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國家實驗研究院

Preliminary Experimental Results of Polarimetric Radar Data Assimilation in the Case of Typhoon Soudelor (2015)

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Zrnic and Rythkov (1999)

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Polarimetric variables

Z_H (dBZ)	Horizontal reflectivity	$Z_H = 10\log Z_{hh}$
	Rain: 25~60 dBZ Snow: -10~35 dBZ Wet snow: 20~45 dBZ Hail: 50~65 dBZ Wet hail: 45~80 dBZ	
Z_{DR} (dB)	Differential reflectivity	$Z_{DR} = 10\log\frac{Z_{hh}}{Z_{vv}}$
	Rain: 0.5~4 dB Snow: -0.5~1 dB Wet snow: 0.5~3 dB Hail: -1~0.5 dB Wet hail: -1~6 dB	
LDR (dB)	Linear depolarization ratio	$LDR = 10\log\frac{Z_{hv}}{Z_{hh}}\ or\ 10\log\frac{Z_{vh}}{Z_{vv}}$
	Mixed phase, random orientation, irregular shape → high LDR	

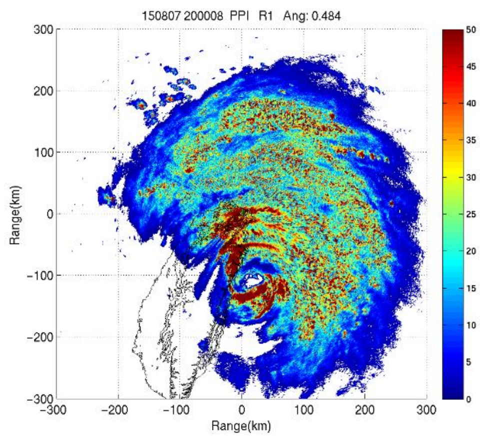
Zrnic and Rythkov (1999)

Polarimetric variables

ρ_{HV}	Co-polar correlation coefficient	$\rho_{HV} = \frac{\langle f_a^* f_b \rangle}{\sqrt{\langle \lvert f_a \rvert^2 \rangle \langle \lvert f_b \rvert^2 \rangle}}$
	Rain: > 0.95 Snow: > 0.95 Wet snow: 0.5~0.9 Hail: 0.9~0.95 Wet hail: > 0.9 Ground clutter: < 0.5	
ϕ_{DP} (°)	Differential phase	$\phi_{DP} = \phi_{hh} - \phi_{vv}$
	Increase as the radar beam penetrates oblate hydrometeors	
K_{DP} (°/km)	Specific differential phase	$K_{DP} = \frac{1}{2}\frac{d\phi_{DP}}{dr}$
	Rain: 0~20 °/km Snow: -1~1 °/km Wet snow: 0~1 °/km Hail: -1~2 °/km Wet hail: 0~20 °/km	

Capabilities of polarimetric radar data

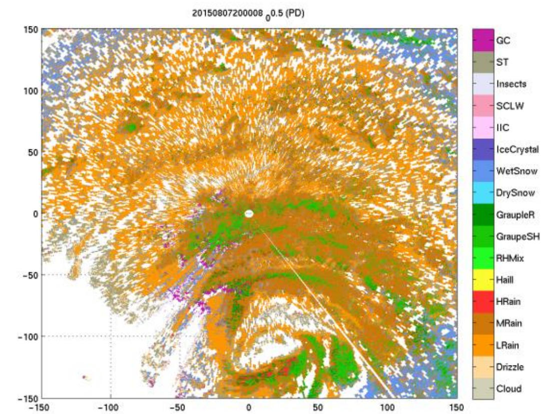
- Quantitative precipitation estimation



$R(K_{DP})$

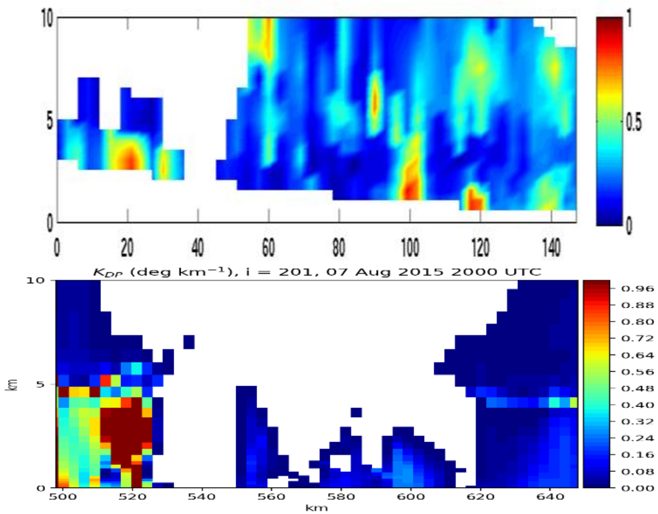
$R(Z_H, Z_{DR})$

- Hydrometeor classification



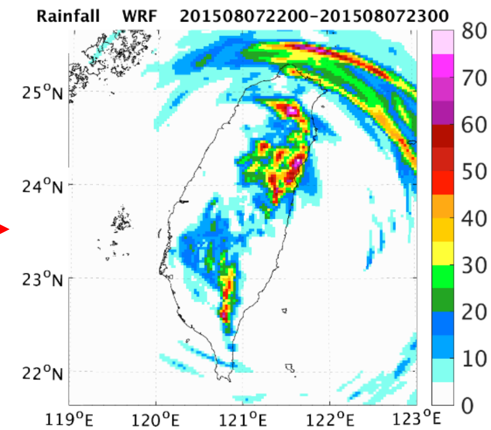
Fuzzy logic

- Verification of numerical simulation



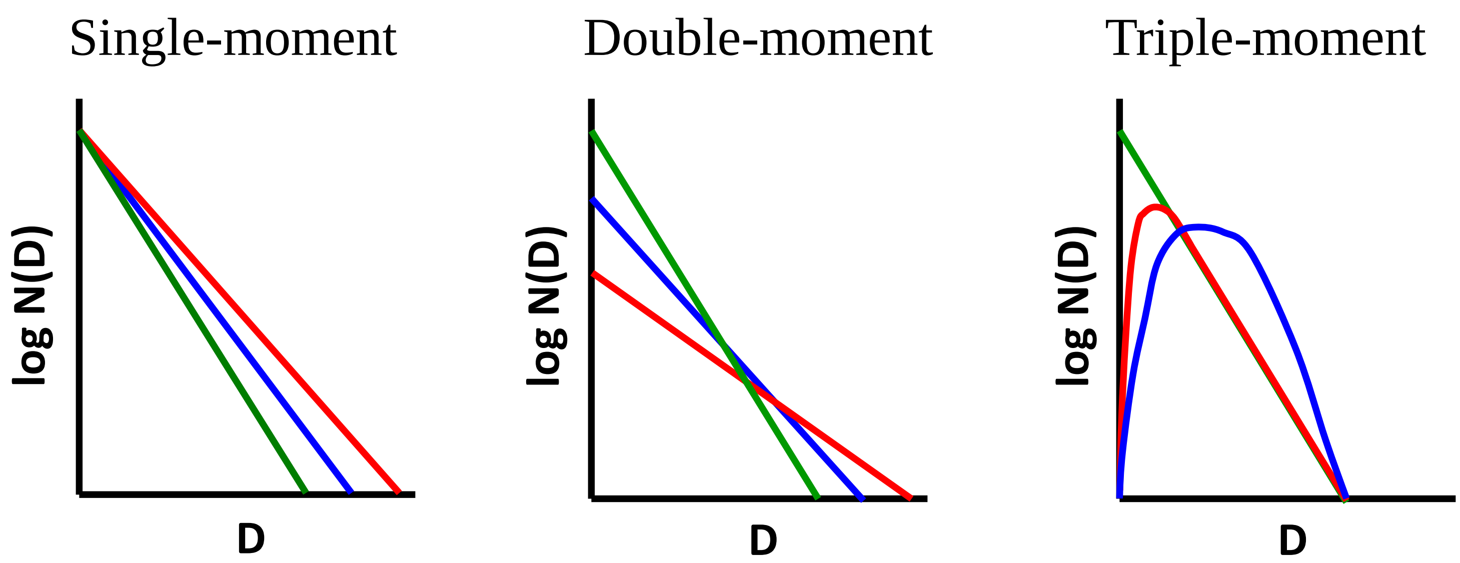
Observation operator

- Data assimilation



Bulk microphysical schemes

- Gamma drop size distribution: $N(D) = N_0 D^{\mu} e^{-\Lambda D}$



	Single-moment	Double-moment	Triple-moment
Fixed parameters:	N_0 、μ	μ	
Variable parameters:	Λ	N_0 、Λ	N_0 、μ 、Λ
Prognostic variables:	q	q 、N_t	q 、N_t 、Z_H

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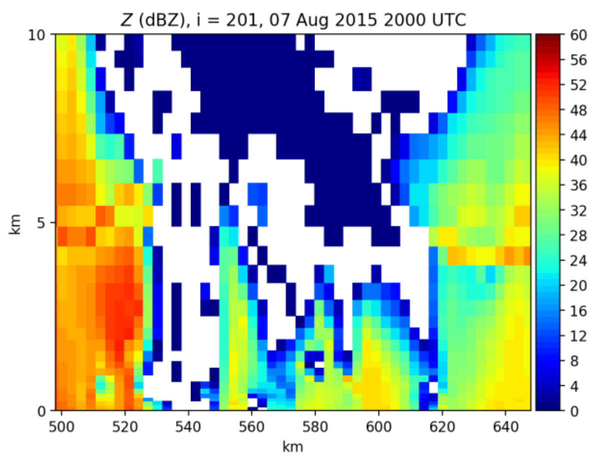
Examples of bulk microphysical schemes

Scheme	Prognostic q	Prognostic N_t	Constant N_0 ($\mathrm{m^{-4}}$)	μ	Constant ρ ($\mathrm{kg\ m^{-3}}$)
Lin	q_c q_r q_i q_s $q_{g(h)}$		$N_{0r}: 8e6$ $N_{0s}: 3e6$ $N_{0g}: 4e6$	$\mu_{rsgh}: 0$	$\rho_r: 1000$ $\rho_s: 100$ $\rho_g: 400$
WSM6			$N_{0r}: 8e6$ $N_{0s}: 2e6$ $N_{0g}: 4e6$ $(N_{0h}: 4e4)$		$\rho_r: 1000$ $\rho_s: 100$ $\rho_g: 500$ $\rho_h: 700$
Goddard			$N_{0r}: 8e6$ $N_{0s}: 1.6e7$ $N_{0g}: 4e6$ $(N_{0h}: 2e5)$		$\rho_r: 1000$ $\rho_s: 100$ $\rho_g: 400$ $\rho_h: 917$
WDM6		N_n N_c N_r	$N_{0s}: 2e6$ $N_{0g}: 4e6$ $(N_{0h}: 4e4)$	$\mu_r: 1$ $\mu_{sgh}: 0$	$\rho_r: 1000$ $\rho_s: 100$ $\rho_g: 500$ $\rho_h: 700$
Morrison		N_r N_i N_s $N_{g(h)}$		$\mu_{rsgh}: 0$	$\rho_r: 997$ $\rho_s: 100$ $\rho_g: 400$ $\rho_h: 900$
Milbrandt -Yau	q_c q_r q_i q_s q_g q_h	N_c N_r N_i N_s N_g N_h			$\rho_r: 1000$ $\rho_s: 100$ $\rho_g: 400$ $\rho_h: 900$

Melting ice model

- Rain-snow (rain-graupel, rain-hail) mixture exists when rain and snow (graupel, hail) coexist.
- The fraction of rain or snow in the mixture form: $F = F_{max}[\min(q_s/q_r\,, q_r/q_s)]^{0.3}$
- The mixing ratio of the rain-snow mixture: $q_{rs} = F(q_r + q_s)$
- The water fraction within the rain-snow mixture: $f_w = q_r/(q_r + q_s)$
- The density of the rain-snow mixture: $\rho_{rs} = \rho_r f_w^2 + \rho_s(1 - f_w^2)$



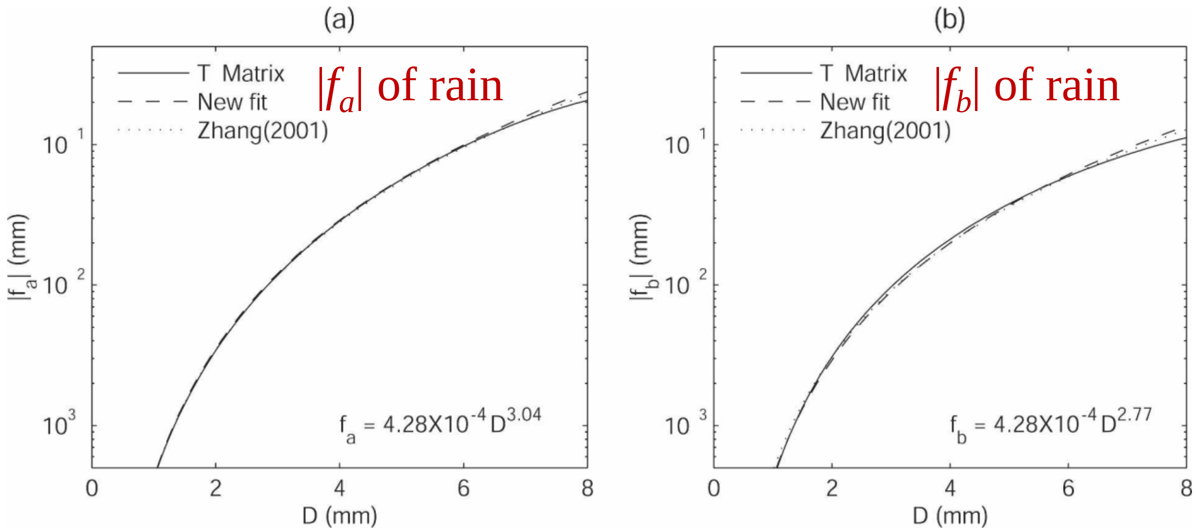
Prognostic q	$F_{max,s}$	$F_{max,g}$	$F_{max,h}$
$q_r\ q_s\ q_g$	0.5	0.4	
$q_r\ q_s\ q_h$	0.5		0.3
$q_r\ q_s\ q_g\ q_h$	0.35	0.25	0.2

Mixed-phase hydrometeor species q_{rs}, q_{rg} and/or q_{rh} are created.

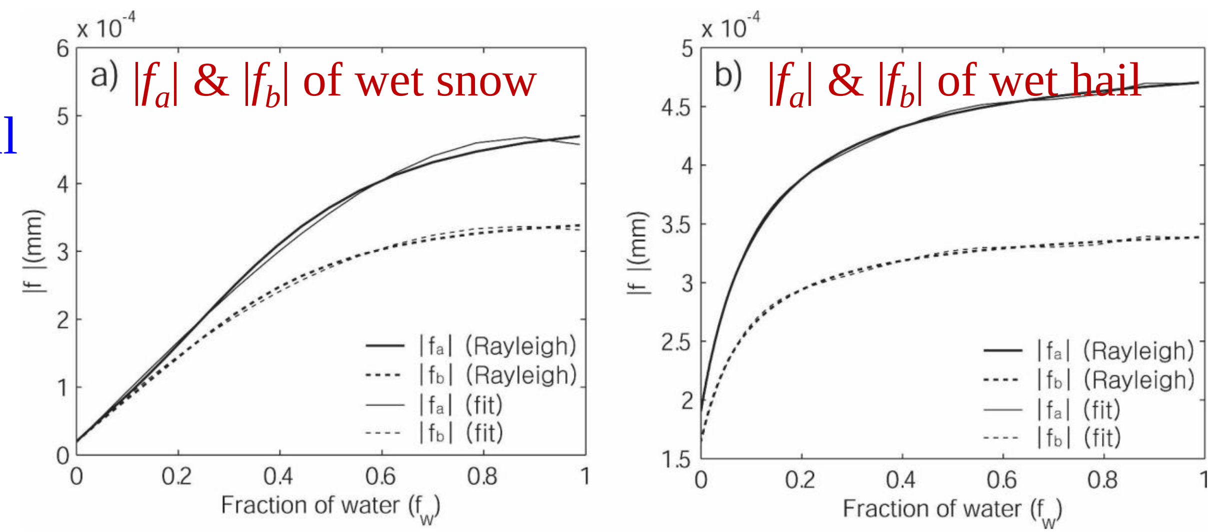
Backscattering amplitudes for H & V polarizations

Horizontal: $|f_a| = \alpha_a D^{\beta_a}$ (mm) Vertical: $|f_b| = \alpha_b D^{\beta_b}$ (mm)

- **Rain:**
  1. T-matrix method
  2. Function of:
     - Wavelength
     - Temperature
     - Drop size
     - Drop axis ratio



- **Dry/wet snow/graupel/hail**
  1. Rayleigh scattering approximation
     $\beta_a = \beta_b = 3$
  2. Drop axis ratio = 0.75



Backscattering amplitudes for H & V polarizations

Horizontal: $\left|f_a\right| = \alpha_a D^{\beta_a}$ (mm) Vertical: $\left|f_b\right| = \alpha_b D^{\beta_b}$ (mm)

	α_a	β_a	α_b	β_b
Rain	4.28×10^{-4}	3.04	4.28×10^{-4}	2.77
Snow	1.94×10^{-5}	3	1.91×10^{-5}	3
Wet snow	$(0.194+7.094f_w+2.135f_w^2-5.225f_w^3)\times10^{-4}$	3	$(0.191+6.916f_w-2.841f_w^2-1.160f_w^3)\times10^{-4}$	3
Graupel	8.1×10^{-5}	3	7.6×10^{-5}	3
Wet graupel	$\left(\begin{matrix}0.081+2.04f_w-7.39f_w^2+18.14f_w^3\\-26.02f_w^4+19.37f_w^5-5.75f_w^6\end{matrix}\right)\times10^{-3}$	3	$\left(\begin{matrix}0.076+1.74f_w-7.52f_w^2+20.22f_w^3\\-30.42f_w^4+23.31f_w^5-7.06f_w^6\end{matrix}\right)\times10^{-3}$	3
Hail	1.91×10^{-4}	3	1.65×10^{-4}	3
Wet hail	$\left(\begin{matrix}0.191+2.39f_w-12.57f_w^2+38.71f_w^3\\-65.53f_w^4+56.16f_w^5-18.98f_w^6\end{matrix}\right)\times10^{-3}$	3	$\left(\begin{matrix}0.165+1.72f_w-9.92f_w^2+32.15f_w^3\\-56.0f_w^4+48.83f_w^5-16.69f_w^6\end{matrix}\right)\times10^{-3}$	3

Consider the cants of hydrometeors

	Mean of canting angles	SD of canting angles
Rain	$\bar{\phi} = 0°$	$\sigma = 0°$
Snow	$\bar{\phi} = 0°$	$\sigma = 20°$
Wet snow	$\bar{\phi} = 0°$	$\sigma = 20°$
Graupel / hail	$\bar{\phi} = 0°$	$\sigma = 60°$
Wet graupel / wet hail	$\bar{\phi} = 0°$	$\sigma = 60°(1 - cf_w)$ $c = 4q_{rg,rh}$ $(\text{when } q_{rg,rh} < 0.2 \text{ g kg}^{-1})$ 0.8 $(\text{when } q_{rg,rh} \geq 0.2 \text{ g kg}^{-1})$

$$A = \langle \cos^4 \phi \rangle = \frac{1}{8}\left(3 + 4\cos 2\bar{\phi} e^{-2\sigma^2} + \cos 4\bar{\phi} e^{-8\sigma^2}\right)$$

$$B = \langle \sin^4 \phi \rangle = \frac{1}{8}\left(3 - 4\cos 2\bar{\phi} e^{-2\sigma^2} + \cos 4\bar{\phi} e^{-8\sigma^2}\right)$$

$$C = \langle \sin^2 \phi \cos^2 \phi \rangle = \frac{1}{8}\left(1 - \cos 4\bar{\phi} e^{-8\sigma^2}\right)$$

$$C_k = \langle \cos 2\phi \rangle = \cos 2\bar{\phi} e^{-2\sigma^2}$$

Diagnose gamma distribution parameters

- Gamma function: $\int_0^{\infty} t^b e^{-at} dt = \frac{\Gamma(b+1)}{a^{b+1}}$
- Total number concentration: $\boldsymbol{N_t} = \int_0^{\infty} \boldsymbol{N_0} D^{\mu} e^{-\boldsymbol{\Lambda} D} dD = \boldsymbol{N_0} \frac{\Gamma(\mu+1)}{\boldsymbol{\Lambda}^{\mu+1}}$
- Mixing ratio:

$$\boldsymbol{q} = \frac{\rho \int_0^{\infty} \frac{4}{3}\pi \left(\frac{D}{2}\right)^3 \boldsymbol{N_0} D^{\mu} e^{-\boldsymbol{\Lambda} D} dD}{\rho_a}$$

$$\frac{\rho_a \boldsymbol{q}}{\rho} = \frac{\pi \boldsymbol{N_0}}{6} \frac{\Gamma(\mu+4)}{\boldsymbol{\Lambda}^{\mu+4}} = \frac{\pi \boldsymbol{N_t} \Gamma(\mu+4)}{6\Gamma(\mu+1)\boldsymbol{\Lambda}^3}$$

Single-moment scheme: $\boldsymbol{\Lambda} = \left[\frac{\pi \rho N_0 \Gamma(\mu+4)}{6\rho_a \boldsymbol{q}}\right]^{\frac{1}{\mu+4}}$

Double-moment scheme: $\boldsymbol{\Lambda} = \left[\frac{\pi \rho \boldsymbol{N_t} \Gamma(\mu+4)}{6\rho_a \boldsymbol{q} \Gamma(\mu+1)}\right]^{\frac{1}{3}}$

Calculate Z_H, Z_{DR} and K_{DP}

$$Z_{hh}=\frac{4\lambda^4}{\pi^4|K_w|^2}\int_0^\infty (A|f_a|^2+B|f_b|^2+2C|f_a||f_b|)N_0D^\mu e^{-\Lambda D}dD$$

$$=\frac{4\lambda^4N_0\Gamma(2\beta_a+\mu+1)}{\pi^4|K_w|^2}\left[\frac{6\rho_a q}{\pi N_0\Gamma(\mu+4)\rho}\right]^{\frac{2\beta_a+\mu+1}{\mu+4}}(A\alpha_a{}^2+B\alpha_b{}^2+2C\alpha_a\alpha_b)$$

$$Z_{vv}=\frac{4\lambda^4}{\pi^4|K_w|^2}\int_0^\infty (B|f_a|^2+A|f_b|^2+2C|f_a||f_b|)N_0D^\mu e^{-\Lambda D}dD$$

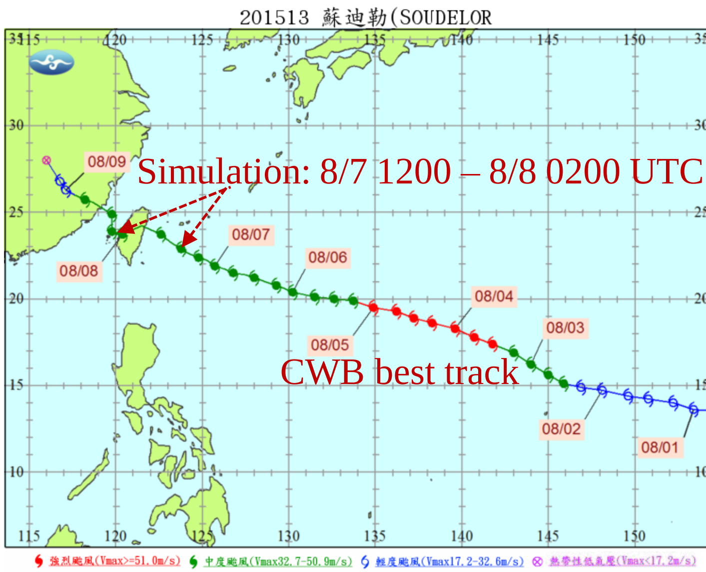
$$=\frac{4\lambda^4N_0\Gamma(2\beta_b+\mu+1)}{\pi^4|K_w|^2}\left[\frac{6\rho_{air} q}{\pi N_0\Gamma(\mu+4)\rho}\right]^{\frac{2\beta_b+\mu+1}{\mu+4}}(B\alpha_a{}^2+A\alpha_b{}^2+2C\alpha_a\alpha_b)$$

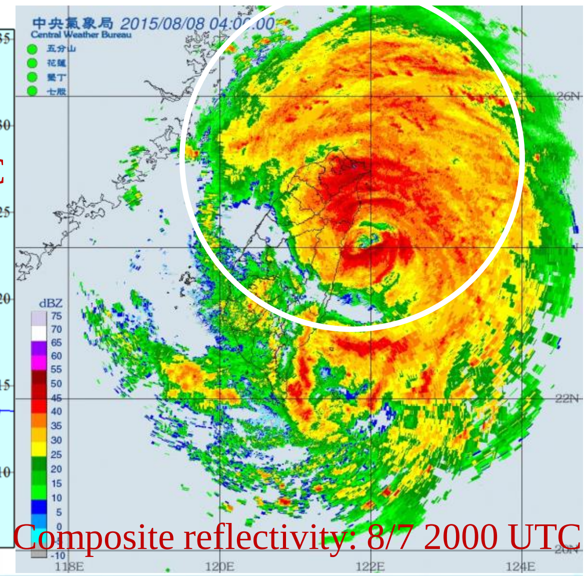
$$K_{dp}=\frac{180\lambda}{\pi}\int_0^\infty C_k\mathrm{Re}(f_a-f_b)N_0D^\mu e^{-\Lambda D}dD$$

$$=\frac{180\lambda N_0C_k}{\pi}\left\{\alpha_a\Gamma(\beta_a+\mu+1)\left[\frac{6\rho_a q}{\pi N_0\Gamma(\mu+4)\rho}\right]^{\frac{\beta_a+\mu+1}{\mu+4}}-\alpha_b\Gamma(\beta_b+\mu+1)\left[\frac{6\rho_a q}{\pi N_0\Gamma(\mu+4)\rho}\right]^{\frac{\beta_b+\mu+1}{\mu+4}}\right\}$$

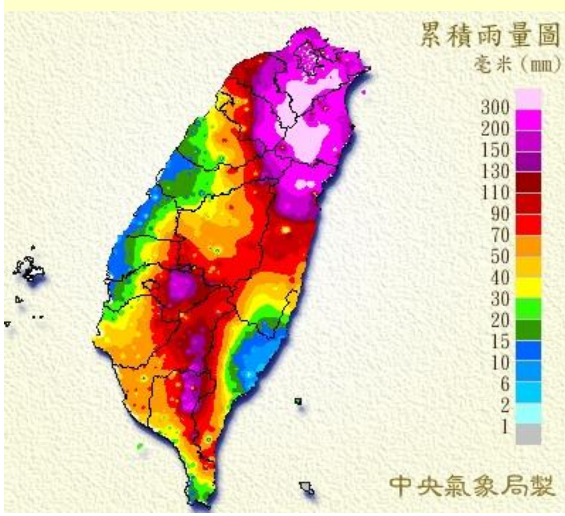
$$Z_H=10\log\left(\sum_x Z_{hh,x}\right)\qquad Z_{DR}=10\log\left(\sum_x Z_{hh,x}\Big/\sum_x Z_{vv,x}\right)\qquad K_{DP}=\sum_x K_{dp,x}$$

Typhoon Soudelor (2015)





Rainfall: 8/7 1600 – 8/8 0400 UTC

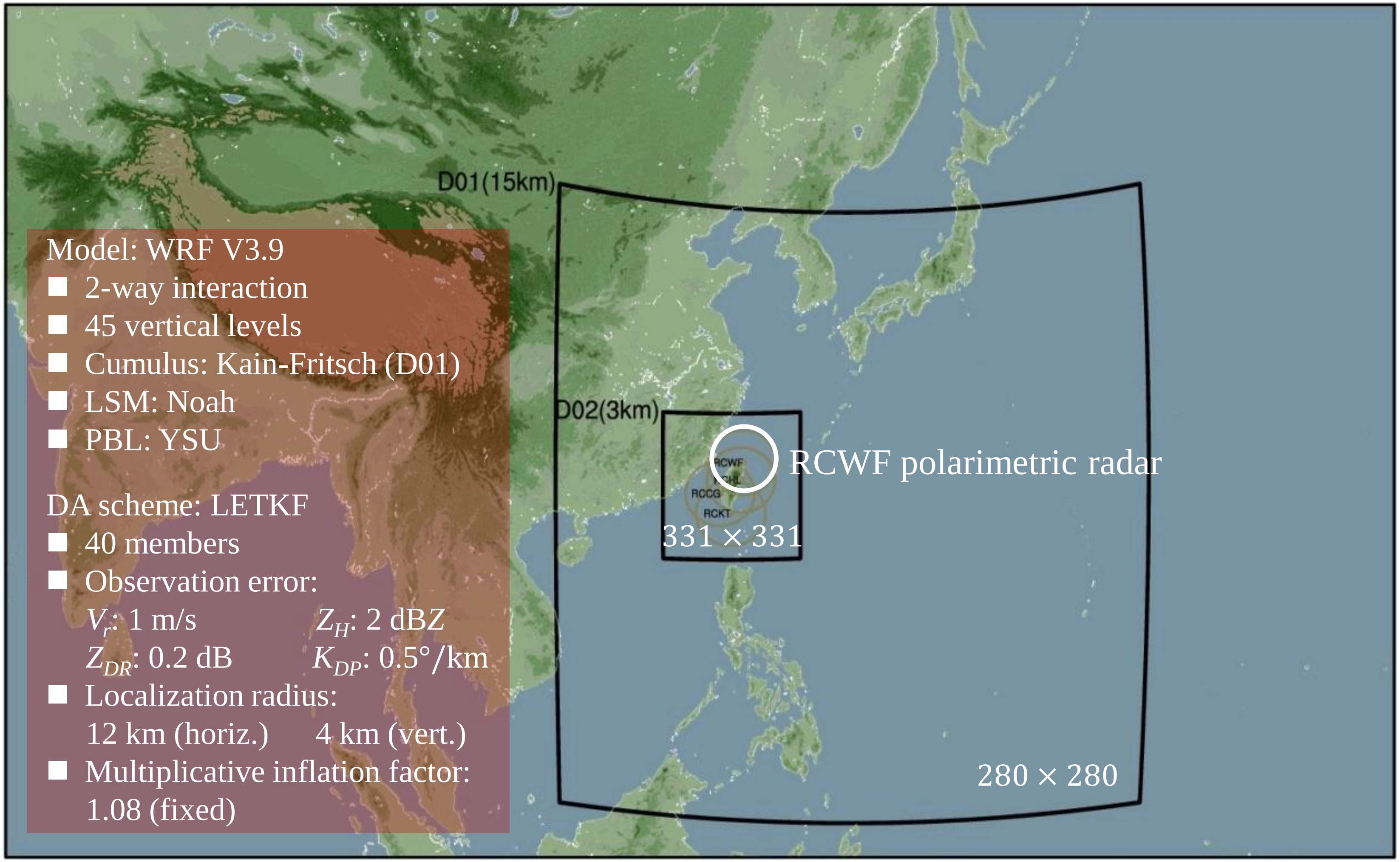


RCWF polarimetric radar

Simulation domains

Model: WRF V3.9
- 2-way interaction
- 45 vertical levels
- Cumulus: Kain-Fritsch (D01)
- LSM: Noah
- PBL: YSU

DA scheme: LETKF
- 40 members
- Observation error:
  V_r: 1 m/s Z_H: 2 dBZ
  Z_{DR}: 0.2 dB K_{DP}: 0.5°/km
- Localization radius:
  12 km (horiz.) 4 km (vert.)
- Multiplicative inflation factor:
  1.08 (fixed)



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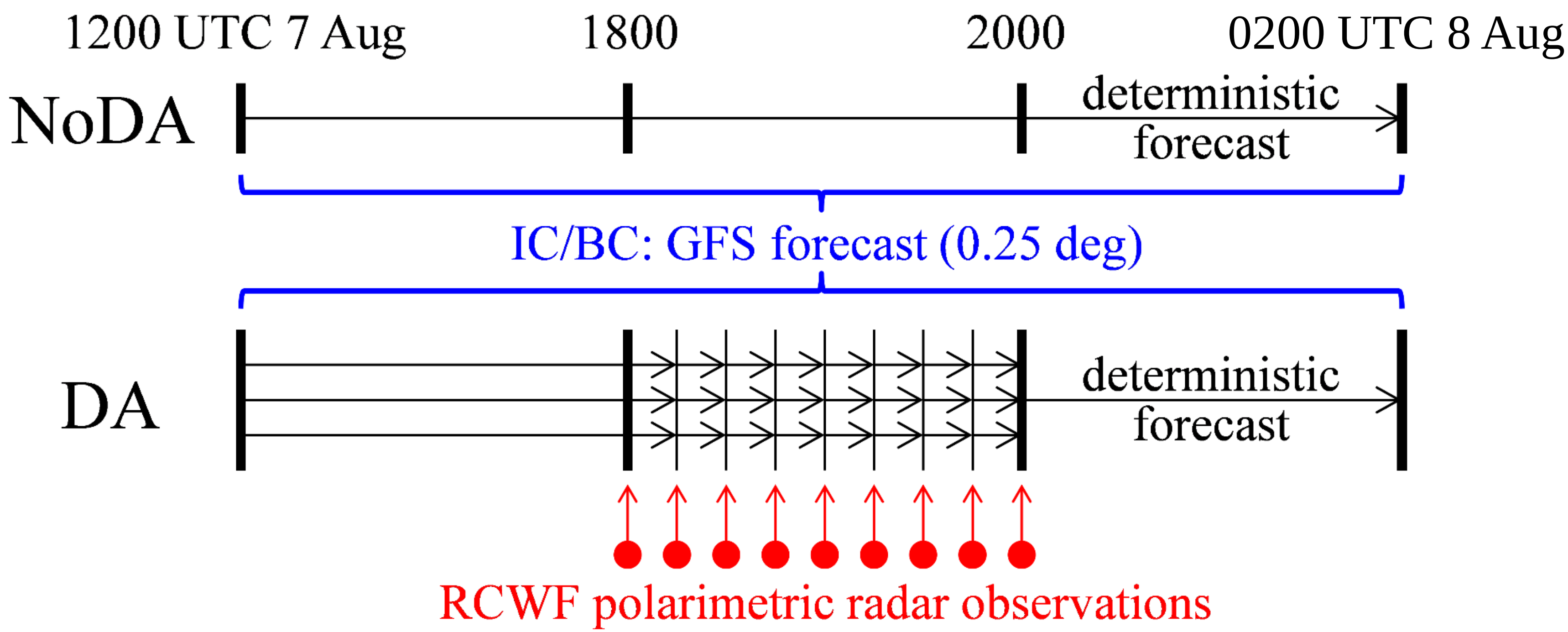
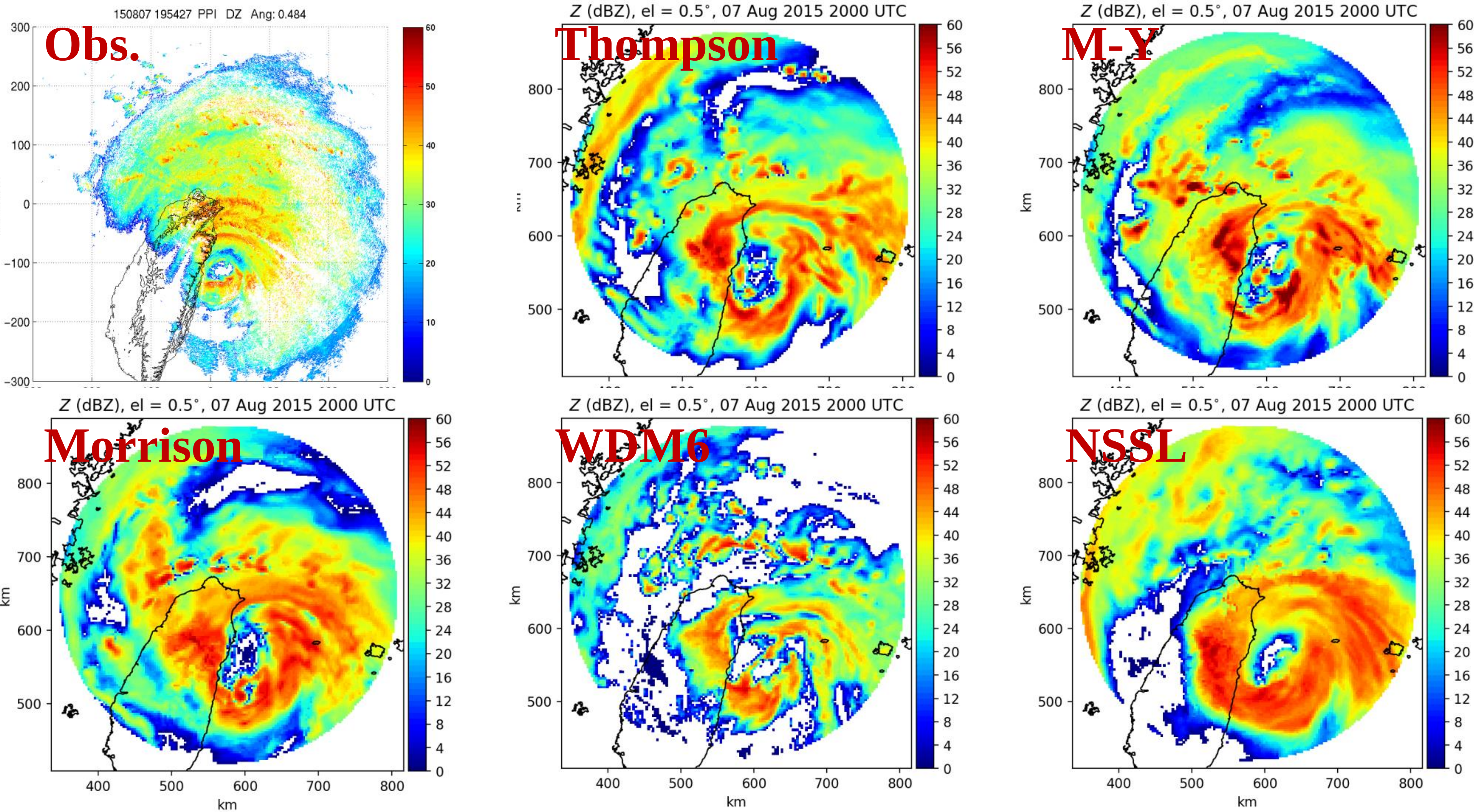
Simulation period

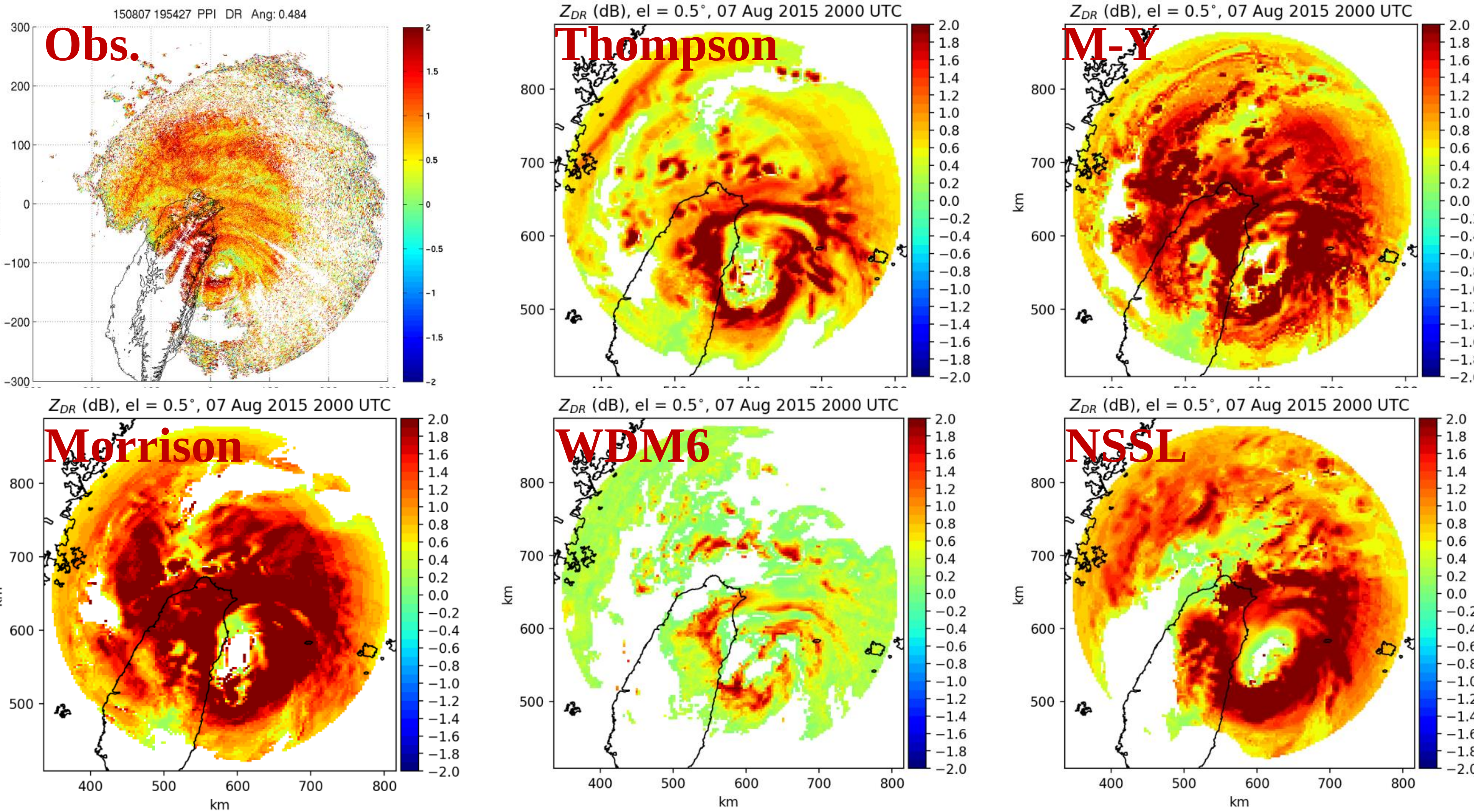


NoDA with various microphysics: Z_H



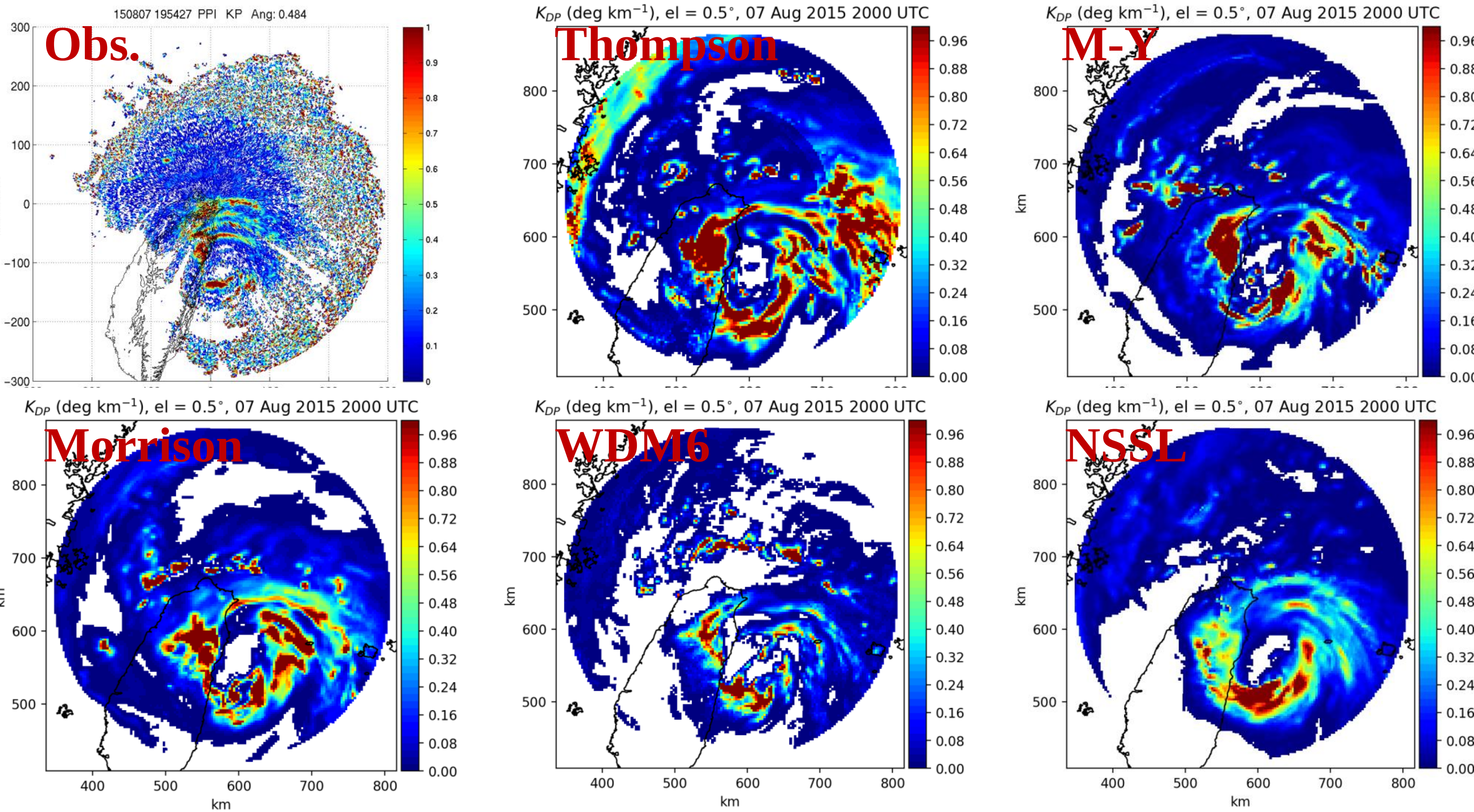
WDM6 gives the least over-forecasting of Z_H with a clear structure of spiral rainbands.

NoDA with various microphysics: Z_{DR}



Similar result with respect to Z_{DR}.

NoDA with various microphysics: K_{DP}

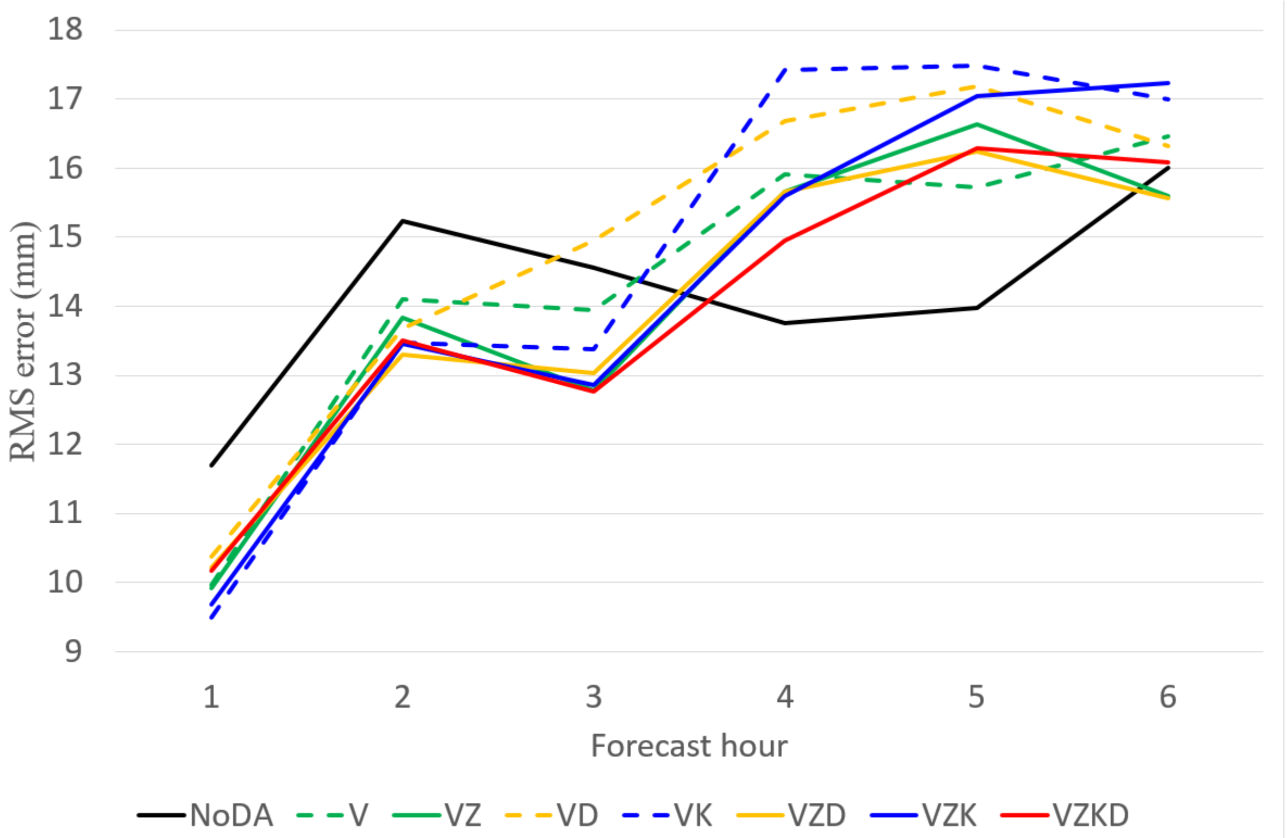


Similar result with respect to K_{DP}. WDM6 is selected for DA experiments.

DA experiments

	Assimilated radar variables
NoDA	——
V	V_r
VZ	V_r Z_H
VD	V_r Z_{DR}
VK	V_r K_{DP}
VZD	V_r Z_H Z_{DR}
VZK	V_r Z_H K_{DP}
VZKD	V_r Z_H Z_{DR} K_{DP}

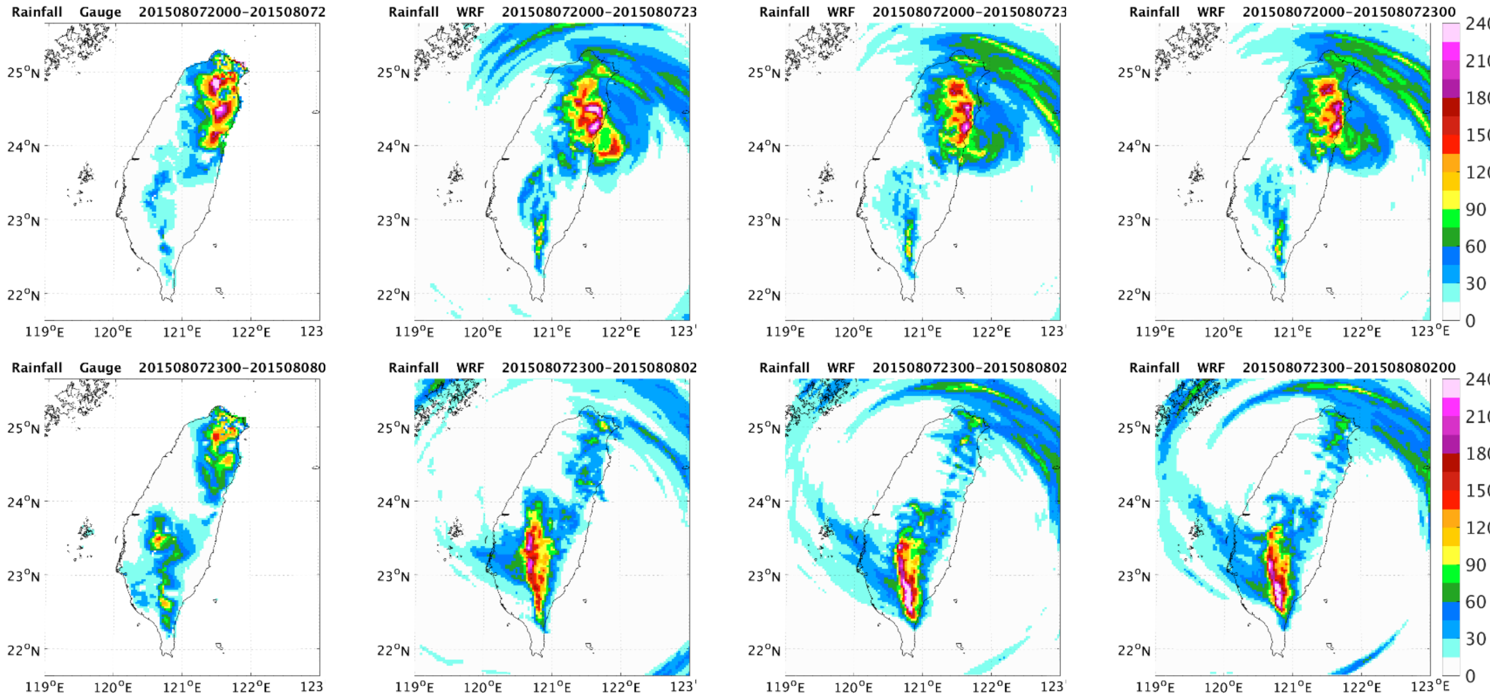
Quantitative precipitation forecasting (QPF)



- Generally speaking, radar DA greatly improves QPF in the first 3 hours, but deteriorates that in the following 3 hours.
- Additional assimilation of Z_H is beneficial for any combination of the rest variables.
- K_{DP} plays a more important role than Z_{DR}.
- Assimilating all variables (VZKD) is a good choice.

Quantitative precipitation forecasting (QPF)

	Obs.	NoDA	VZ	VZKD
8/7 2000 – 8/7 2300 UTC				
8/7 2300 – 8/8 0200 UTC				



- In the first 3 hours:
  Radar DA leads to more accurate intensity and distribution of QPF in northern Taiwan.
- In the following 3 hours:
  The deterioration results from the over-forecasting in southern Taiwan using the analysis ensemble mean beyond RCWF's coverage.

Summary

- An observation operator for Z_H, Z_{DR} and K_{DP} is incorporated into a WRF-LETKF system and tested with a typhoon case.

- WDM6 is found to give the least over-forecasting with a clear structure of spiral rainbands in this typhoon case.

- Preliminary results:
  1. With the limited coverage of RCWF, radar DA greatly improves QPF in northern Taiwan for 3 hours.
  2. However, the analysis ensemble mean beyond RCWF's coverage results in worse QPF than NoDA in southern Taiwan.
  3. It is a good choice to assimilate all variables, among which Z_H and K_{DP} are more important than Z_{DR}.

- Sensitivity tests in future prospects:
  1. Assimilation of other observations, including radars in southern Taiwan
  2. Assimilation strategies
  3. Source of the background ensemble

Thank you very much!