of "assemblages of fractal-like aggregated crystals"

- Values of m-*D* parameter (c, d) directly affect values of size distribution parameters (λ_s, N_{0s})
- Thus, all expressions that depend on λ_s, N_{0s} are affected

i.e. <u>all</u> microphysical source/sink terms and sedimentation

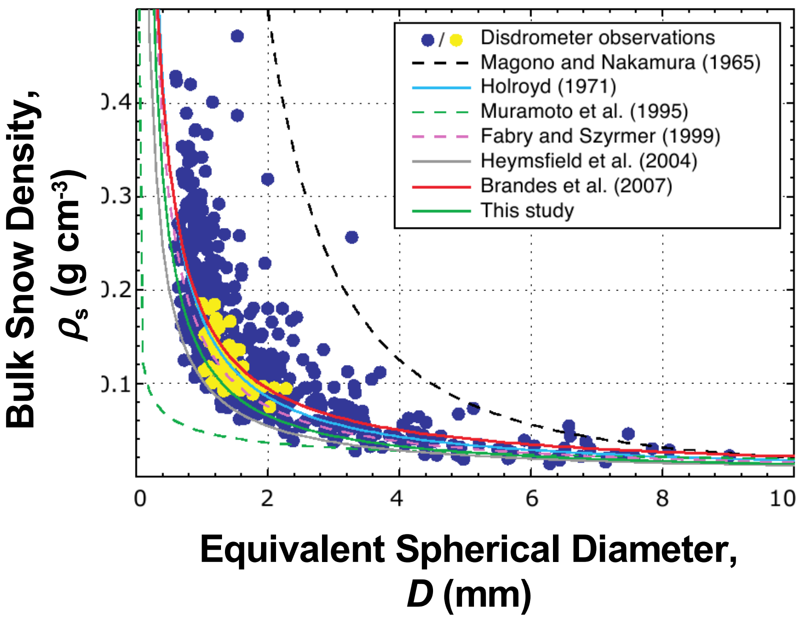
Note: In the new m-*D* relation, *D* represents the *maximum crystal dimension*

* following Thompson et al. (2008)

<u>New approach:</u>*

$m(D) = cD^d$ (c = 0.062, d = 2)

- Based on obs of "assemblages of fractal-like aggregated crystals"



→ $\rho_s = f(D_s^{-1})$

where $D_s = f(Q_s, N_s)$

(double-moment)

Consistent with distrometer observations*

* Thompson et al. (2008)

Prognostic Density of Precipitating Snow*

(not just bulk density of *SNOW* category)

*** Snow = *ICE* + *SNOW* + *GRAUPEL***

(i.e. ice crystals + snow crystals/aggregates + rimed crystals)

APPROACH:

- use the mass-weighted bulk densities (prescribed or diagnosed) of ***ICE***, ***SNOW***, and ***GRAUPEL*** to obtain the "prognostic" snow density

$$\rho_{snow} = \frac{(q_i \rho_i) + (q_s \rho_s) + (q_g \rho_g)}{q_i + q_s + q_g}$$

ρ_i = 500 kg m^{-3}

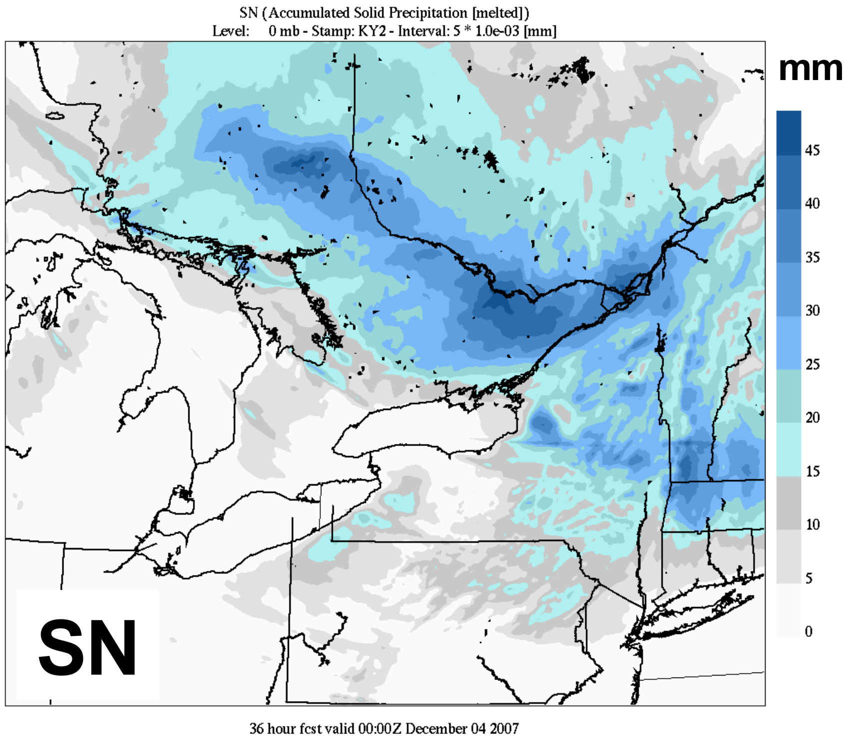
$\rho_s = f(D_s)$

ρ_g = 400 kg m^{-3}

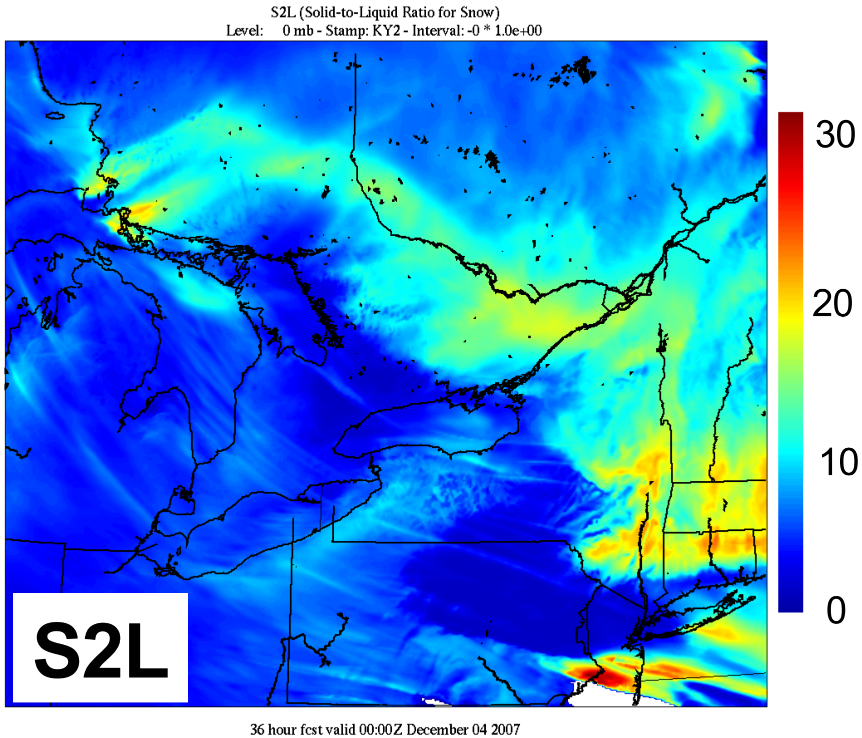
↑

applied to total mass flux (sedimentation rate) of *ICE* + *SNOW* + *GRAUPEL* to obtain **instantaneous snow rate**, cm s^{-1} (unmelted)

Accum. Pcp. (liquid-equivalent)

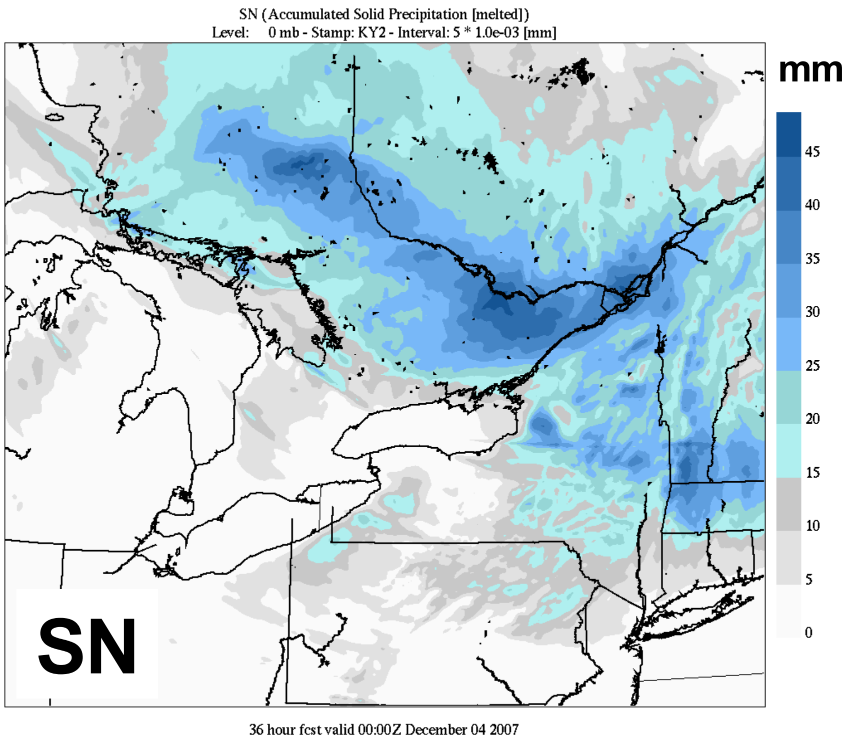


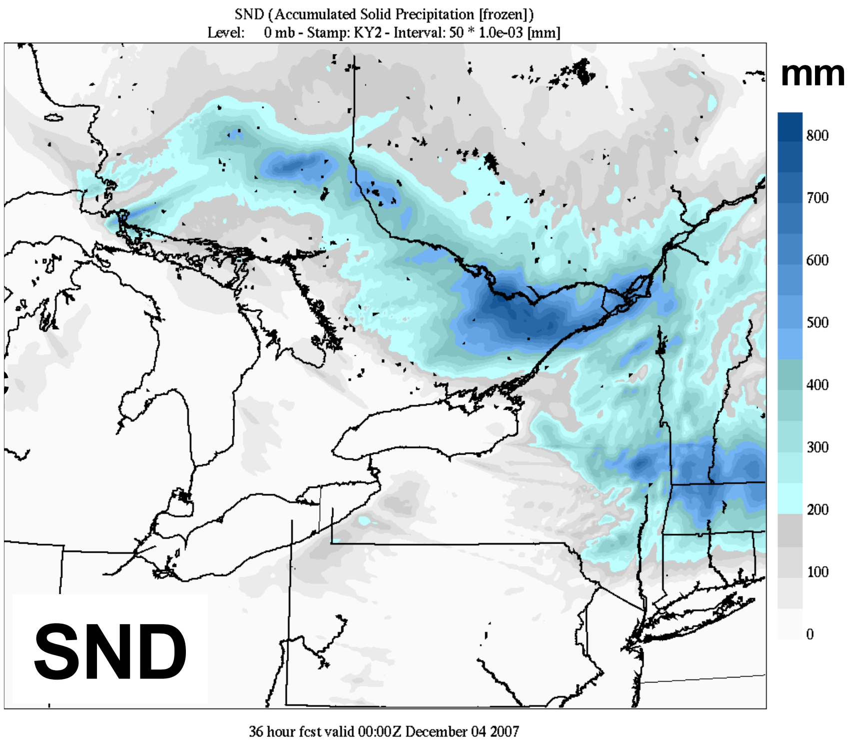
Solid:Liquid Ratio



36-h QPF

Accum. Pcp. (liquid-equivalent) | Accum. Pcp. (unmelted)





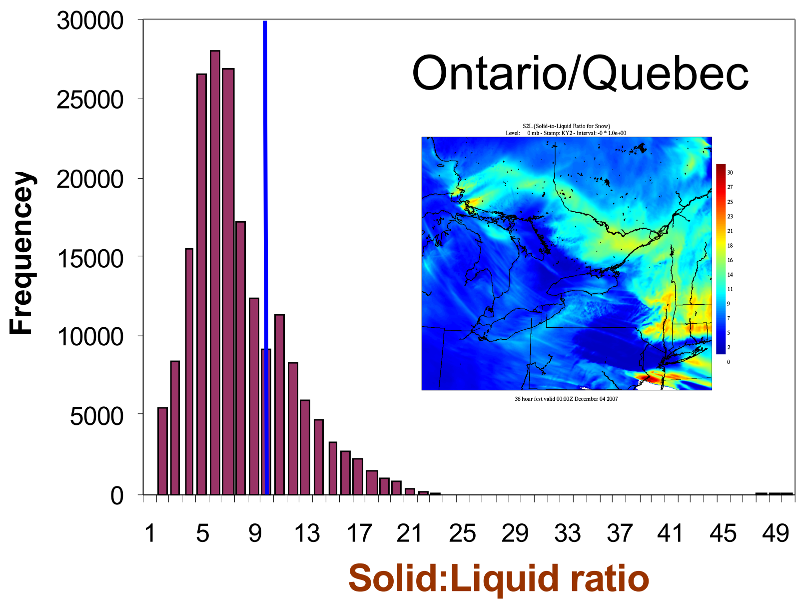
36-h QPF

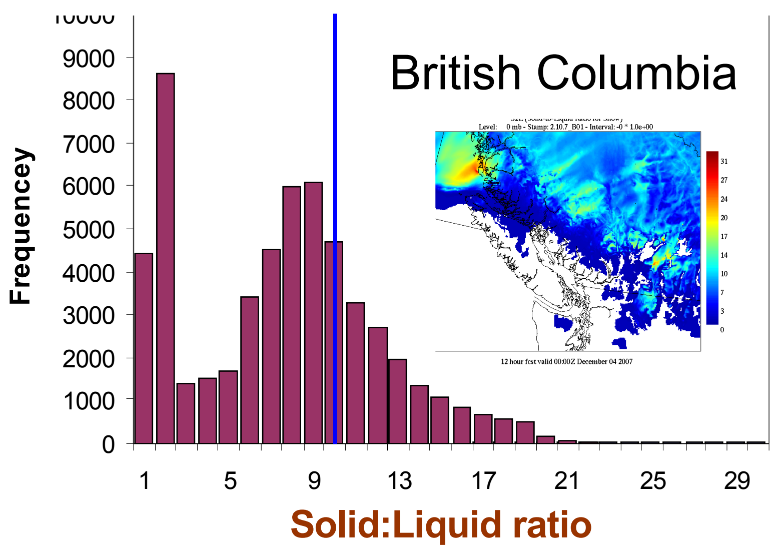
NOTE: SND ≠ SN · S2L

rather, RSND = RSN · RS2L (<u>instantaneous</u>)

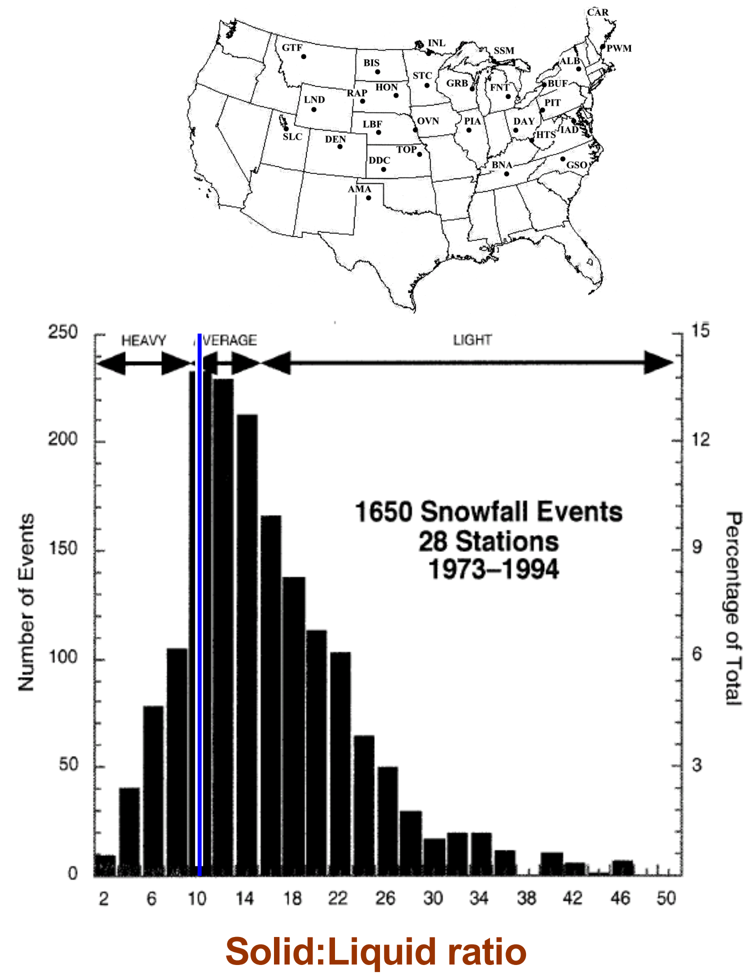
2. Recent Developments – New Diagnostics

3 Dec 2007 (LAM-2.5km):





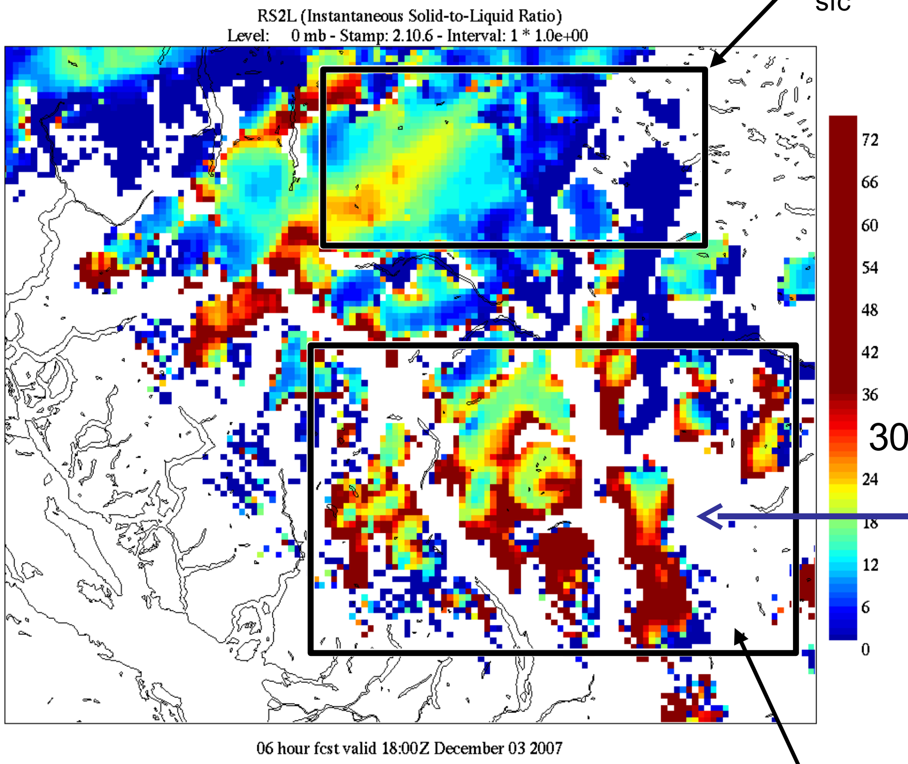
Climatology (north-east USA):



Roebber et al. (2003)
Weather and Forecasting

Solid-to-Liquid Ratio (instantaneous)

$T_{sfc} < 0°C$



Very large solid:liquid ratios (low density) for melting snow

→ Unrealistically large snow depths

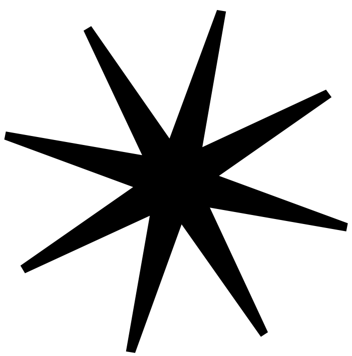
$T_{sfc} > 0°C$

Proposed Solution to Treat Melting Snow:

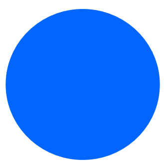
if $T > 0°C$: $$\rho_{s\_melting} = \frac{q_s \rho_s(D_s) + q_r \rho_L}{q_s + q_r}$$

Actual model representation:

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



$\boldsymbol{q_s}$

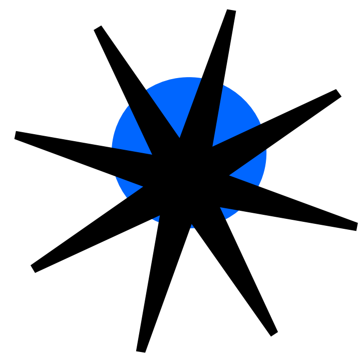


$\boldsymbol{q_r}$

(where $\boldsymbol{q_r}$ originates directly from $\boldsymbol{q_s}$ due to melting)

Approximate view of melting snow:

$\rho_{s\_melting}$

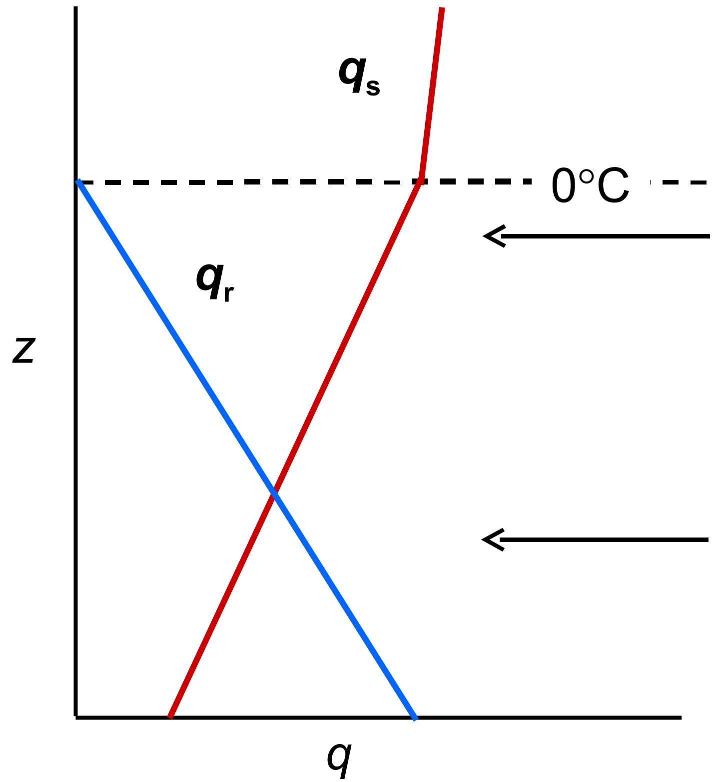


$$\frac{q_r}{q_r + q_s}$$ is the liquid fraction of melting snow

Proposed Solution:

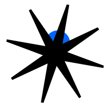
- approximate **liquid fraction** of melting snow by $q_r / (q_r + q_s)$
- use mass-weighted density to approximate density of melting snow

if $T > 0°\text{C}$: $$\rho_{s\_melting} = \frac{q_s \rho_s (D_s) + q_r \rho_L}{q_s + q_r}$$

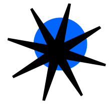


e.g. Assume D_s = 5 mm → $\rho_s(D_s)$= 26 kg m^{-3} :

$$\rho_{s\_melting} = \frac{0.95(26\,\text{kg m}^{-3}) + 0.05\rho_L(1000\,\text{kg m}^{-3})}{1.00} = 75\,\text{kg m}^{-3}$$

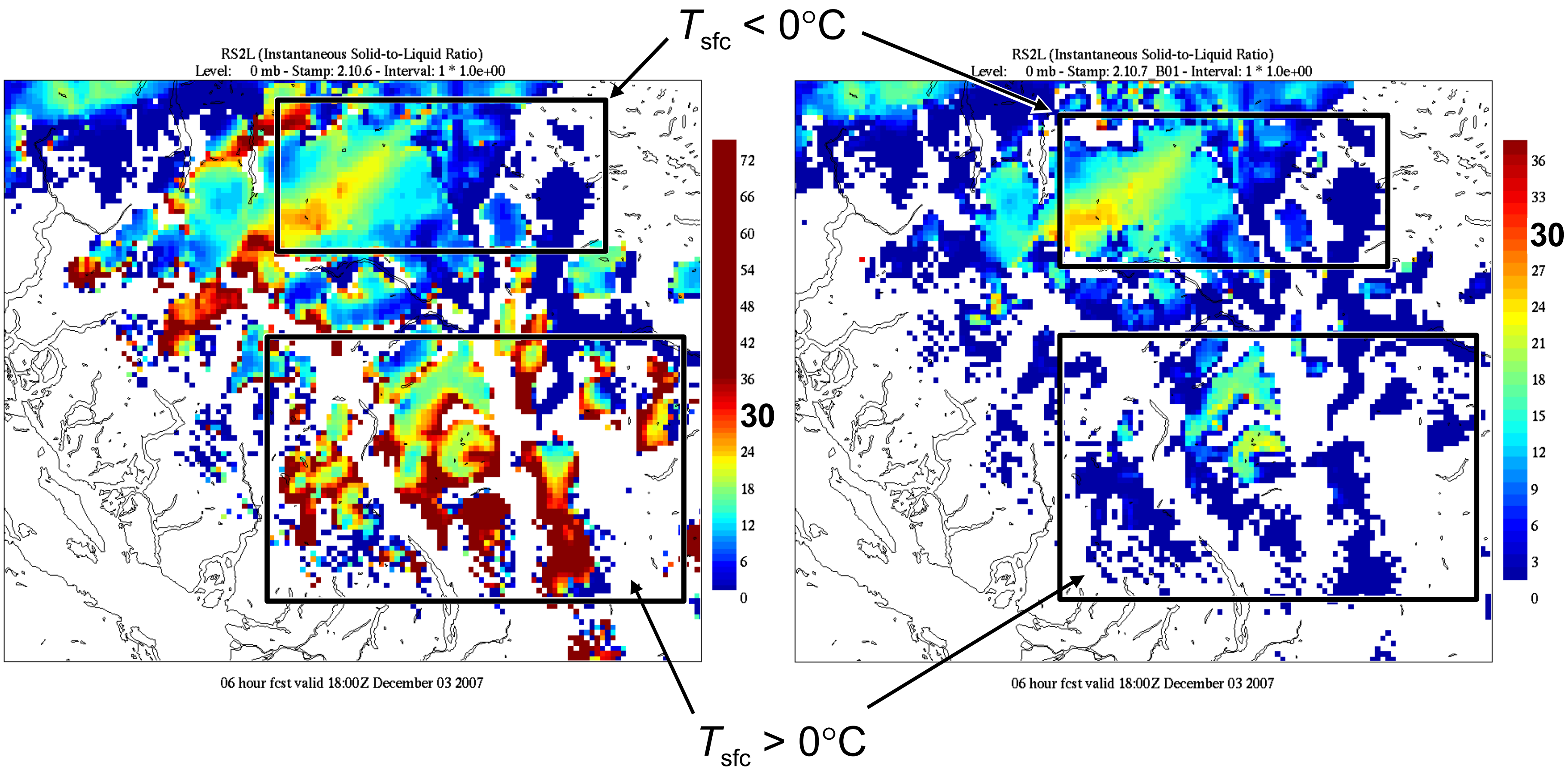


$$\rho_{s\_melting} = \frac{0.50(26\,\text{kg m}^{-3}) + 0.50\rho_L(1000\,\text{kg m}^{-3})}{1.00} = 513\,\text{kg m}^{-3}$$



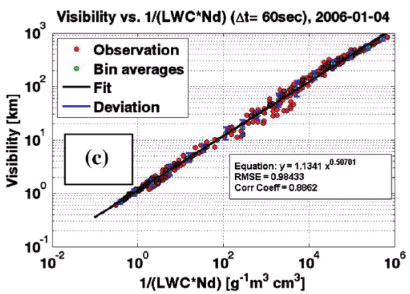
Solid-to-Liquid Ratio (instantaneous)

Before Correction | **After Correction**

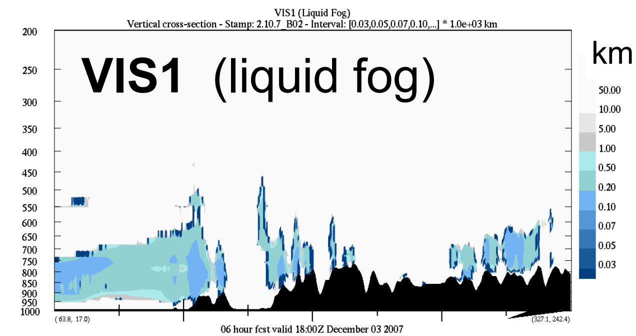


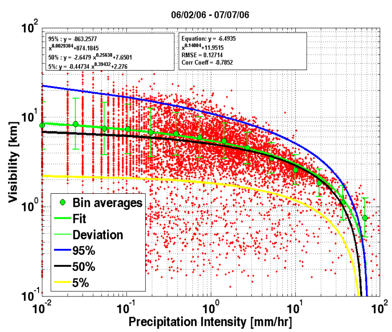
3D fields for **VISIBILITY** due to ***fog***, ***rain***, and ***snow***

(parameterizations* based on observations taken during **FRAM**)

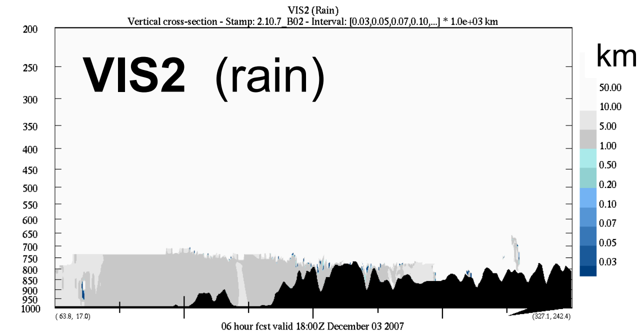


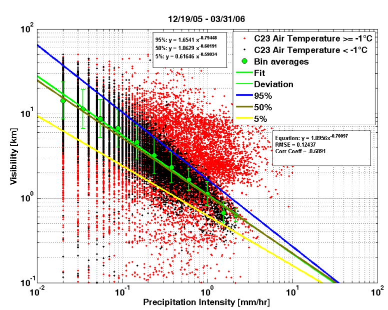
$\text{VIS1} = f\,(q_c, N_c)$



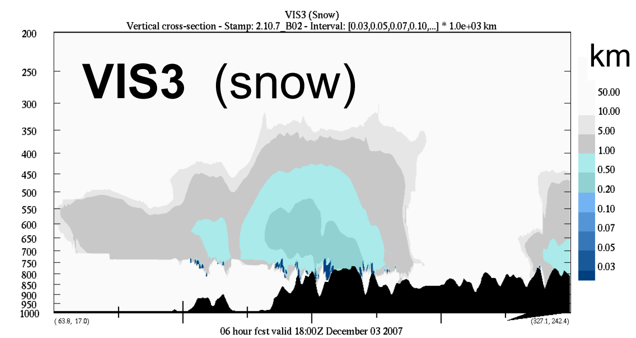


$\text{VIS2} = f\,(RRN2)$





$\text{VIS3} = f\,(RSN2)$



*Gultepe and Milbrandt (2007)

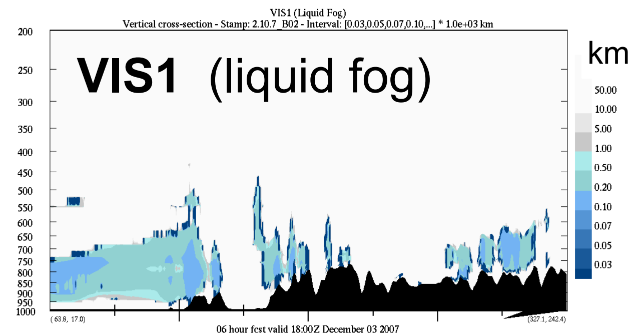
3D fields for **VISIBILITY** due to ***fog***, ***rain***, and ***snow***

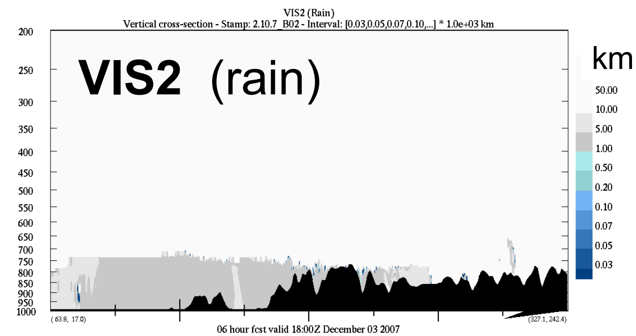
(parameterizations* based on observations taken during **FRAM**)

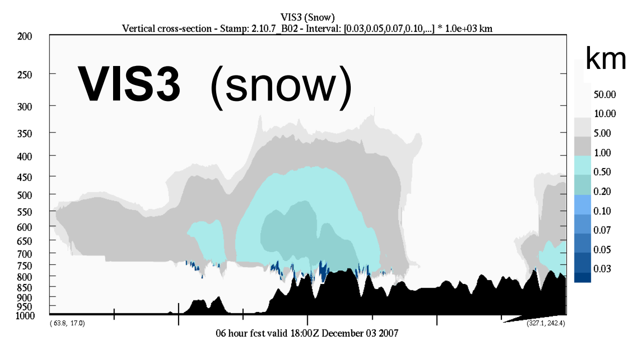
VISIBILITY due to the combined effects of liquid **FOG**, **RAIN**, and **SNOW**:

$$VIS = -\ln(\varepsilon)\beta_{ext}^{-1}$$

$$\rightarrow \quad VIS = \left(\frac{1}{VIS1} + \frac{1}{VIS2} + \frac{1}{VIS3} \right)^{-1}$$

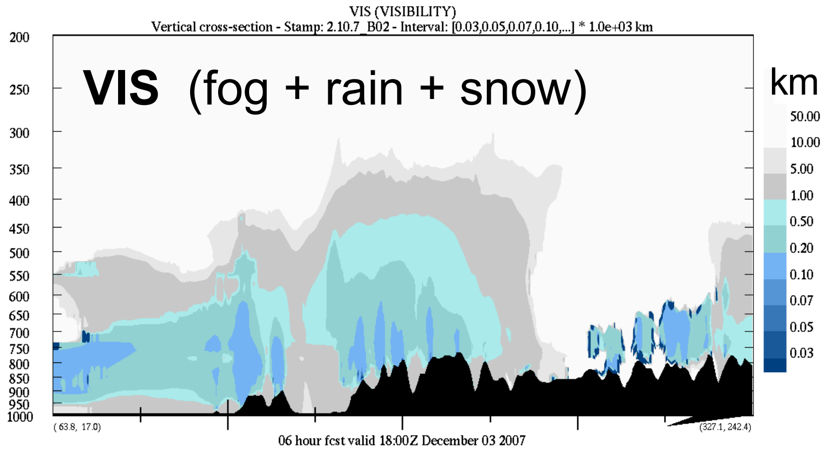


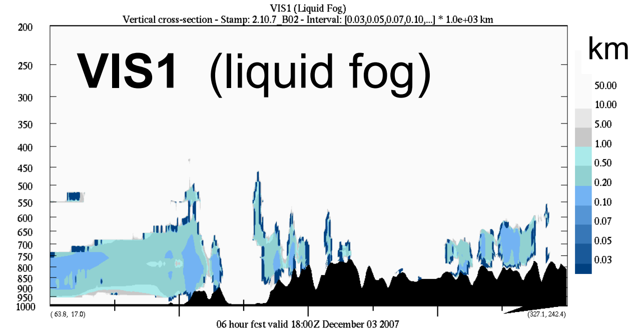


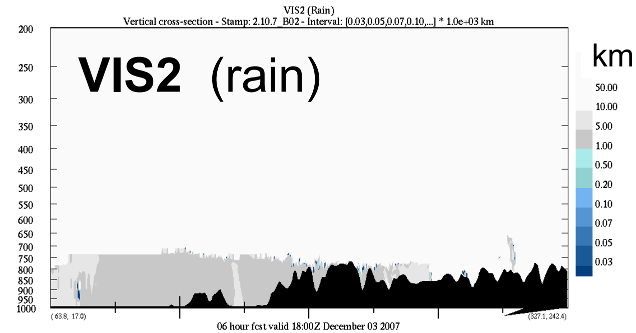


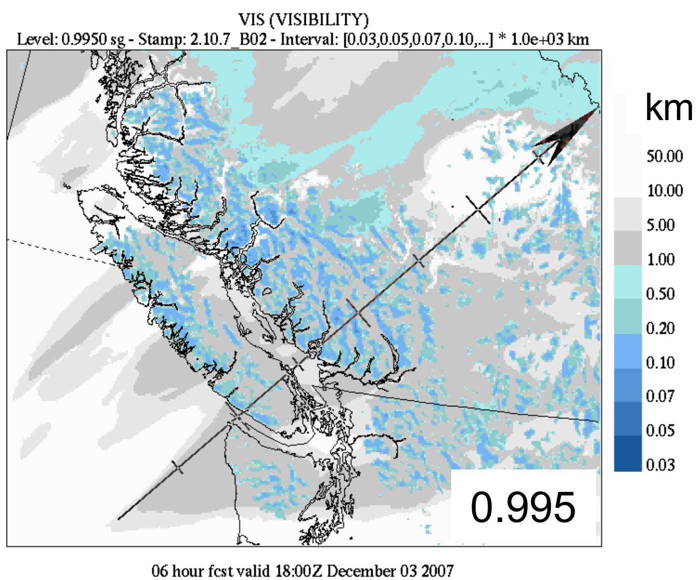
3D fields for **VISIBILITY** due to ***fog***, ***rain***, and ***snow***

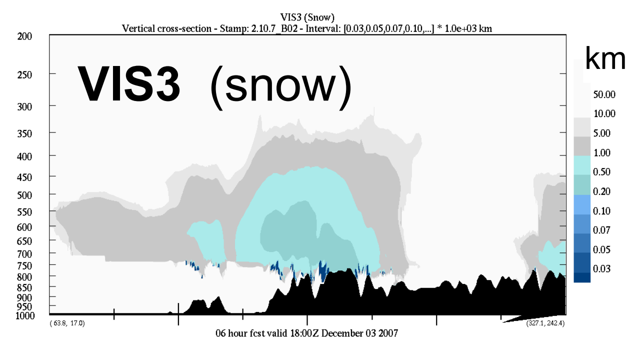
(parameterizations based on observations taken during **FRAM**)





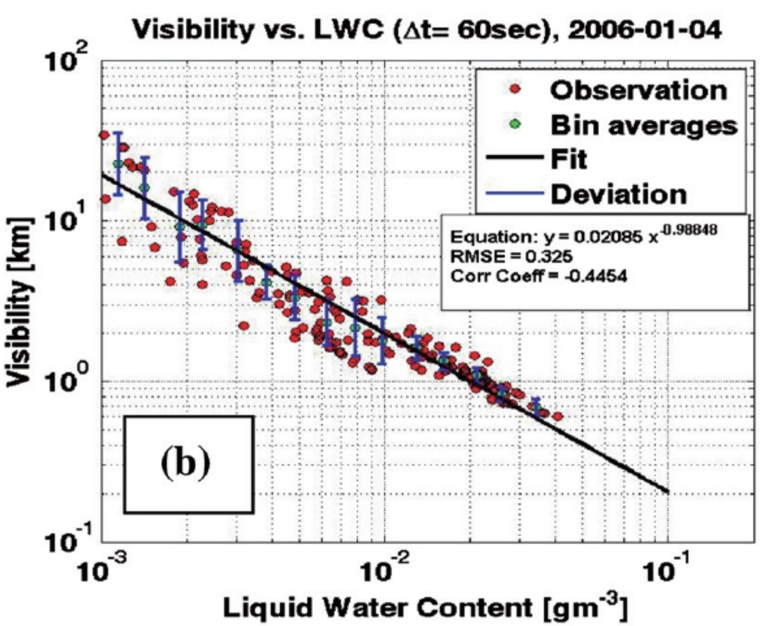




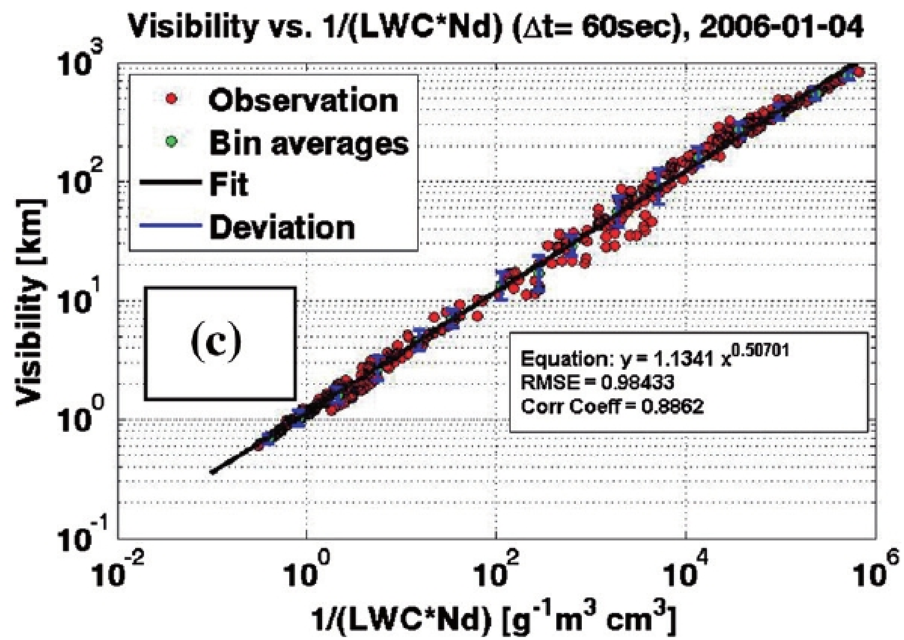


VIS1 (liquid fog)

Single-Moment: VIS1 = *f* (*QC*)



Double-Moment: VIS1 = *f* (*QC*,***NC***)



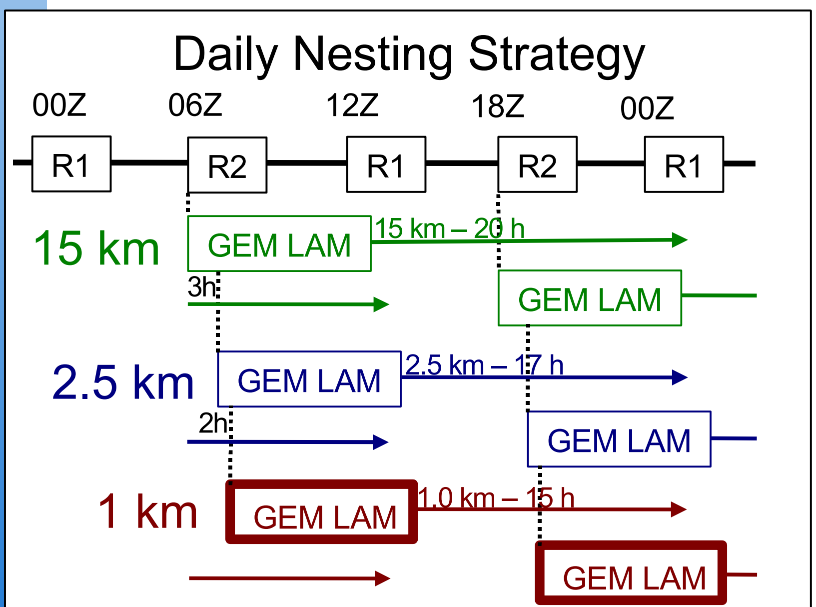
- VIS1 is parameterized **better for double-moment**,
- **BUT** low-level LWC (*QC*) is the weakest link (not *NC*)

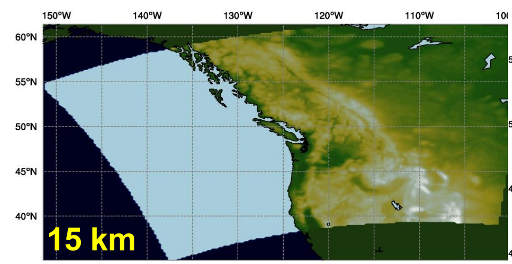
Gultepe and Milbrandt (2007)

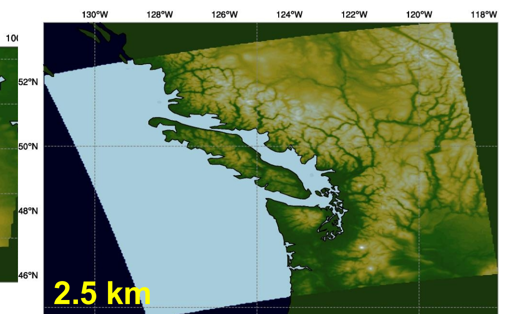
3. Evaluation of VO2010 Tests

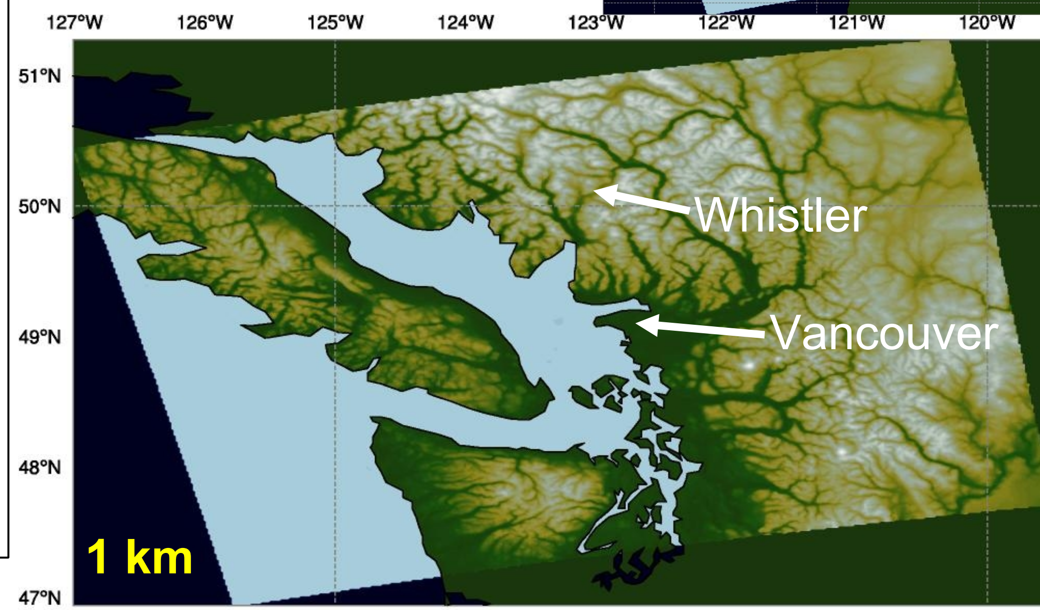
VO2010 High-Resolution Forecast System

- Triple-nested LAM integrations twice daily from 0600 and 1800 UTC GEM Regional forecasts:
  - LAM-15km → 2.5km → 1km









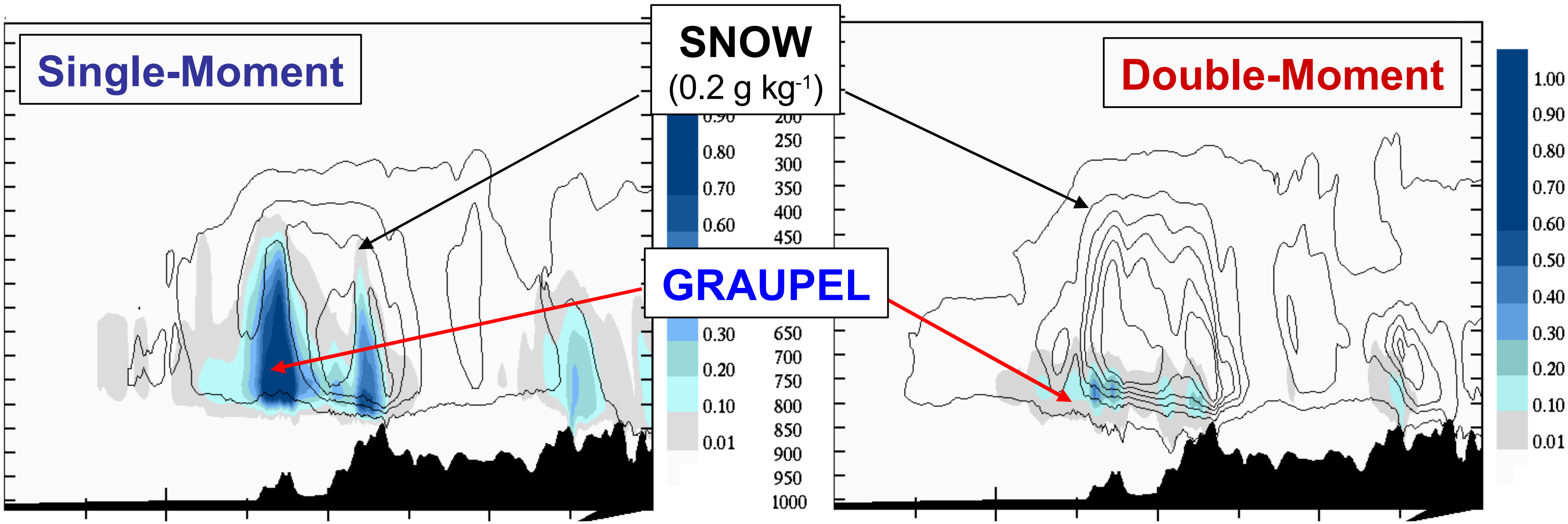
- 10 winter cases (2007-2008) selected
- New features: evaluation in 3 steps

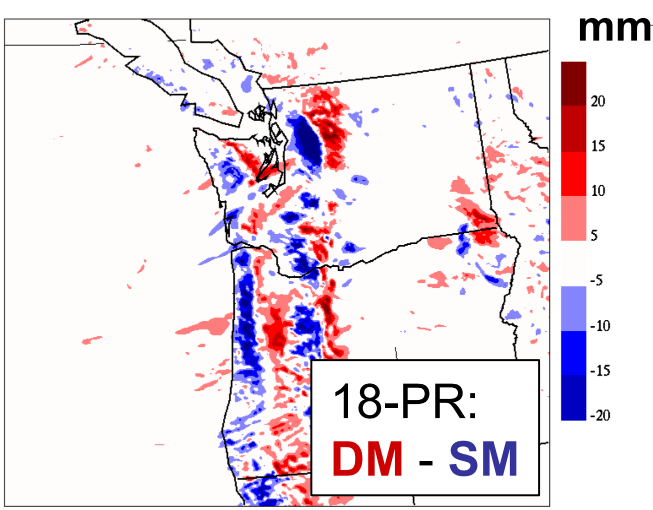
1. geophysical fields using GenPhysX and new database at 90-m res
2. CCCmarad radiation scheme **(single-moment M-Y, v4)**
3. **Milbrandt-Yau double-moment bulk microphysics scheme (v5)**

Following Comparison: Step 2 vs. Step 3

i.e. **SINGLE-MOMENT vs. DOUBLE-MOMENT**

New SNOW-GRAUPEL mass balance → modifies precipitation



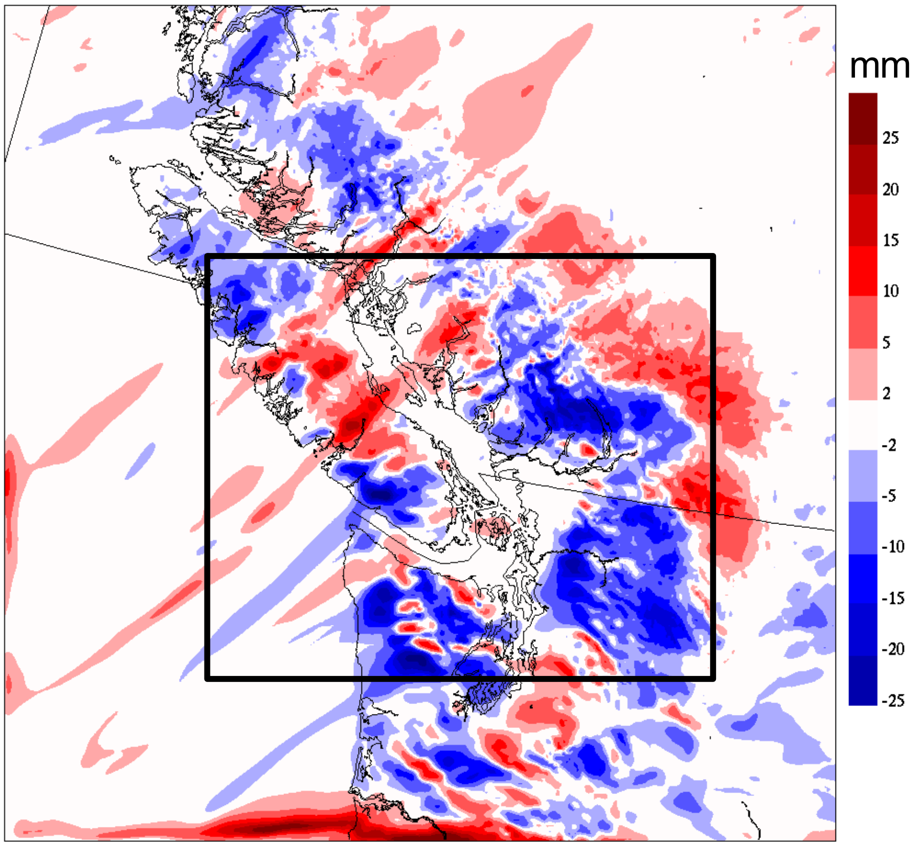


- ↑SNOW ↓GRAUPEL in **Double-Moment**
- downwind shift in surface pcp
- general reduction in pcp along coast and upwind side of mountains

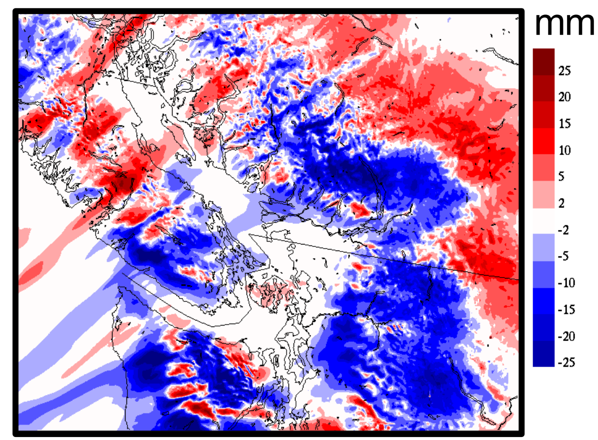
6-h PR 2007-12-03: 12-18 UTC

DOUBLE-MOMENT - SINGLE-MOMENT

2.5-km run:



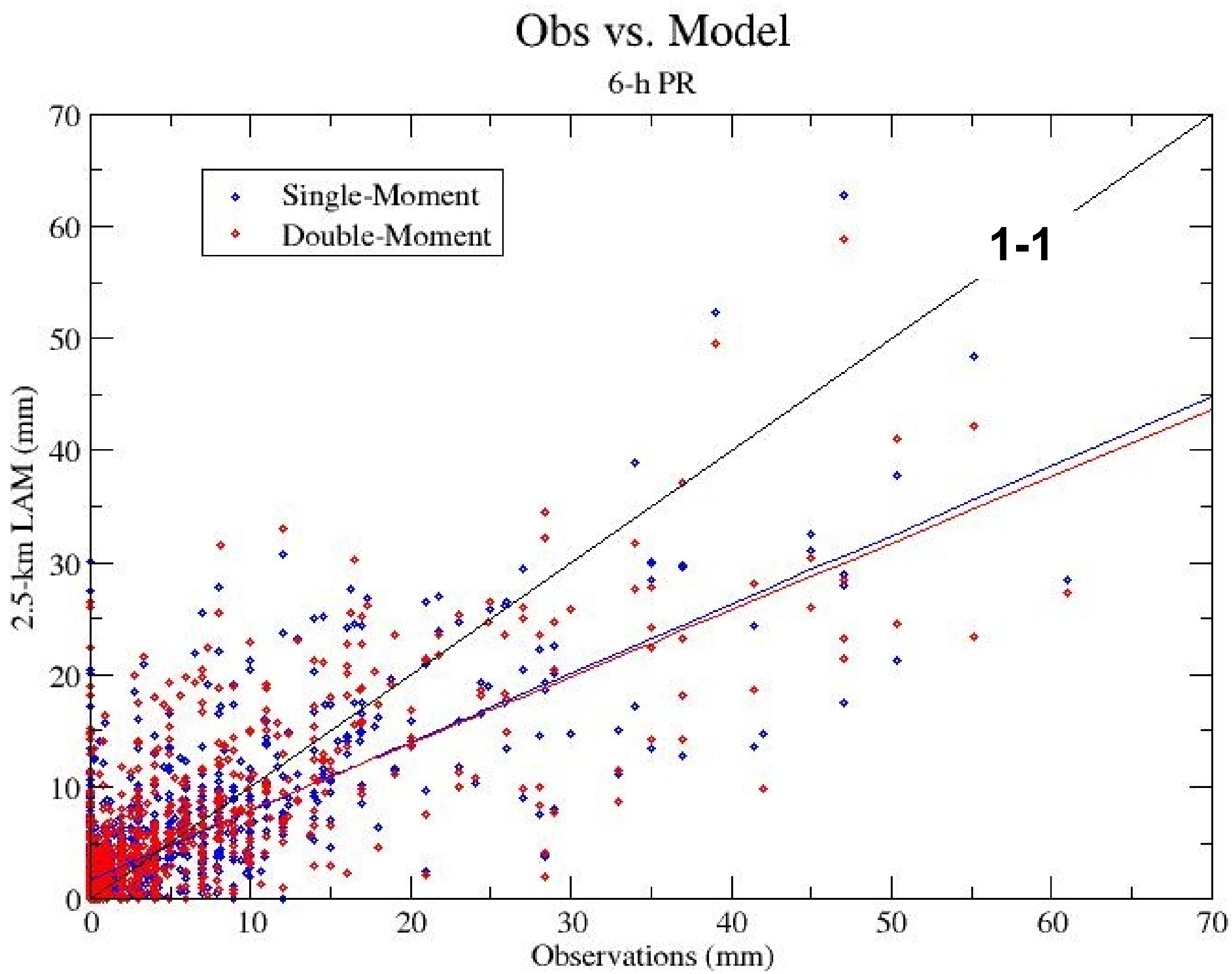
1-km run:



Similar response to schemes
→**Focus analysis on 2.5-km grid**
(larger grid, more rain gauges)

10 Winter Cases, 20 6-h periods, 50-70 obs. points per period:

1335 gauge vs. model (2.5-km) points



Regression Curves

3. Evaluation – Accumulated Precipitation

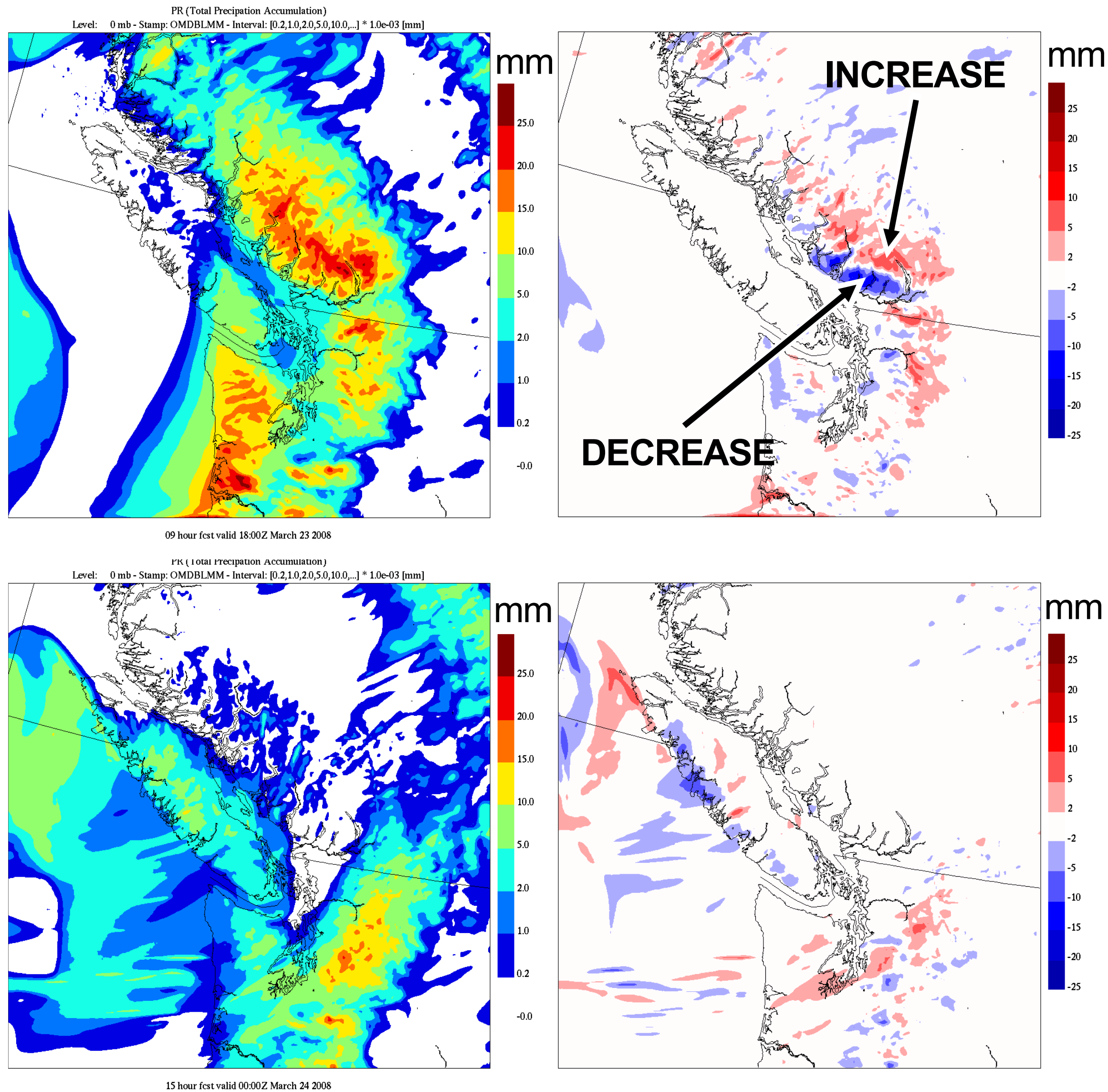
CASE 9 – 2008-03-23

6-h PR
2.5-km

DM | **DM - SM**

Period:
3-9 h

Period:
9-15 h



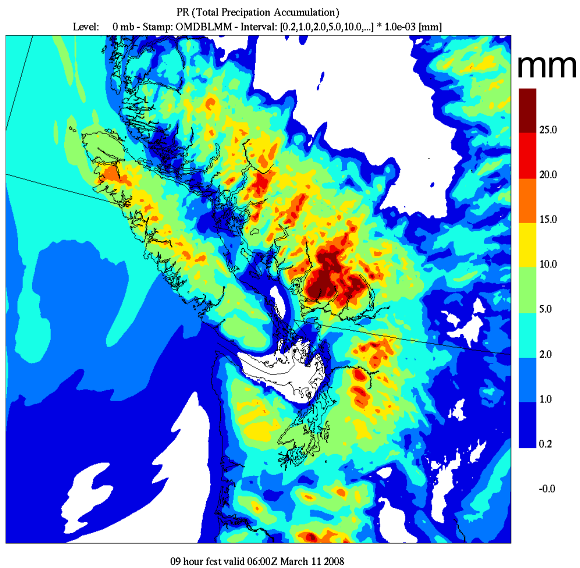
3. Evaluation – Accumulated Precipitation

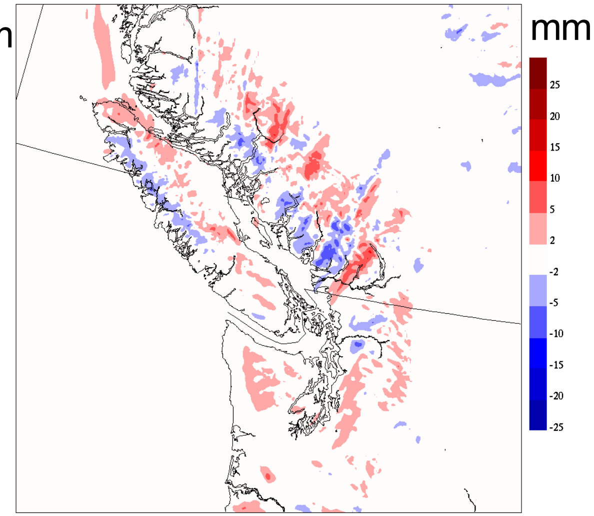
CASE 7 – 2008-03-11

6-h PR
2.5-km

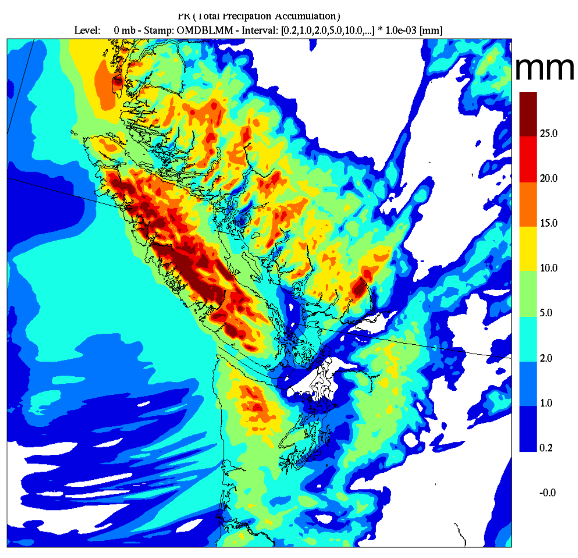
DM | **DM - SM**

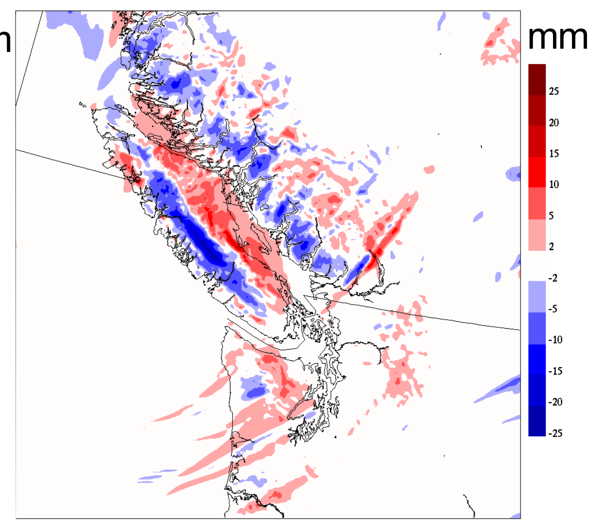
Period:
3-9 h





Period:
9-15 h





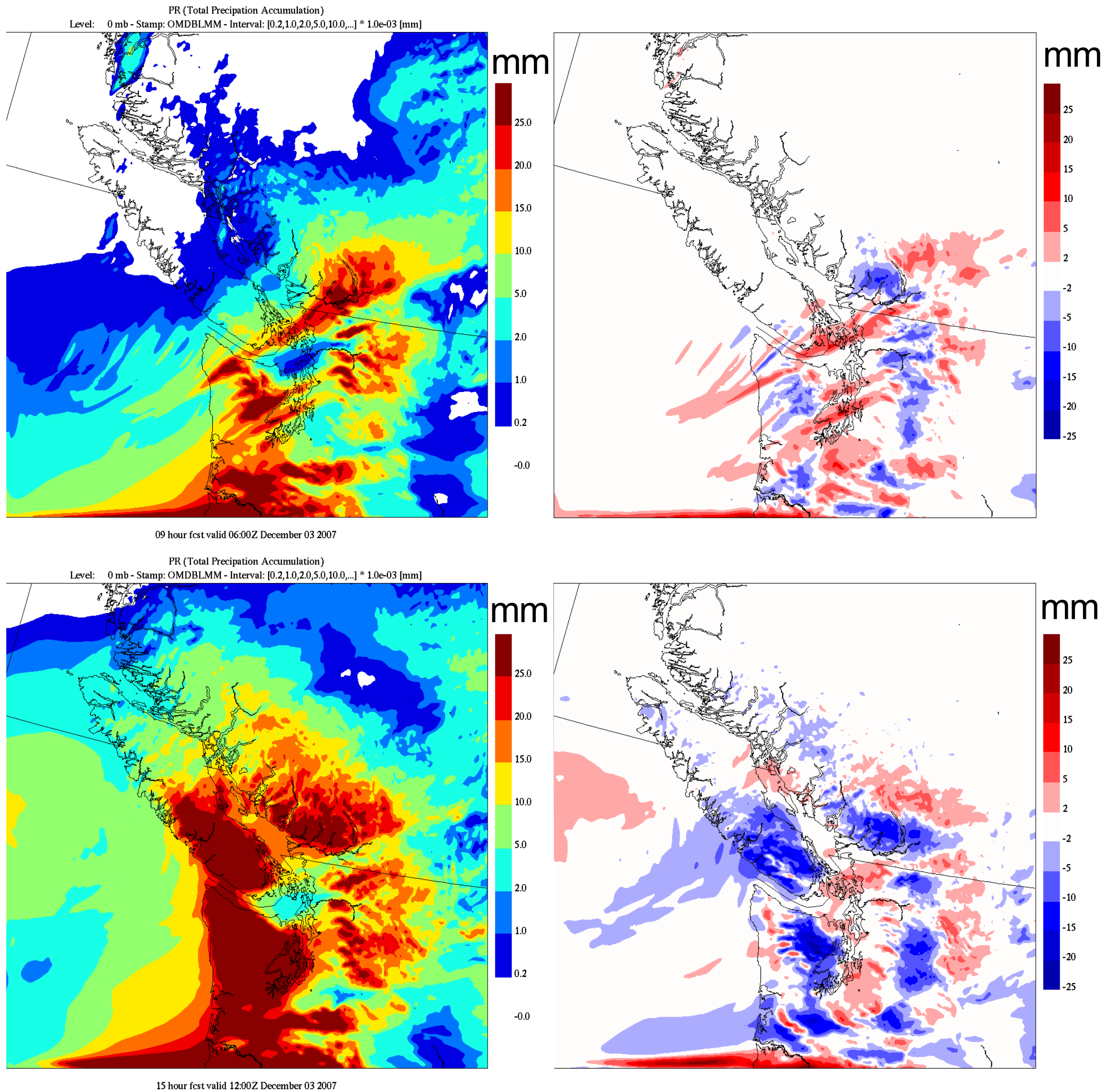
CASE 3 – 2007-12-03

6-h PR
2.5-km

DM | **DM - SM**

Period:
3-9 h

Period:
9-15 h



3. Evaluation – Accumulated Precipitation

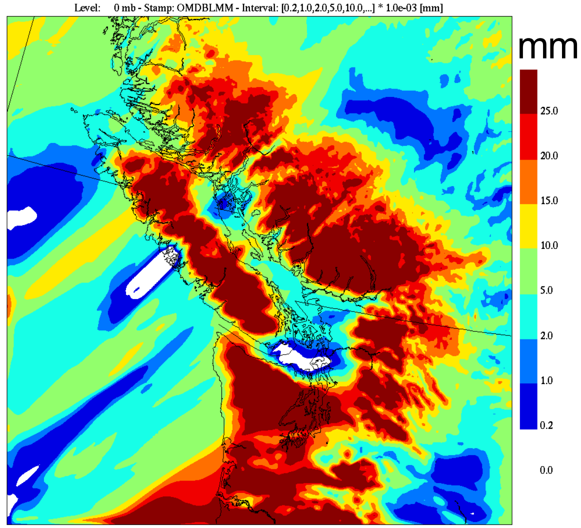
CASE 4 – 2007-12-03

6-h PR
2.5-km

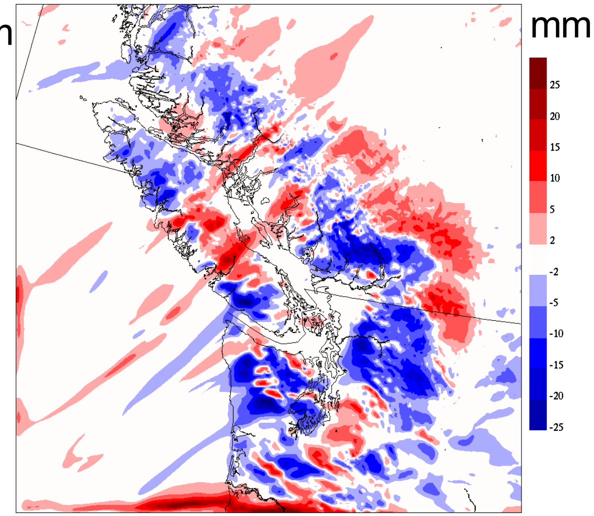
DM | **DM - SM**

Period:
3-9 h

PR (Total Precipation Accumulation)
Level: 0 mb - Stamp: OMDBLMM - Interval: [0.2,1.0,2.0,5.0,10.0,...] * 1.0e-03 [mm]

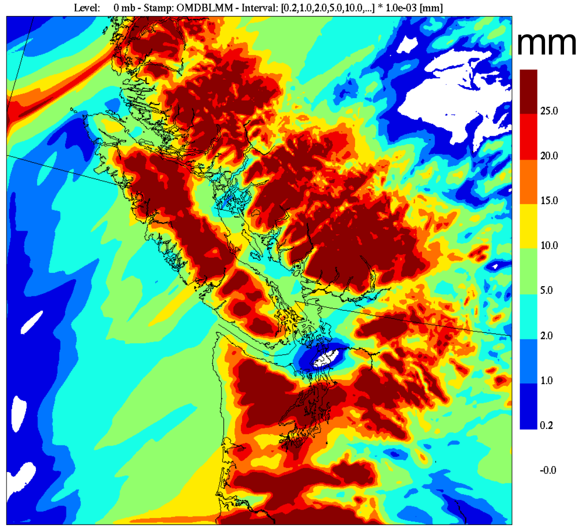


09 hour fcst valid 18:00Z December 03 2007

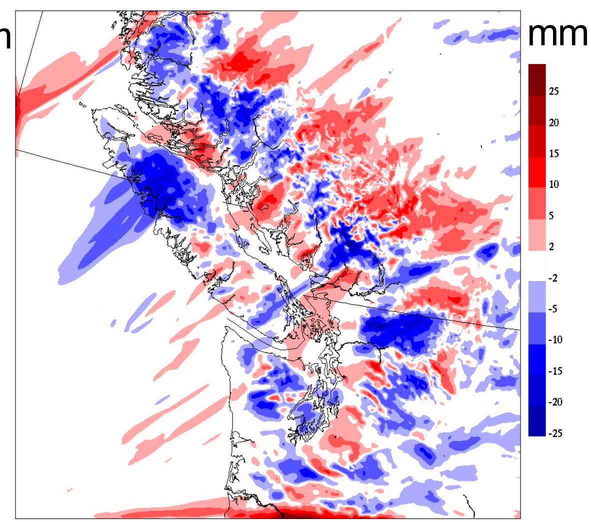


Period:
9-15 h

PR (Total Precipation Accumulation)
Level: 0 mb - Stamp: OMDBLMM - Interval: [0.2,1.0,2.0,5.0,10.0,...] * 1.0e-03 [mm]

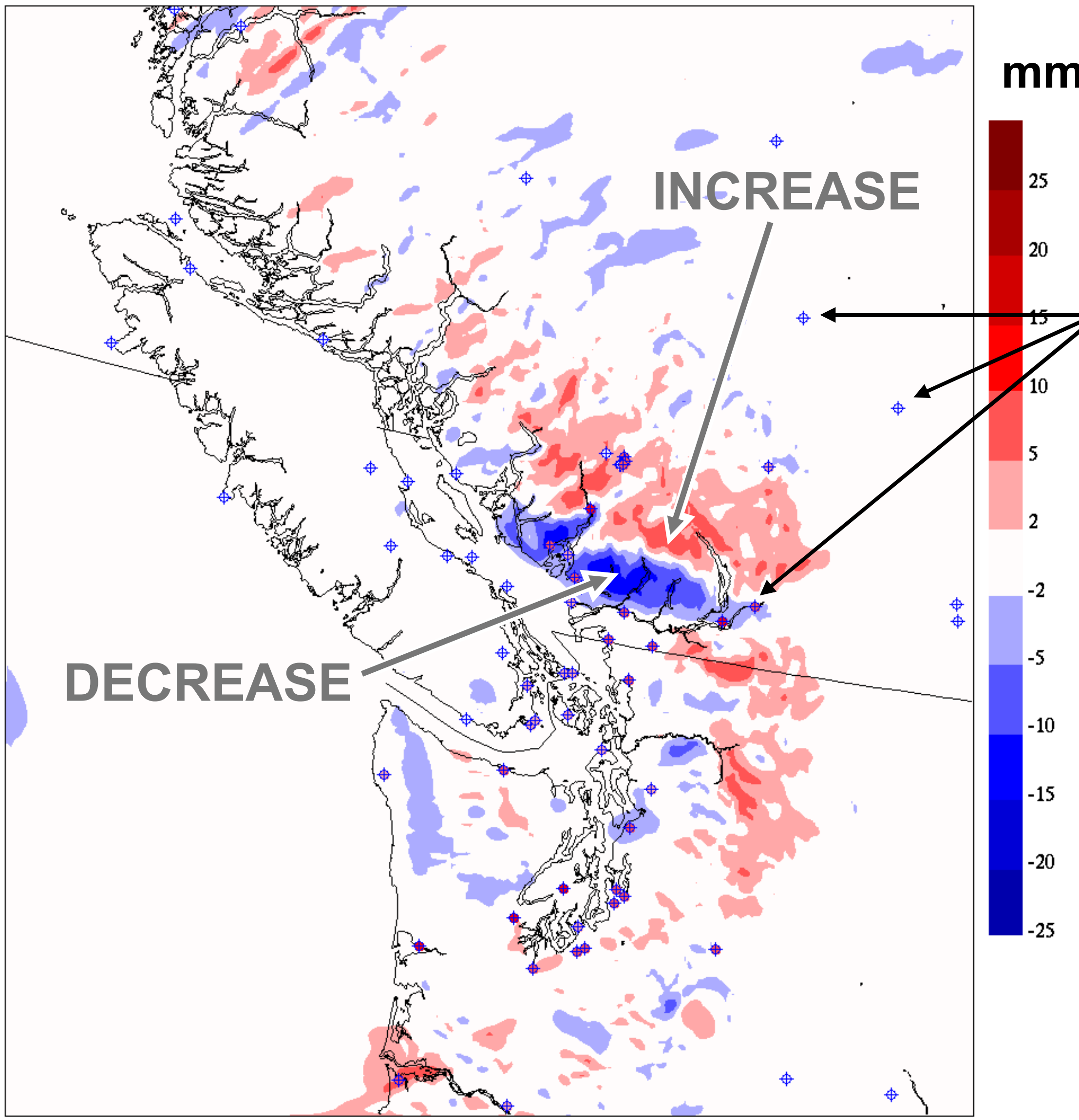


15 hour fcst valid 00:00Z December 04 2007



6-h PR
2.5-km

DOUBLE-MOMENT - SINGLE-MOMENT



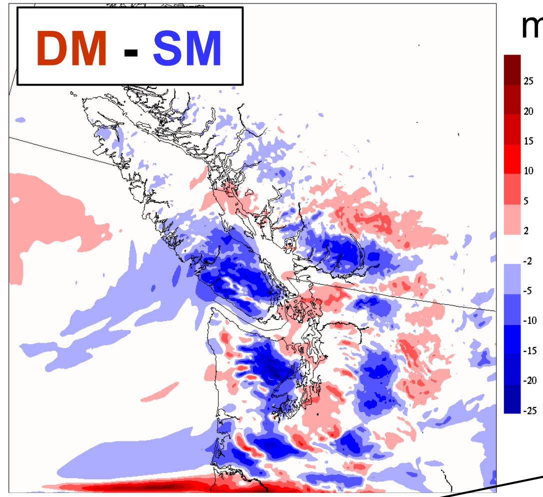
RAIN GAUGES
(synop network)

Objective:
Evaluate models against observations in regions of large differences (between models)

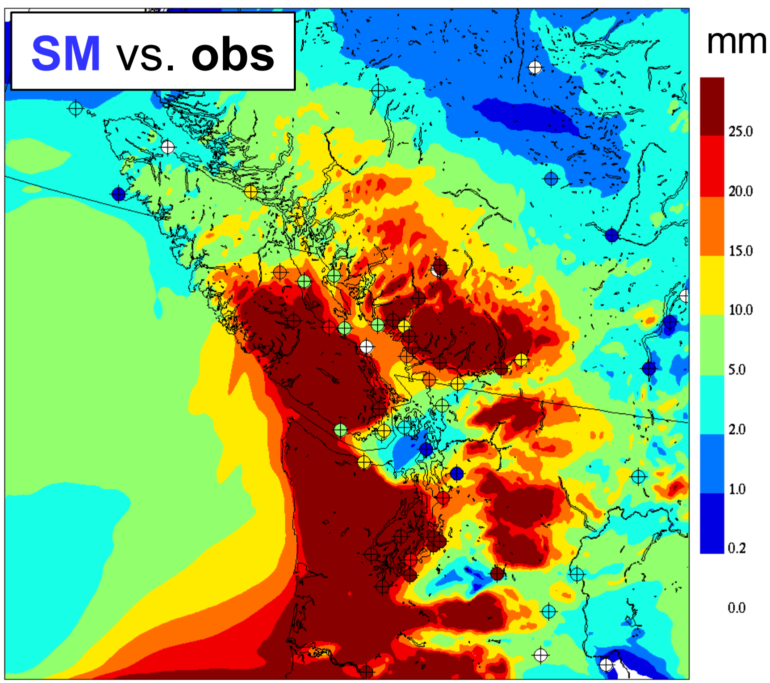
3. Evaluation – Accumulated Precipitation

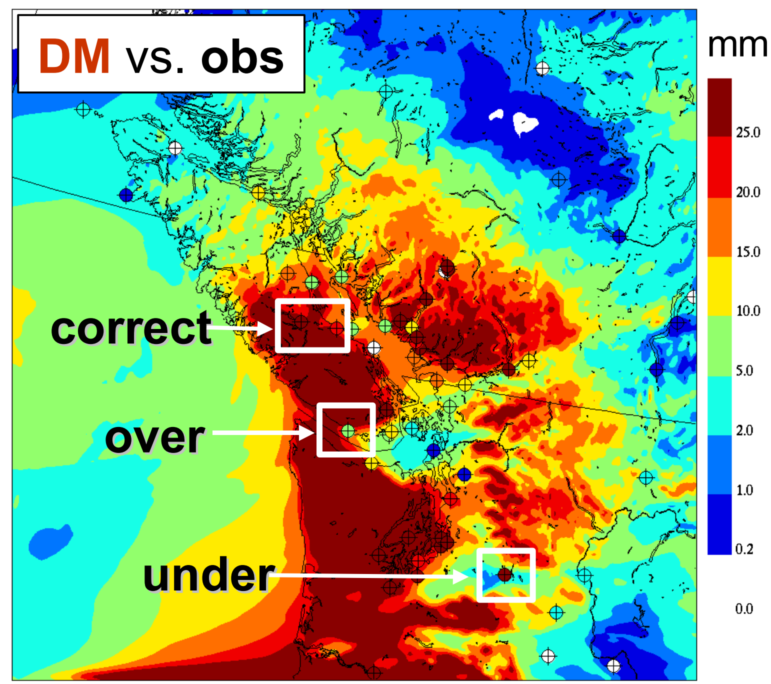
CASE 3b – 2007-12-03

6-h PR
2.5-km



RAIN GAUGES
Same color scale as model

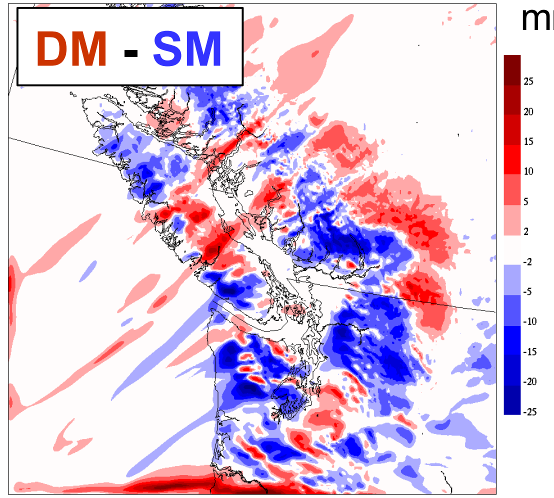


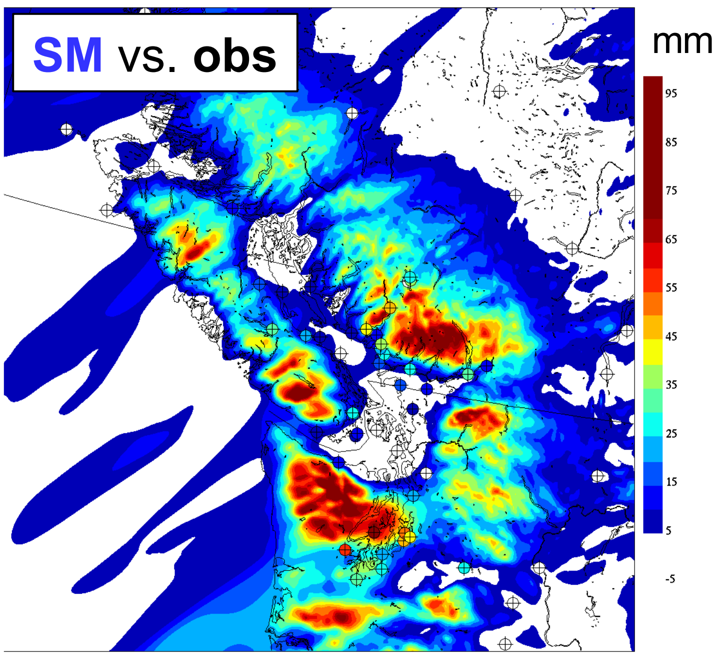


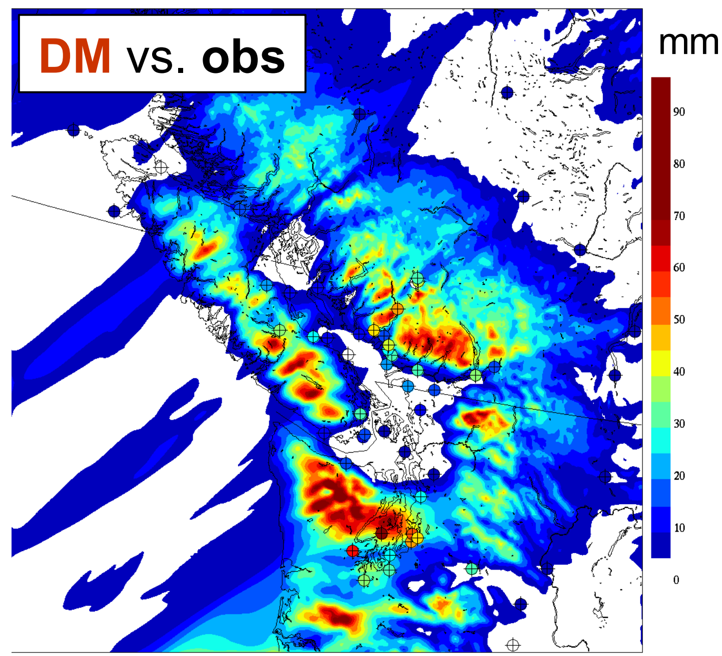
3. Evaluation – Accumulated Precipitation

CASE 4a – 2007-12-03

6-h PR
2.5-km



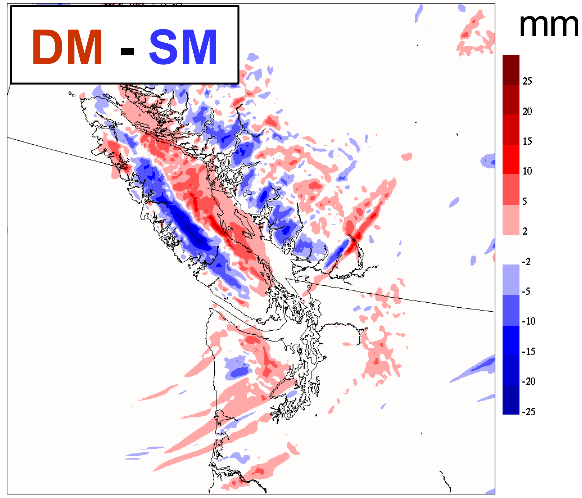


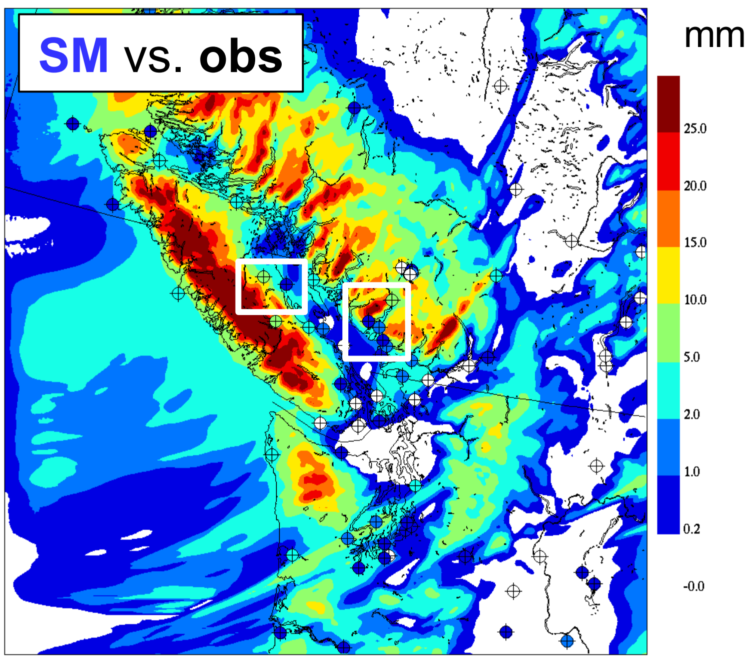


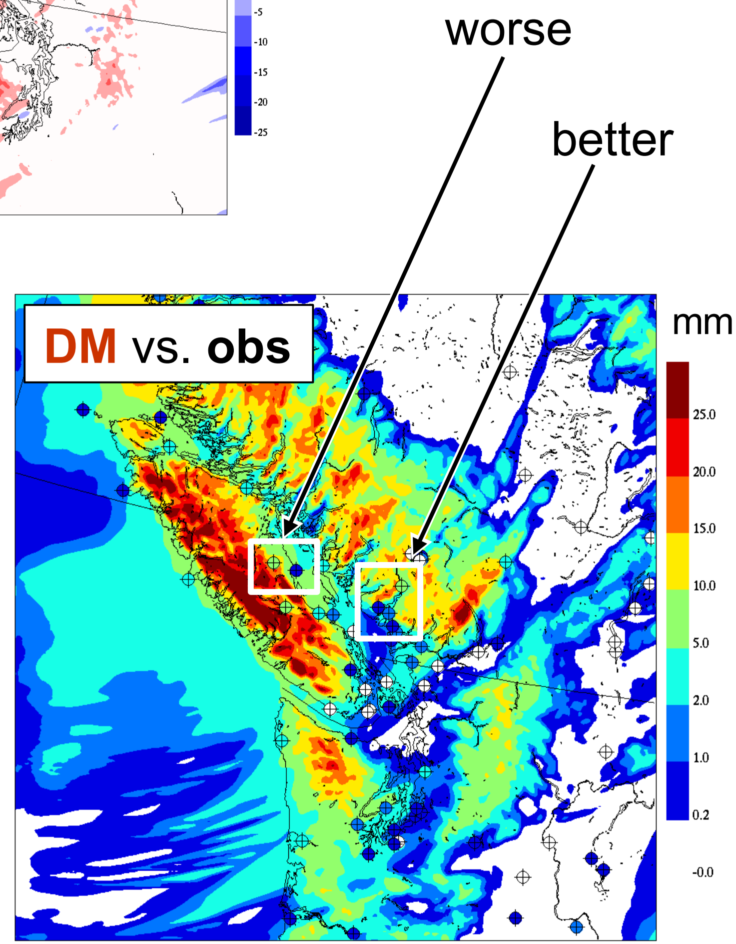
3. Evaluation – Accumulated Precipitation

CASE 7b – 2008-03-11

6-h PR
2.5-km

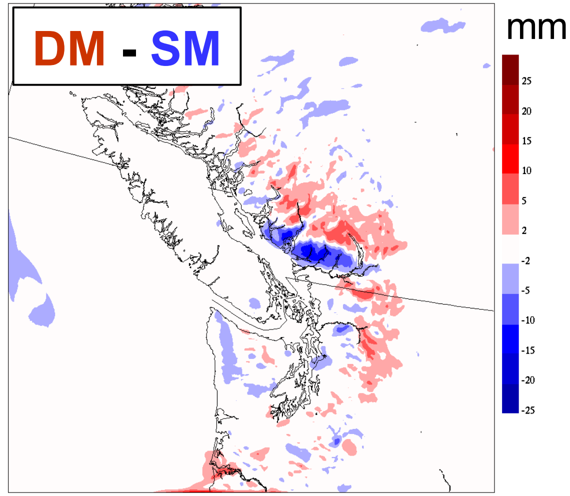




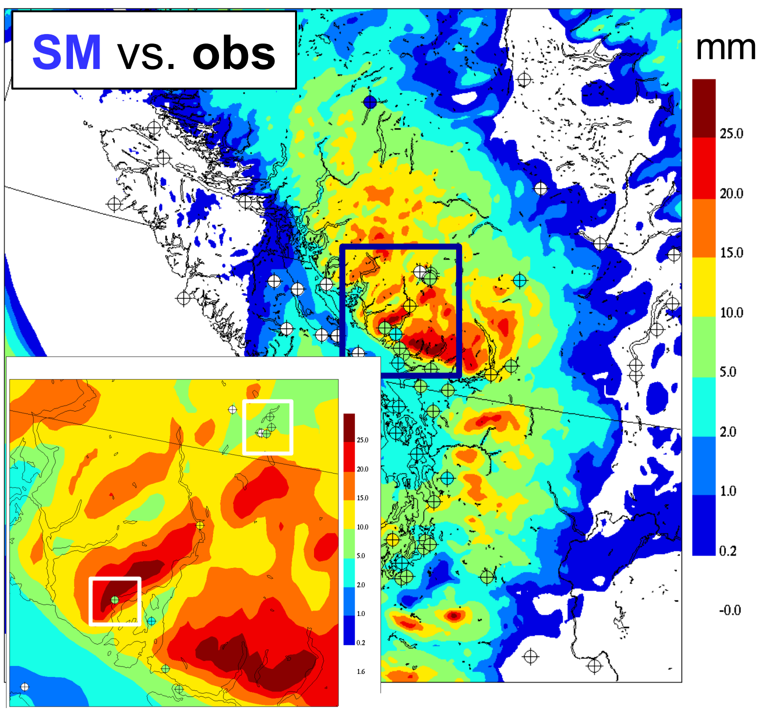


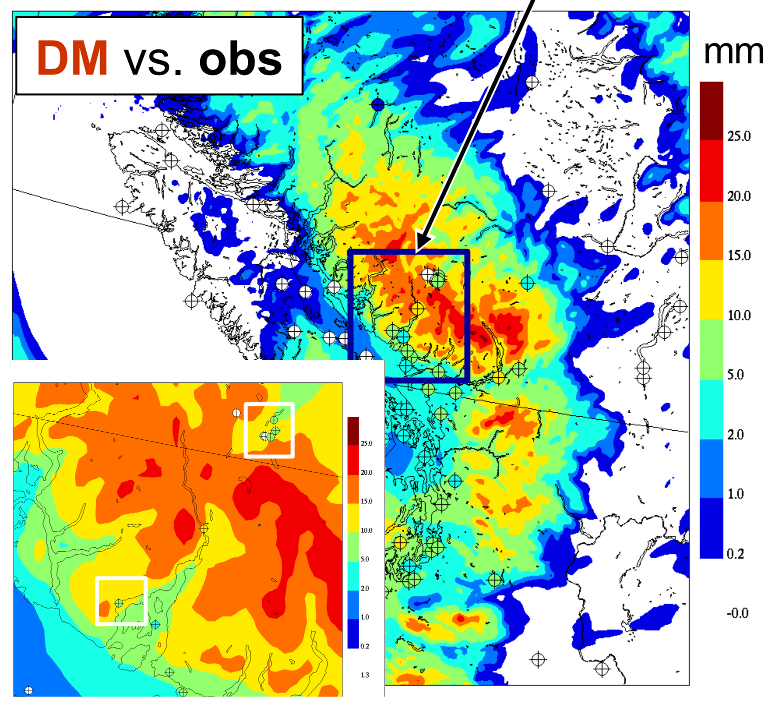
CASE 9a – 2008-03-23

6-h PR
2.5-km

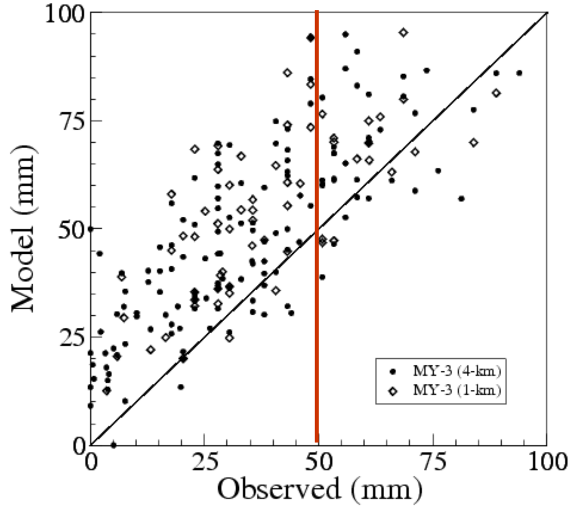


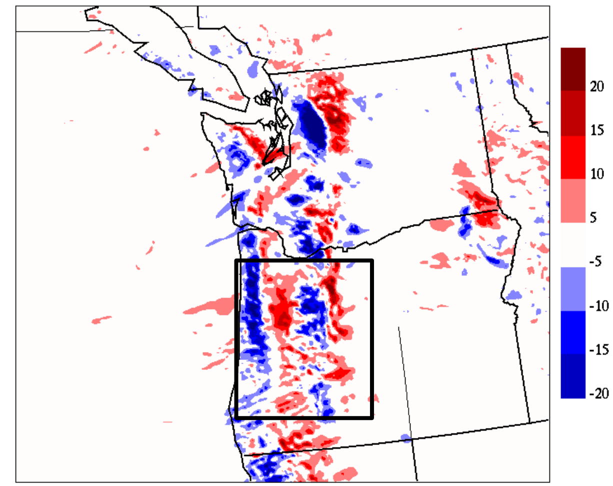
better

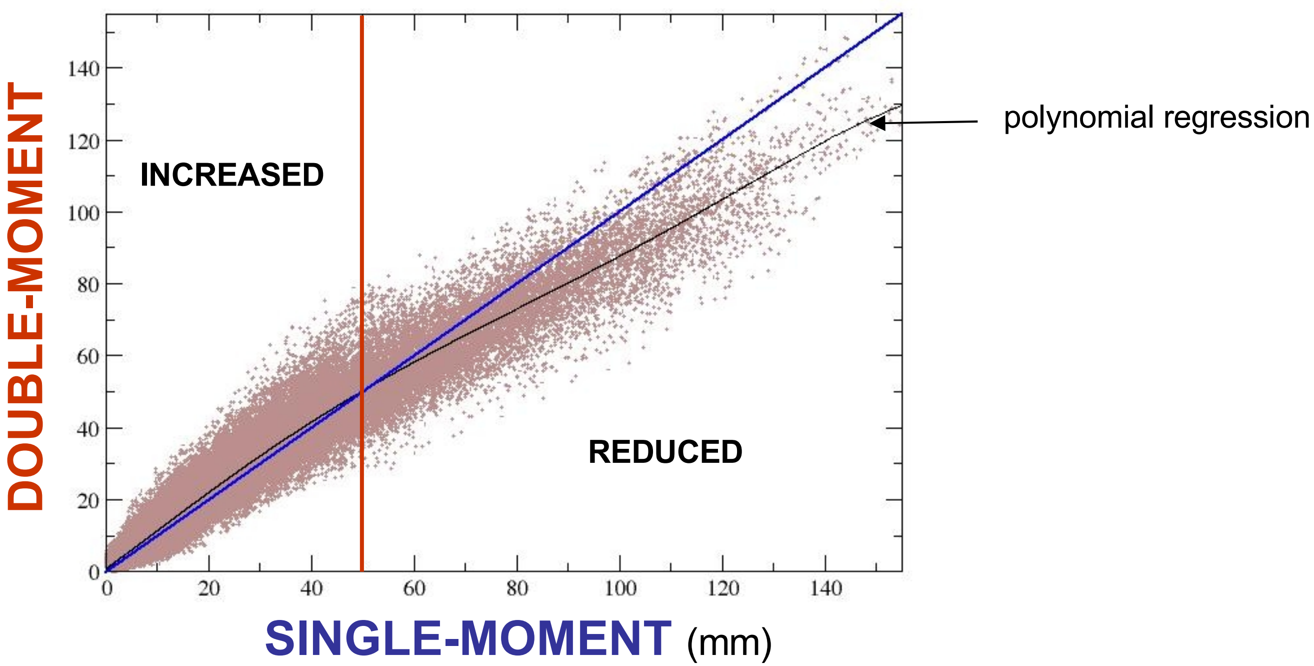




3. Evaluation – Accumulated Precipitation







From 10 Cases, 20 6-h periods, 50-70 obs. points per period:
(1335 gauges vs. model (2.5-km) points)

- **Insufficient data to compute meaningful statistics**
- **Subjective evaluation indicates:**
  - general tendency of reduced QPF (for large amounts)
  - systematic downwind shift in location (along coast and mountains)
  - location of gauges makes evaluation difficult

  → but this appears to be a general improvement (consistent with change in snow-graupel mass balance)

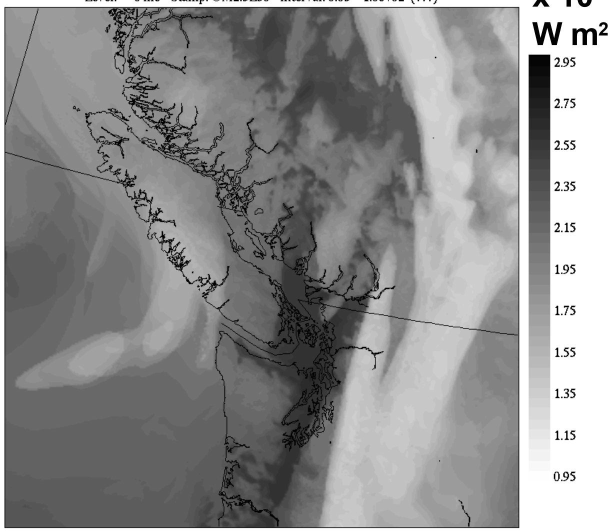
3. Evaluation – Microphysical Fields and Outgoing Longwave Radiation

2.5-km

Single-Moment | **Double-Moment**

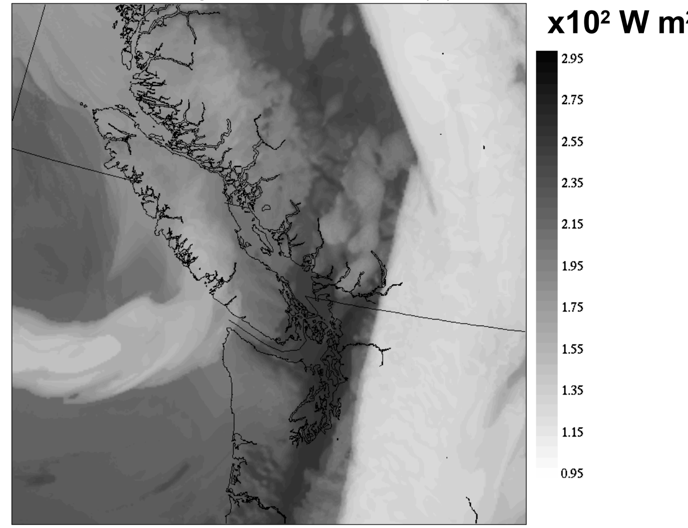
EI:

EI
Level: 0 mb - Stamp: OM2.5L58 - Interval: 0.05 * 1.0e+02 (???)



09 hour fcst valid 05:30Z March 11 2008

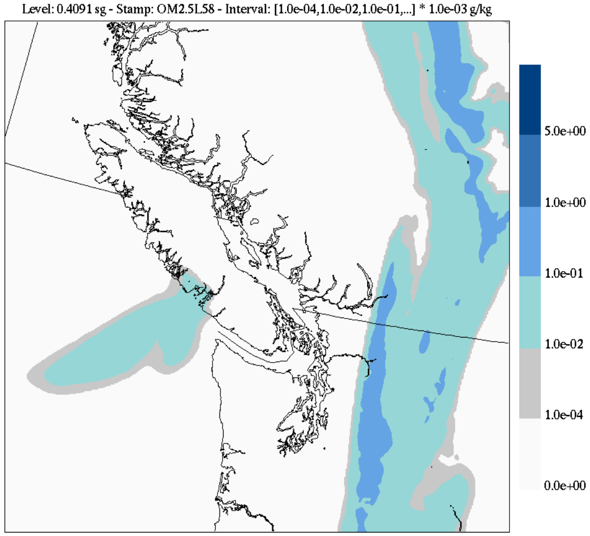
EI
Level: 0 mb - Stamp: OMDBLMM - Interval: 0.05 * 1.0e+02 (???)



09 hour fcst valid 06:00Z March 11 2008

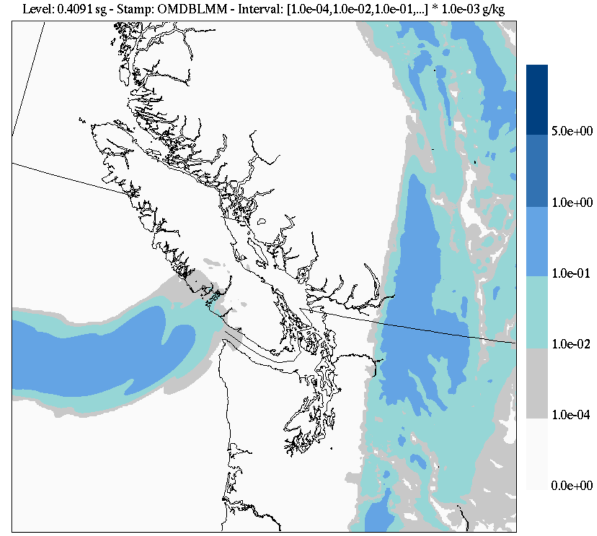
QI:
(0.4091)

Q_i (ICE Mixing Ratio)
Level: 0.4091 sg - Stamp: OM2.5L58 - Interval: [1.0e-04,1.0e-02,1.0e-01,...] * 1.0e-03 g/kg



09 hour fcst valid 06:00Z March 11 2008

Q_i (ICE Mixing Ratio)
Level: 0.4091 sg - Stamp: OMDBLMM - Interval: [1.0e-04,1.0e-02,1.0e-01,...] * 1.0e-03 g/kg

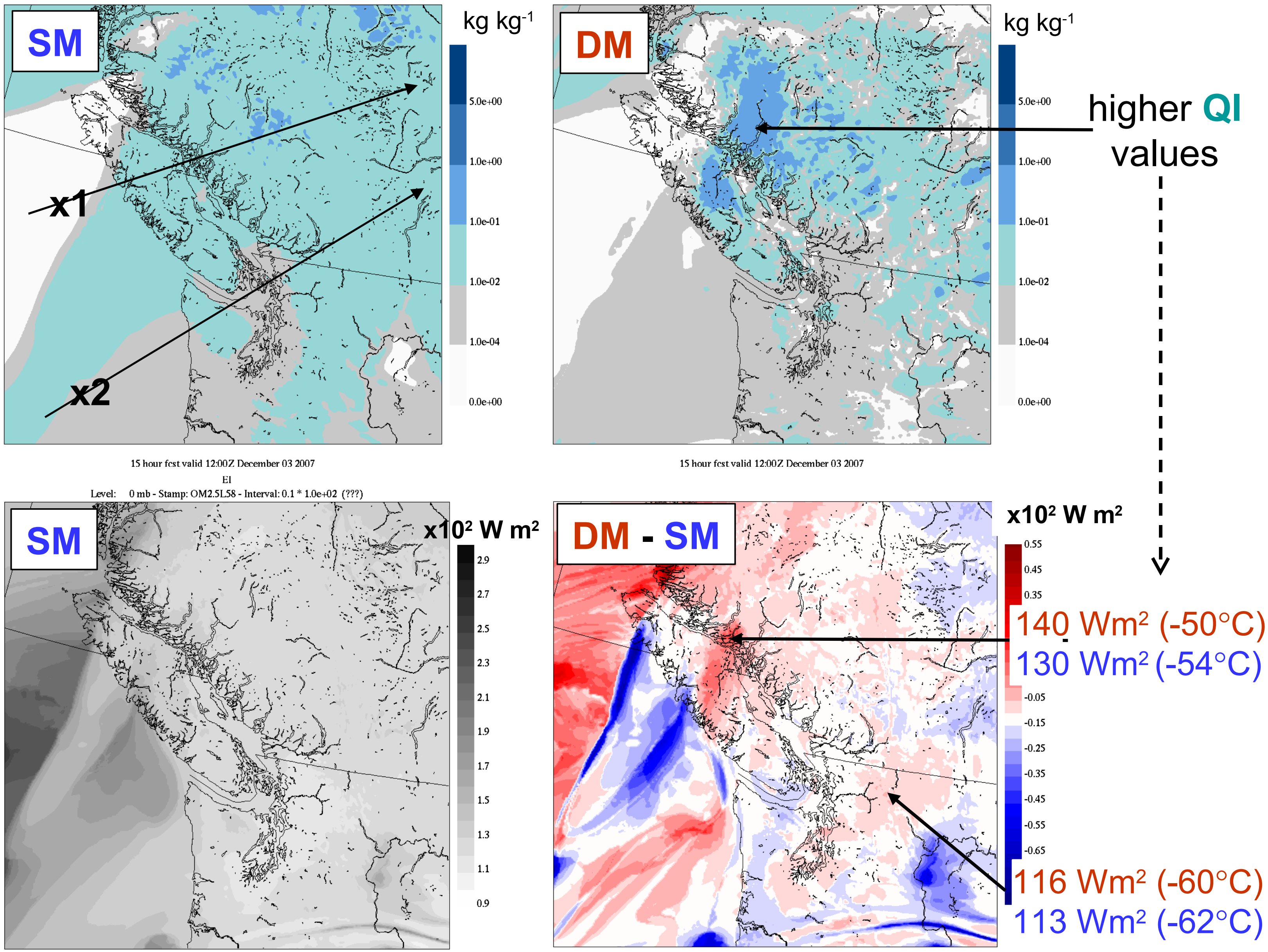


09 hour fcst valid 06:00Z March 11 2008

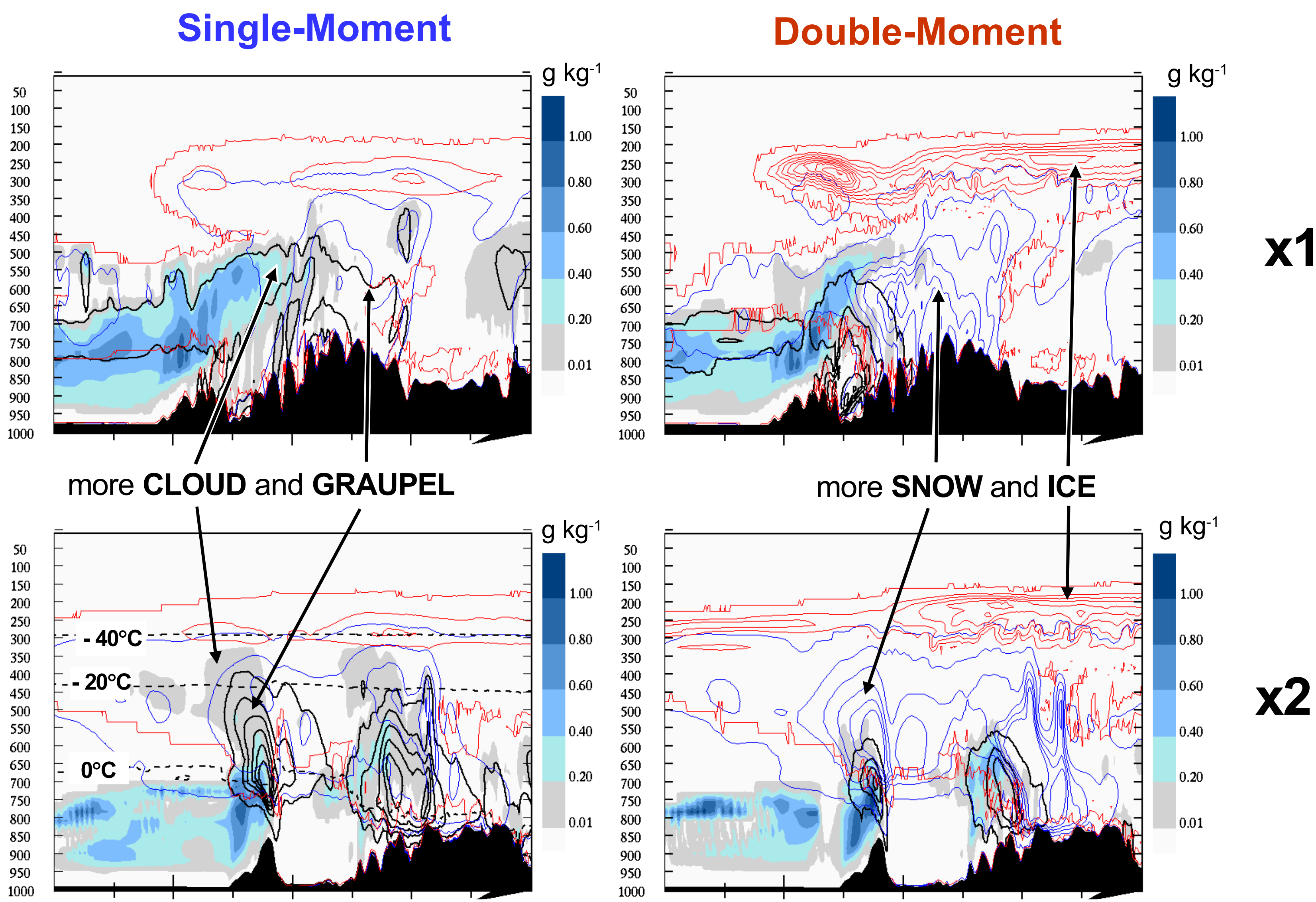
3. Evaluation – Microphysical Fields and Outgoing Longwave Radiation

QI:
(0.4091)

EI:



3. Evaluation – Microphysical Fields and Outgoing Longwave Radiation



QI, QN, QG, *QC*

(QR [and QH] not shown)

OVERALL DIFFERENCES:

- Broader and brighter OLR patterns (in **DM**) associated with larger quantities of upper-level *ICE*
- Improvement in *CLOUD* at high levels (no unrealistic large LWC at very cold temperatures)
- More *ICE* and *SNOW* ↔ less *CLOUD* and *GRAUPEL* (consistent with downwind shift in precipitation)

MORE REALISTIC?

- yes and no (probably more yes than no)
- tunable, given more understanding of biases

3. Evaluation – Near Surface Temperature and Winds

2.5 km

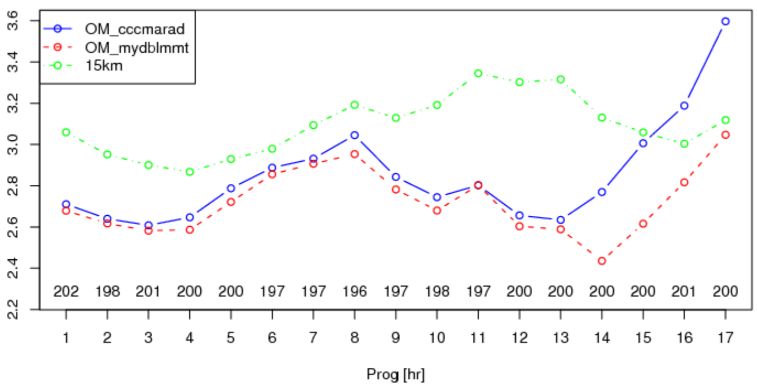
Average of 10 Cases

Temperature (2 m)

Wind Speeds (10 m)

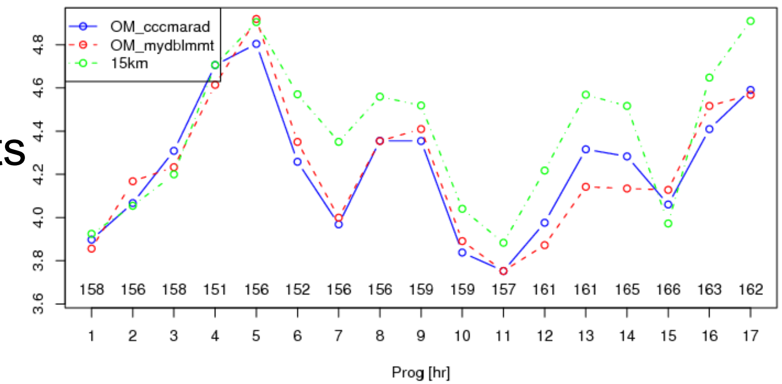
TT_MYDBLMMT_OM all_cases RMS ERROR

°C



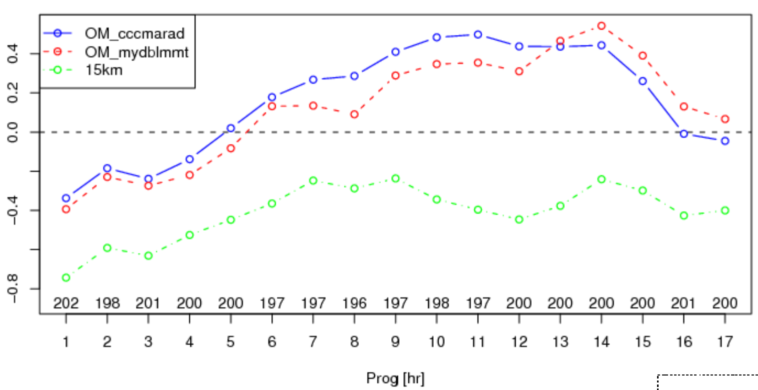
UV_10mMYDBLMMT_OM all_cases RMS ERROR

kts



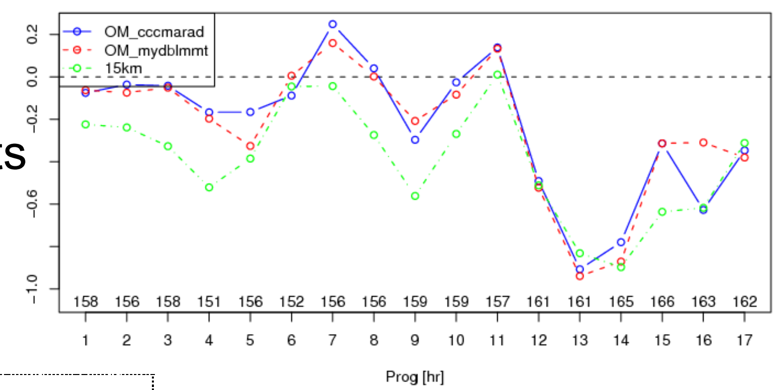
TT_MYDBLMMT_OM all_cases BIAS

°C



UV_10mMYDBLMMT_OM all_cases BIAS

kts



REG-15
Single-Moment
Double-Moment

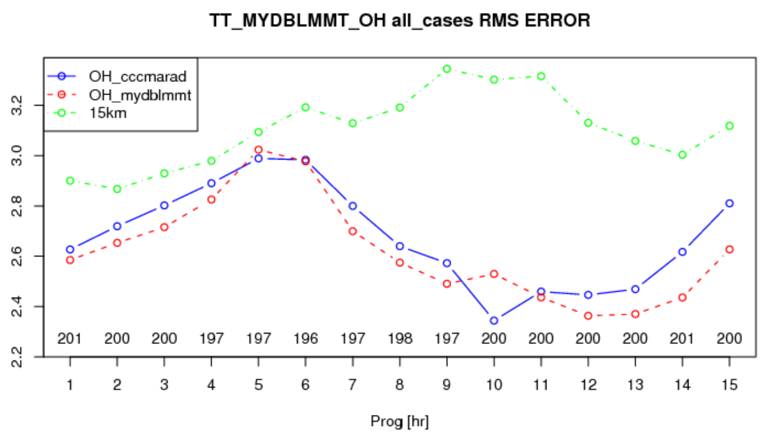
1 km

Average of 10 Cases

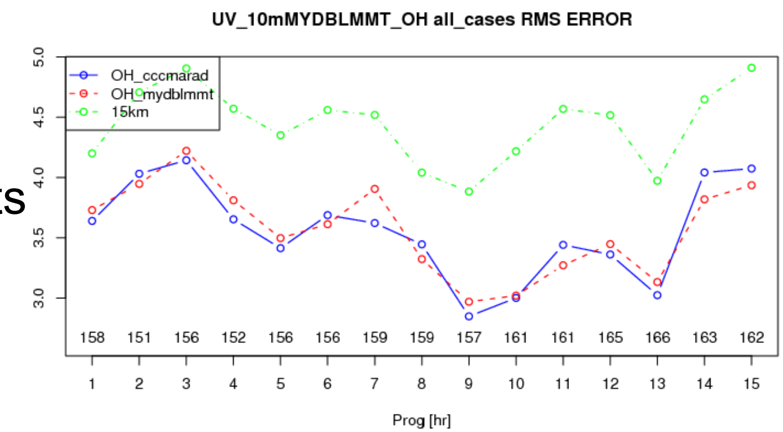
Temperature (2 m)

Wind Speeds (10 m)

°C

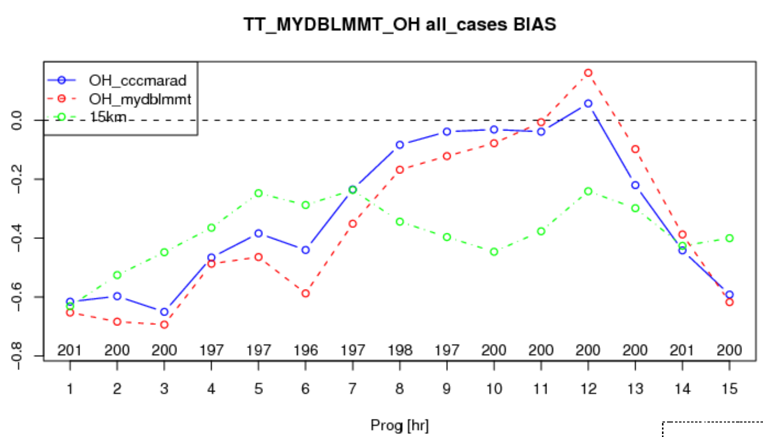


kts

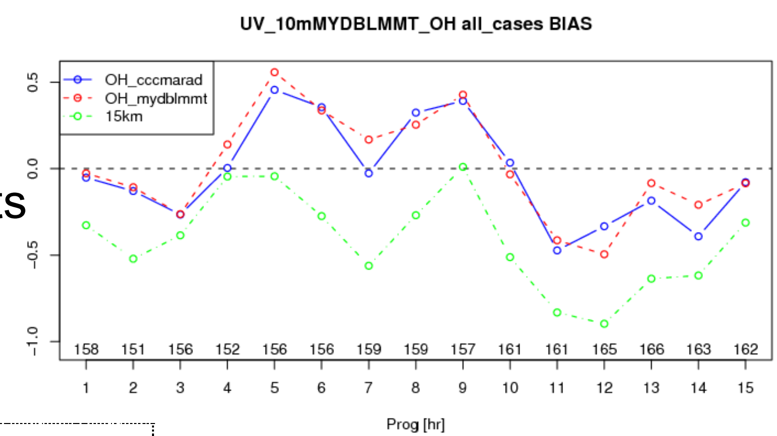


RMS

°C



kts



BIAS

REG-15
Single-Moment
Double-Moment

Computational Cost:

10% additional total CPU time

With Double-Moment vs. Single-Moment

(ave. of 10 runs)

4. Current and Upcoming Research

1. Snow Density

- Collaboration with Severe Weather National Laboratory (Denis Jacob)
- Verification against observations (regular GEM-LAM-2.5 grids)
- Comparison to other techniques (e.g. Dubé method)

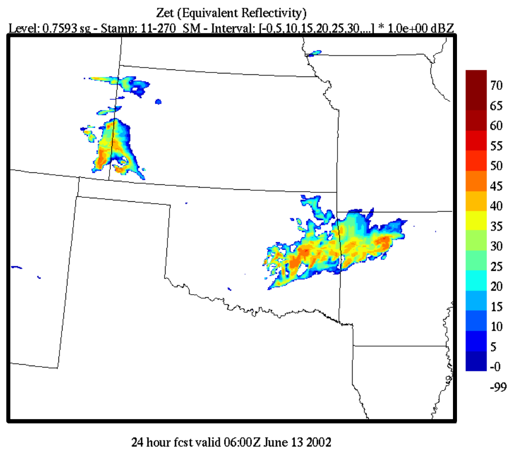
2. Summer Convection

- Comparative study (against other microphysics schemes) on the ability to simulate the **cold pool** in a mid-latitude squall line

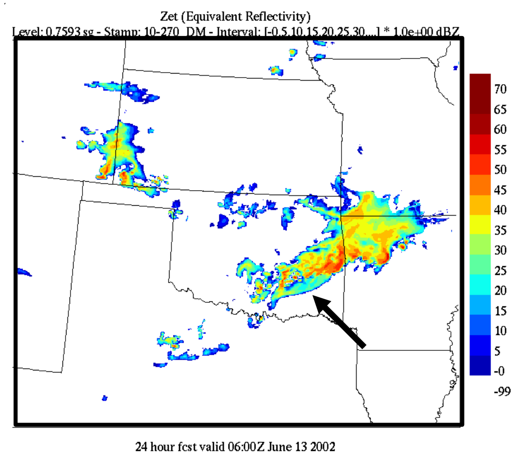
WMO 2008 International Cloud Modeling Workshop CASE 3:

Reflectivity at 2 km AGL, 0600 UTC 13 June 2002 (36-h fcst)

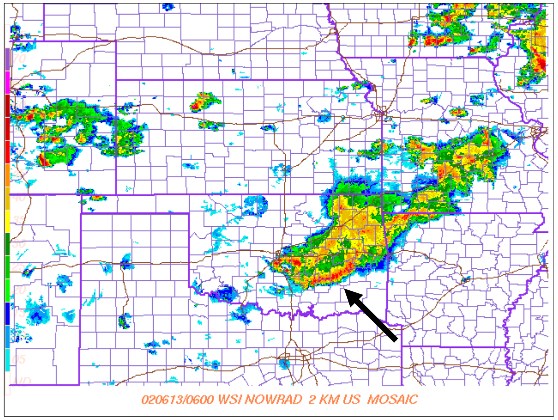
SINGLE-Moment



DOUBLE-Moment



WSI RADAR

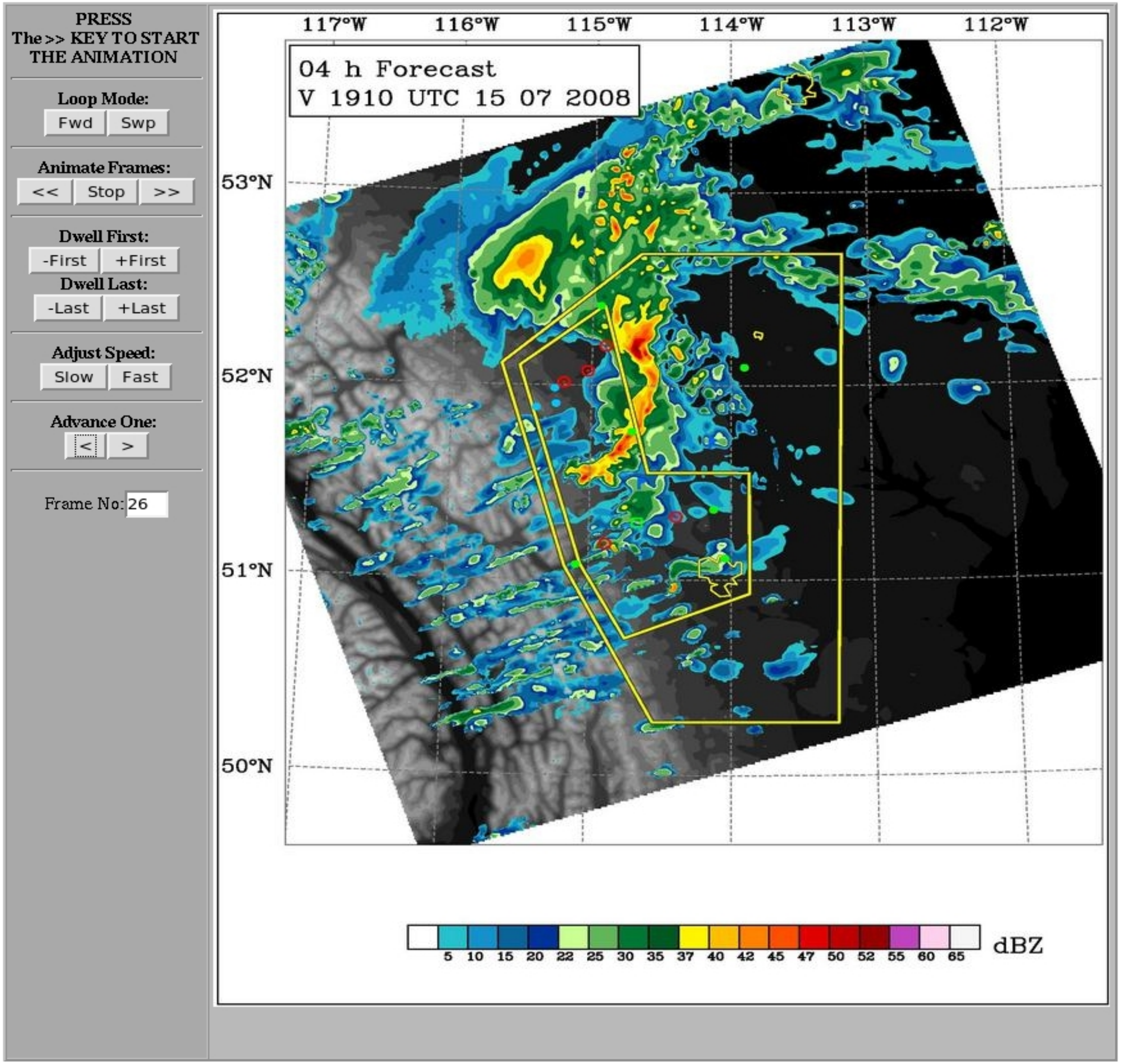


2.5-km GEM-LAM simulations

- Initialized from 0000 UTC 12 June 2002 CMC analysis
- operational “regional” configuration (global-variable, Δx ~ 15-km over North America)
- Nested to $\boldsymbol{\Delta x}$ **~ 2.5-km** grid at 1200 UTC (using Milbrandt-Yau cloud scheme)

2. Summer Convection

- Comparative study (against other microphysics schemes) on the ability to simulate the cold pool in a mid-latitude squall line
- Performance of double-moment scheme for UNSTABLE



Website snapshot for GEM-LAM-1km run (using double-moment M-Y)

2. Summer Convection

- Comparative study (against other microphysics schemes) on the ability to simulate the cold pool in a mid-latitude squall line
- Performance of double-moment scheme for UNSTABLE
  a) 3 months of summer 2008 runs (archived)
  b) 8 cases during IOP to be examined in detail

3. **Large-scale** ($\Delta x \geq 10$ km) **version of M-Y scheme**

- Introduction of subgrid-scale **cloud fraction**

  → for application in GEM-REG or meso-Global configurations

- Proper interaction of double-moment variables with radiation scheme (Polar-GEM, **Frederick Chosson**)

4. Other research projects (using M-Y scheme)

- **Xue / Dawson** – University of Oklahoma: using triple-moment scheme to simulate tornadic supercells
- **Benoit / Gayraud** – Université de Montréal: using double-moment (v5) scheme to simulate icing events in Gaspé region
- **Yau / Naishi** – McGill University: using multi-moment scheme to simulate squall lines
- **etc.**

CONCLUSION

- The double-moment version of the M-Y scheme has been further optimized and developed, with emphasis on improving the *snow* category
- Several new fields are now available, including a prognostic snow density (giving an instantaneous solid-to-liquid ratio)
- Comparison to single-moment runs for 10 winter cases on the new VO2010 high-res forecast system reveal systematic differences in the new double-moment version
  - Increased *ice* and *snow* and reduced *cloud* and *graupel* masses
  - corresponding downwind shift in the location of precipitation

CONCLUSION

The improvements to the proposed double-moment scheme are scientifically valid

While objective verification of high-resolution models remains difficult, our subjective evaluation indicates an overall improvement

MERCI

Environment Canada Environnement Canada

Canada