Uncertainty in model representations of microphysics…

…or: *Airing the dirty laundry of microphysics schemes*

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Thanks to: Marcus van Lier-Walqui, Wojciech Grabowski

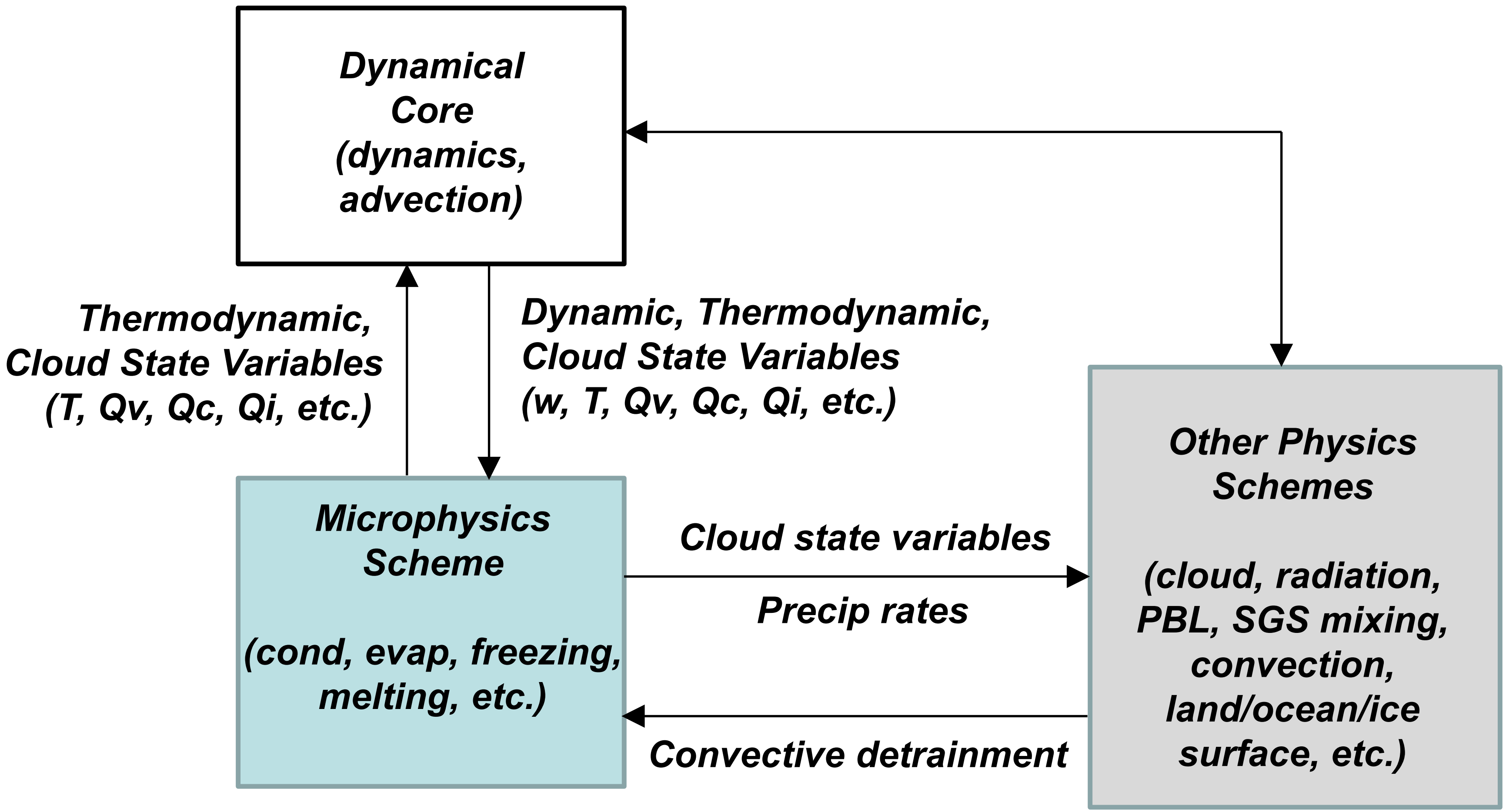
OU/CIMMS Workshop on Uncertainty in Radar Retrievals, Model Parameterizations, Assimilated Data and In-situ Observations: Implications for the Predictability of Weather

NCAR
NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

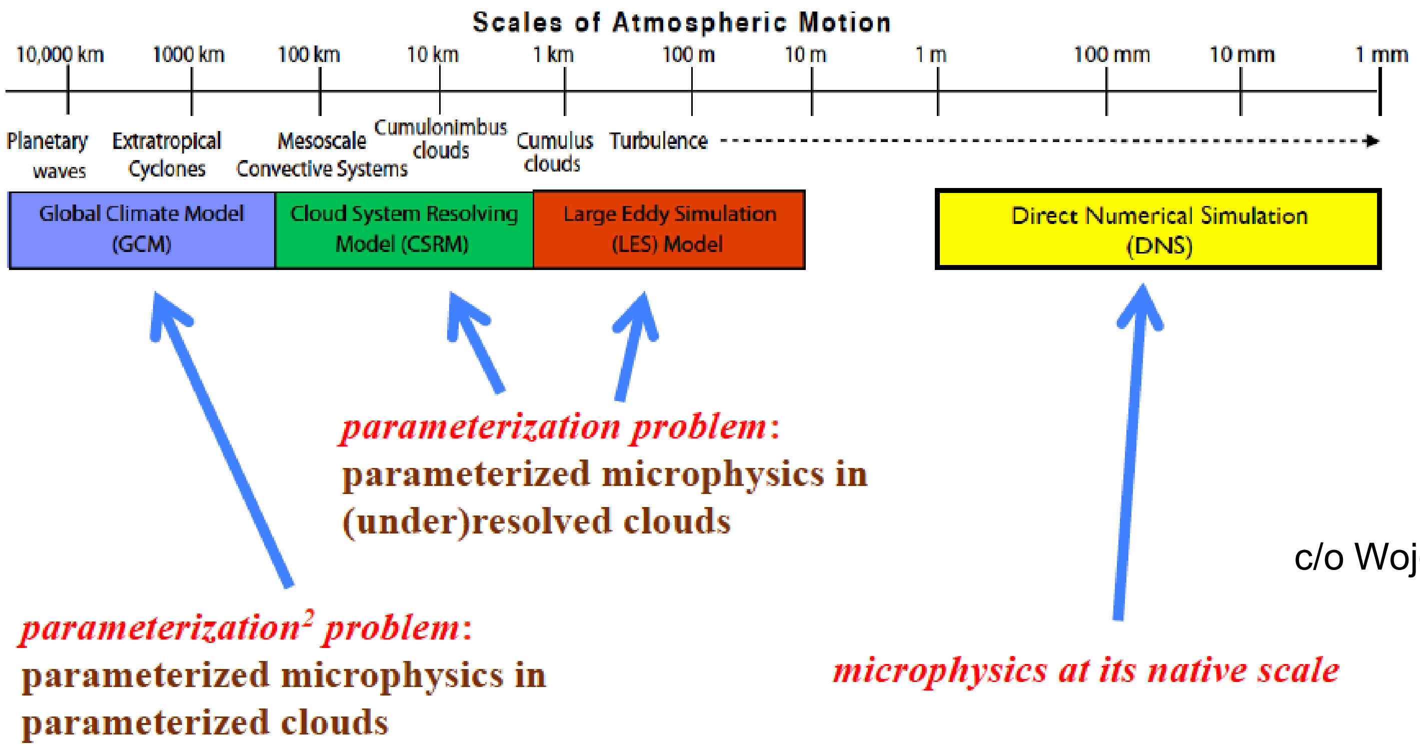
October 31, 2018

NSF

Microphysics parameterization schemes in cloud, weather, and climate models



The parameterization problem:



c/o Wojciech Grabowski

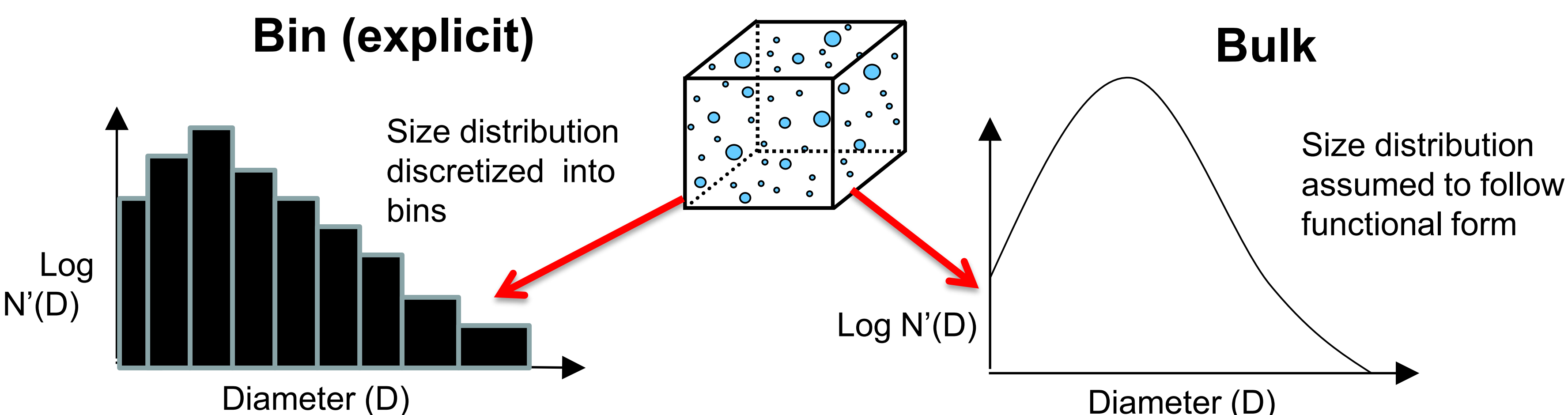
There are *two* critical aspects for microphysics:

- ***<u>Inability to resolve relevant scales</u> (i.e., the traditional "parameterization problem" in models)***
- ***<u>Uncertainty in microphysics at its native scale</u> (e.g., drop breakup or ice crystal growth rates)***

A (very) brief history of cloud microphysics schemes…

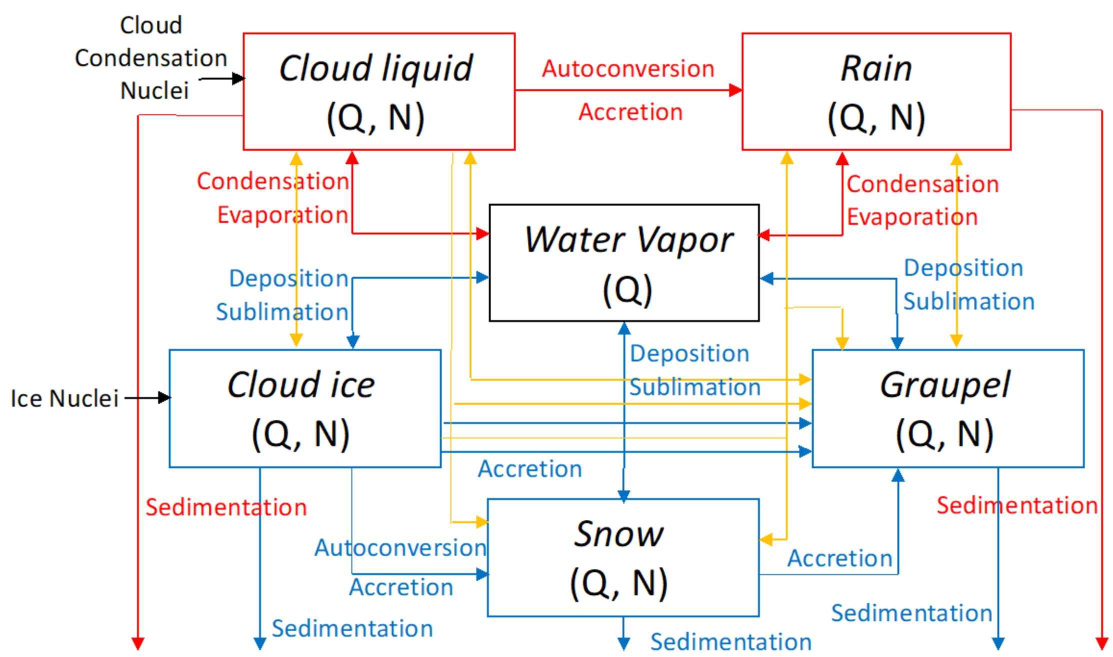
- **Bulk schemes → 1960's to present**
  - **1970's-1980's…** ***inclusion of ice microphysics***
  - **1980's-2000's…** ***2-moment schemes***
  - **2000's-2010's…** ***3-moment schemes***
  - **2000's-2010's….** ***ice particle property based schemes***

- **Bin schemes → 1960's to present**
  - **1980's-2000's…** ***inclusion of ice microphysics***
  - **1980's-2000's…** ***multi-moment (in each bin) schemes***
  - **2000's-2010's….** ***multi-dimensional (in bin space)***



Bulk schemes remain the workhorses of weather and climate models because they are simple and cheap. Lots of complexity has been added in recent years (e.g., 1-moment to 2-moment schemes…).

State-of-the-art 2-moment scheme



Added complexity (more detailed process formulations, more moments, more prognostic variables) means more degrees of freedom and (presumably) better realism in representing cloud evolution. *Has this actually resulted in better forecasts?*

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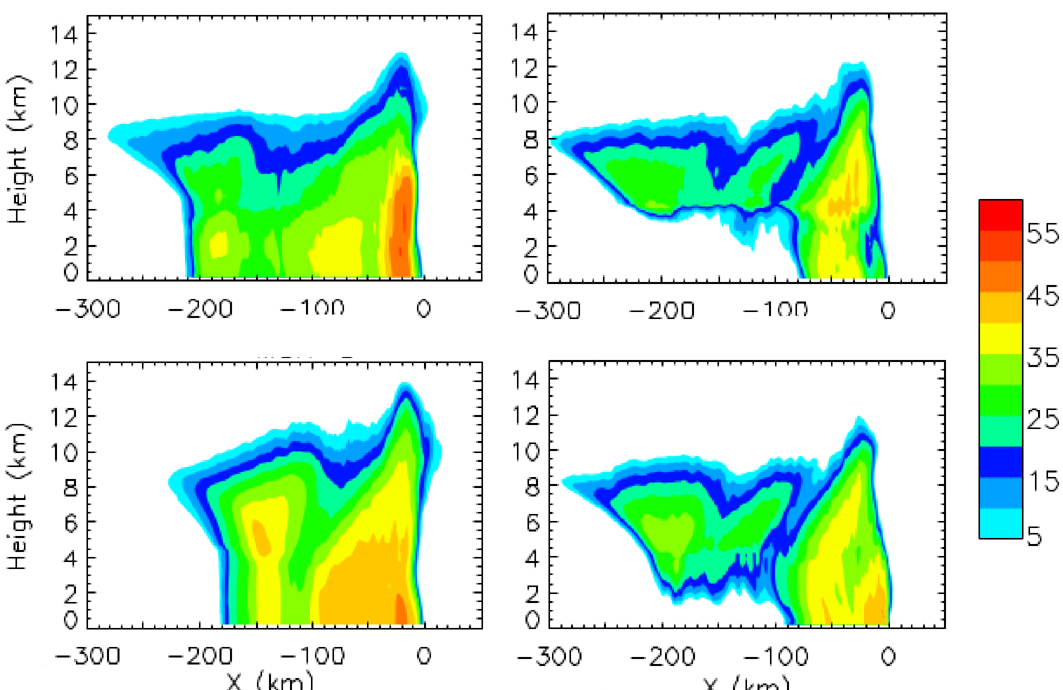
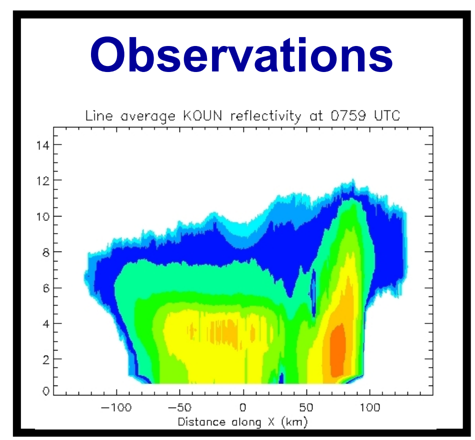
Moreover, <u>solution spread</u> generally is *not* reduced by adding complexity.



WRF squall line simulations of June 20, 2007 OK case.

Morrison et al. (2015), *JAS*



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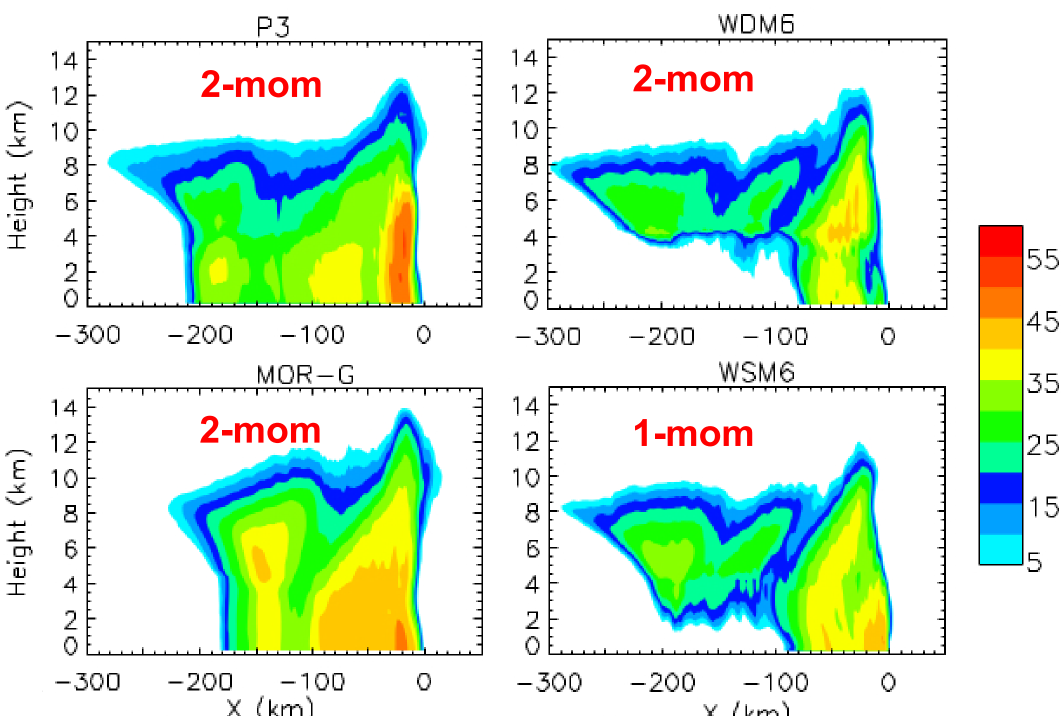

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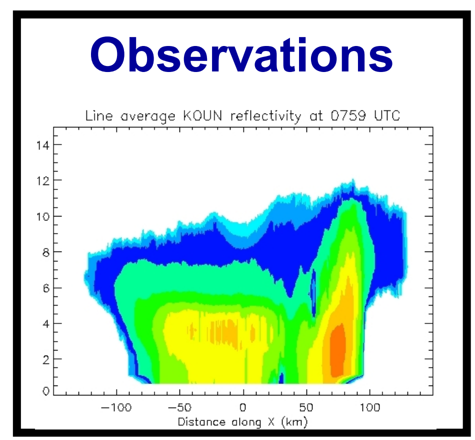


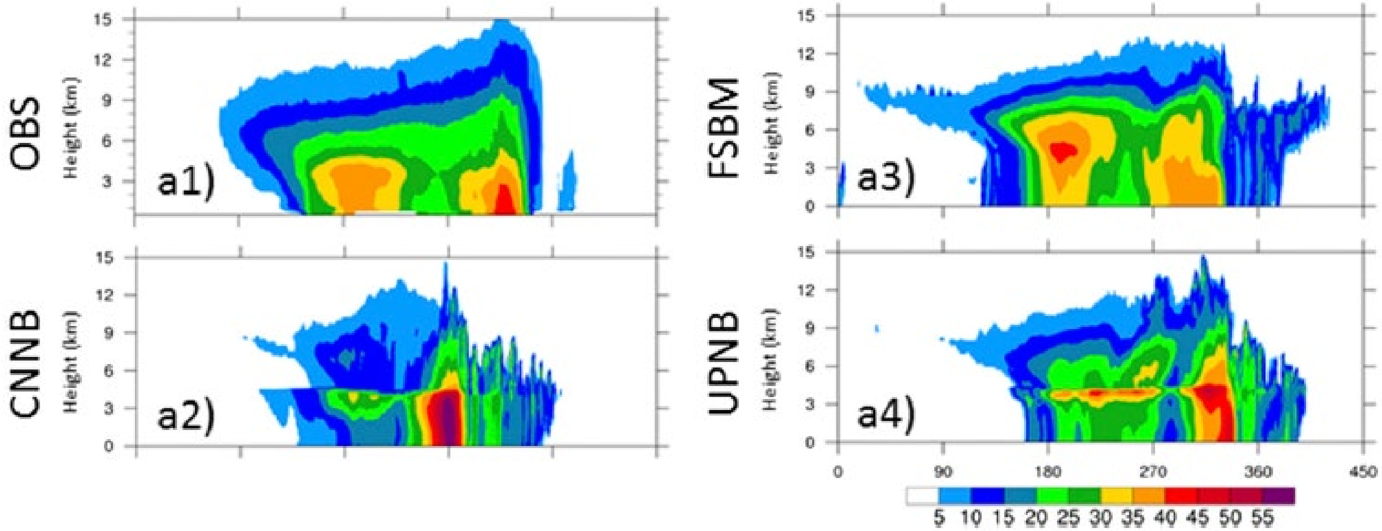
Bin schemes are expensive but widely used now as computer power keeps increasing.

- **Process level microphysical studies**
- **Developing/testing bulk schemes**

Have a more detailed representation of process rates than bulk schemes, but face challenges (*Grabowski et al. 2018, BAMS in review*):

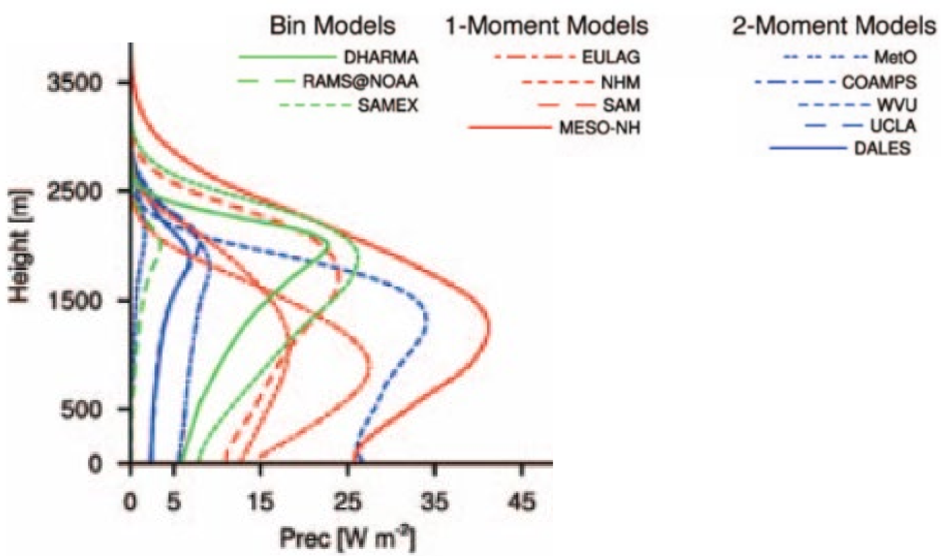
- **Drop size distribution broadening may often be dominated by *unphysical* vertical numerical diffusion.**
- **Impact of statistical fluctuations on collision-coalescence neglected.**
- **Expensive to add rigorous treatment of *N* particle properties (scales as number of bins to power of *N*).**
- **Doesn't address *fundamental process rate uncertainty*.**

There is NOT better convergence using different bin schemes compared to bulk schemes…



Intercomparison of bin microphysics schemes in WRF

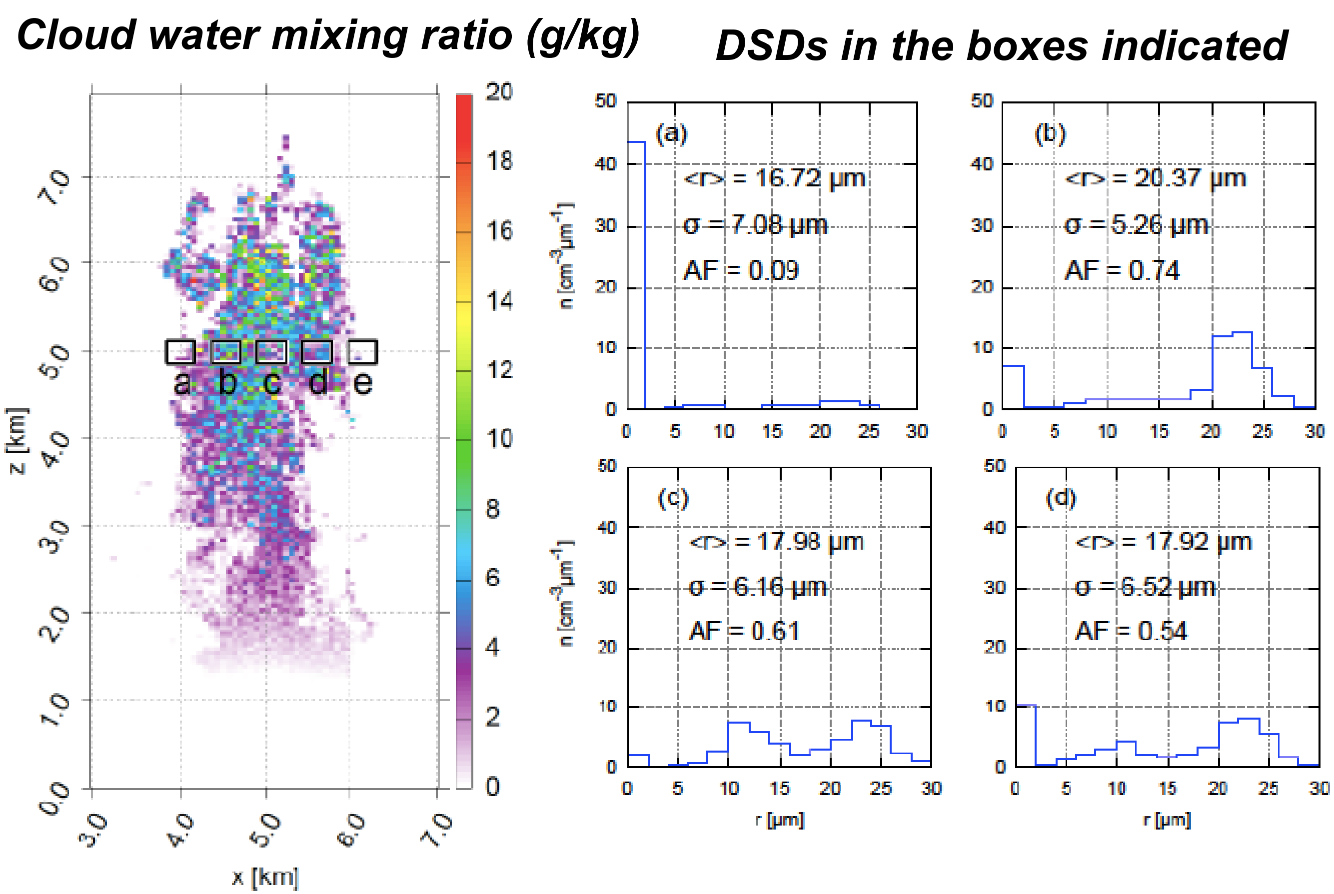
Xue et al. (2017), *MWR*



Intercomparison of LES of shallow precipitating convection from RICO

vanZanten et al. (2011), *JAMES*

<u>Lagrangian particle-based schemes</u> (e.g., *super-droplet method*) address many difficulties facing bin schemes.



Shallow cumulus simulations using the University of Warsaw Lagrangian Cloud Model (led by Dziekan, Pawlowska)

Grabowski et al. (2018), *in review, BAMS*

However, there is *still fundamental process rate uncertainty*.

Where things stand…

- **There is a constant march toward <u>increasing complexity</u> of schemes.**

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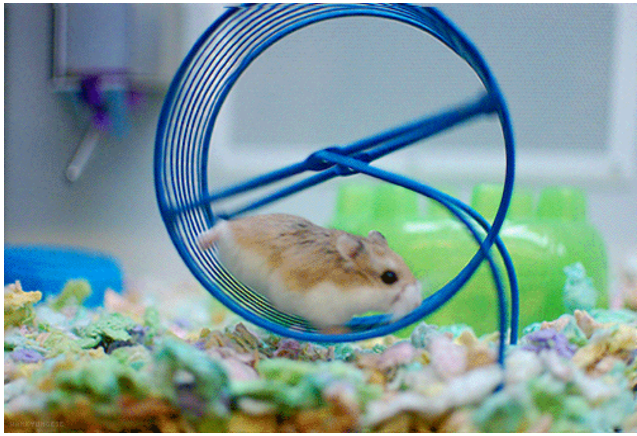
- There is a constant march toward <u>increasing complexity</u> of schemes.

- Progress has been made over the decades, but fundamentally microphysics is ***<u>highly uncertain</u>*** and will remain so into the foreseeable future:

  → We have poor understanding of the underlying physics, especially for ice microphysics, and thus ***<u>no benchmark</u>***!
  (this is fundamentally different from dynamics, turbulence, and radiation but perhaps similar to e.g. land surface processes…)

  → Thus, there is generally NOT convergence using different schemes as schemes become more complex…



A microphysics scheme developer?

As a community, we as microphysics scheme developers have *not* adequately confronted this uncertainty!

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On the other hand, we now have a wealth of cloud/precip <u>observations</u> for constraining schemes…

Ground-based remote sensing

Aircraft in-situ

Surface in-situ (e.g. disdrometer)

Satellite

Etc.

...

The BIG question:

How **to use these observations to constrain schemes?**

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- **Very challenging because we generally cannot measure microphysical processes directly, only their net effects on clouds and precipitation.**

- **As more complex schemes are developed this makes constraint with observations even more difficult!**

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- **Continue developing better process models (e.g. *Lagrangian particle based schemes*) and constraining process rates (e.g. *lab studies*).**

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- **Focus on the role of microphysics uncertainty, and leverage this to develop novel approaches that facilitate constraint by observations (e.g., statistical-physical schemes).**

Some ideas for moving forward…

- **Continue developing better process models (e.g. *Lagrangian particle based schemes*) and constraining process rates (e.g. *lab studies*).**

- **Focus on the role of microphysics uncertainty, and leverage this to develop novel approaches that facilitate constraint by observations (e.g., statistical-physical schemes).**

Simply stated: we want to incorporate (somewhat uncertain) observations into uncertain models in a rigorous way, and quantify model uncertainty.

→ *this is a Bayesian problem, and we can therefore use Bayesian statistics to address it rigorously…*

Example: A *statistical-physical* microphysics parameterization framework (BOSS):

B*ayesian* **(we treat uncertainty robustly)**

O*bservationally-constrained* **(scheme is rigorously informed by observations using MCMC)**

S*tatistical-physical* **(we don't want just a statistical scheme or rely solely on standard machine learning, but we will use statistics and automated learning)**

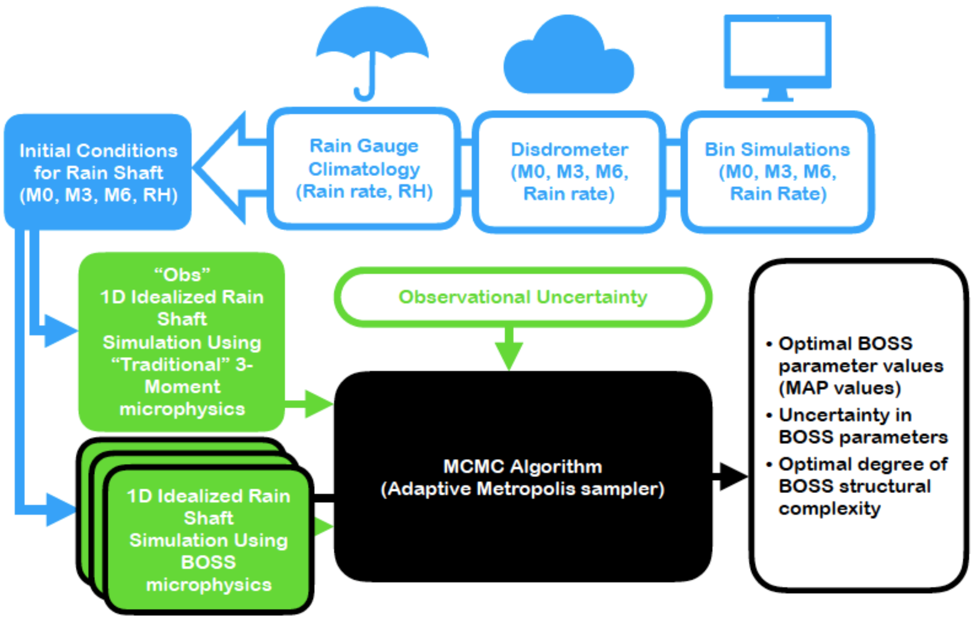
S*cheme* **(bulk microphysics parameterization scheme, currently warm cloud-rain only)**

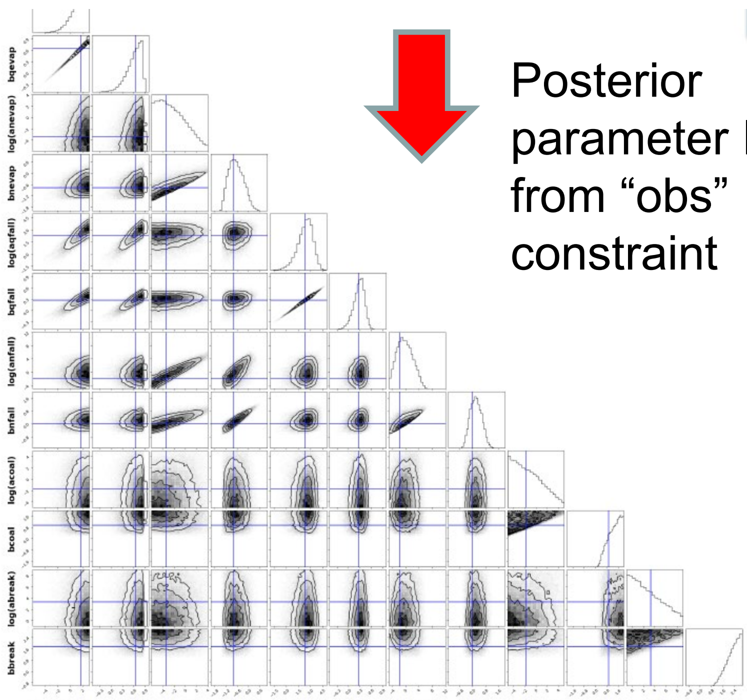
Morrison et al., in prep. (scheme description)
van Lier-Walqui et al., in prep. (application of MCMC)

BOSS

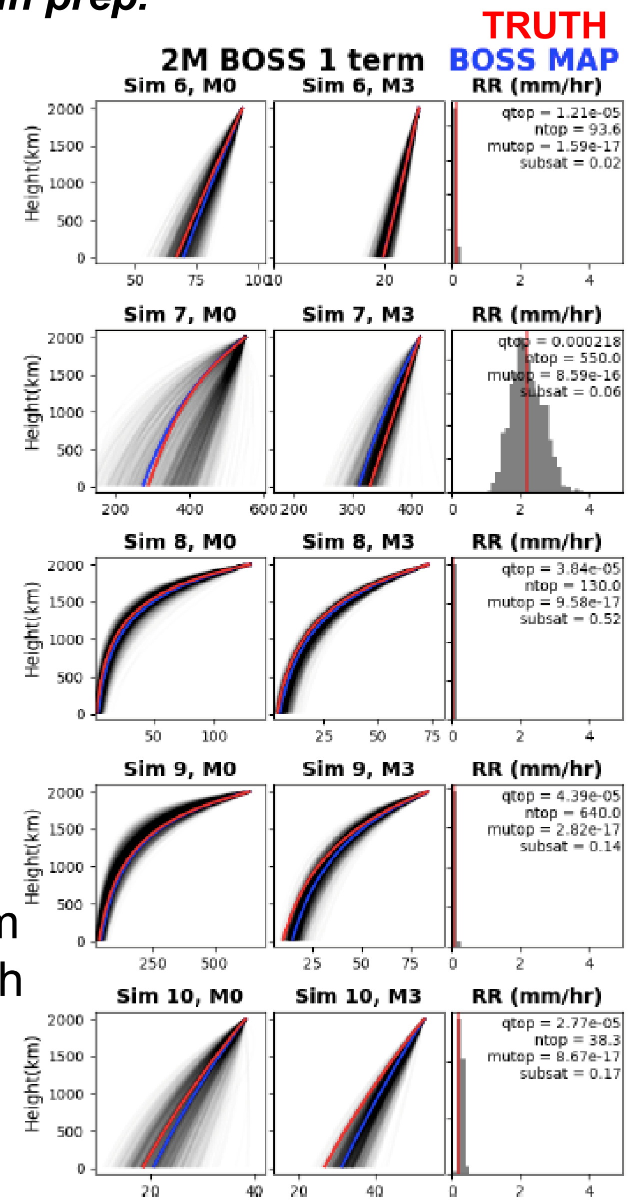
van Lier-Walqui et al., in prep.

BOSS schematic





Posterior parameter PDFs from "obs" constraint



Forward simulated from joint PDFs with independent randomly selected IC's

Concluding Remarks

- **The parameterization of microphysics is currently dominated by *uncertainty*, and will be into the foreseeable future → *no benchmark!!!***

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Concluding Remarks

- **The parameterization of microphysics is currently dominated by *uncertainty*, and will be into the foreseeable future → *no benchmark!!!***

  → Reducing uncertainty will require continued advances in *observing* clouds and precip (including lab studies)

  → Confronting uncertainty may also require a re-thinking of *scheme design*:

  - ***simplification*, reducing the number of poorly constrained parameters, i.e., the level of complexity should match our fundamental knowledge of the physics and our ability to inform schemes with observations**

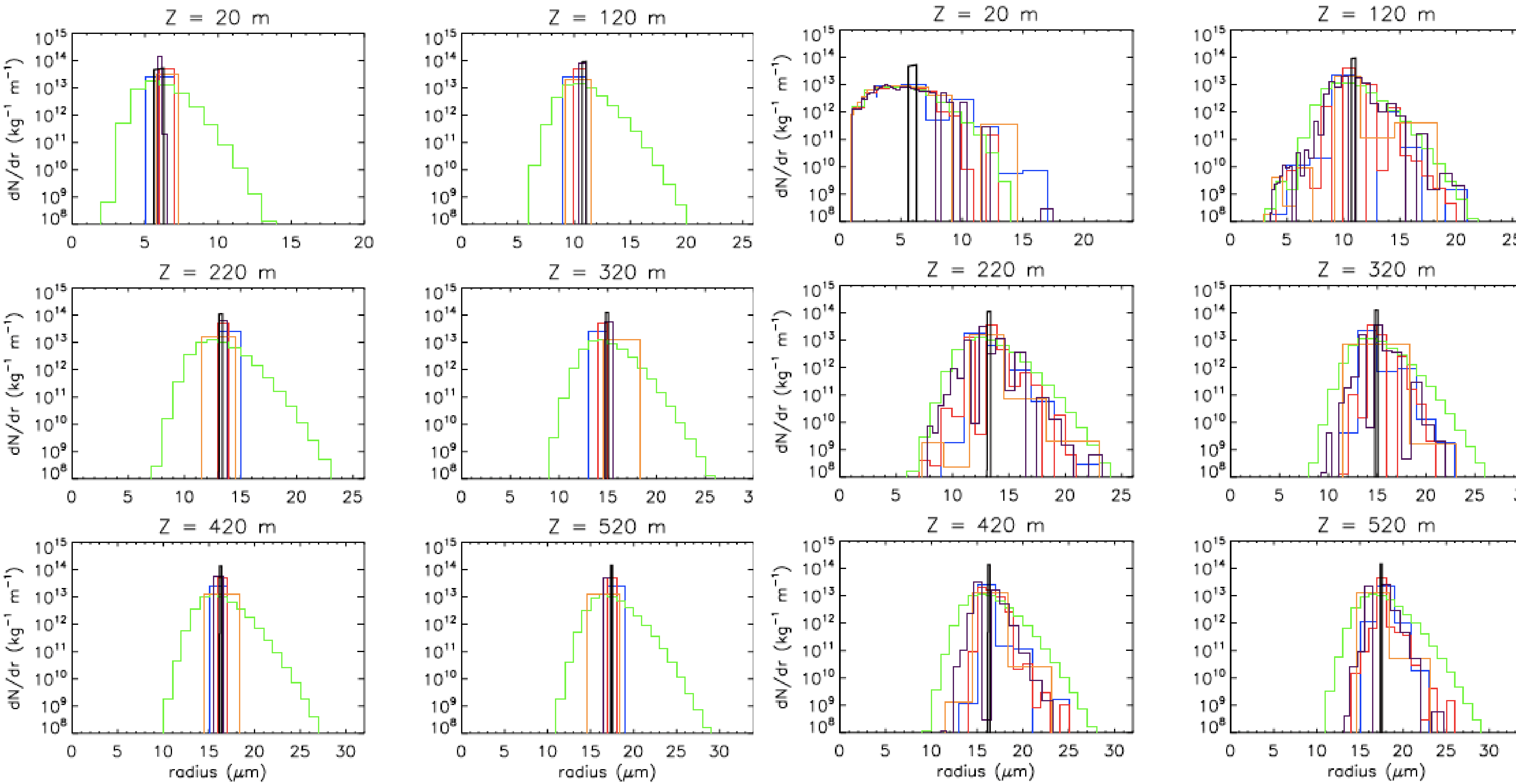
  - ***statistical methods* and *automated learning* to rigorously constrain schemes using observations and to characterize uncertainty (e.g., BOSS)**

Thank you!
Questions?

Unphysical size distribution broadening from <u>vertical numerical diffusion</u> may often dominate bin model solutions!

Morrison et al. (2018), in press JAS

Parcel **1D**

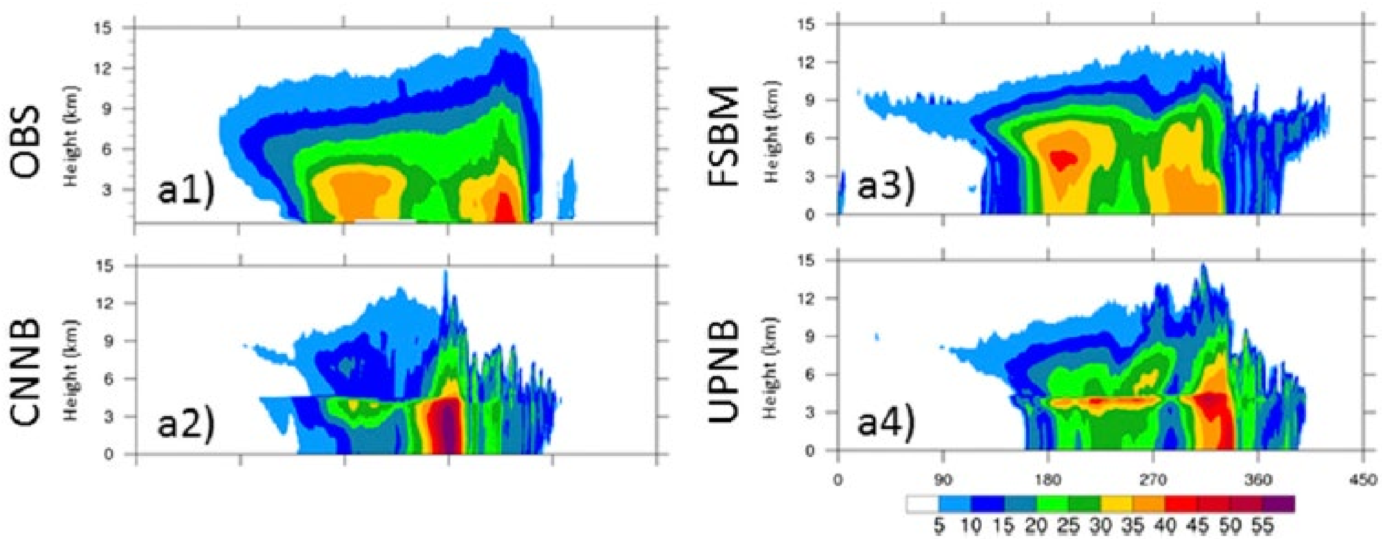


The role of uncertainty in microphysics schemes

- **Fundamentally, microphysics is *highly uncertain* and will remain so into the foreseeable future:**

  → We have poor understanding of the underlying physics, especially for ice microphysics, and thus *no benchmark*!
  (this is fundamentally different from dynamics, turbulence, radiation but perhaps similar to e.g. land surface processes…)

  → There is NOT convergence using different schemes as schemes become more complex…



Intercomparison of bin microphysics schemes in WRF

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The BIG question:

How to use these observations to constrain schemes?

- **Very <u>challenging</u> because we generally cannot measure microphysical processes directly, only their net effects on clouds and precipitation.**

- **As more complex schemes are developed this makes constraint with observations even more difficult!**

Simply stated: we want to incorporate (somewhat uncertain) observations into uncertain models in a <u>rigorous</u> way.

→ this is a <u>Bayesian</u> problem, and we can therefore use Bayesian statistics to address it rigorously…

Some potential applications:

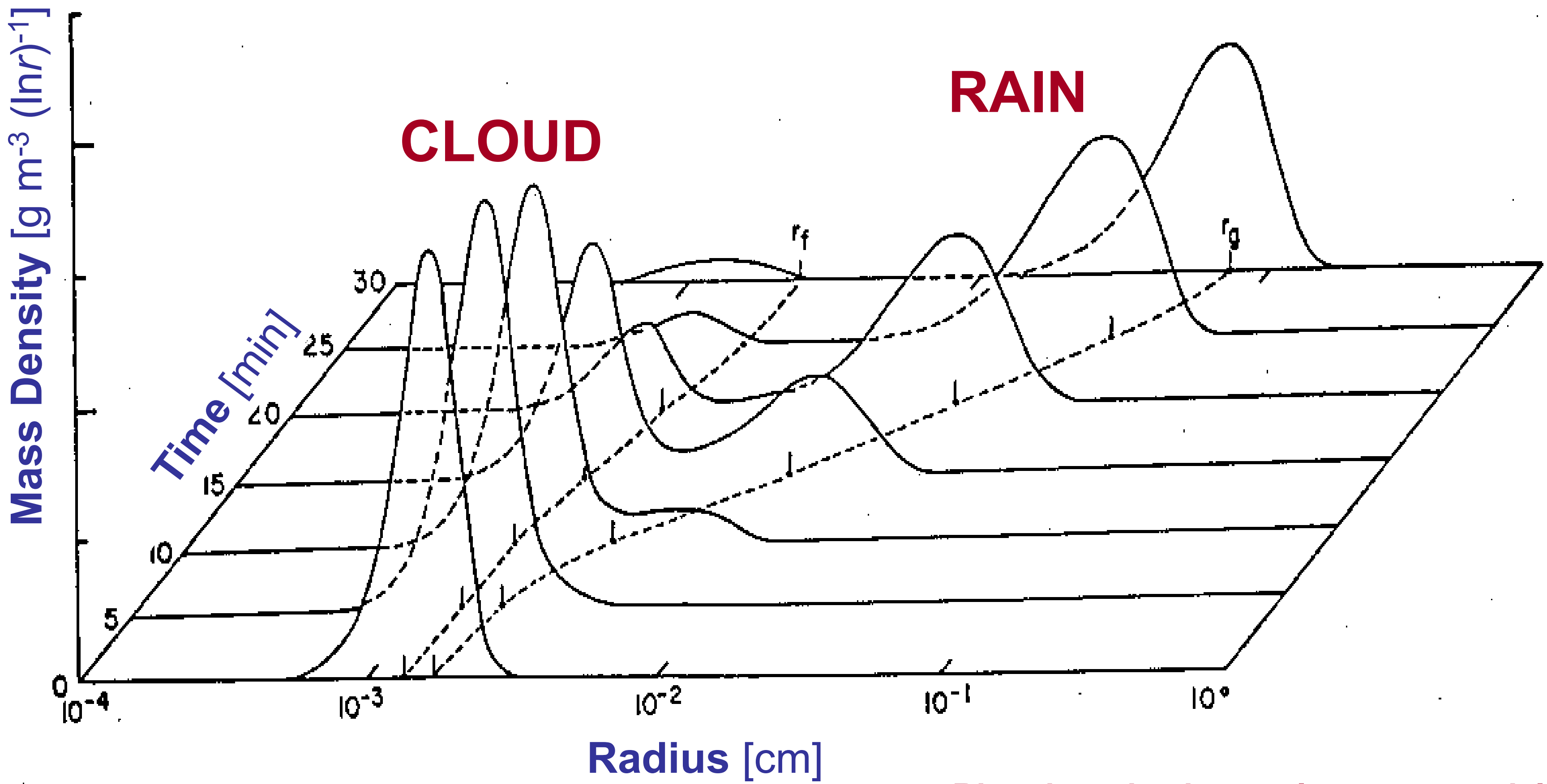
- **Microphysical process “fingerprinting”**
- **Quantification of process uncertainty/sensitivity in system-wide context**
- **Quantifying information content from observations**
- **Stochastic microphysics (stochastic sampling from the parameter PDFs) → ensemble prediction**

Stay tuned for Marcus’s seminar on April 5!

Liquid Phase

"Warm rain" coalescence process:

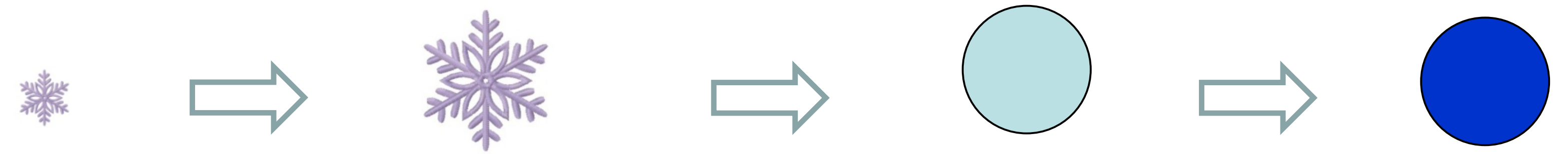
→ **2-moment, 2-category bulk schemes model this process well**



Bin microphysics coalescence model
Berry and Reinhardt (1974)

Ice Phase

Traditional bulk approach:



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

"SNOW"
ρ_s = 100 kg m^{-3}
$m = cD^2$
$V = a_s D^{bs}$

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

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

← abrupt / unphysical conversions

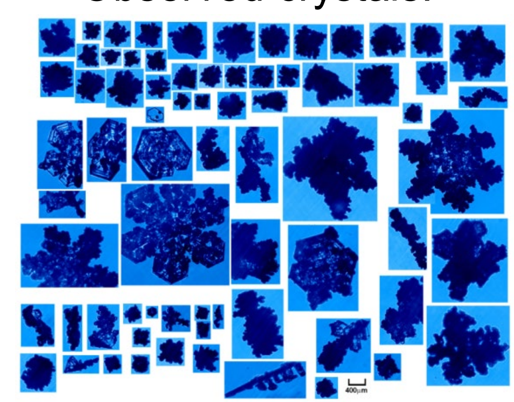
Problems with pre-defined ice categories:

1. Real ice particles have complex shapes

2. Conversion between categories is ad-hoc

3. Conversion leads to large, discrete changes in particle properties

Observed crystals:

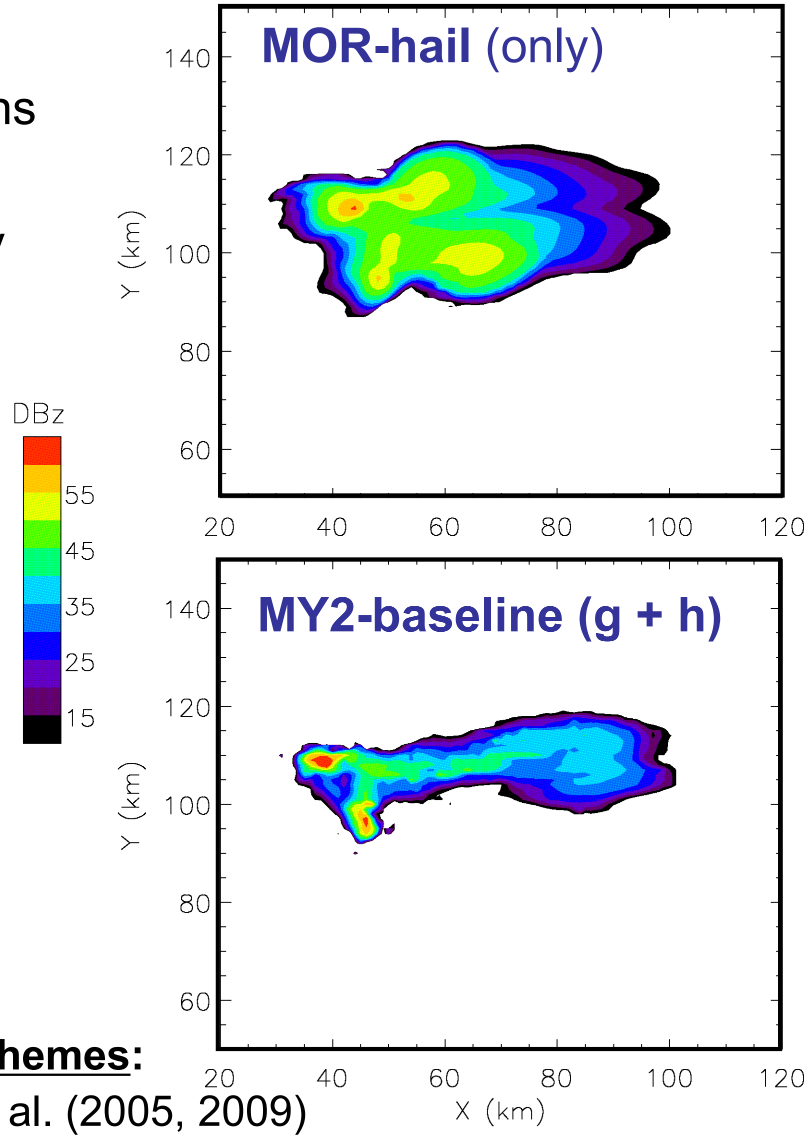


c/o Alexi Korolev

NOTE: *Bin microphysics schemes have the identical problem*

The simulation of ice-containing cloud systems is often *very sensitive* to how ice is partitioned among categories

- idealized 1-km WRF simulations (em_quarter_ss)
- base reflectivity



Microphysics Schemes:

MOR: Morrison et al. (2005, 2009)

MY2: Milbrandt and Yau (2005)

Morrison and Milbrandt (2011), *MWR*

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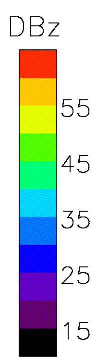

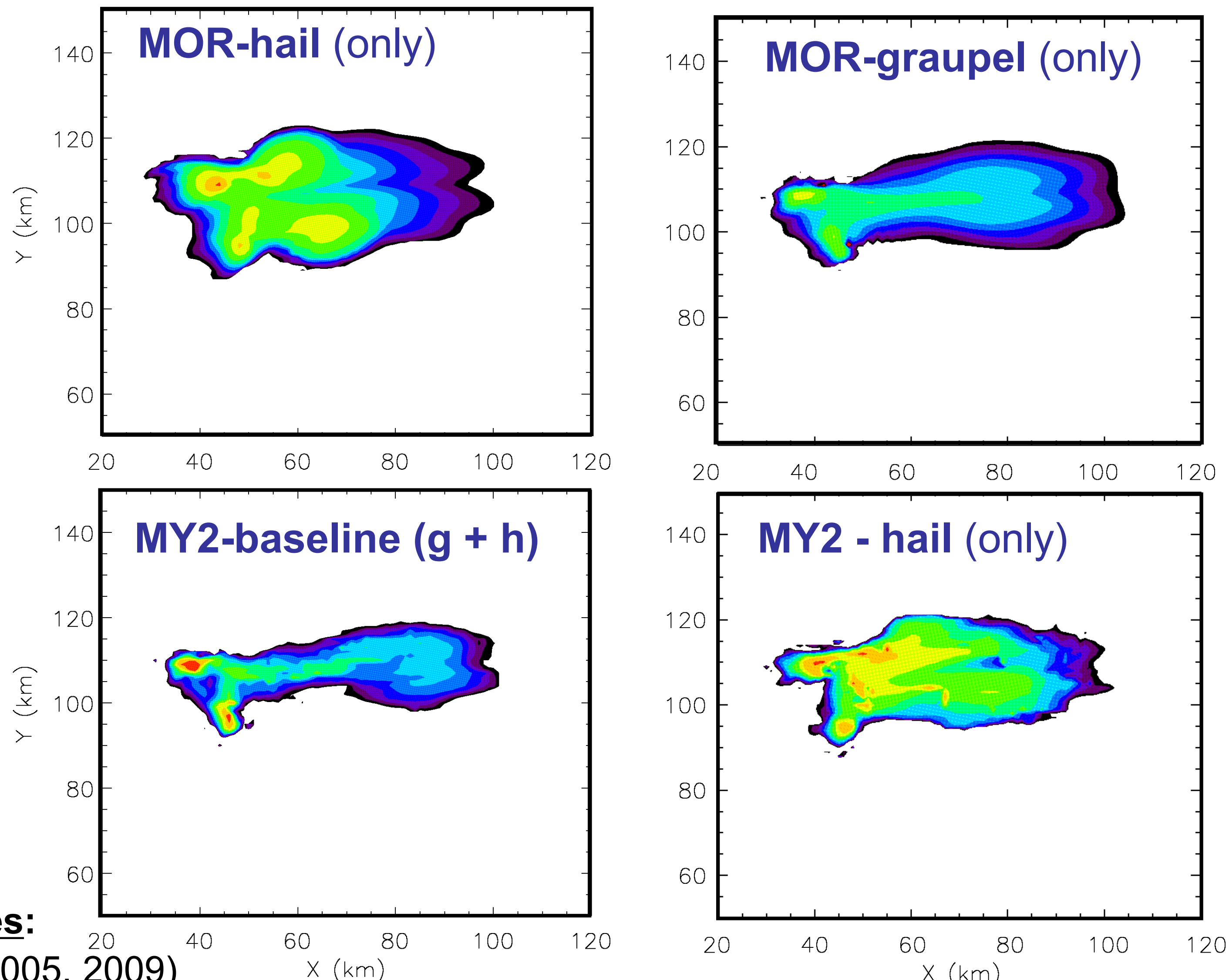

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Recent shift (in parameterization of ice phase):

Representation by fixed hydrometeor *categories*

to

Prediction of hydrometeor *properties*

- Predicted rime/axis ratio (bin scheme) – *Hashino and Tropoli (2007)*
- Predicted rime fraction – *Morrison and Grabowski (2008), Lin and Colle (2011) (diagnostic F_r)*
- Predicted crystal axis ratio and density – *Harrington et al. (2013), Jensen et al. (2017)*
- Predicted Particle Properties (P3) - *Morrison and Milbrandt (2015)*

2. Overview of the P3 microphysics scheme

New Bulk Microphysics Scheme:

Predicted Particle Properties (P3)

NEW CONCEPT

"free" ice category – predicted properties, thus freely evolving type

vs.

"pre-defined" ice category – traditional; prescribed properties

(e.g. "ice", "snow", "graupel", etc.)

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

- avoids some necessary evils (ad-hoc category conversion, fixed properties)
- is better linked to observations
- is more computationally efficient

Morrison and Milbrandt (2015), *JAS* - Part 1
Morrison et al. (2015), *JAS* - Part 2
Milbrandt and Morrison (2016), *JAS* - Part 3

Prognostic Variables: (advected)

LIQUID PHASE: 2 categories, 2-moment:

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

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

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

A given (*free)* category can represent any type of ice-phase hydrometeor

Prognostic Variables:

Q_{dep} – deposition ice mass mixing ratio [kg kg^{-1}]

Q_{rim} – rime ice mass mixing ratio [kg kg^{-1}]

N_{tot} – total ice number mixing ratio [# kg^{-1}]

B_{rim} – rime ice volume mixing ratio [m^3 kg^{-1}]

Predicted Properties:

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

ρ_{rim} – rime density, $\rho_{rim} = Q_{rim} / B_{rim}$ [kg m^{-3}]

D_m – mean-mass diameter, $D_m \propto Q_{tot} / N_{tot}$ [m]

V_m – mass-weighted fall speed, $V_m = f(D_m, \rho_{rim}, F_{rim})$ [m s^{-1}]

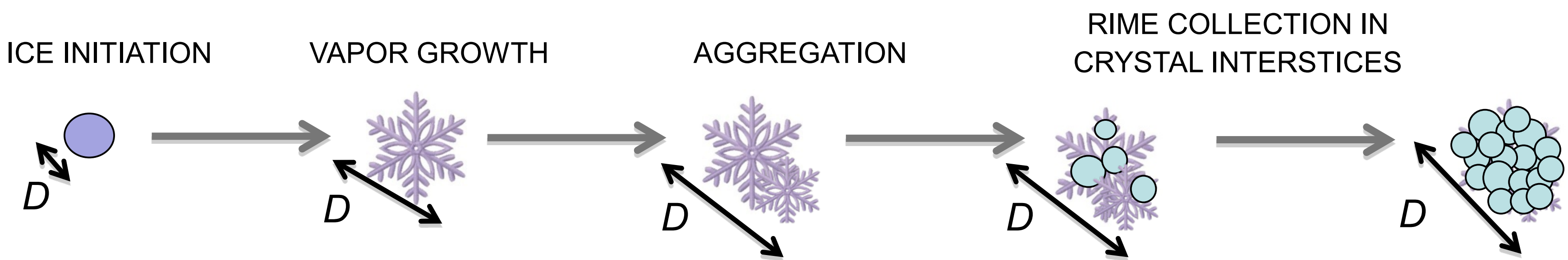
etc.

Diagnostic Particle Types:

Based on the predicted properties (rather than pre-defined)

P3 SCHEME – Determining $m(D) = \alpha D^{\beta}$ for regions of D: Similar for $A(D)$; $V(D)$ calculated from m and A…

Conceptual model of particle growth following Heymsfield (1982):



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

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

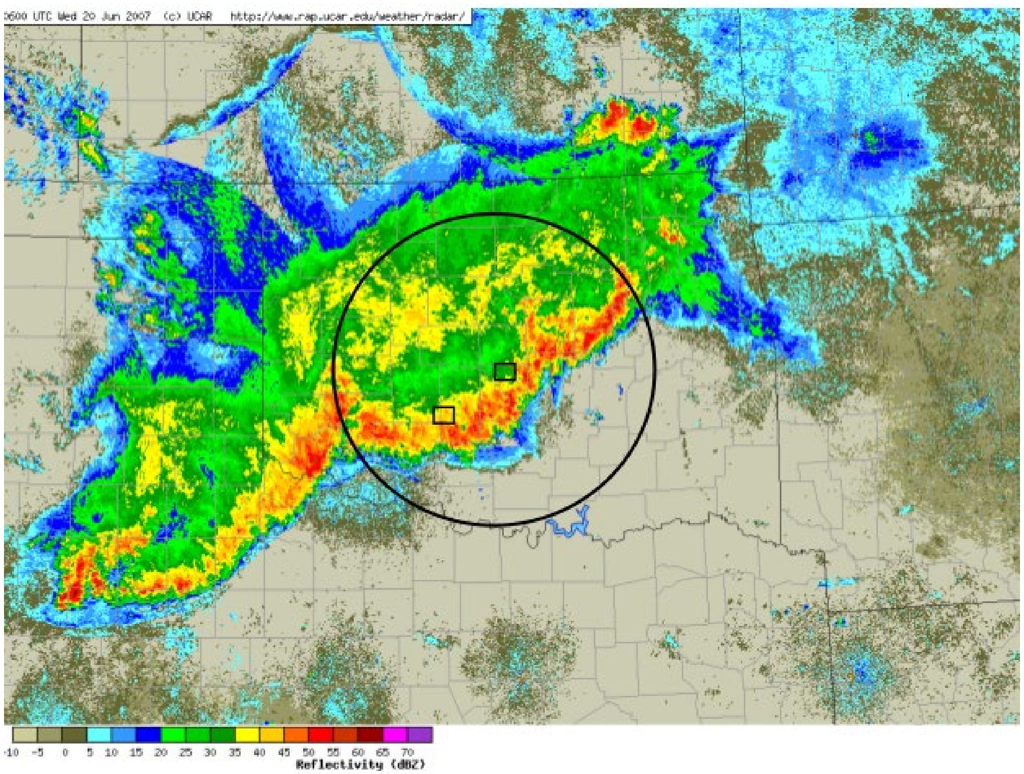
partially rimed crystal
$\alpha = f(F_{rim}, \rho_{\text{rim}})$
$\beta \sim 2$

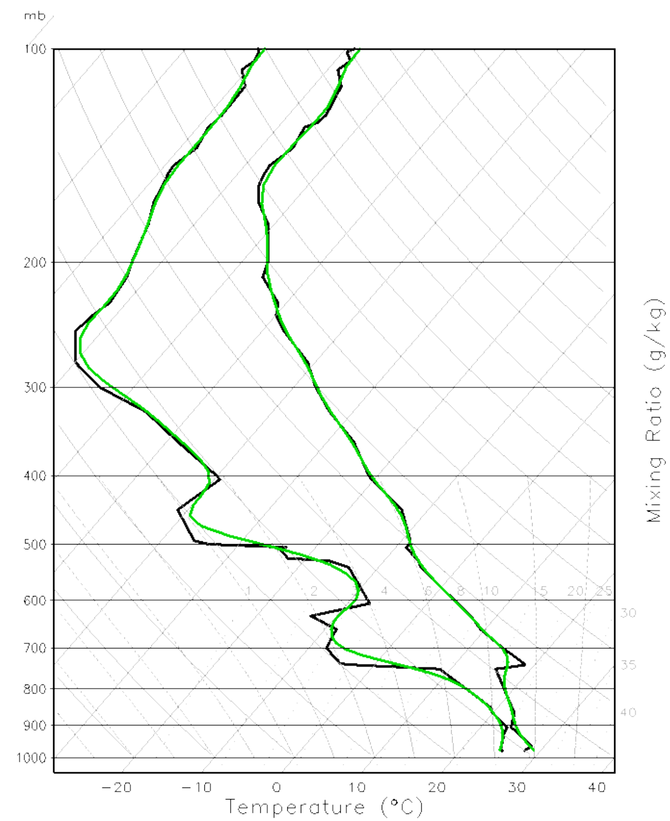
spherical graupel
$\alpha = f(F_{rim}, \rho_{\text{rim}})$
$\beta = 3$

3D Squall Line case:

(June 20, 2007 central Oklahoma)

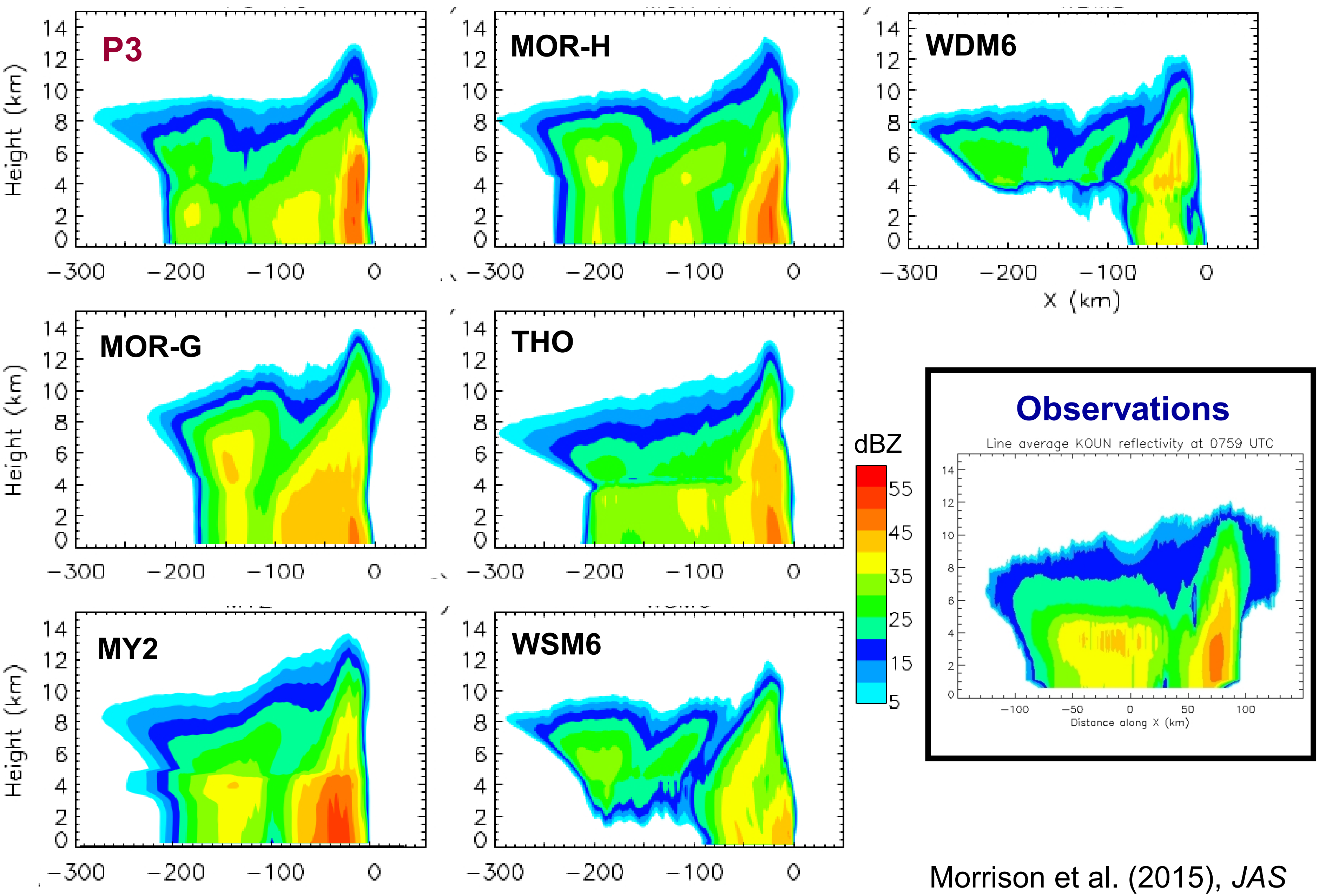
- WRF_v3.4.1, Δx = 1 km, Δz ~ 250-300 m, 112 x 612 x 24 km domain
- initial sounding from observations
- convection initiated by *u*-convergence
- no radiation, surface fluxes





Morrison et al. (2015), *JAS*

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



Morrison et al. (2015), *JAS*

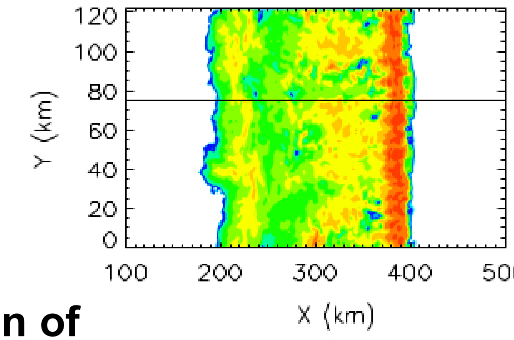
Ice Particle Properties:

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

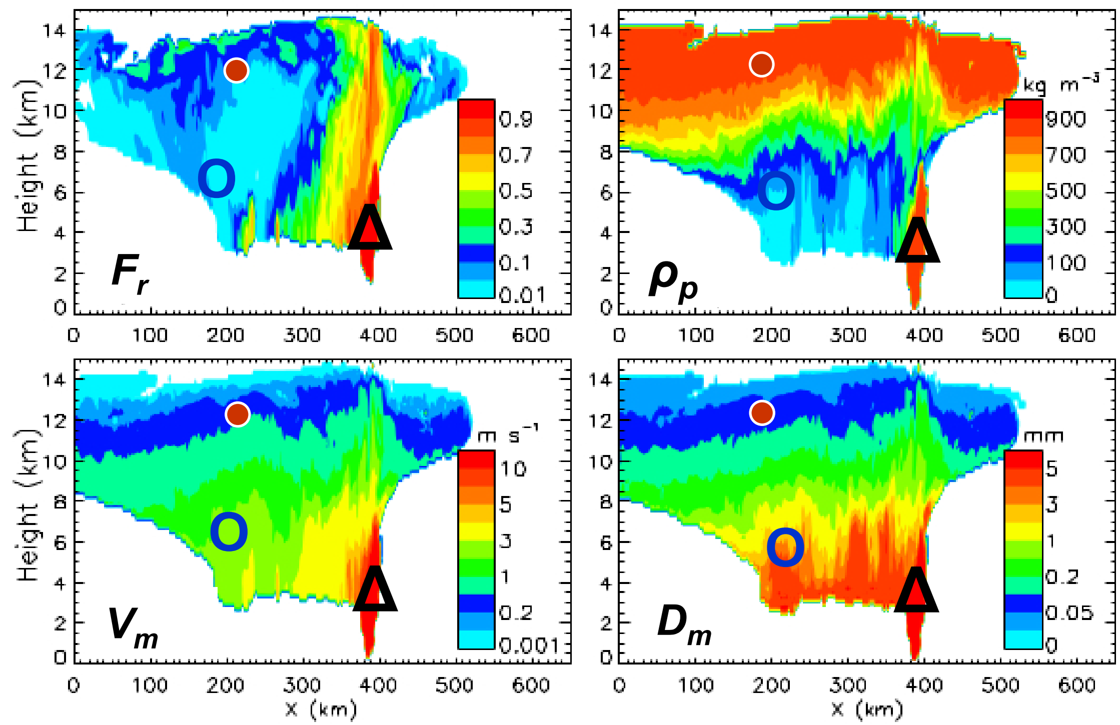
$F_r \sim 0$
$\rho \sim$ 50 kg m-3
$V \sim 1$ m s^{-1}
$D_m \sim$ 3 mm
→ ***aggregates***

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

etc.



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

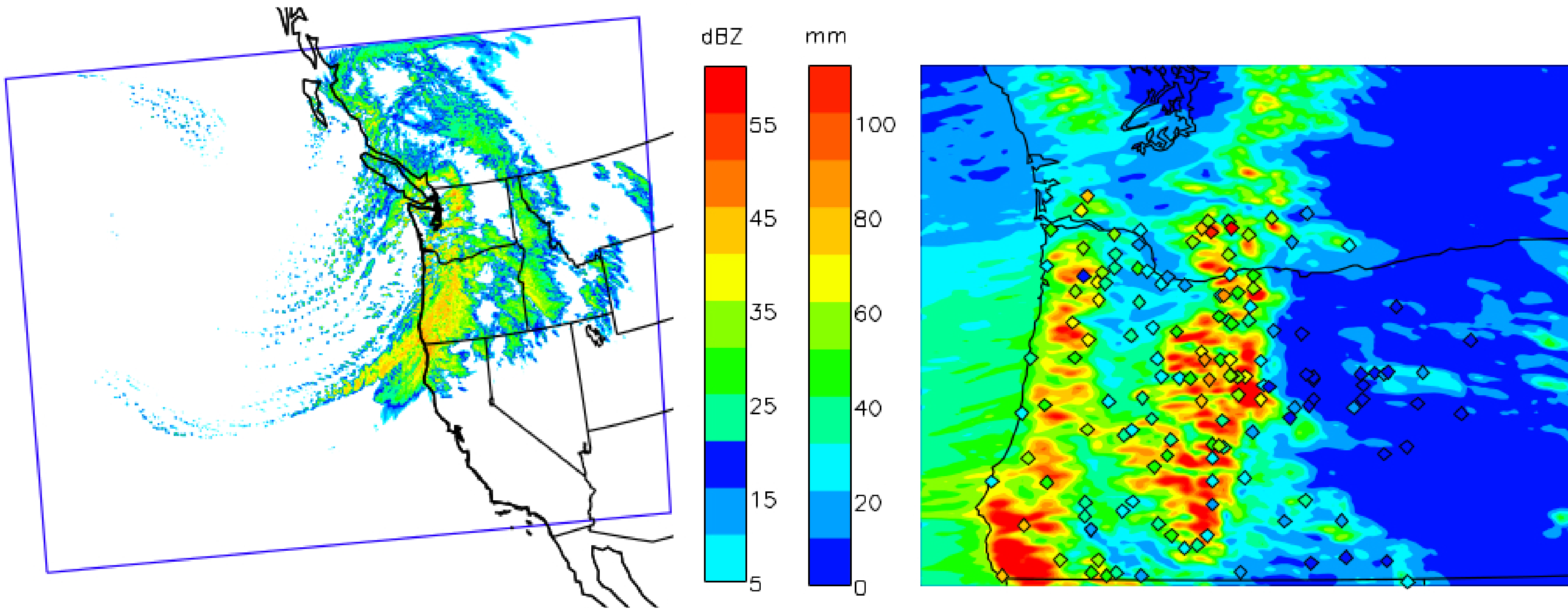


Note – *only* *<u>one</u>* *(free) category*

Morrison et al. (2015), *JAS*

Frontal/orographic case:
IMPROVE-2, 13-14 December 2001

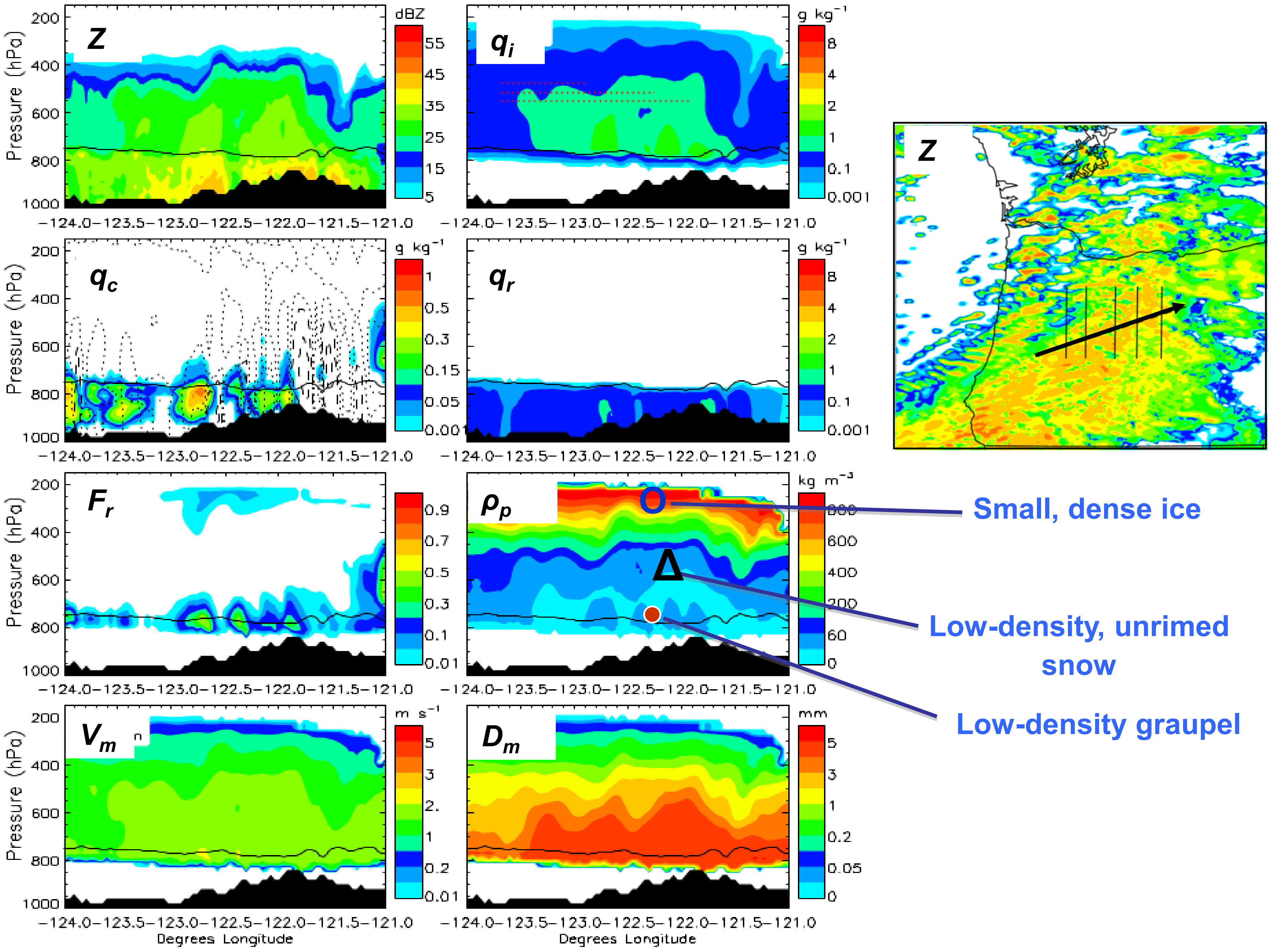
- WRF_v3.4.1, Δx = 3 km, 72 stretched vertical levels



Simulated lowest level **REFLECTIVITY**
(00 UTC December 14)

Accumulated **PRECIPITATION**
(14 UTC Dec 13 - 08 UTC Dec 14)

Morrison et al. (2015), *JAS*


Z
q_i
q_c
q_r
F_r
ρ_p
V_m
D_m
Pressure (hPa)
Degrees Longitude
dBZ
g kg^{-1}
kg m^{-3}
m s^{-1}
mm
Small, dense ice
Low-density, unrimed snow
Low-density graupel

Timing Tests for 3D WRF Simulations

Scheme	Squall line case	Orographic case	# prognostic variables
P3 – 1 Cat	**1.043**	**1.013**	**7**
MY2	1.485	1.495	12
MOR-H	1.203	1.200	9
THO	1.141	1.174	7
WSM6	**1.000**	**1.000**	**5**
WDM6	1.170	1.148	8

- Times relative to those of WSM6 are indicated parenthetically.

→ P3 in WRF is relatively fast…

Morrison et al. (2015), *JAS*

Issues with advection and microphysics…

- Much of the cost of microphysics schemes is advecting hydrometeor variables (a few % total run time per scalar in WRF).

- A new method called *Scaled Flux Vector Transport* can reduce the cost of advection for multi-moment bulk schemes including P3 (Morrison et al. 2016, *MWR*).

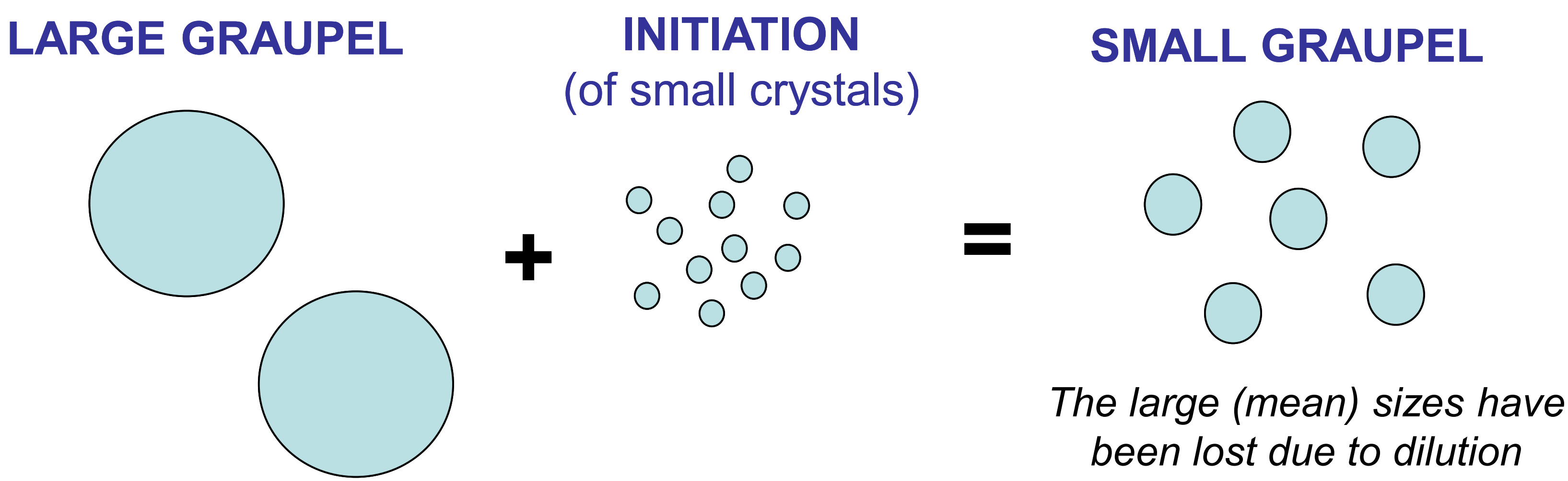
  → advects the mass mixing ratio variables using the unmodified scheme and the "secondary" variables (e.g. number mixing ratios) by appropriately scaling the mass mixing ratio fluxes.

  → Total model run time for P3 reduced by ~10% while producing very similar solutions and retaining accuracy in analytic benchmark tests.

So far – despite using only 1 ice-phase category, P3 performs well compared to detailed, established (well-tuned), traditional bulk schemes

However – with 1 category, P3 has some *intrinsic limitations*:

- it cannot represent more than one bulk type of particle in the same point in time and space
- As a result, there is an inherent "***dilution problem***"; the properties of particle populations from different origins get averaged upon mixing



Single-Category Version

Morrison and Milbrandt (2015) [P3, part 1]

All ice-phase hydrometeors represented by a single category, with Q_{dep}, Q_{rim}, N_{tot}, B_{rim}

Processes:

1. Initiation of new particles
2. Growth/decay processes
   - interactions with water vapor
   - interactions with liquid water
   - self-collection
3. Sedimentation

Multi-Category Version

Milbrandt and Morrison (2016) [P3, part 3]

All ice-phase hydrometeors represented by a ***nCat* categories**, with Q_{dep}**(*n*)**, Q_{rim}**(*n*)**, N_{tot}**(*n*)**, B_{rim}**(*n*)** [$n = 1..nCat$]

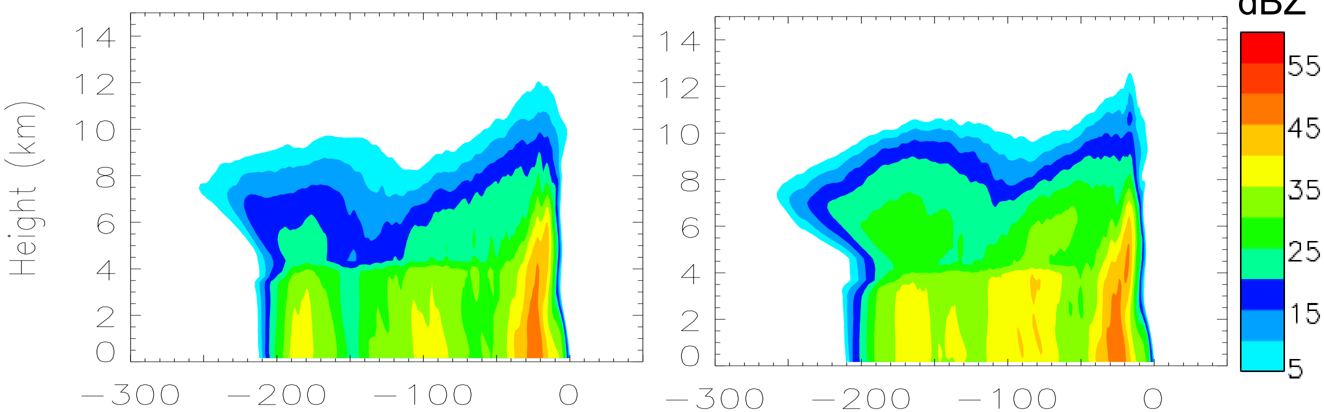
Processes:

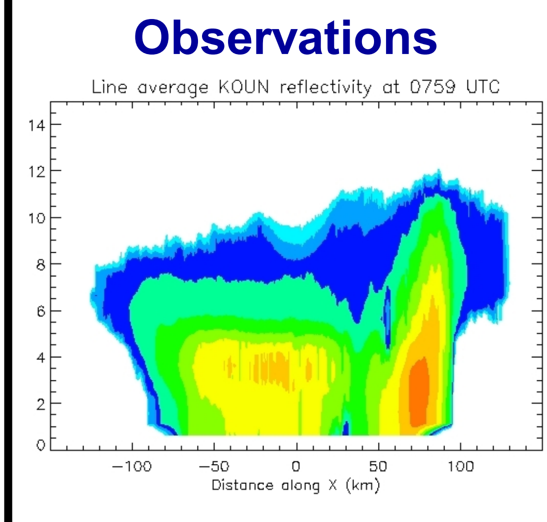
1. Initiation of new particles → **determine destination category**
2. Growth/decay processes
   - interactions with water vapor
   - interactions with liquid water
   - self-collection
   - **collection amongst other ice categories**
3. Sedimentation

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

P3 - 1 category
w/o H-M*

P3 - 2 category
w/ H-M*





Morrison et al. (2015), *JAS*

*Hallet-Mossop rime splintering → generation of new crystals splintering of rimed ice

**Uses WRFV3.9.1 instead of V3.5.1 in earlier slides.

Current Status of P3 (in WRF)

WRF THE WEATHER RESEARCH & FORECASTING MODEL

Spring 2017: Released in WRFV3.9

- ***MP option*** **50 (Single category P3 with specified cloud droplet number)**
- ***MP option*** **51 (Single category P3 with prognostic cloud droplet number and simple coupling with aerosols)**

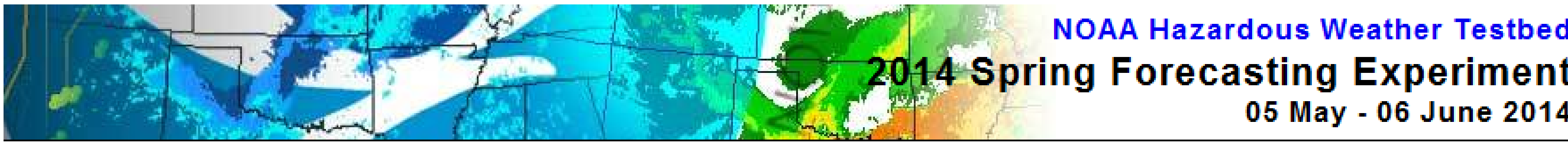
August 2017: P3 code updated for WRFV3.9.1 release

Spring 2018: To be released in WRFV4.0

- ***MP option*** **52 (Two-category P3 with prognostic cloud droplet number and simple coupling with aerosols)**
- **Updates to single-category P3 options**

Status for real-time NWP

NOAA NSSL Spring Hazardous Weather Testbed



- **Run in the OU CAPS WRF ensemble since 2014**

Operational NWP in Canada

Environment and Climate Change Canada
Environnement et Changement climatique Canada

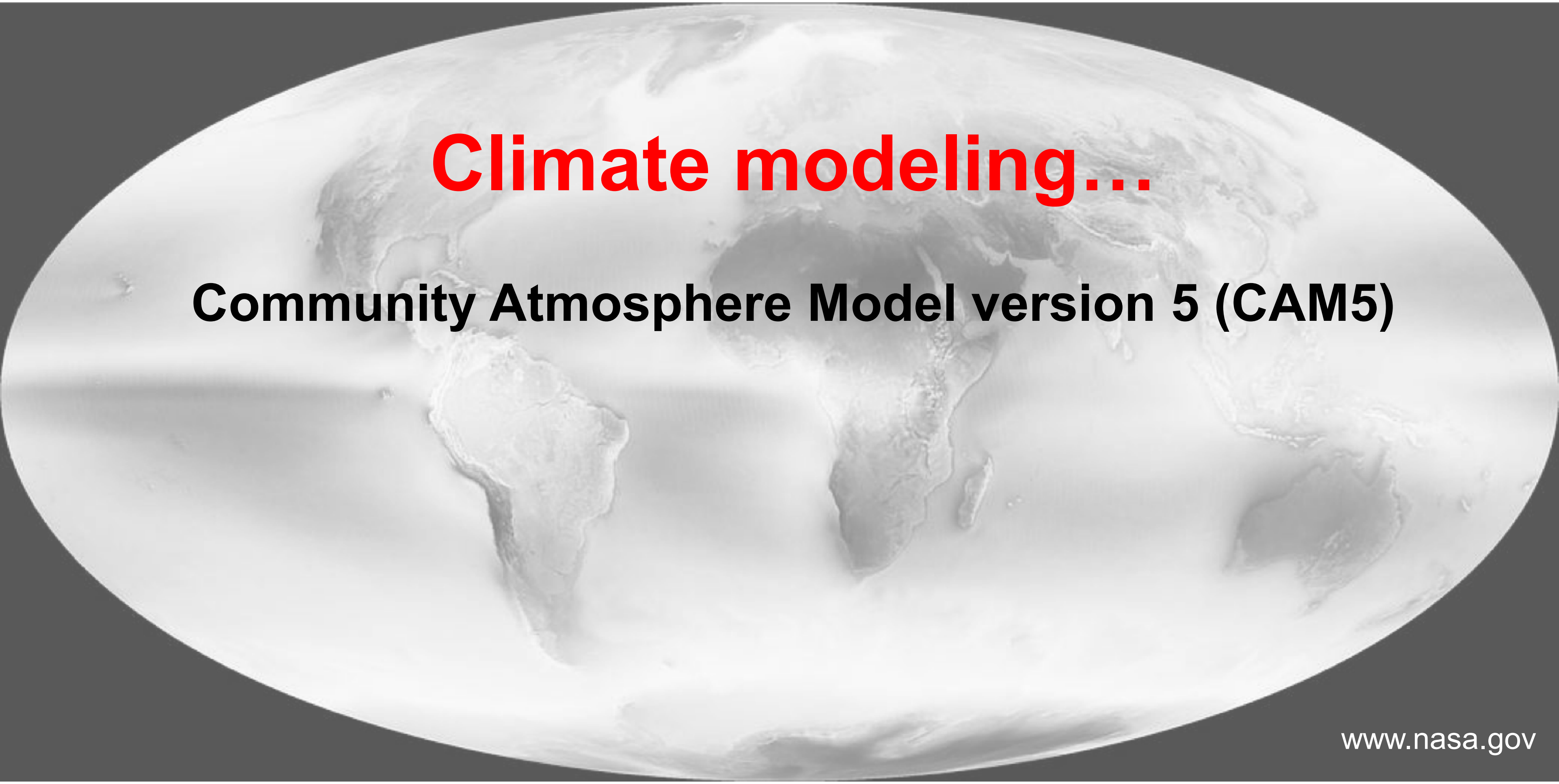
- **Currently (as of Jan 2018) running in ECCC's operational high-resolution 3 km pan-Arctic system in support of the International Year of Polar Prediction (YOPP) experiment**

- **To be implemented (summer 2018) into ECCC's operational high-resolution 2.5 km pan-Canadian NWP system**

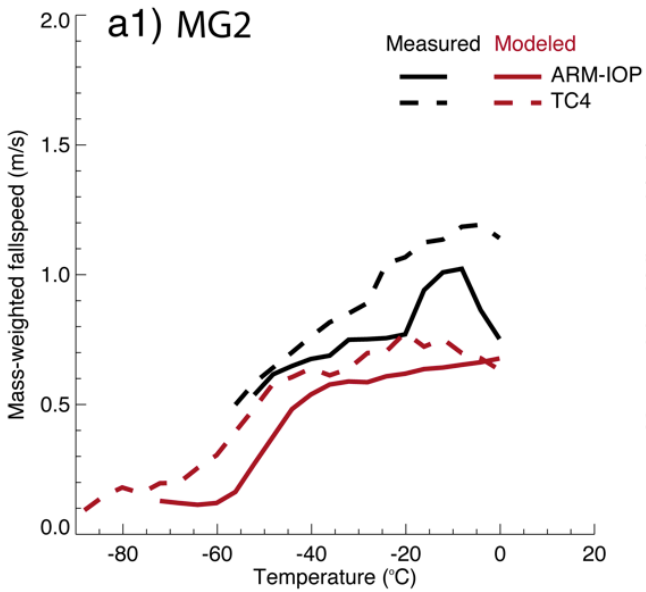
- **Currently being adapted for planned use in coarser grid ECCC operational NWP systems**

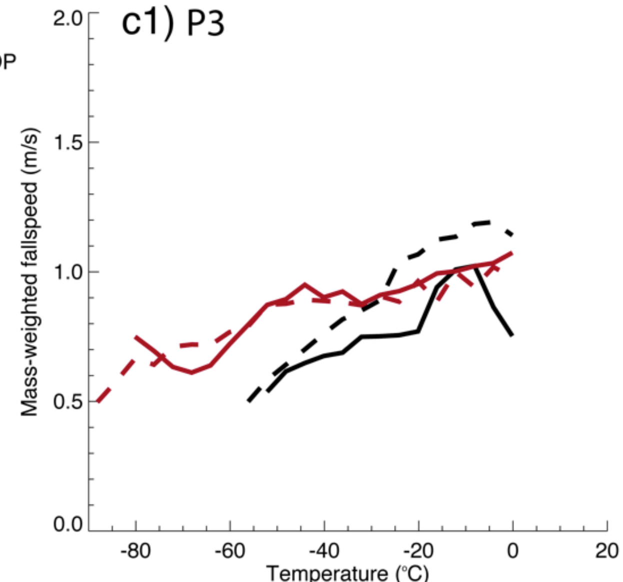
Climate modeling…

Community Atmosphere Model version 5 (CAM5)

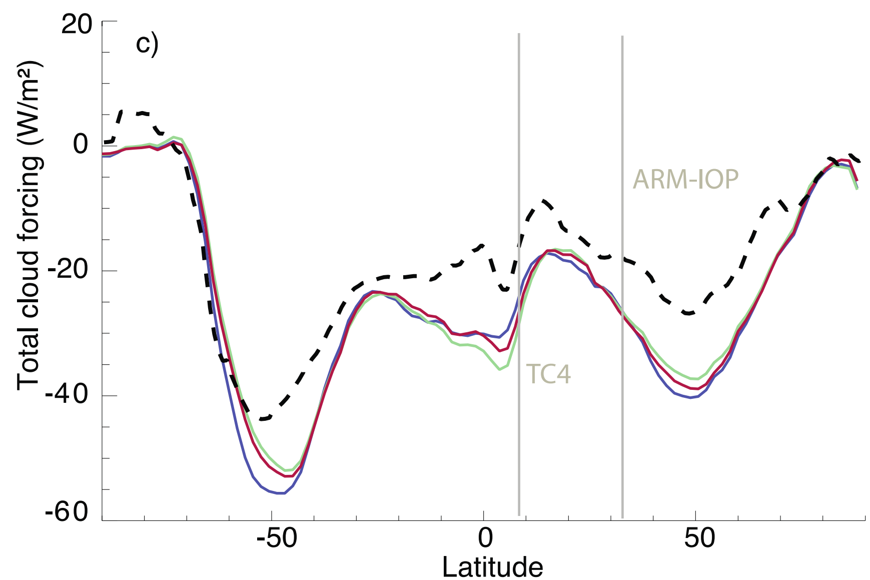


Simplified P3 implemented in CAM5





Total cloud radiative forcing



The physical basis of ice microphysics is improved while not "breaking" the simulated climate…

Eidhammer et al. (2017), *J. Climate*

3. Current developments and broader outlook + commentary

(a.k.a. the part of the talk I will say controversial things…)

Broader outlook

- **There is a steady march towards *greater complexity* in microphysics schemes in weather and climate models. *Does this always make sense?***

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  → With increased scheme complexity comes:

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  - greater challenge in systematically constraining with observations

  - greater cost which could be used for other modeling aspects (e.g., increased grid resolution)

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  → **With increased scheme complexity comes:**

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  - greater challenge in systematically constraining with observations

  - greater cost which could be used for other modeling aspects (e.g., increased grid resolution)

There will be a role for simple microphysics schemes in the future…

P3 and BOSS were developed in this spirit.

Thanks!

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DOE ASR DE-SC0005336
DOE ASR DE-SC0016579
DOE ASR DE-SC0016476
NASA NNX12AH90G
NASA ROSES
NSF base funding

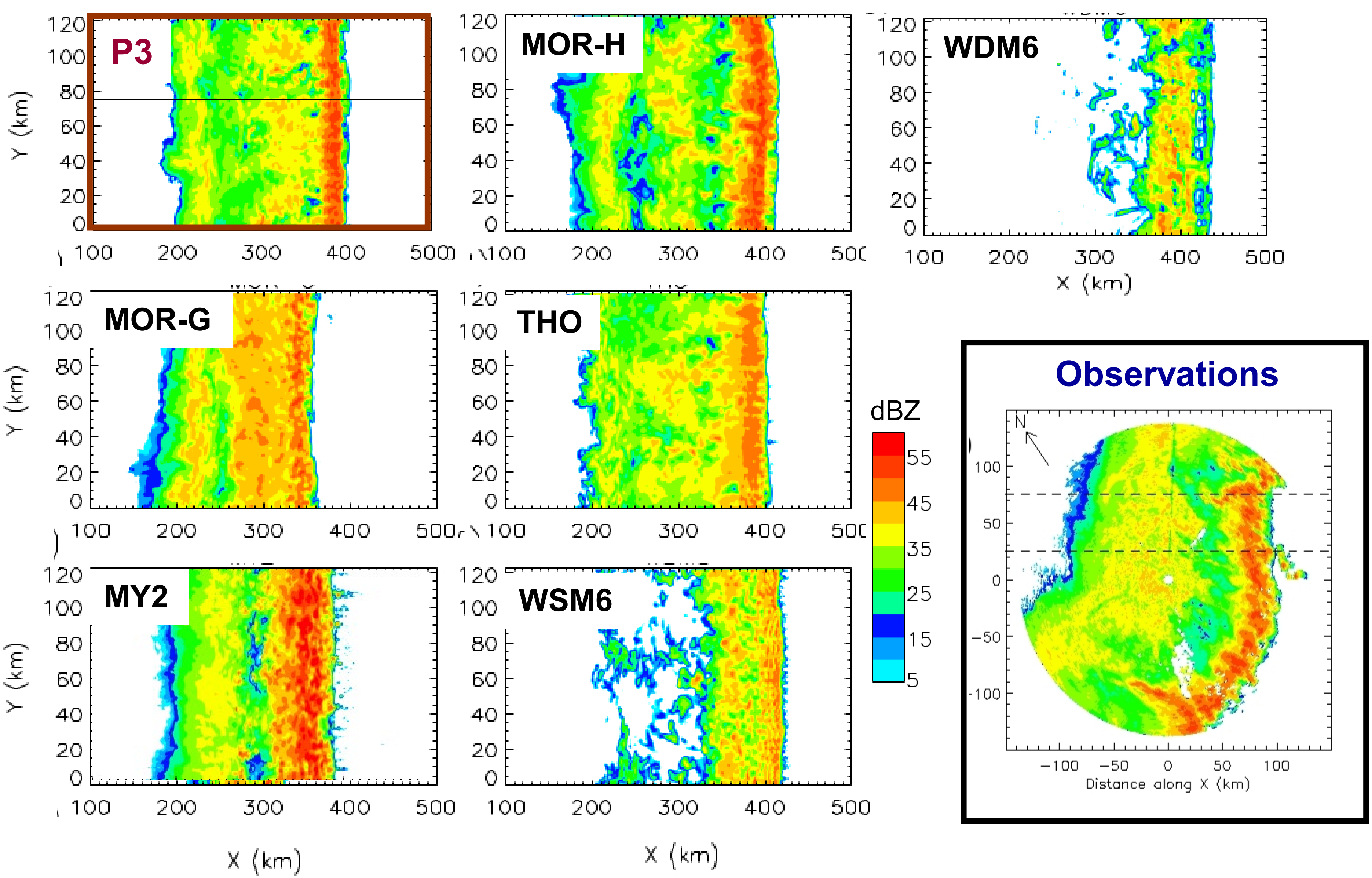
EXTRA

What we want in advection schemes (for clouds/precip):

- Positive definite for mass (needed for water conservation), or even better monotonic, but <u>not</u> as critical for *non-mass* microphysical variables
- Preserves initial linear relationships between advected quantities
- Accurate
- Efficient

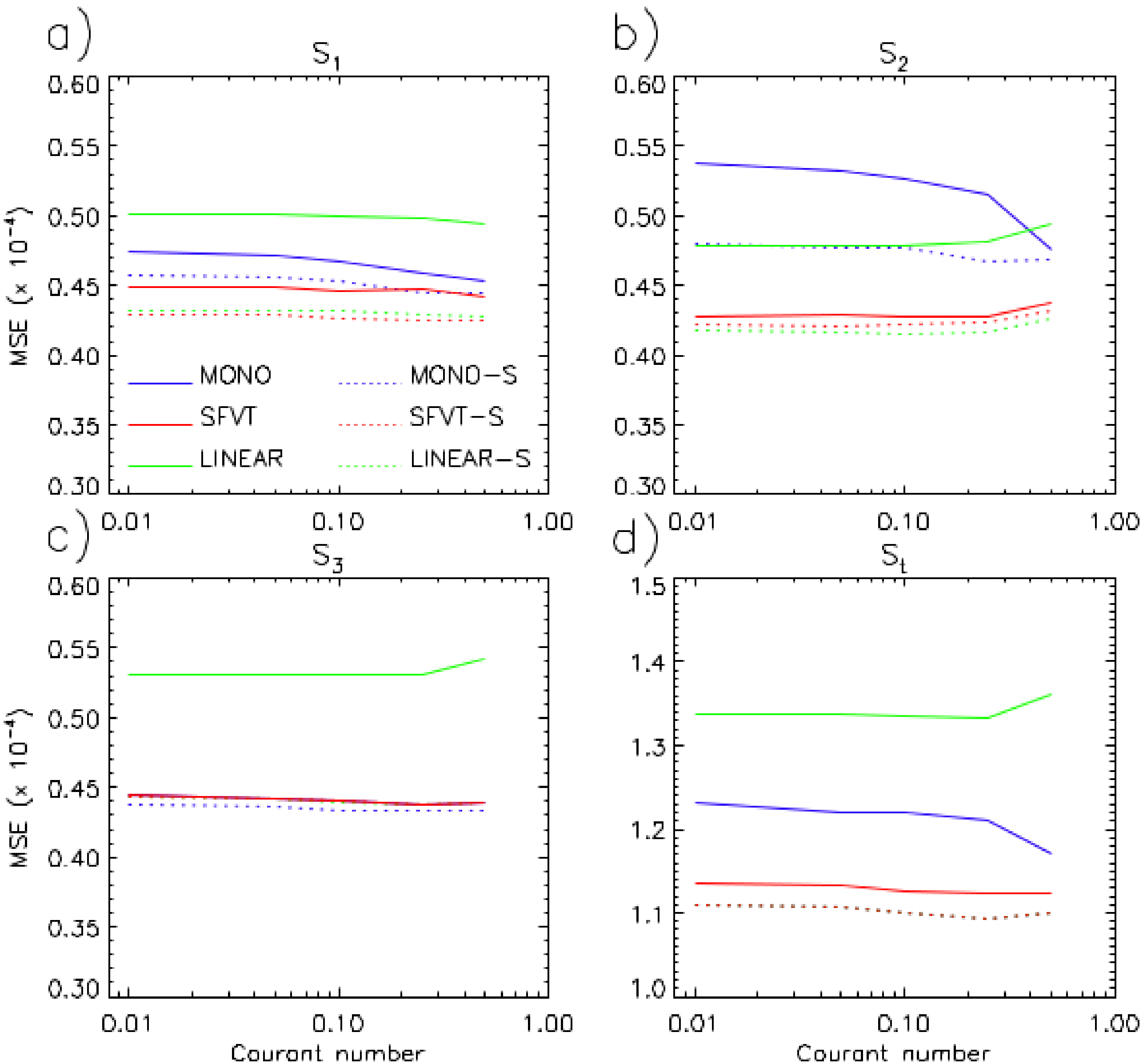
There are trade-offs!

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



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

1D analytic test cases



Mean error as a function of Courant number

Issues with advection and microphysics…

- The traditional approach is to advect each cloud/precipitation prognostic variable independently.

- **Potential problems:**

- Slow

- Derived quantities (e.g., ratios) may not be monotonic even if each scalar is advected using a monotonic scheme

New method: *Scaled Flux Vector Transport*

Morrison et al. (2016, *MWR*)

Scales mass mixing ratio fluxes to advect "secondary" microphysical scalars:

1) Mass mixing ratio (*Q*) quantities are advected using the unmodified scheme

2) "Secondary" non-mass scalars (*N*, *Z*, *V*, etc.) then advected by scaling of *Q* fluxes using higher-order <u>linear</u> weighting

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2) "Secondary" non-mass scalars (*N*, *Z*, *V*, etc.) then advected by scaling of *Q* fluxes using higher-order linear weighting

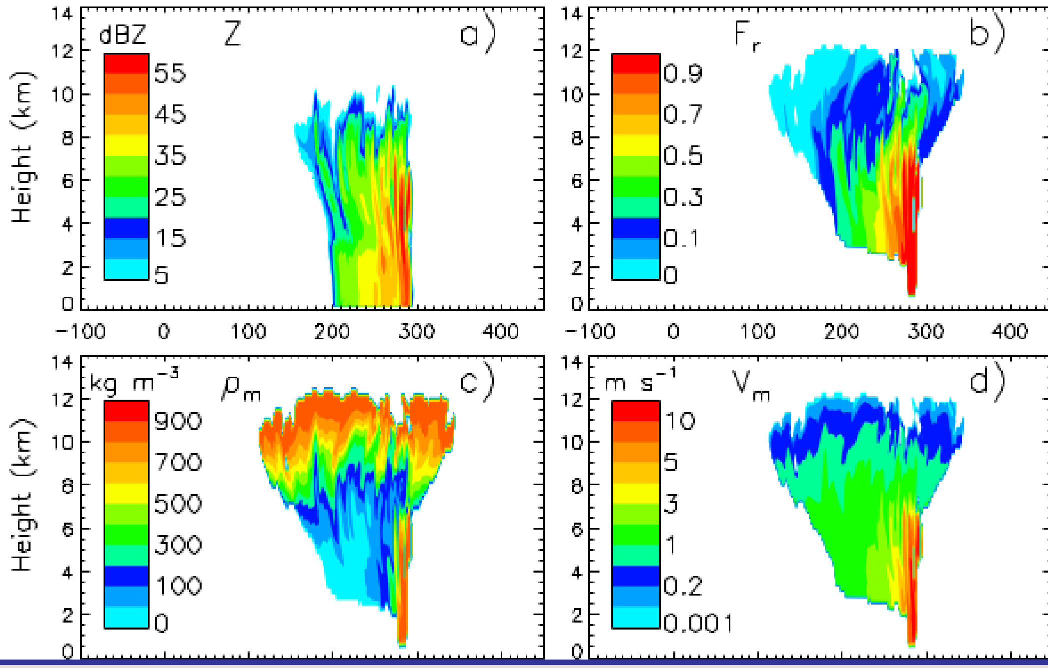
Retains features of applying unmodified scheme to ALL scalars, but at a reduced cost..

→ Accurate (for analytic test cases), fast, and preserves initial linear relationships

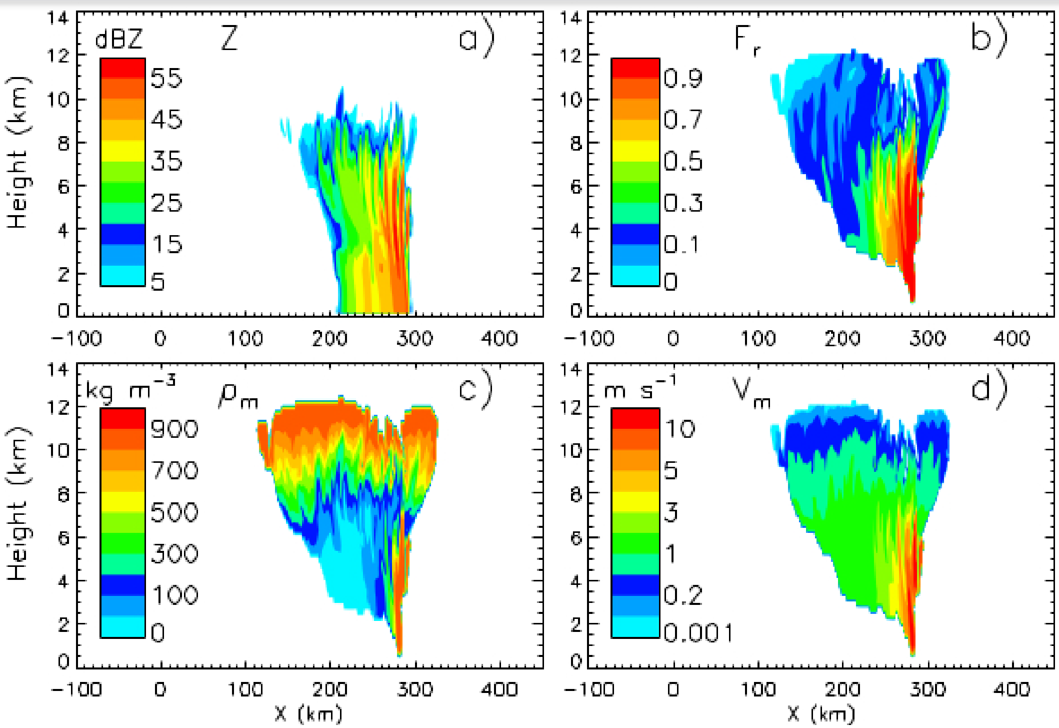
WRF 2D squall line test

t = 4 h

WRF-PD (5th order horizontal 3rd order vertical)



WRF-PD w/ SFVT



11% reduction in *total* model run time

Morrison et al. (2016), *MWR*

- **The <u>efficiency</u> of *SFVT* increases as the number of secondary scalars increases relative to the number of mass variables.**

- **Thus *SFVT* works well with P3 because there are 3 secondary variables for each “free” ice category.**

- **It is particularly well-suited for <u>bin schemes</u> using the total bulk mass as the “lead” variables and the individual bin masses/numbers as the secondary scalars.**

P3-like modifications to CAM5

- **Modification of Morrison-Gettelman version 2 (MG2) scheme to combine "*cloud ice*" and "*snow*" in a single ice category and use physical representations of mass-size (m-D) and projected area-size (A-D) relationships.**

- **Allows consistent linkages between fallspeed and effective radius (both depending on m-D and A-D), and removes the need for cloud ice to snow autoconversion.**

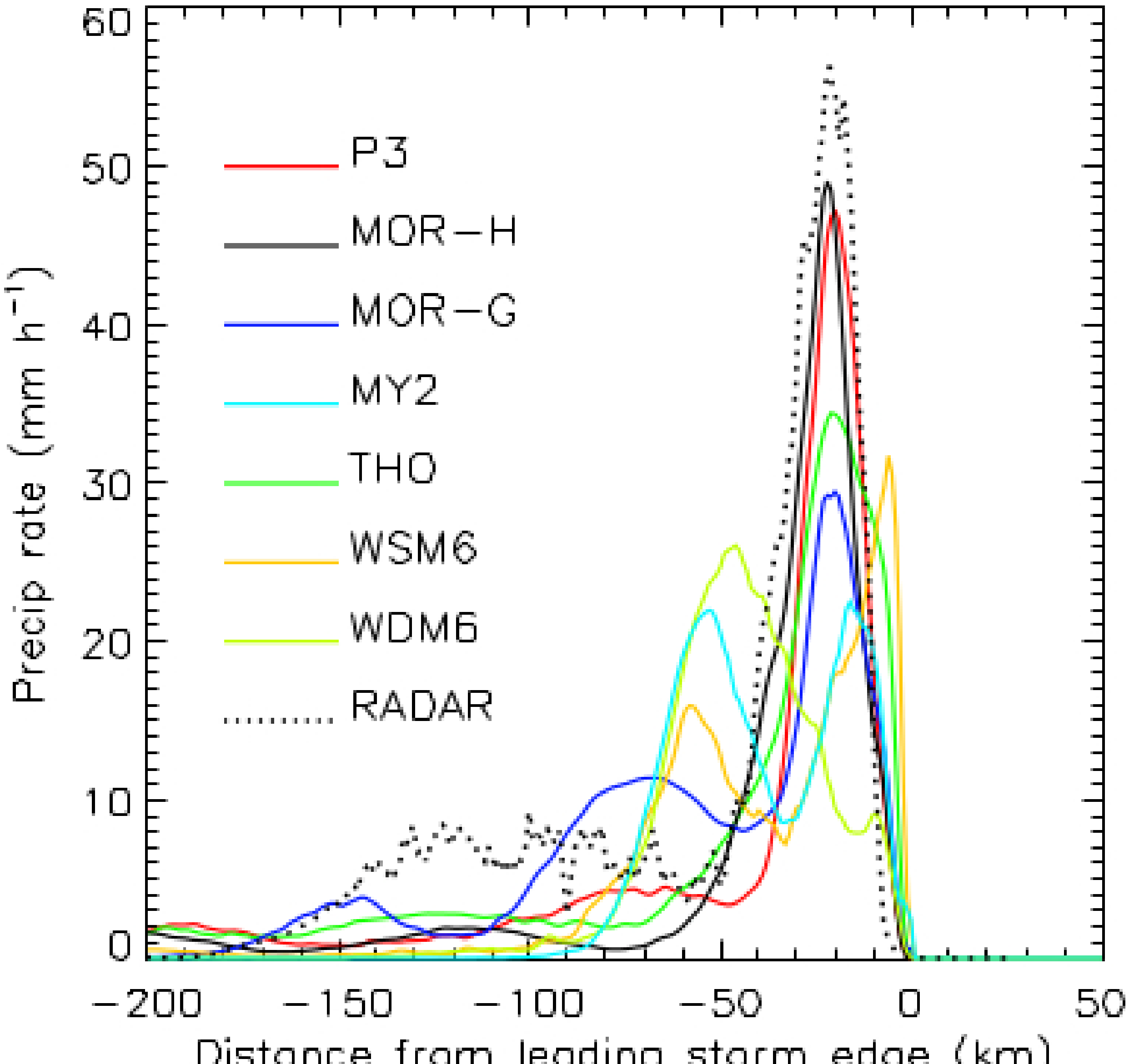
- **Two methods for specifying m-D and A-D:**

- *P3:* constant m-D and A-D parameters, follows original P3 except representation of rimed ice is neglected

- *EM16:* varying m-D and A-D parameters from Erfani and Mitchell (2016)

Eidhammer et al. (2017), *J. Climate*

WRF Results: Line-averaged precipitation rate at 1 km height



Time-averaged from 6-7 h

Morrison et al. (2015), *JAS*