Uncertainty of Ground-based Radar Observations and Their Usage

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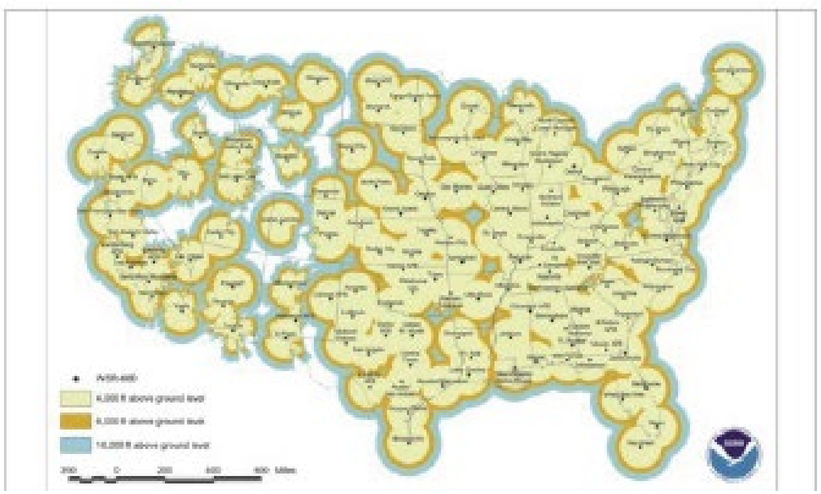
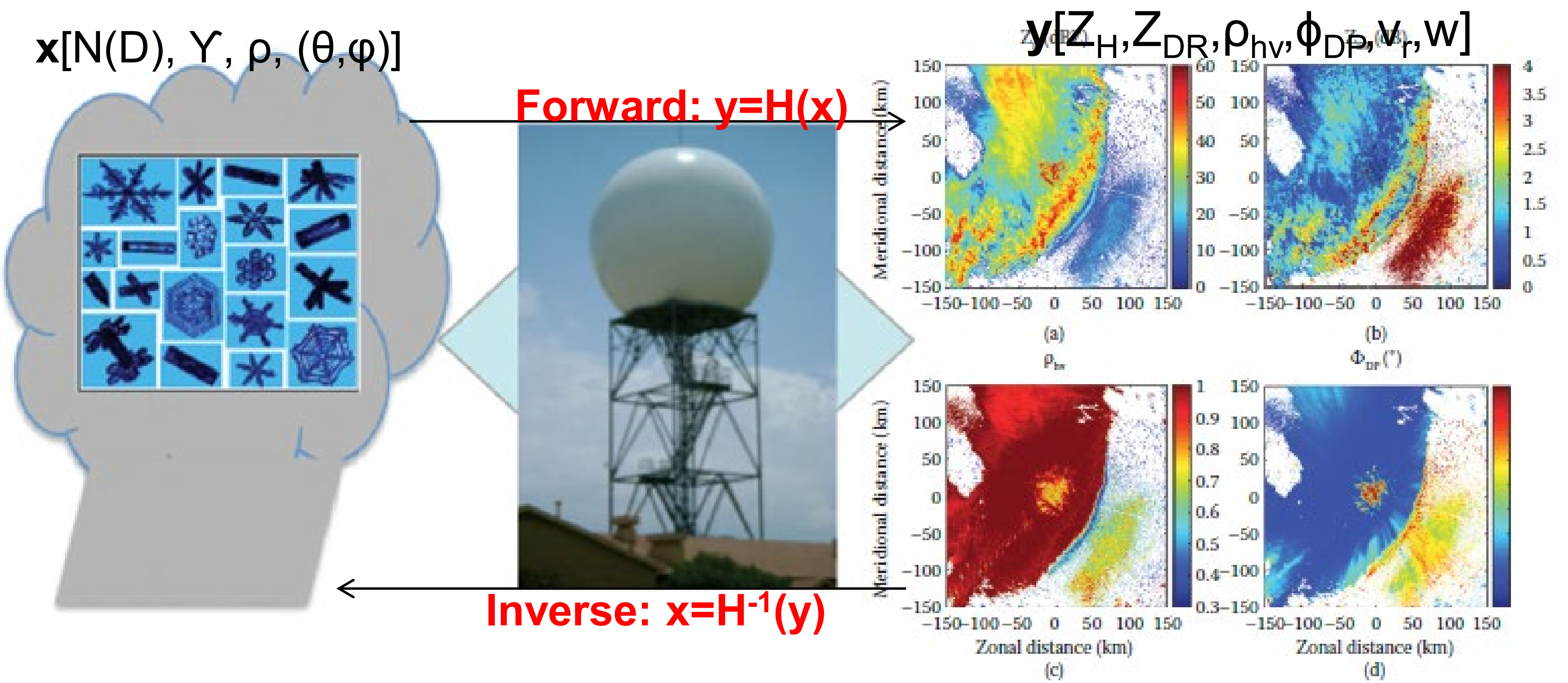
NWC Uncertainty Workshop



What are sources of uncertainty?
How to reduce and represent errors?

Radar Observations and Connection with Weather State



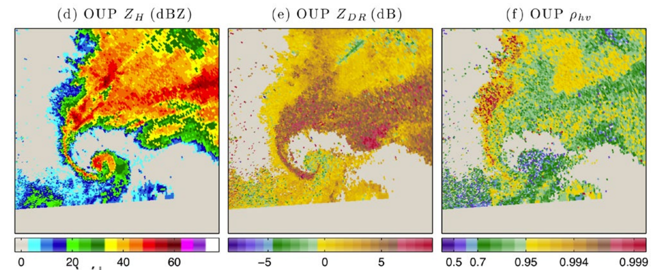
- Multi-parameter Doppler polarimetric radar measurements (data) (**y**) allow better characterization of weather: microphysical parameterization and initial condition
- More measurements mean more errors and more difficult to use, need better understanding and representation of physics and errors/uncertainties.
  - State representation x
  - Observation operator H(x)
  - Measurements y

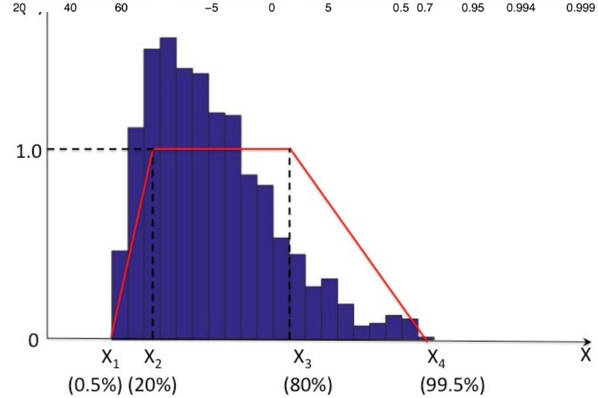
Current Status of Using PRD

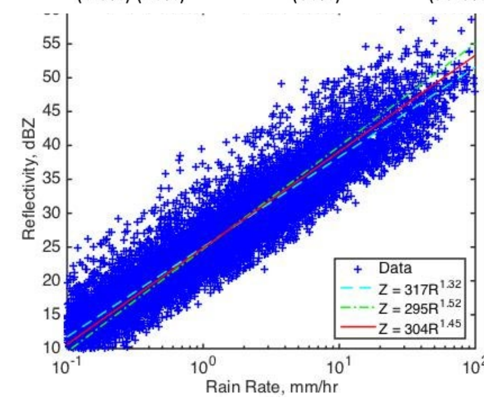
- Common usage
  - Observation study (Kumjian&Ryzhkov 2008)
  - HCA (Park et al. 2009):
  - QPE: $Z = 300R^{1.4} \Leftrightarrow R = 0.017Z^{0.714}$
  - QPF (Smith et al. 1975):

$$Z_{ex} = \frac{|K_x|^2}{|K_w|^2}\left(\frac{\rho_x}{\rho_r}\right)^2 Z_x \Leftrightarrow q_r = \left(\frac{Z\pi^{1.75}N_0^{0.75}\rho_r^{1.75}}{10^{18}\times 720\rho^{1.75}}\right)^{4/7}$$

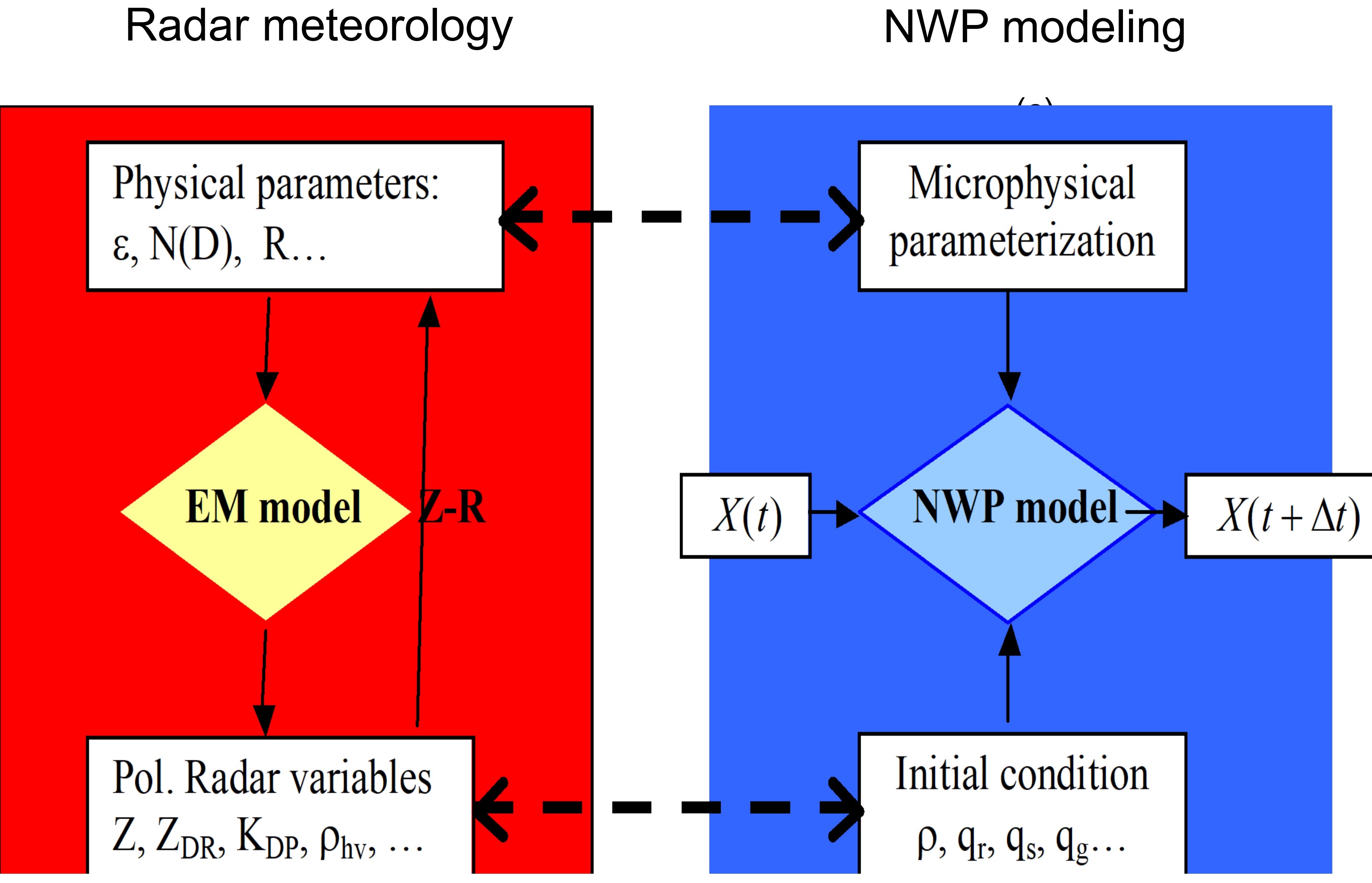
- Limitations
  - Empirical, not accurate
  - No error statistics, not optimal
  - Do not produce other NWP model state parameters: N(D), N_t, $Z = M_6 \neq Z_h$….







What is the optimal way to use radar data?


Radar meteorology
NWP modeling
Physical parameters:
ε, N(D), R…
EM model
Z-R
Pol. Radar variables
Z, Z_DR, K_DP, ρ_hv, …
Microphysical parameterization
NWP model
X(t)
X(t + Δt)
Initial condition
ρ, q_r, q_s, q_g…

Optimal Use of Radar Data

Assimilation: the process of taking in and fully understanding information or ideas

- Bayesian retrieval

  The posterior PDF of the state **x** when measurement **y** is given

$$p(\mathbf{x}\,|\,\mathbf{y}) = \frac{p(\mathbf{y}\,|\,\mathbf{x})\,p(\mathbf{x})}{p(\mathbf{y})}$$

  When x and y are jointly Gaussian distributed, maximum a posteriori probability (MAP) estimate, maximizing p(x|y) is equivalent to minimizing the cost function *J*

- Variational analysis (Lorenc 1986).

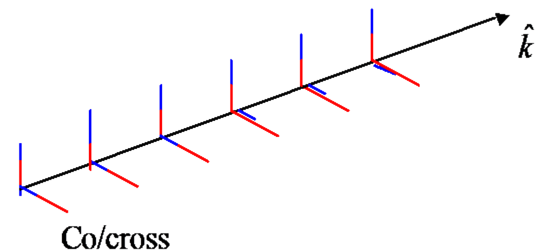
$$J = [\mathbf{x}-\mathbf{x}_{\mathrm{b}}]^t \mathbf{B}^{-1}[\mathbf{x}-\mathbf{x}_{\mathrm{b}}] + [\mathbf{y}-\mathbf{H}(\mathbf{x})]^t \mathbf{R}^{-1}[\mathbf{y}-\mathbf{H}(x)]$$

- Observation errors
  - Represented by observation error covariance **R**
  - Can occur in observation **y** and observation operator **H**

Radar Measurement Errors: **R**

- Sampling errors, understood and manageable

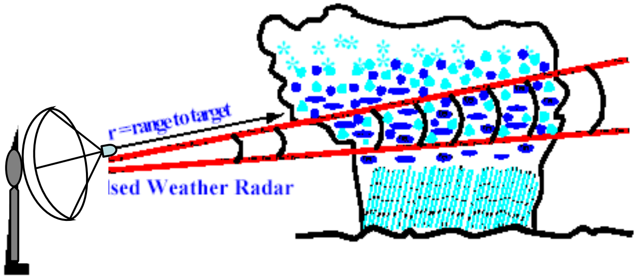
Variable	Range	Error	Rel. error
Z_H (dBZ)	0~70	1.0	<10%
v_r (m/s)	-25~25	1.0	<10%
Z_{DR} (dB)	0~4	0.2	~100%
K_{DP} (°/km)	0~3	0.2	~100%
ρ_{hv}	0.9~1	0.01	~50%*



- Calibration error (Zrnic et al. 2016; Ice et al. 2014)
- Clutter and noise contamination (Torres and Ward 2014)
- Non-uniform beam filling (Ryzhkov 2006)
- System performance issues: Hardware instability, signal processing, mode of operation, post processing (QC)
- Inflated error values used in DA (e.g., 5dB vs 1dB for Z_H)

Forward Observation Operator: **H(x)**

- "the heart of a successful and accurate retrieval method is the forward model" (Rodgers 2000), not another set of Z-R type of empirical relations.
- A few polarimetric radar operators have been developed (Smith et al 1975, Zhang et al. 2001, Jung et al. 2008&2010, Ryzhkov et al. 2011). But the best operators have not been obtained
- The best observation operators is the ones that are
  - physically accurate/representative,
  - numerically efficient, and
  - easily differentiable



Formulation for PRD operators

Intrinsic variables:

$$Z_{hh,vv} = \frac{4\lambda^4}{\pi^4 |K|^2} \int \left| s_{hh,vv}(\pi, D) \right|^2 N(D)\, dD$$

$$Z_{DR} = 10 \log \frac{Z_{hh}}{Z_{vv}} \qquad Z_{H,V}(r) = 10\log_{10}\left[Z_{hh,vv}(r)\right]$$

$$\tilde{\rho}_{hv} = \frac{\int s_{hh}^*(\pi, D) s_{vv}(\pi, D) N(D)\, dD}{\left[\int |s_{hh}(\pi, D)|^2 N(D)\, dD \int |s_{vv}(\pi, D)|^2 N(D)\, dD\right]^{1/2}}$$

$$K_{DP} = \frac{180\lambda}{\pi} \int \mathrm{Re}[s_{hh}(0, D) - s_{vv}(0, D)] N(D)\, dD$$

Observed variables

$$Z'_{H,V}(r) = Z_{H,V}(r) - 2\int_0^r A_{H,V}(l)\, dl$$

$$Z'_{DR}(r) = Z_{DR}(r) - 2\int_0^r A_{DP}(l)\, dl$$

$$\phi_{DP} = 2\int_0^r K_{DP}(\ell)\, d\ell$$

$$\Phi_{DP} = \phi_{DP} + \delta = \frac{180}{\pi}(\phi_{dp} + \delta_d)$$

$$Z \equiv M_6 = \int D^6 N(D)\, dD$$

(Smith et al. 1975: Rayleigh scattering appr. & constant density)

$$Z_{hh,vv} = \frac{4\lambda^4}{\pi^4 |K|^2} N_0 \alpha^2 \Lambda^{-(\mu+2\beta+1)} \Gamma(\mu + 2\beta + 1$$

(Zhang et al. 2001&Jung et al. 2008: fitting & analytical integration

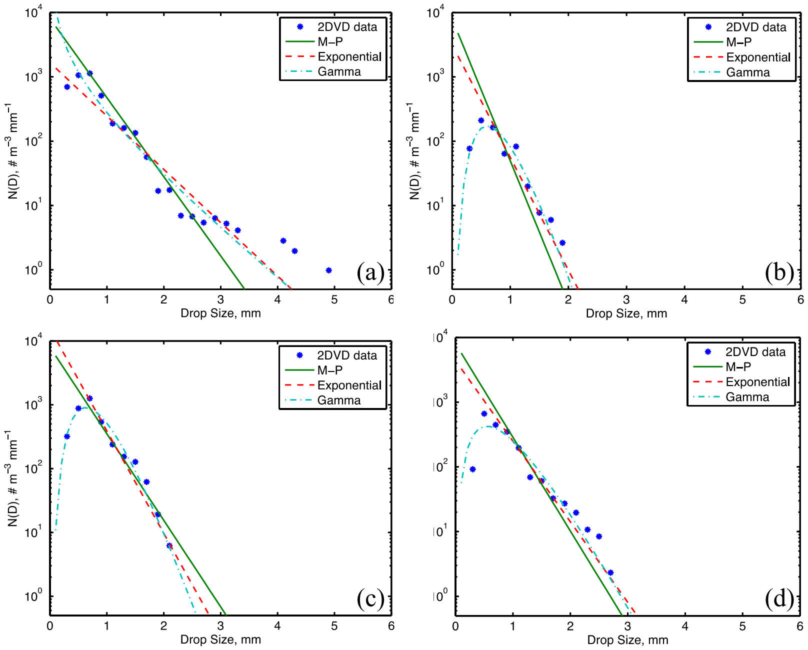
$$Z_{hh,vv} = \frac{4\lambda^4}{\pi^4 |K|^2} \sum_{i=1}^{L} \left| s_{hh,vv}(\pi, D_i) \right|^2 N(D_i) \Delta D$$

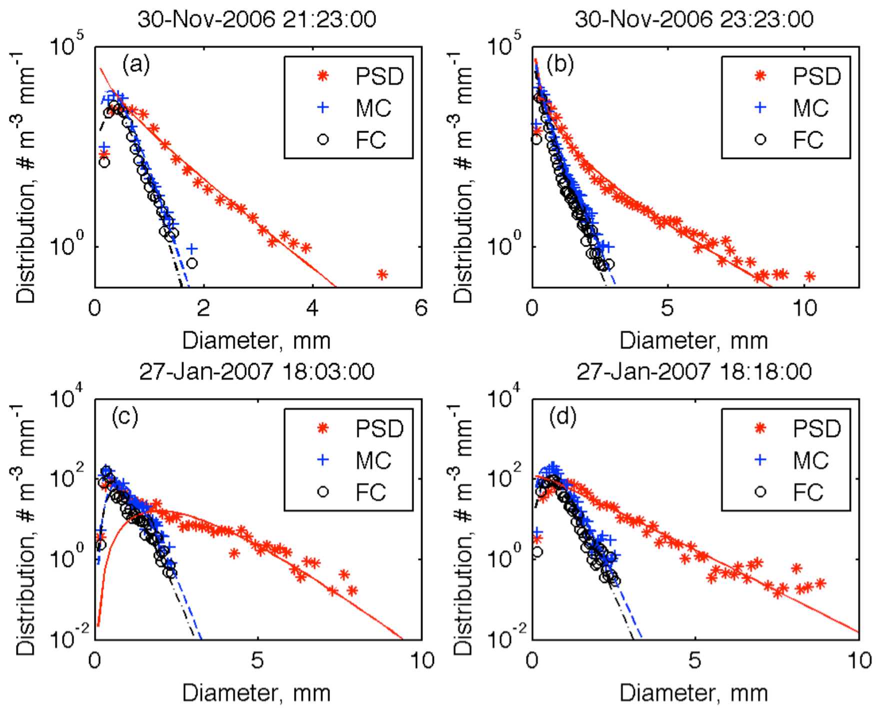
(Jung el al. 2010: T-matrix calculation, numerical integration)

- *Two issues*
  - *Microphysics (MP) modelling*
  - *Electromagnetic (EM) modelling*

Microphysics (MP) Modeling Error

- Drop/Particle Size Distribution (DSD/PSD) modelling





$$N(D) = N_0 \exp(-\Lambda D)$$

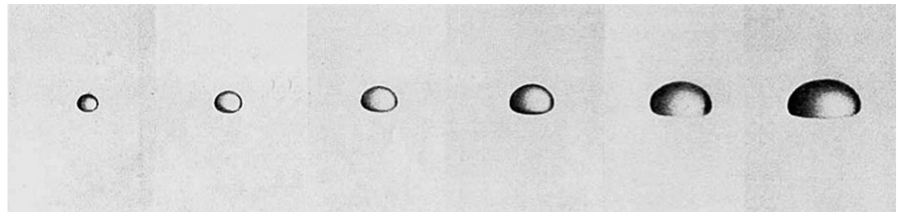
$$N(D) = N_0 D^{\mu} \exp(-\Lambda D)$$

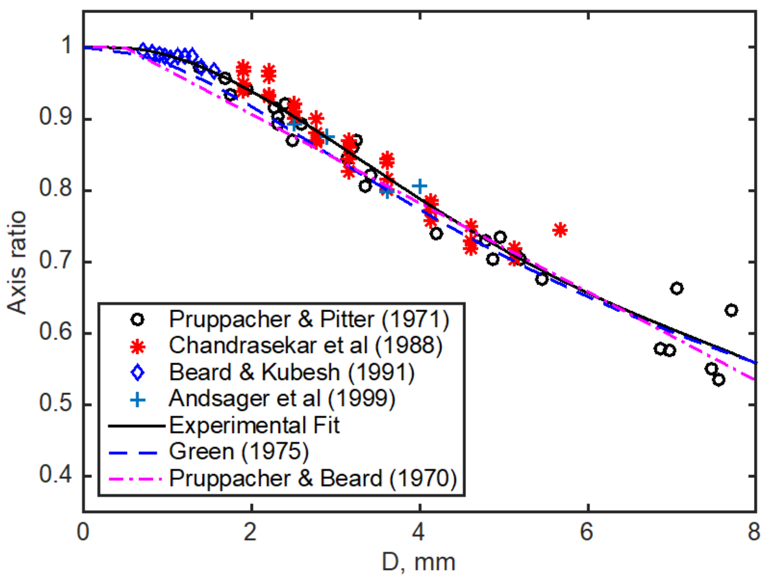
$$N_t = \int_0^{D_{\max}} N(D)\, dD$$

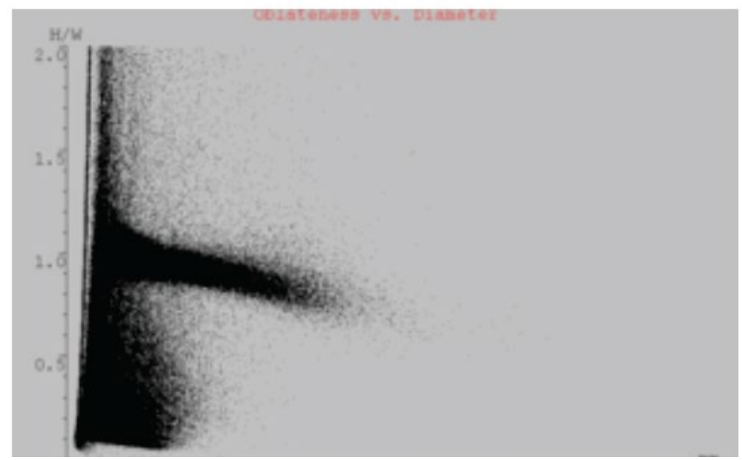
$$W \equiv \rho q_r = \frac{\pi}{6} \rho_w \int_0^{D_{\max}} D^3 N(D)\, dD$$

Microphysics (MP) Modeling Error (continued)

- Shape







$$\gamma = 0.9951 + 0.0251D - 0.03644D^2 + 0.005303D^3 - 0.0002492D^4$$

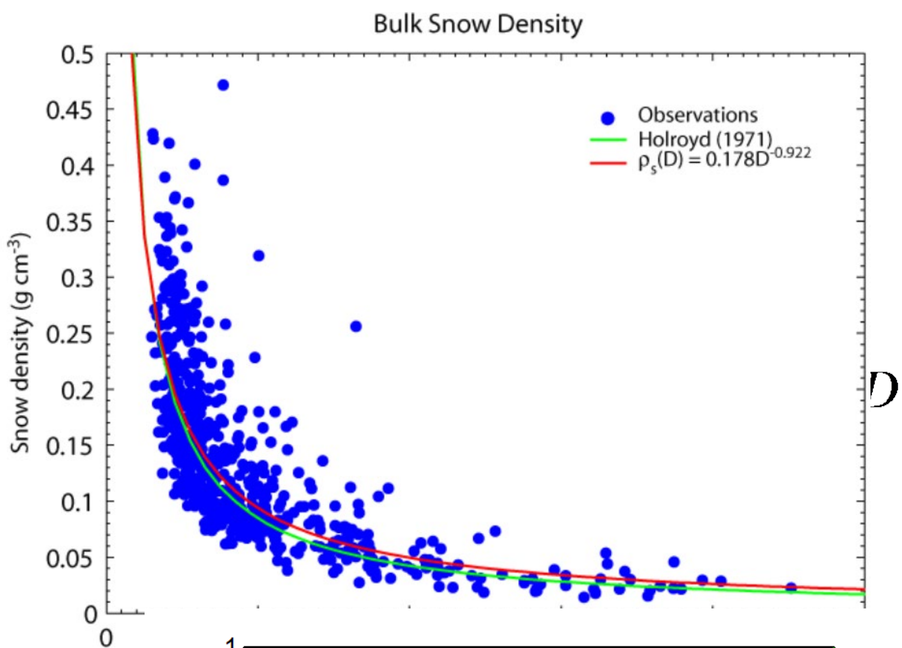
Microphysics (MP) Modeling Error (continued)

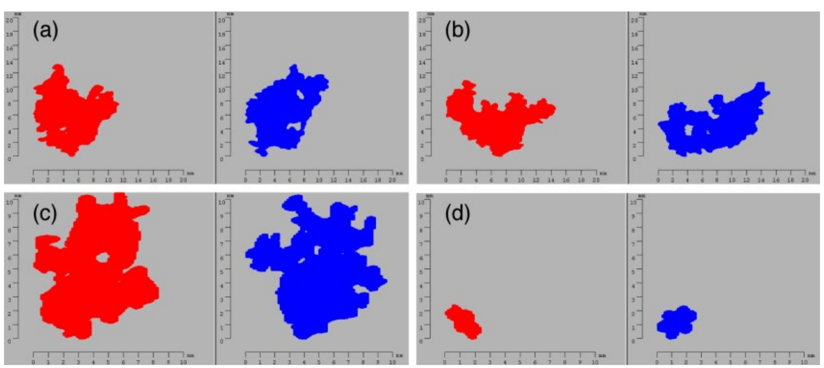
- Dry snow density

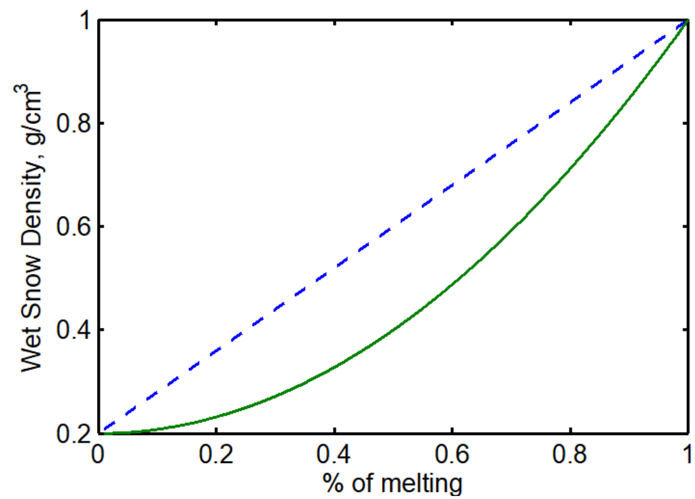
$$\rho_s = 0.178 D^{-0.922}$$

- Wet snow density

$$\rho_{ws} = \rho_{ds}(1-\gamma_w^2) + \rho_w \gamma_w^2$$



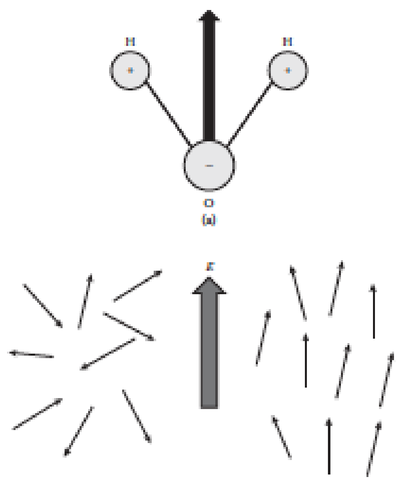


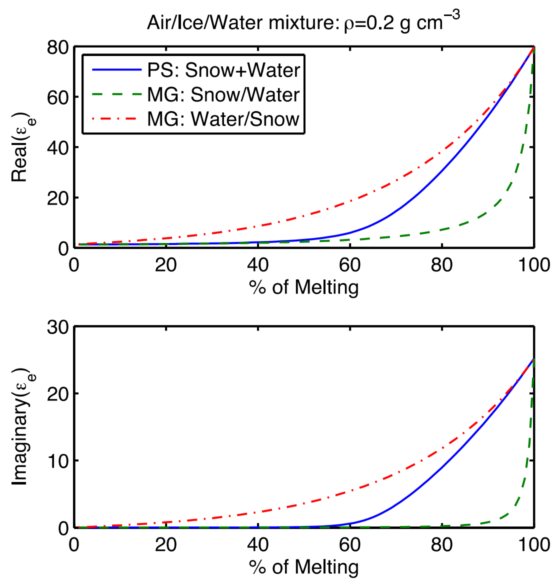


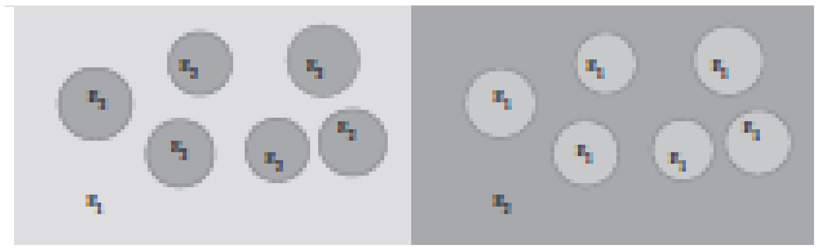
Electromagnetic (EM) Modelling Error

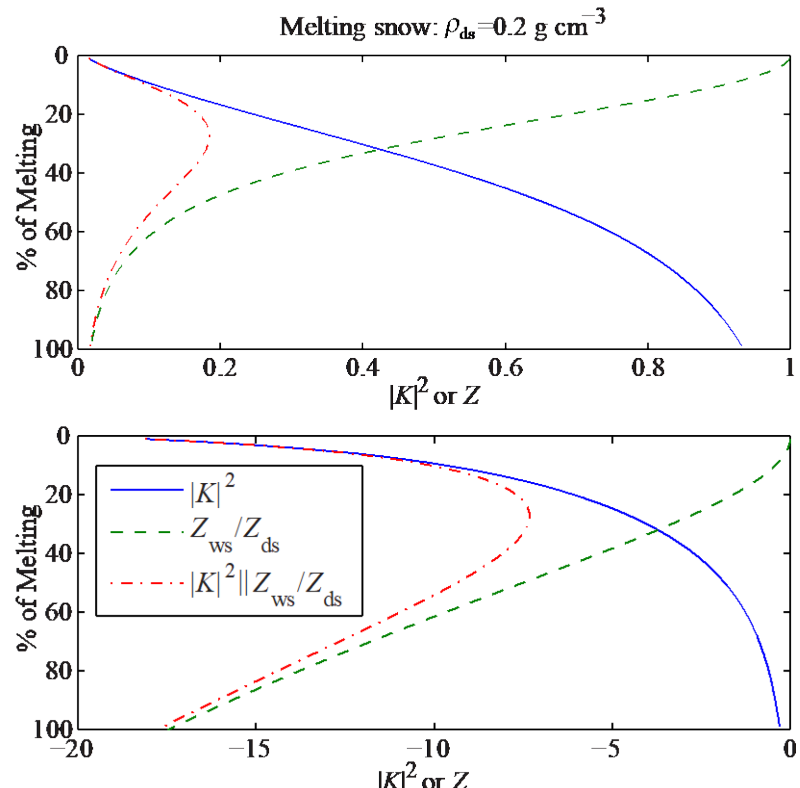
- Mixing vs layered model $\vec{P} = (\varepsilon_r - 1)\varepsilon_0 \vec{E}$
- Different mixing models: background vs inclusion

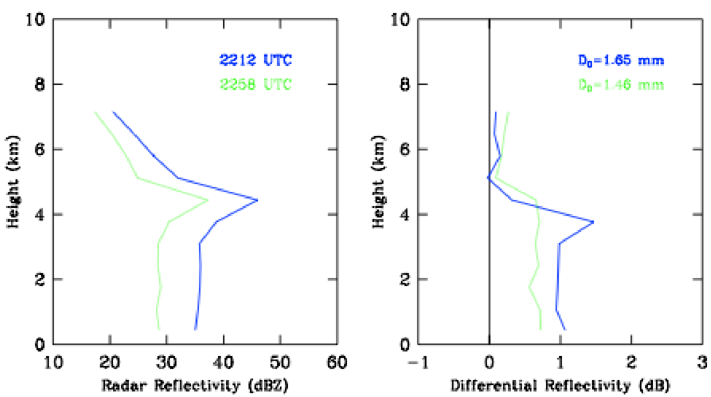
H_2O









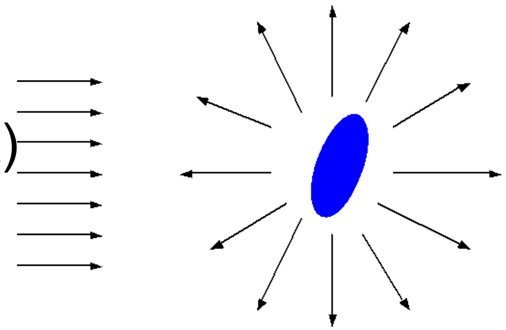


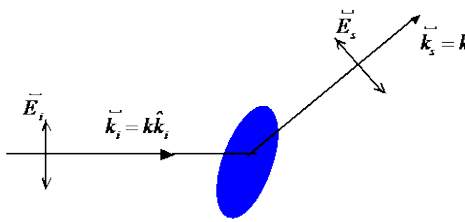
$$\eta = \frac{\pi^5}{\lambda^4} |K|^2 Z$$

$$|K|^2 = \left| \frac{\varepsilon_r - 1}{\varepsilon_r + 2} \right|^2$$

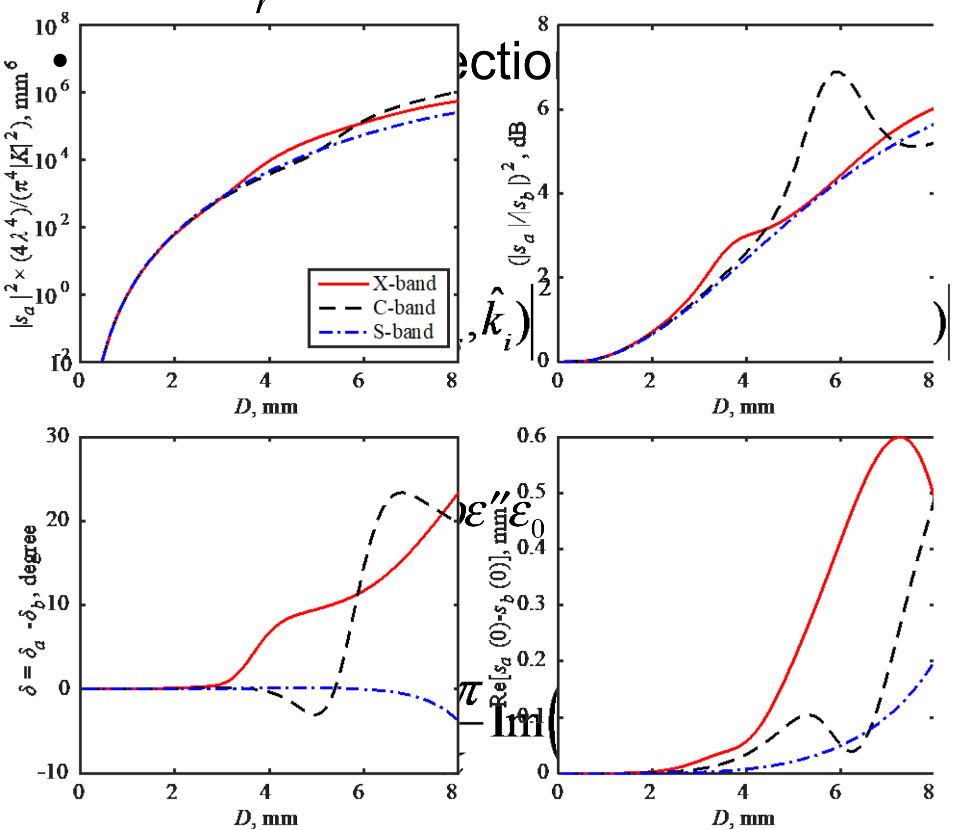
Electromagnetic (EM) Modelling Error (continued: scattering calculation)

- Dielectric constant calculation
- Scattering calculation (T-matrix)
- Scattering amplitude/matrix



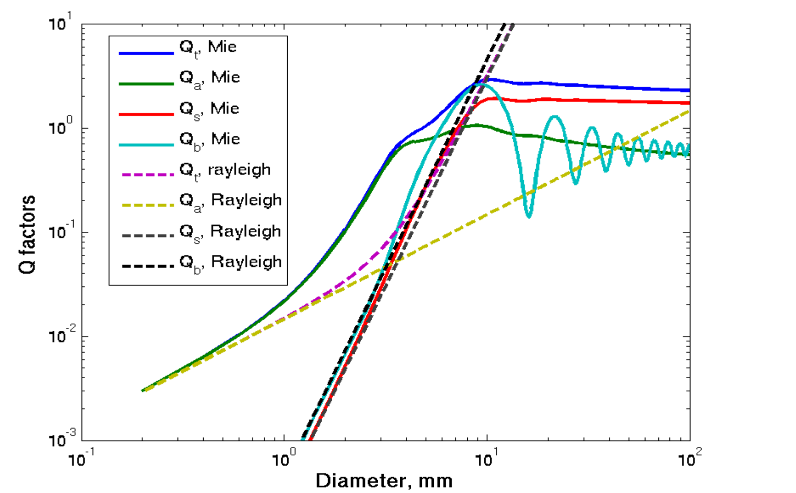


$$\vec{E}_s = \frac{e^{-jkr}}{r}\vec{s}(\hat{k}_s,\hat{k}_i);\quad \vec{E}_i = \hat{e}_i e^{-jkr}$$



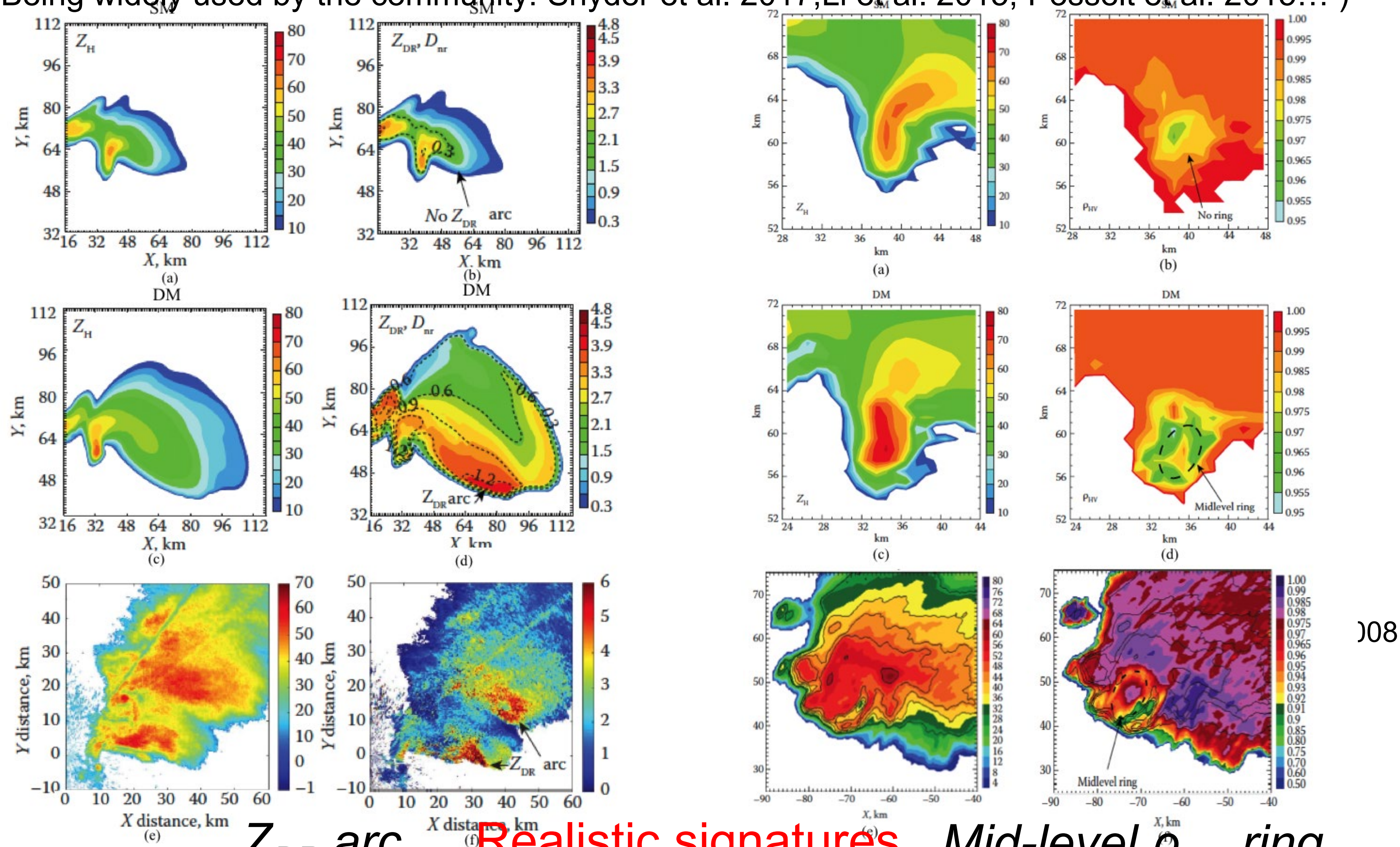
$$\begin{bmatrix} E_{sh} \\ E_{sv} \end{bmatrix} = \frac{e^{-jkr}}{r}\begin{bmatrix} s_{hh} & s_{hv} \\ s_{vh} & s_{vv} \end{bmatrix}\begin{bmatrix} E_{ih} \\ E_{iv} \end{bmatrix}$$

- Mie (1908) vs Rayleigh scattering (1871)
-



Simulation of Polarimetric Signatures with Single and Two Moment Microphysics

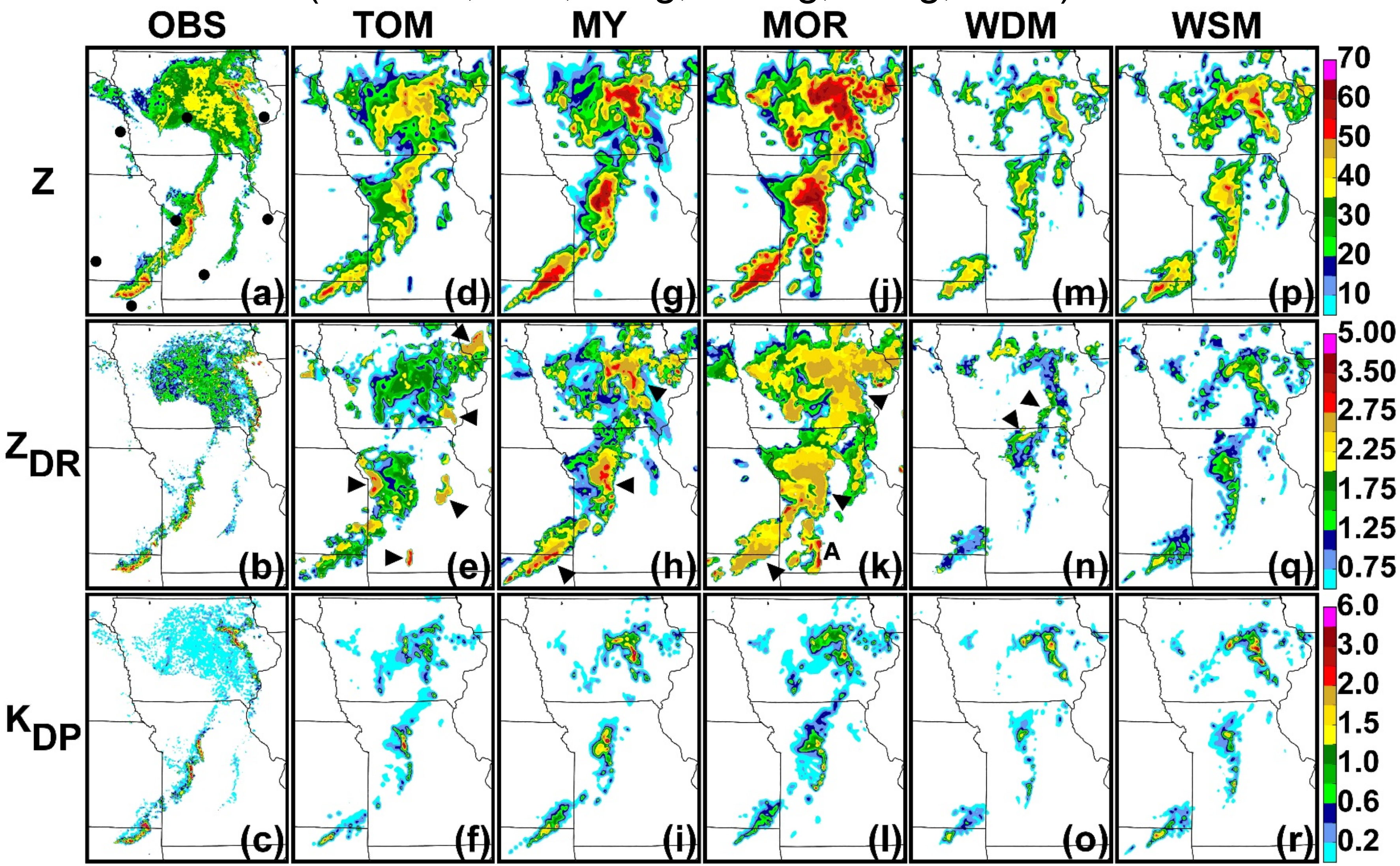
(Jung, Xue, Zhang 2008a&b, 2010; Program available on ARPS website
Being widely used by the community: Snyder et al. 2017,Li et al. 2015, Posselt et al. 2015…)



Z_{DR} *arc* Realistic signatures *Mid-level* ρ_{hv} *ring*

Simulated Polarumetric Signatures With Different Microphysics Parameterization Schemes

(Putnam, Xue, Jung, Zhang, Kong, 2016)



2100 UTC 20 May 2013

New Parameterized Dual-Pol Operators

- Most operational NWP models use one or double moment microphysics parameterization schemes
- Polarimetric radar variables are calculated and fitted with two state parameters of mean mass-weighted diameter (D_m) and water content ($W_x = \rho q_x$).
- For rain, we have:

$$Z_h \approx \rho_a q_r \left(-1.725 + 28.49 D_m + 36.046 D_m^2 - 1.746 D_m^3 - 0.4899 D_m^4\right)^2$$

$$Z_{dr} \approx 1.019 - 0.143 D_m + 0.317 D_m^2 - 0.065 D_m^3 + 0.00416 D_m^4$$

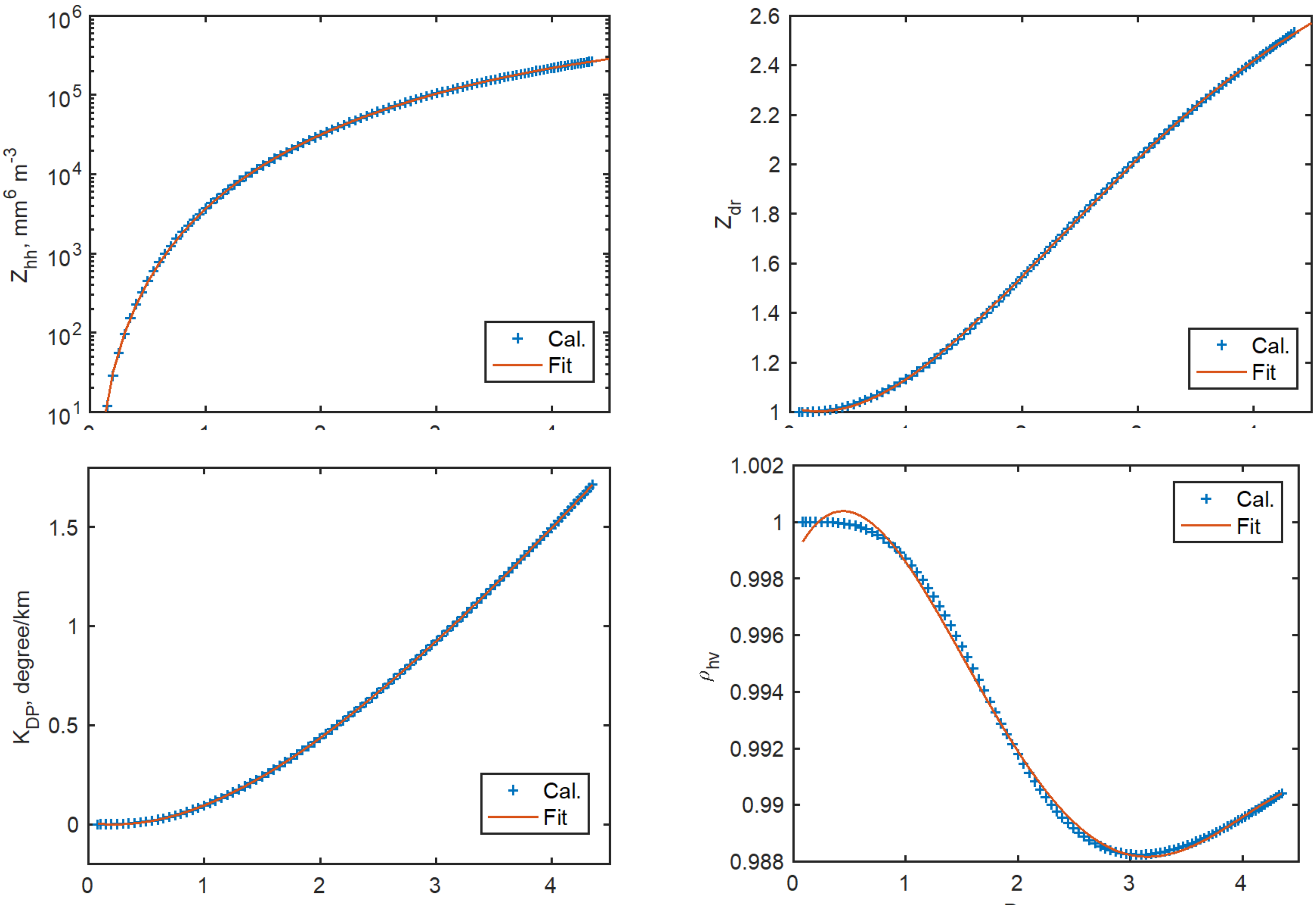
$$K_{DP} \approx \rho_a q_r \left(-0.0356 D_m + 0.132 D_m^2 + 0.00320 D_m^3 - 0.00302 D_m^4\right)$$

$$\rho_{hv} \approx 0.999 + 0.00826 D_m - 0.0117 D_m^2 + 0.00361 D_m^3 - 0.000344 D_m^4$$

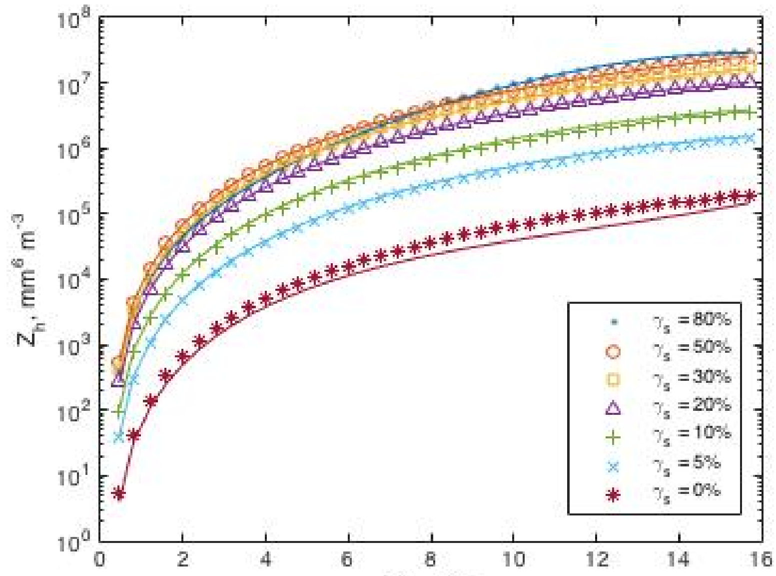
- For mixed phases, we use

$$V_X = \left(\rho q_x\right)^{\alpha} \sum_{m=0}^{M} \left(a_{Xm}(\gamma_x) D^m\right)^2 \qquad a_{Xm}(\gamma_x) = \sum_{n=1}^{N} c_{Xmn} \gamma_x^n$$

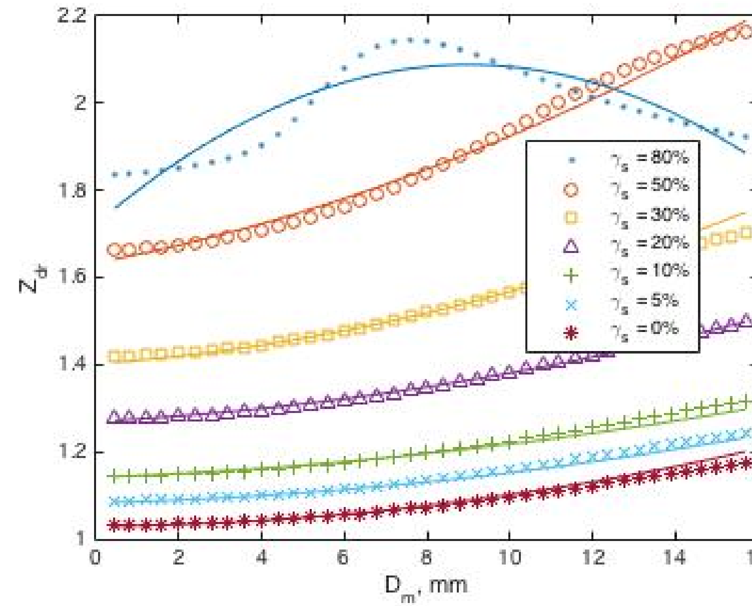
Rain



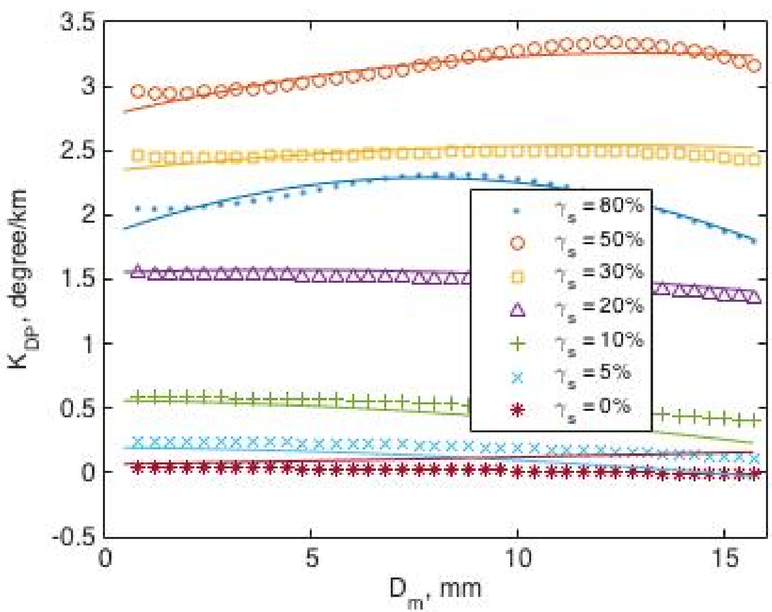
Snow



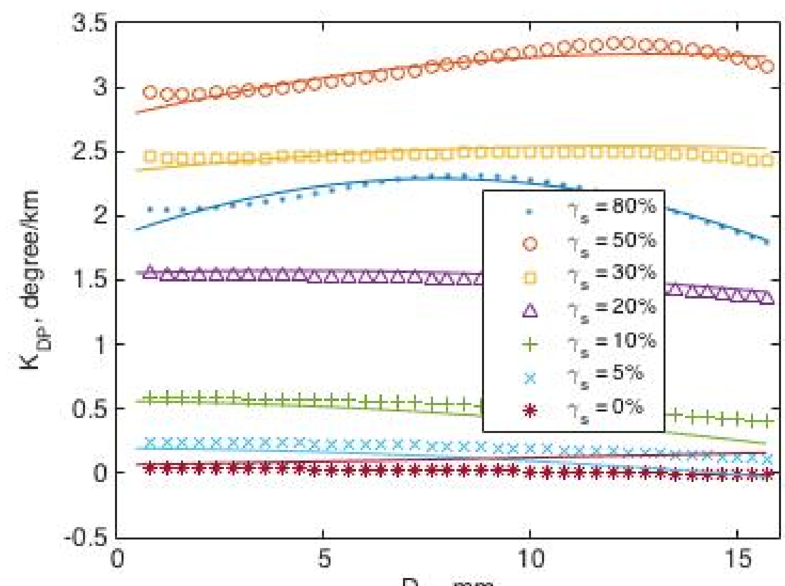
Z_h, $mm^6\ m^{-3}$
10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8
0 2 4 6 8 10 12 14 16
γ_s = 80%
γ_s = 50%
γ_s = 30%
γ_s = 20%
γ_s = 10%
γ_s = 5%
γ_s = 0%



Z_{dr}
1 1.2 1.4 1.6 1.8 2 2.2
0 2 4 6 8 10 12 14 16
D_m, mm
γ_s = 80%
γ_s = 50%
γ_s = 30%
γ_s = 20%
γ_s = 10%
γ_s = 5%
γ_s = 0%

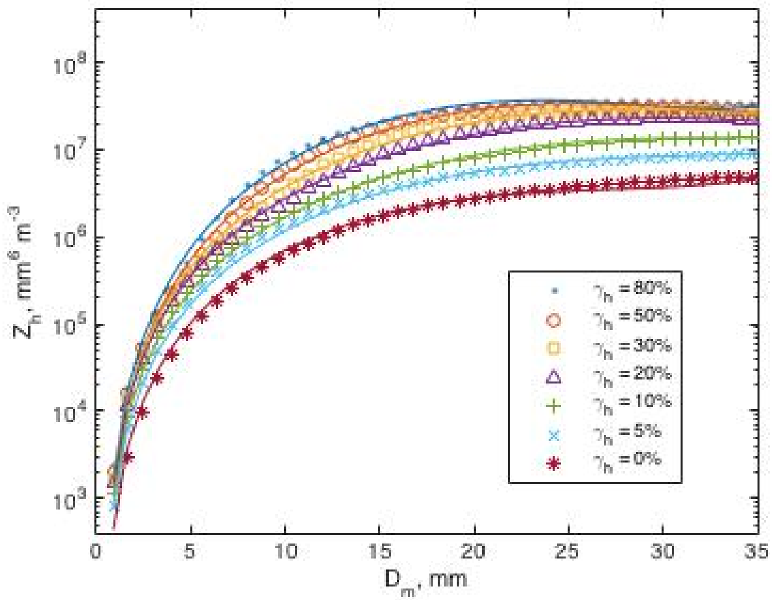


K_{DP}, degree/km
-0.5 0 0.5 1 1.5 2 2.5 3 3.5
0 5 10 15
D_m, mm
γ_s = 80%
γ_s = 50%
γ_s = 30%
γ_s = 20%
γ_s = 10%
γ_s = 5%
γ_s = 0%

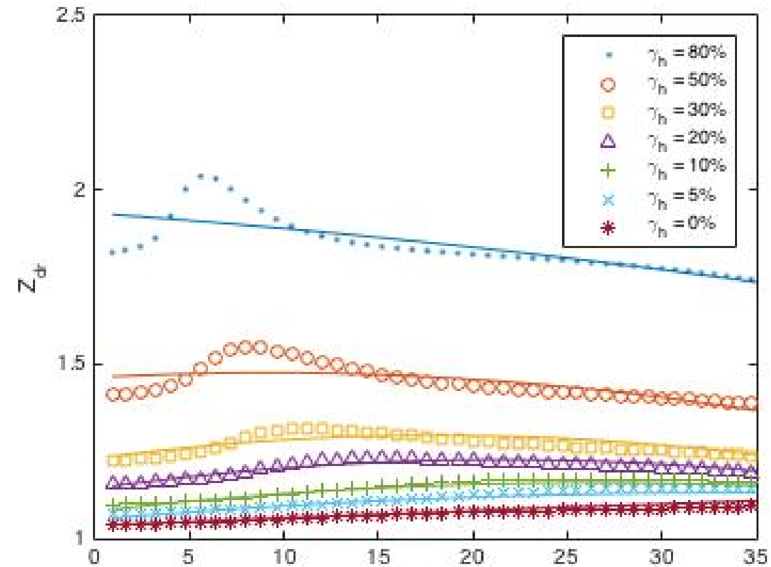


K_{DP}, degree/km
-0.5 0 0.5 1 1.5 2 2.5 3 3.5
0 5 10 15
γ_s = 80%
γ_s = 50%
γ_s = 30%
γ_s = 20%
γ_s = 10%
γ_s = 5%
γ_s = 0%

Hail



Z_h, $mm^6\ m^{-3}$
D_m, mm
γ_h = 80%
γ_h = 50%
γ_h = 30%
γ_h = 20%
γ_h = 10%
γ_h = 5%
γ_h = 0%



Z_{dr}
γ_h = 80%
γ_h = 50%
γ_h = 30%
γ_h = 20%
γ_h = 10%
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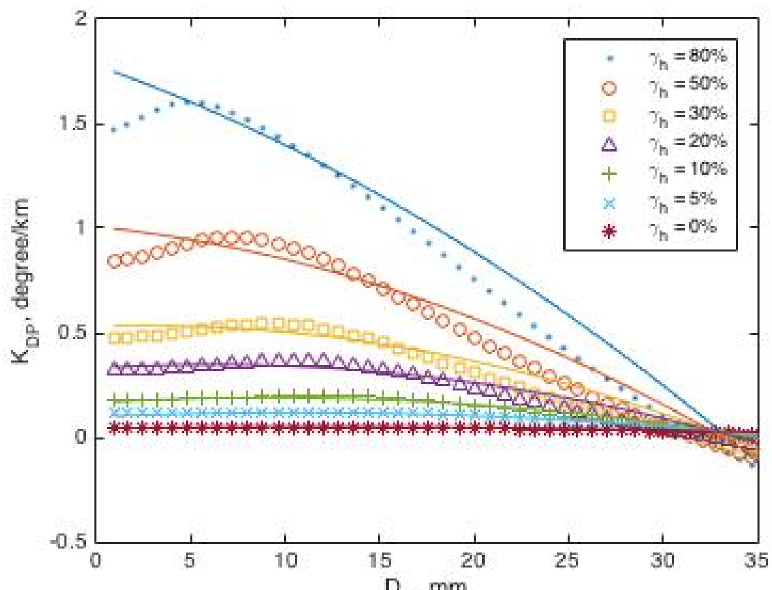
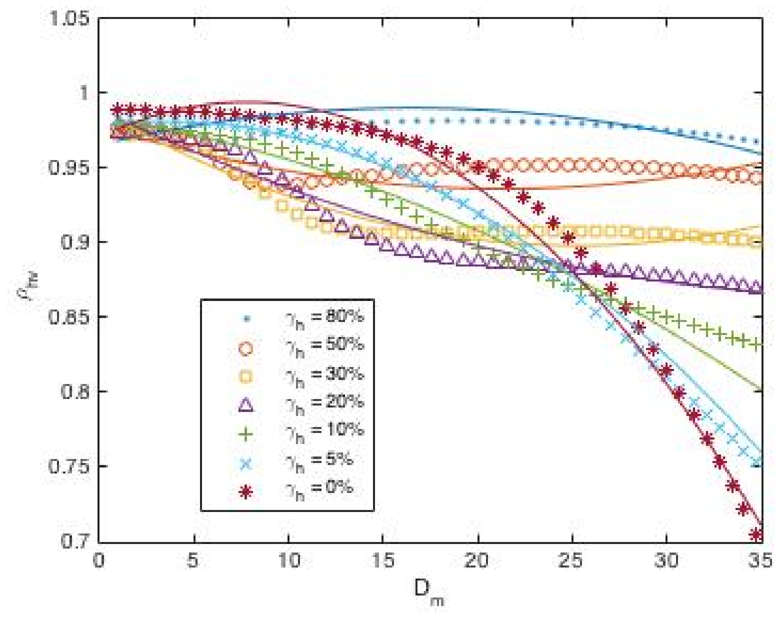
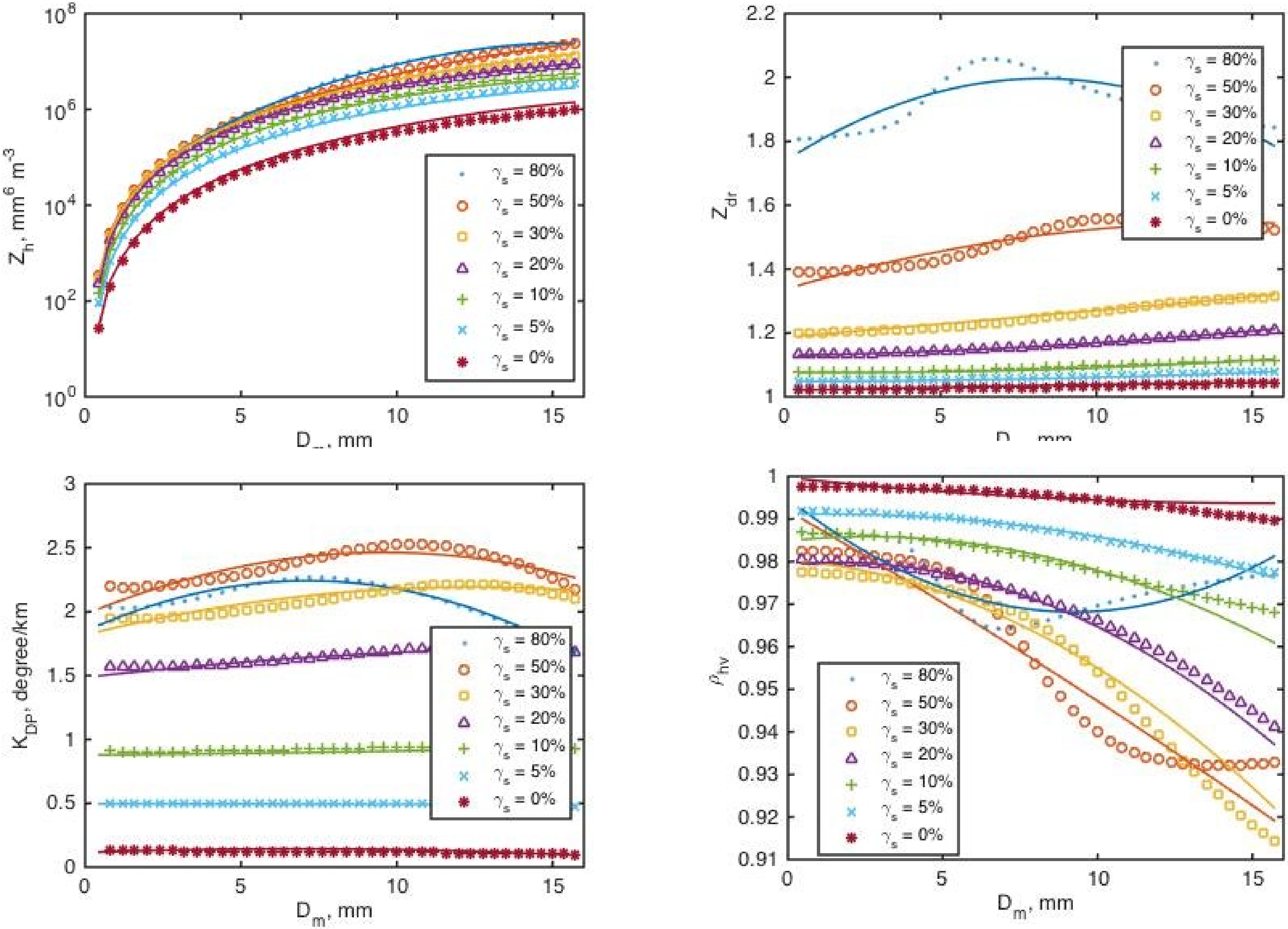


K_{DP}, degree/km
γ_h = 80%
γ_h = 50%
γ_h = 30%
γ_h = 20%
γ_h = 10%
γ_h = 5%
γ_h = 0%



ρ_{hv}
D_m
γ_h = 80%
γ_h = 50%
γ_h = 30%
γ_h = 20%
γ_h = 10%
γ_h = 5%
γ_h = 0%

Graupel



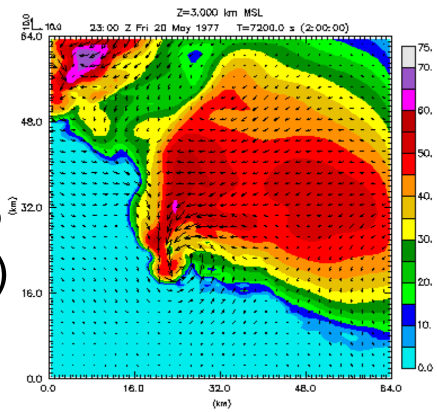
Z_h, mm^6 m^{-3}
D_m, mm
Z_{dr}
K_{DP}, degree/km
ρ_{hv}
γ_s = 80%
γ_s = 50%
γ_s = 30%
γ_s = 20%
γ_s = 10%
γ_s = 5%
γ_s = 0%

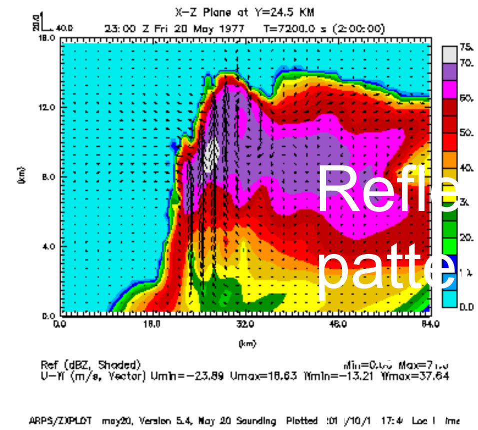
Idealized Case Study

- Integrate a convective scale model ARPS 2-h to get rain, snow, graupel, and hail mixing ratios for an idealized thunderstorm with the NSSL 2-moment microphysics scheme.
- Model parameters: dx = dy = 1 km, dz = 500 m; nx=ny=64; nz=35
- Use the above dual-pol simulators to calculate dual-pol variables: Z_h, Z_{DR}, K_{DP}, ρ_{hv}
- Compare the new simulators with the relatively complicated T-Matrix method published by Jung et al. (2010), and a relatively simple parameterized scheme.

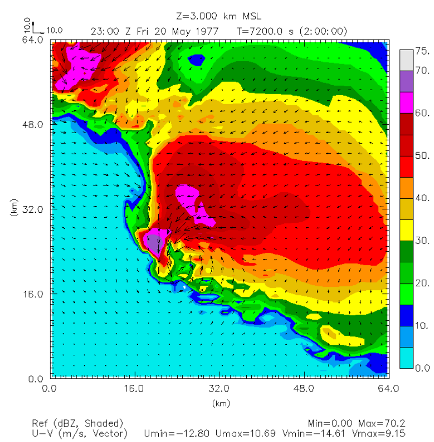
Reflectivity Z_H

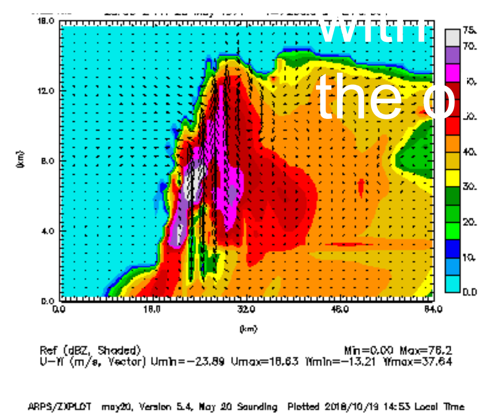
Old Operator
(Smith et al. 1975
Ferrier et al. 1994)





New
Operator



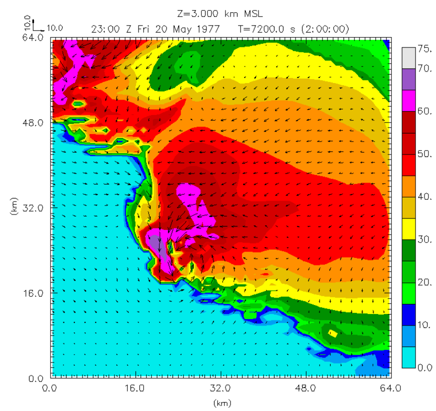


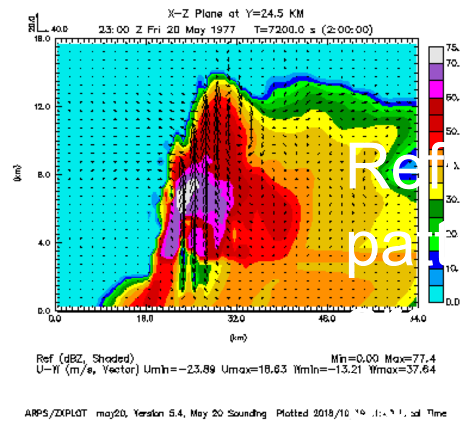
Horizontal

Vertical

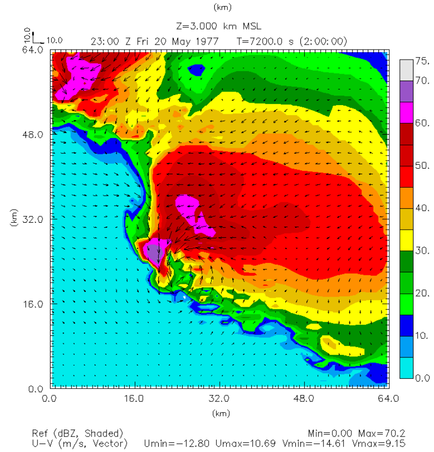
Reflectivity Z_H

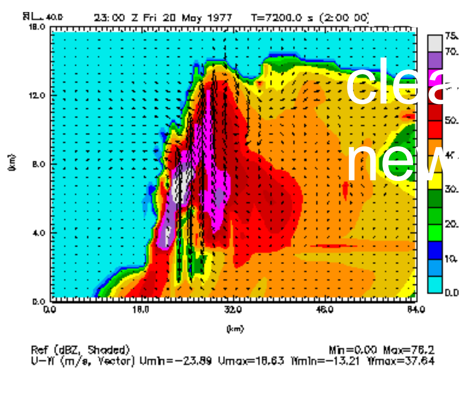
Old Operator
Jung et al.
(2010, MWR)





New
Operator



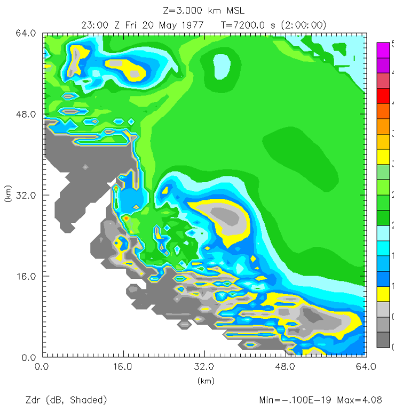


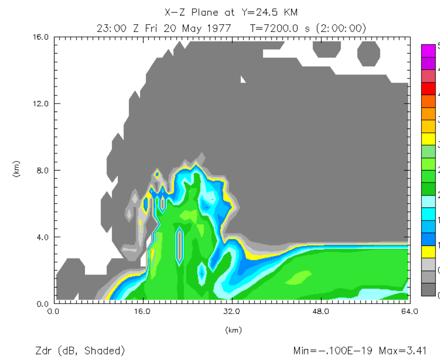
Horizontal

Vertical

Differential Reflectivity Z_{DR}

Jung et al. 2010





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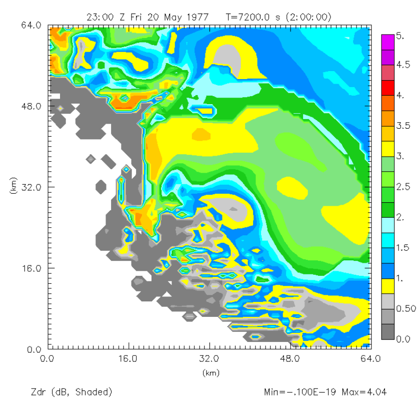
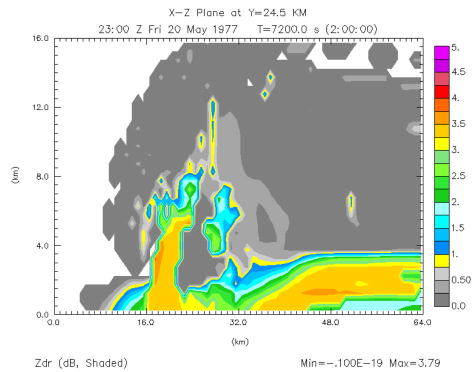


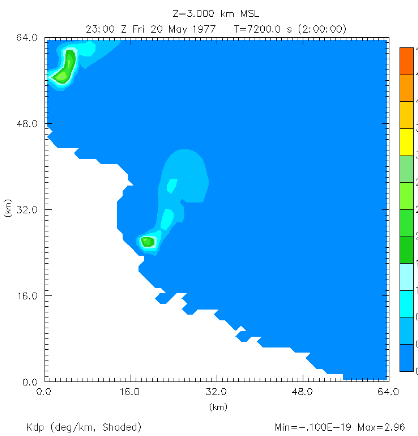


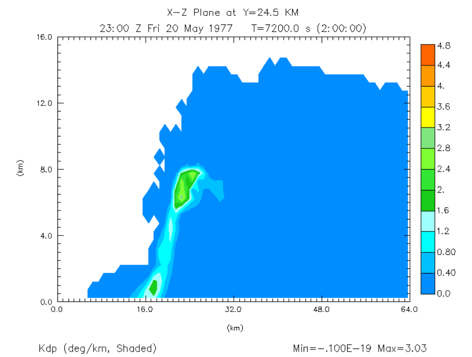
Horizontal

Vertical

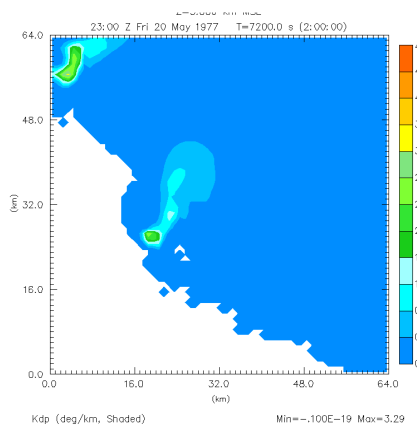
Specific differential phase K_{DP}

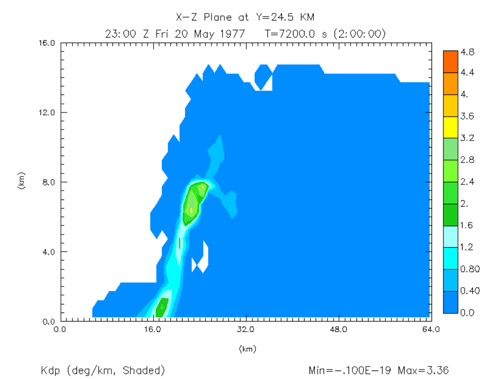
Jung et al. 2010





New Operator



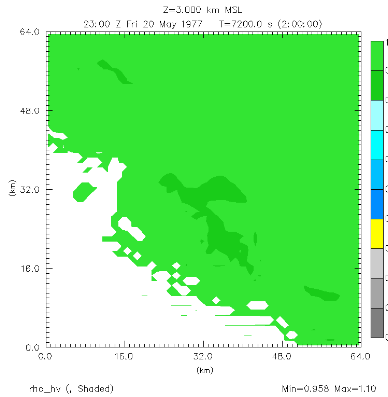


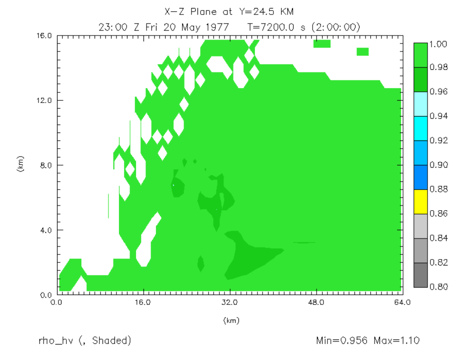
Horizontal

Vertical

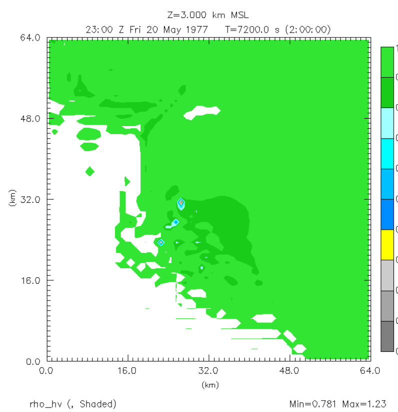
Co-polar correlation coefficient ρ_{hv}

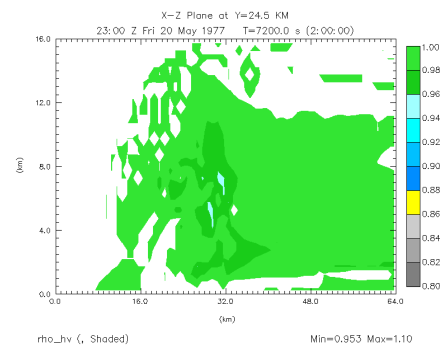
Jung et al. 2010





New Operator





Horizontal

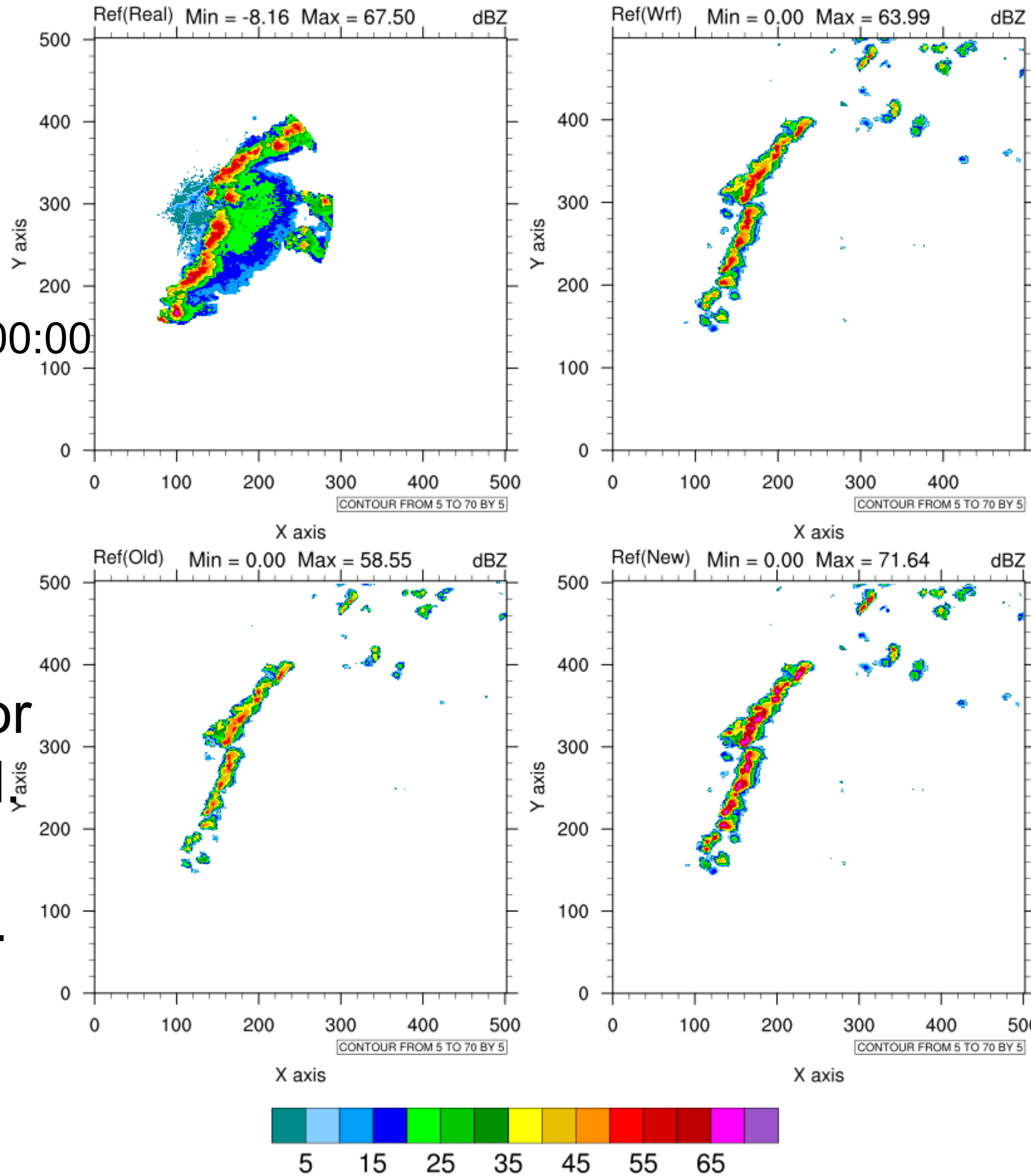
Vertical

Reflectivity Compare (Z=0)

Radar Obs.

KUEX
20180501 22:00:00

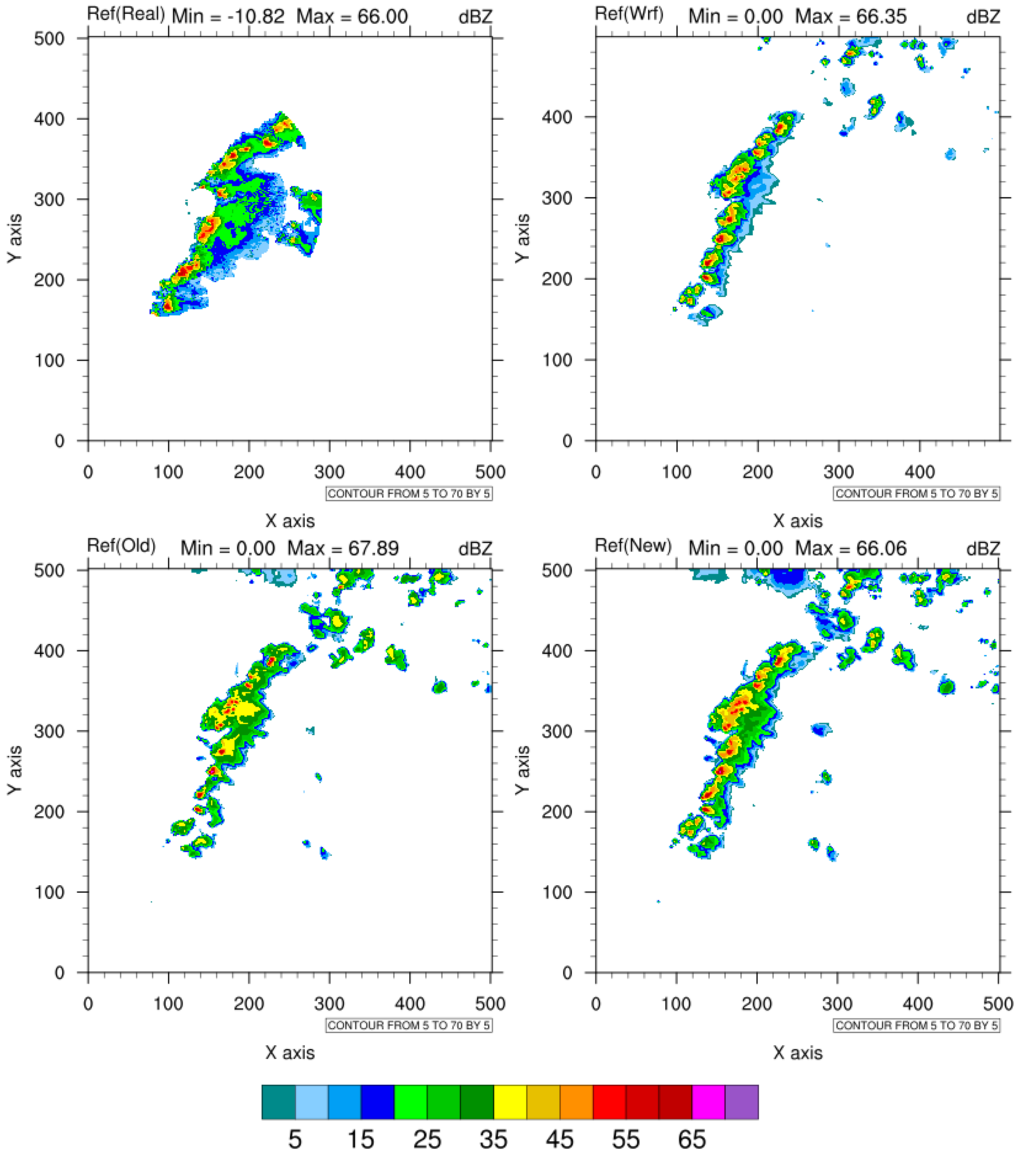
Jung et al. 2010.



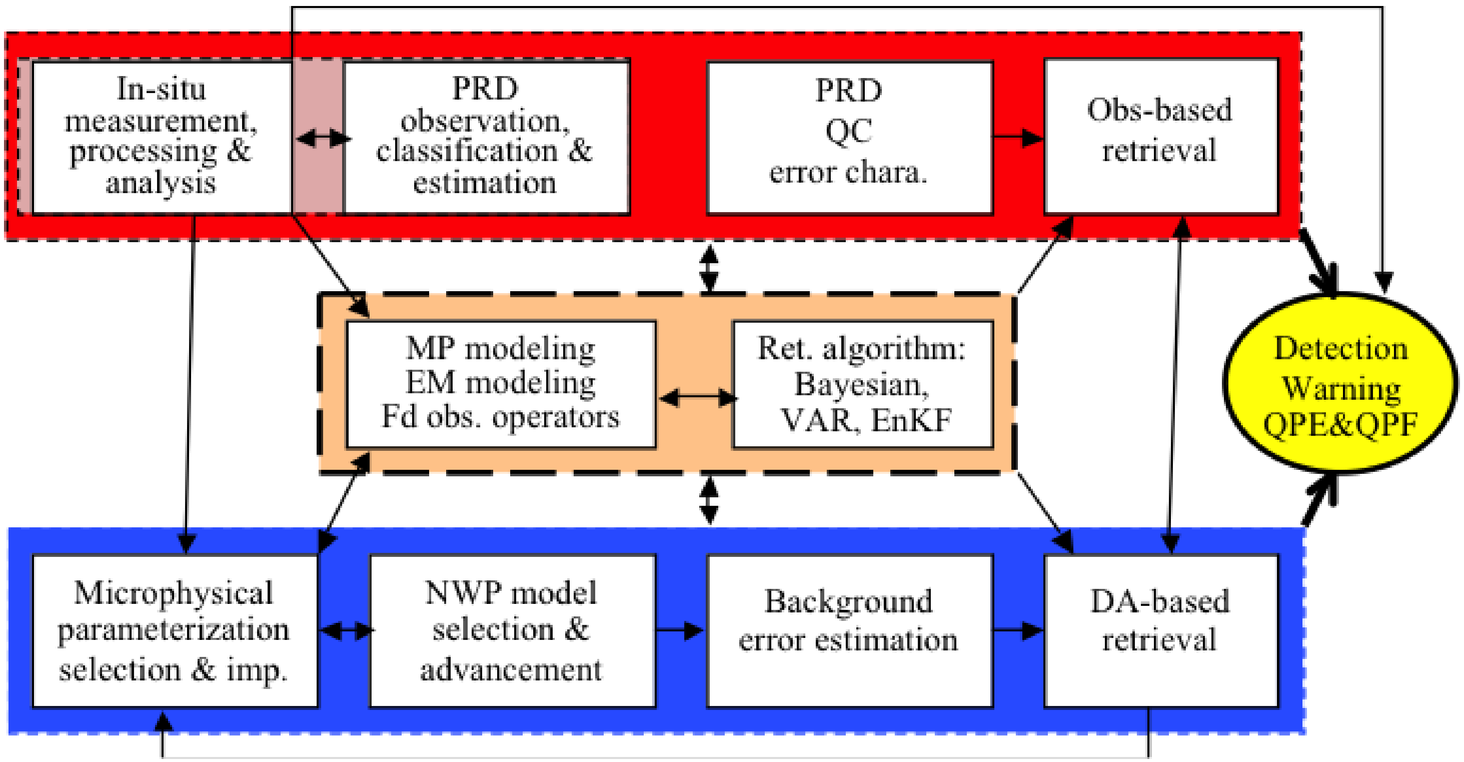
Old Operator (Smith et al. 1975 JAM; Ferrier et al. 1994, JAS

New Operator

Reflectivity Compare (Z=20)



To Achieve Our Goal of Improving Weather Understanding and Forecasts



- Efficiently utilize all the radar measured information and physics constraints
- All compatibility and connection among different components
- Minimize the uncertainty in all the components

Summary

- There are large uncertainties in ground-based radar observation and their error characterization (can be 100% error in Z_{DR} and K_{DP})
- There are uncertainties in radar observation operators (can be 10dB error in Z_H). A set of accurate and efficient radar operators is needed and being developed
- Apply the new operators to observation-based retrieval, showing the feasibility, and align with DA usage
- Simulated PRD from NWP model output and compared with the existing operators. Further test, enhancement and usage need to be explored
- The uncertainty in NWP model microphysics is still a major error source in DA use of PRD, comparison with real radar data is a way to reveal the deficiency and improve model physics.

Thank you!

Questions?