The WRF Double-Moment Cloud Microphysics Scheme (WDM)

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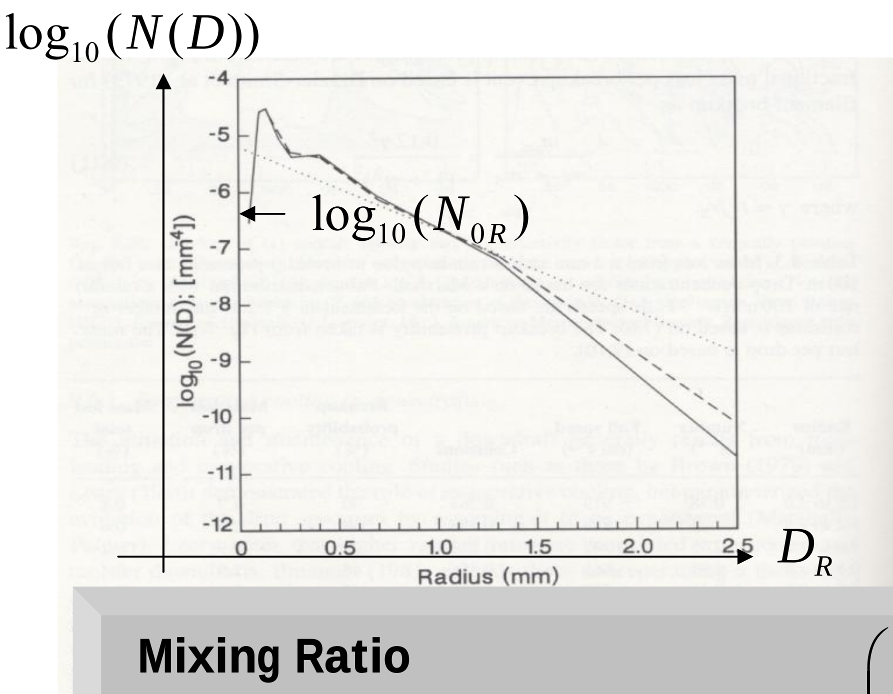
Acknowledgements : Jimy Dudhia (NCAR)
Hue Morrison (NCAR)
Cohard and Pinty

Introduction

- ✓ The WRF Single-Moment 6 class (WSM6) scheme with the revised ice physics of Hong et al. (2004) has been one of the microphysics options in the WRF model since August 2004.
- ✓ The WSM6 has been widely evaluated and showed a good performance against the Purdue-Lin scheme in resolving precipitating convective systems (e.g., Klemp 2006, Kuo 2006, Hong et al. 2009- Reprints in front desk). However, WSM6 scheme tends to produce excessive light rain (Shi et al, 2007). The intensity for convective core is too strong. Simulated radar reflectivity is too weak (Kain 2008)
- ✓ The double moment approach for the bulk microphysics schemes allows more flexibility of the size distribution and has become one of the promising methods to improve the microphysical process in the mesoscale modeling area (e.g., Morrison et al. 2009, Thompson et al. 2008)

What is Double moment ???



Single moment scheme

$$dN_{DR} = N_{0R}\exp(-\lambda_R D_R)dD_R$$

Double moment scheme

$$dN_{DR} = N_R\lambda_R^2(N_R)D_R\exp(-\lambda_R D_R)dD_R$$

Mixing Ratio

(1-moment/ 2-moment scheme)

$$\left(\int \frac{dM(D_R)}{dt}dN_{DR}\right)/\rho = \frac{dq}{dt}(kgkg^{-1}s^{-1})$$

Number concentration

(2-moment scheme)

$$\left(\int \frac{d\,\mathrm{Pr}\,ob(D_R)}{dt}dN_{DR}\right) = \frac{dN}{dt}(m^{-3}s^{-1})$$

Strategy for WDM scheme development

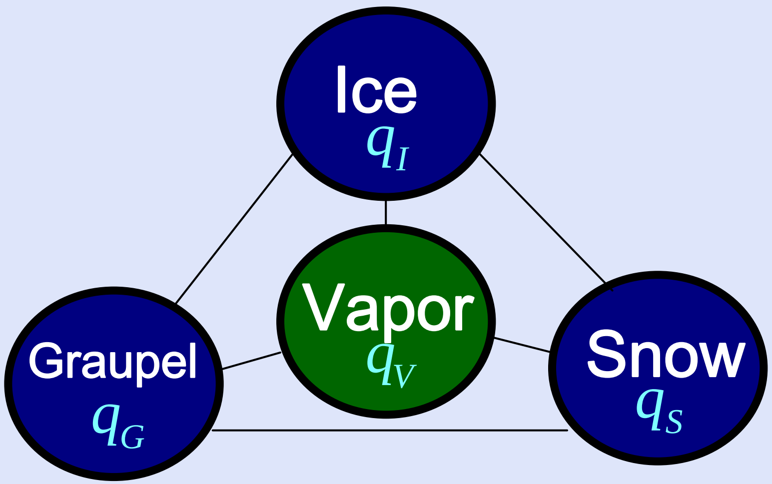
Only double warm-rain microphysics that predicts the number concentrations of cloud and rain waters are added to the corresponding single-moment scheme (WSM6)

Ice-microphysics of Hong et al. (2004) are identical for both the WSM6 and WDM6 schemes
(Double moment for snow and graupel is much less impact than that for rain (Morrison et al. 2009)

A prognostic treatment of cloud condensation nuclei (CCN) is introduced for the WDM6 scheme to activate cloud waters

Cold rain processes :

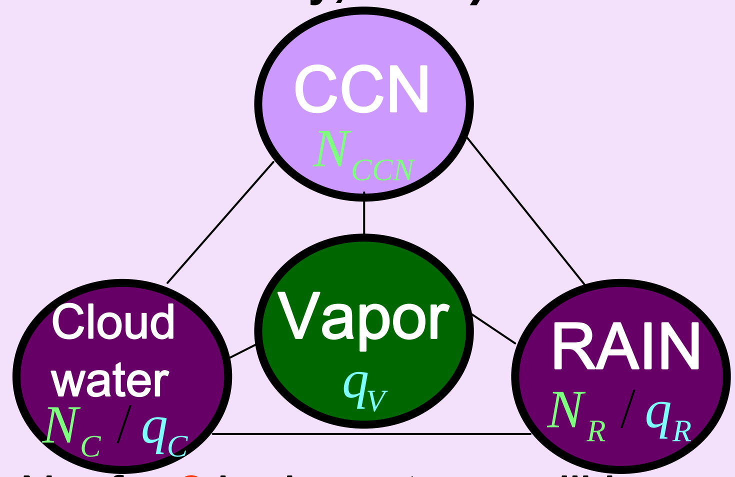
(Hong et al.,2004; Hong and Lim 2006)



q for 4 hydrometeors will be predicted (Single Moment)

Warm rain processes :

(Khairoutdinov and Kogan, 2000; Cohardt and Pinty, 2000)

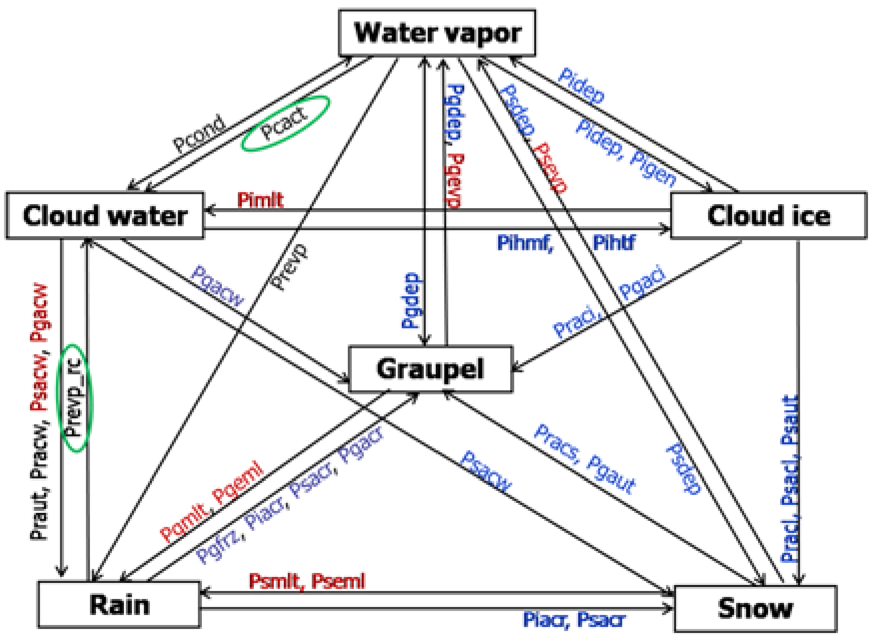


N,q for 2 hydrometeors will be predicted (Double Moment)

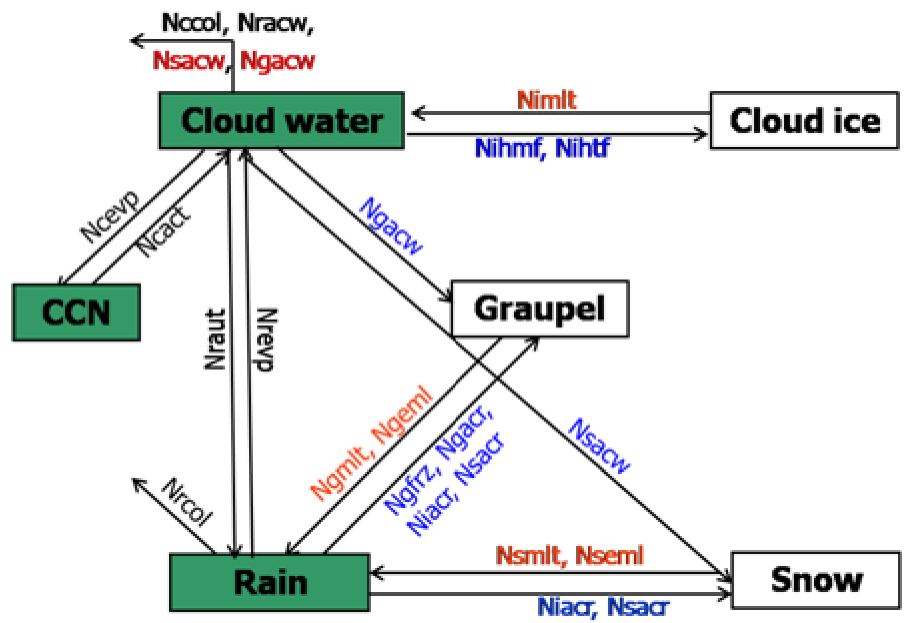
WDM6

Flowchart of the microphysics processes in the WDM6

Mixing Ratio (q)



Number Concentration (N)



Prediction of number concentration of the warm hydrometeors

$$\frac{\partial N_X}{\partial t} = -\vec{V}\nabla_3 N_X - \frac{N_X}{\rho_a}\frac{\partial}{\partial z}(\rho_a V_X) + S_X$$

a. Production term for CCN number concentration

$$S_{CCN} = -Ncact + Ncevp$$

b. Production term for Cloud water number concentration

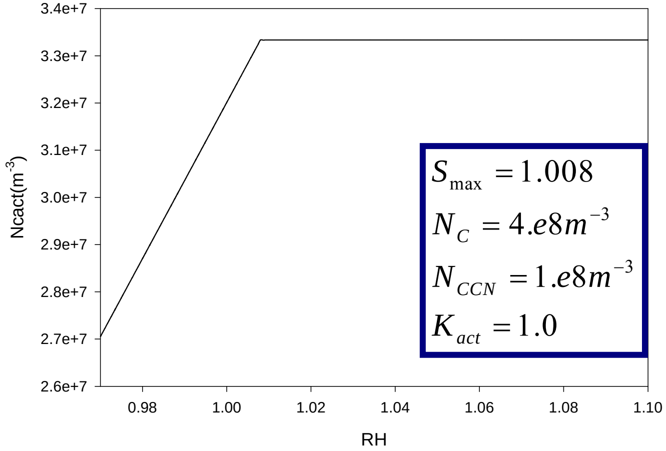
$$T < T_0; \quad S_C = Ncact - Ncevp - Nracw - Nccol - Nihmf - Nihtf - Nsacw - Ngacw$$

$$T > T_0; \quad S_C = Ncact - Ncevp - Nracw - Nccol - Nsacw - Ngacw + \frac{N_I}{q_I}(Pimlt)$$

c. Production term for rain number concentration

$$T < T_0; \quad S_R = Nraut - Nrcol - Nrevp - Ngfrz - Niacr - Nsacr - Ngacr$$

$$T > T_0; \quad S_R = Nraut - Nrcol - Nrevp - + \frac{N_{0G}}{q_G \lambda_G}(pgmlt + pgeml) + \frac{N_{0S}}{q_S \lambda_S}(psmlt + pseml)$$



$$S_{\max} = 1.008$$
$$N_C = 4.e8 m^{-3}$$
$$N_{CCN} = 1.e8 m^{-3}$$
$$K_{act} = 1.0$$

$$Ncact = \frac{\max\left\{0, (n + N_C)\min\left[1, (S/S_{\max})^{k_{act}}\right] - N_C\right\}}{\Delta t}$$

Activation of CCN (KK2000)

Prediction of number concentration of the warm hydrometeors

Autoconversion

$$Nraut[m^{-3}s^{-1}] = 3.5\times 10^{9}\frac{\rho L}{\tau}$$

$$= \frac{N_R}{q_R}\Pr aut \quad \text{(In feeding regime)}$$

Accretion of cloud water

$$Nracw[m^{-3}s^{-1}] = \frac{\pi}{6}\frac{\rho_W}{\rho_a}K_1\frac{N_C N_R}{\lambda_C^3}\left\{\frac{2}{\lambda_C^3}+\frac{24}{\lambda_R^3}\right\} \qquad D_R > 100\mu m$$

$$= \frac{\pi}{6}\frac{\rho_W}{\rho_a}K_2\frac{N_C N_R}{\lambda_C^3}\left\{\frac{6}{\lambda_C^6}+\frac{5040}{\lambda_R^6}\right\} \qquad D_R < 100\mu m$$

Cloud self collection

$$Nccol[m^{-3}s^{-1}] = \frac{K_1 N_C^2}{\lambda_C^3} \qquad D_C > 100\mu m$$

$$= \frac{2K_2 N_C^2}{\lambda_C^6} \qquad D_C < 100\mu m$$

Rain self collection & break-up

$$Nrcol[m^{-3}s^{-1}] = \frac{5040 K_2 N_R^2}{\lambda_R^6} \quad D_R < 100\mu m$$

$$= \frac{24 K_1 N_R^2}{\lambda_R^3} \qquad 100\mu m < D_R < 600\mu m$$

$$= \frac{24 E_C K_1 N_R^2}{\lambda_R^3} \quad 600\mu m < D_R < 2000\mu m$$

Major Differences in warm-rain microphysical properties

Properties	Option	Value
Auto-Conversion	WSM6	$\frac{0.104gE_C\rho_0^{4/3}}{\mu(N_C\rho_W)^{1/3}}q_C^{7/3}H(q_C-q_{C0})$
	WDM6	L/τ $\quad L=2.7\times10^{-2}\rho_a q_C\left(\frac{1}{16}\times10^{20}\sigma_C^3 D_C-0.4\right)$ $\quad \tau=3.7\frac{1}{\rho_a q_C}\left(0.5\times10^6\sigma_C-7.5\right)^{-1}$
Accretion	WSM6	$\frac{\pi a_R E_{RC} N_{0R} q_C}{4}\left(\frac{\rho_0}{\rho_a}\right)^{\frac{1}{2}}\frac{\Gamma(3+b_R)}{\lambda_R^{3+b_R}}$
	WDM6	$\frac{\pi}{6}\frac{\rho_W}{\rho_a}K_1\frac{N_C N_R}{\lambda_C^3}\left\{\frac{2}{\lambda_C^3}+\frac{24}{\lambda_R^3}\right\}$, if $D_R\geq100$ µm
		$\frac{\pi}{6}\frac{\rho_W}{\rho_a}K_2\frac{N_C N_R}{\lambda_C^3}\left\{\frac{6}{\lambda_C^6}+\frac{5040}{\lambda_R^6}\right\}$, if $D_R<100$ µm
N_R Size Dist.	WSM6	$N_R\lambda_R\exp\{-(\lambda_R D_R)\}$
	WDM6	$N_R\lambda_R^2 D_R\exp\{-(\lambda_R D_R)\}$
N_C Size Dist.	WSM6	Constant value with $N_C=3\times10^8\ \mathrm{m}^{-3}$
	WDM6	$N_C(D_C)=3N_C\lambda_C^3 D_C^2\exp\{-(\lambda_C D_C)^3\}$

Major Differences in other double moment schemes in WRF (Thompson, Morrison schemes)

Nc (Nccn) are prescribed in Thompson and Morrison schemes

Melting of snow and graupel for rain number formation is excluded in the Morrison

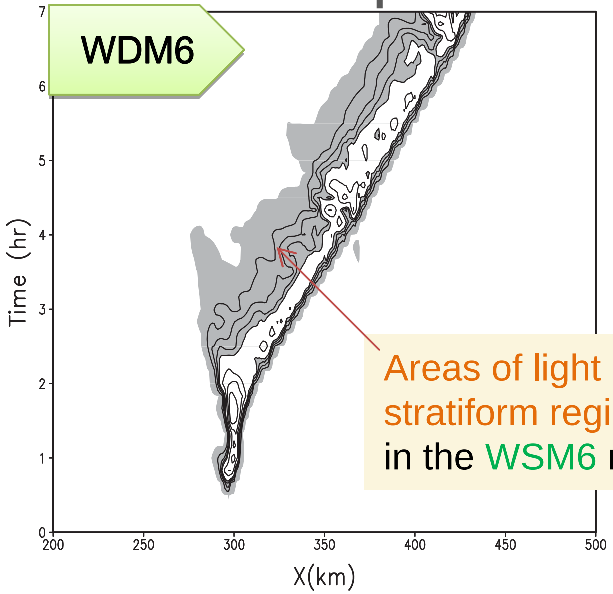
Ng, Ns are diagnosed in the WDM6

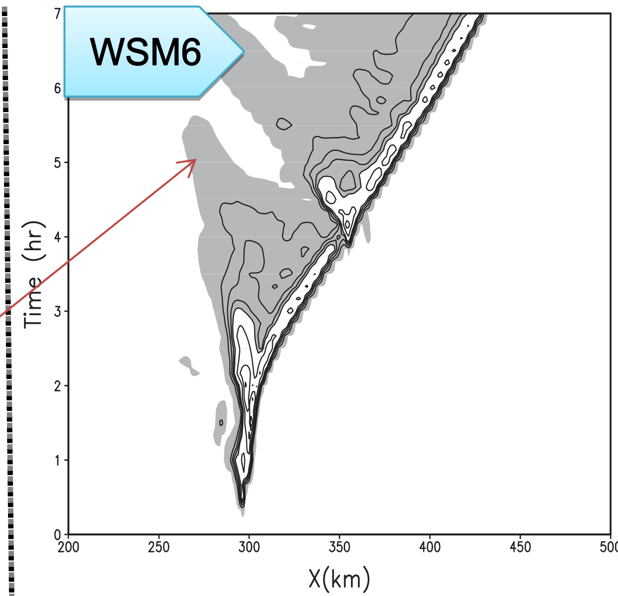
2D squall line test – present option in the WRF

DX = 1 km, Integration time = 7 hours [Morrison et al. 2009]

2D Idealized Squall Line: Hovmoller Plots

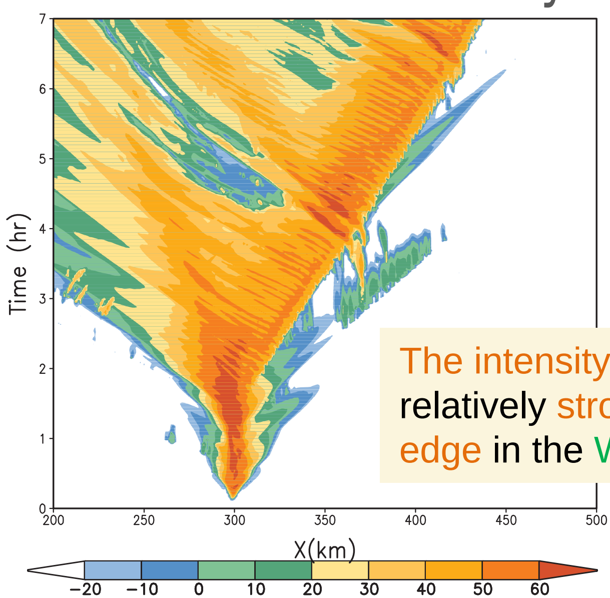
Surface Precipitation

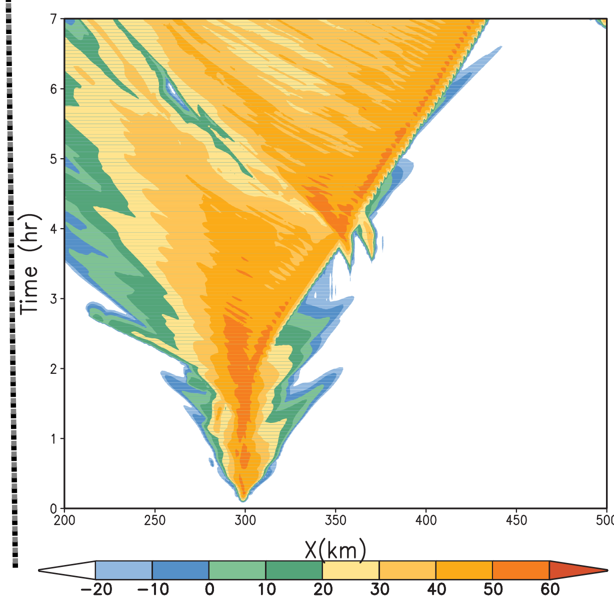




Areas of light rain rate in the stratiform region are much larger in the WSM6 run.

Maximum Reflectivity



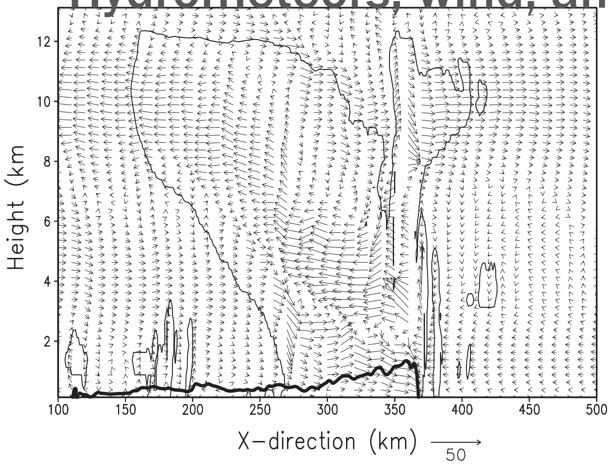


The intensity of the reflectivity is relatively strong in the leading edge in the WDM6 experiment.

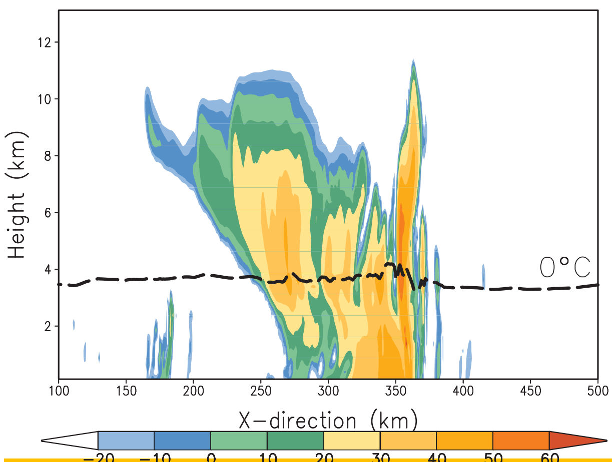
Simulated Storm Features at 4hour

WDM6

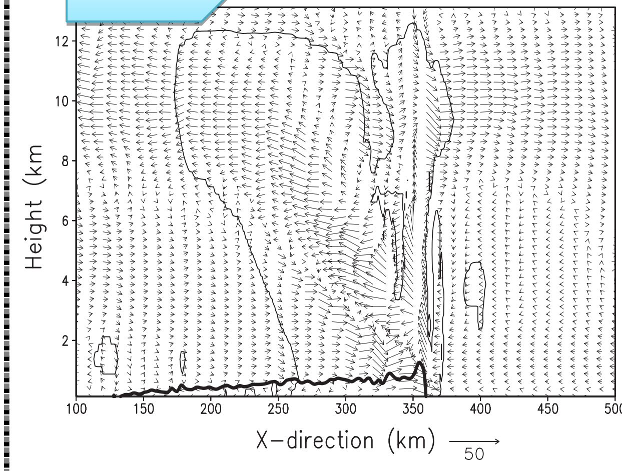
Hydrometeors, wind, and Cold pool

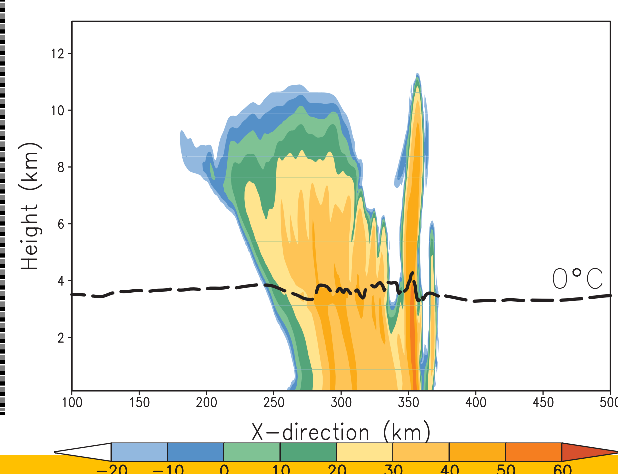


Reflectivity



WSM6



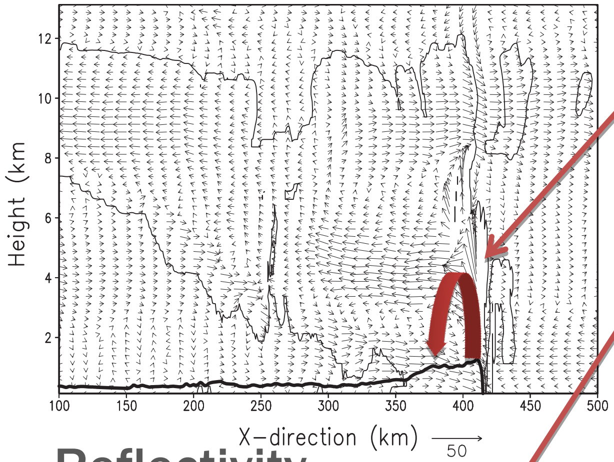


The separation of the stratiform rain from the convective core is more distinct accompanying the weak reflectivity approximately at 300 km in the WDM run than in the WSM run.

Simulated Storm Features at 6hour

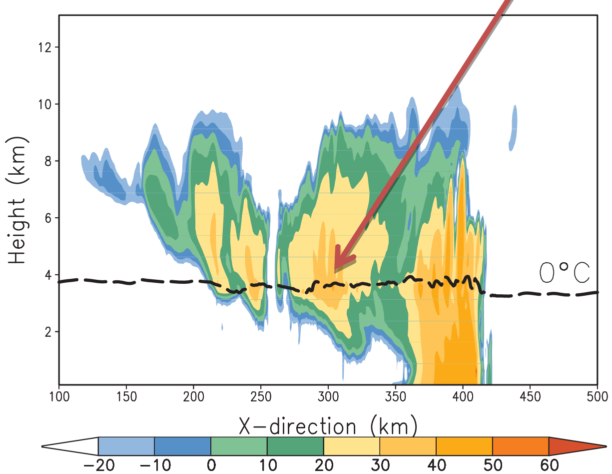
WDM6

Hydrometeors, wind, and Cold pool

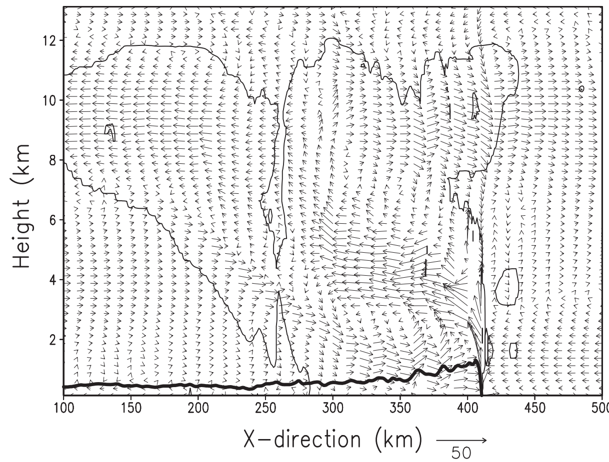


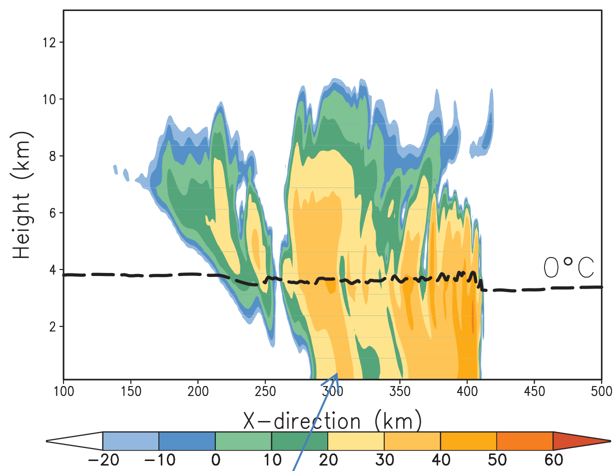
"Distinct slantwise circulation" with strengthened cold pool and distinct "bright band" around the melting level in the WDM6.

Reflectivity



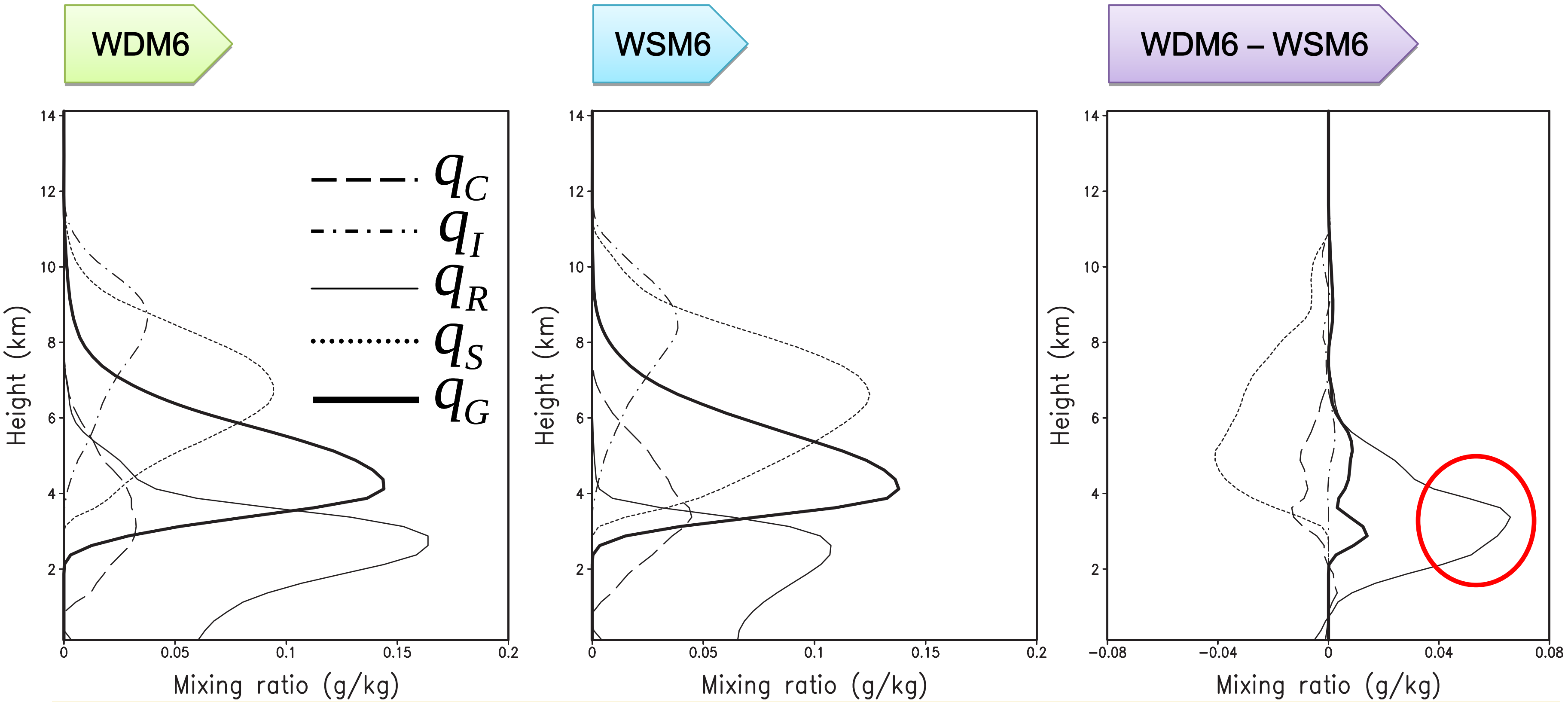
WSM6





The relatively extensive area of stratifrom rain in the WSM6 run.

Vertical distribution of the domain-averaged water species



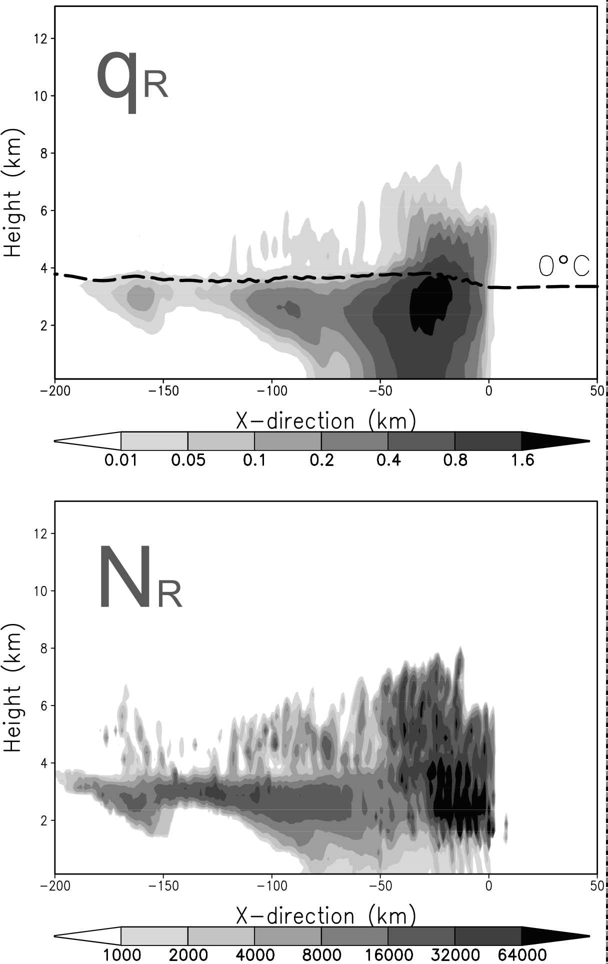
Similar profiles of ice-phases such as ice, snow, and graupel

The increase of rain water mixing ratio below 5 km with less cloud droplets is pronounced in the WDM6

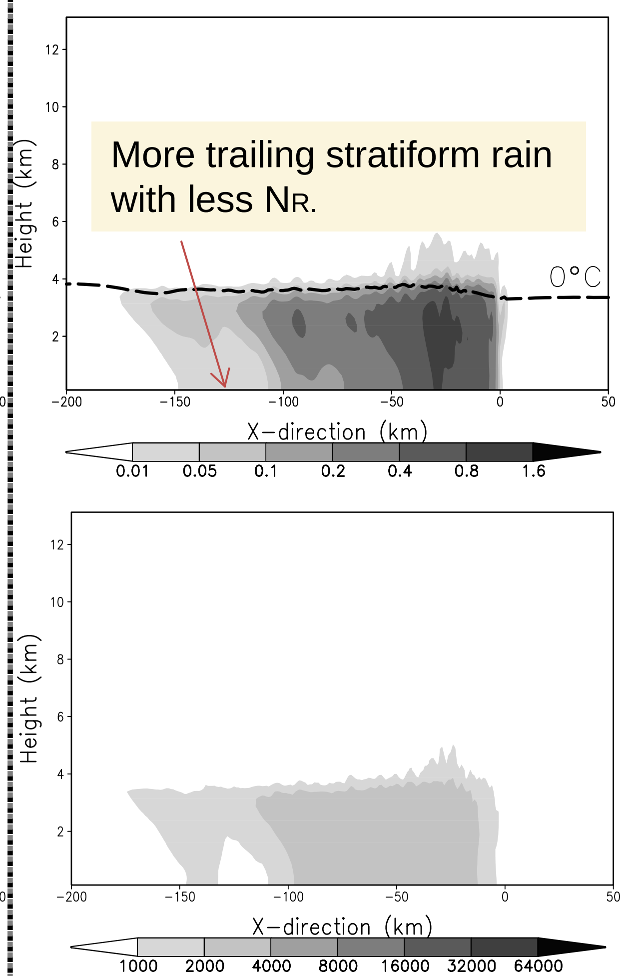
Vertical distributions of rain water are sensitive to the method of treating warm-rain microphysical process.

Rain mixing ratio (qR) and Rain number concentration (NR)

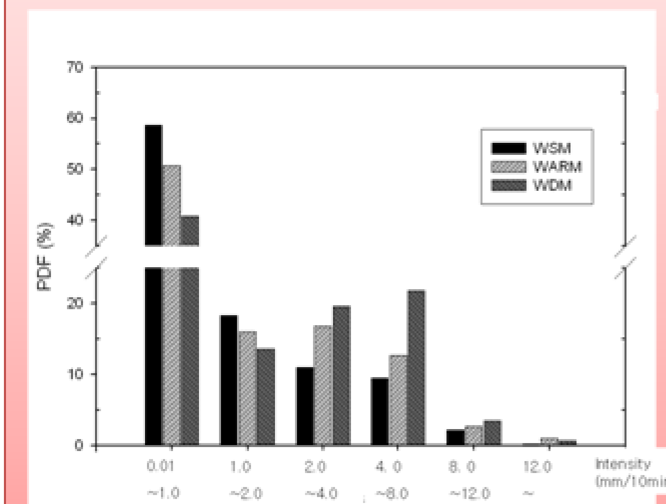
WDM6



WSM6



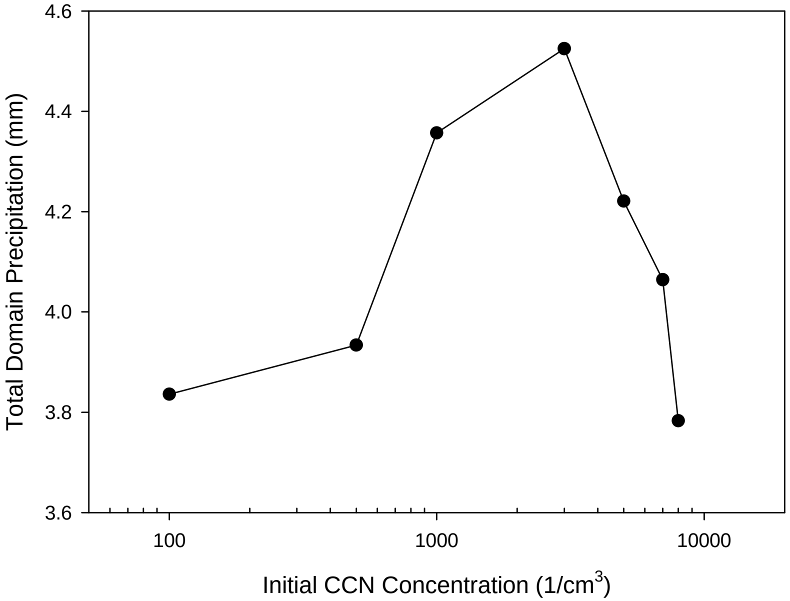
PDF of accumulated rainfall intensity



The WDM6 experiment tends to reduce the light precipitation activity

More NR over the convective core region than in the trailing stratiform region in the WDM6.

CCN Effects : Total Precipitation



✓ The enhanced precipitation with increasing aerosols at lower CCN is explained by the suppressed conversion of cloud droplets to raindrops, but enhanced convective strength, which causes less efficient warm rain but more mixed-phase processes.

✓ Meanwhile, the decreased precipitation in the high CCN condition is due to the extremely suppressed conversion from cloud droplets to raindrops.

However, the responses of aerosols on precipitation could be non-monotonic and vary under different meteorological and aerosol conditions because of the complicated coupling between the cloud microphysics and dynamics (Seifert and Beheng 2006; Li et al. 2008).

3D real case test

Cyclone over East Asia : April 2008 (48km)

Short-range forecasts over Korea : June-Aug., 2008 (5km, 15km)

IHOP over the Great Plains in US : June 13th, 2002 (1km, 3km, 9km)

Heavy rainfall over South Korea : July 15-16, 2006 (3km, 12km, 48 km)

Cyclogenesis over South Korea : May 21th, 2009 (3km, 12km, 48 km)

Precipitation in Spring

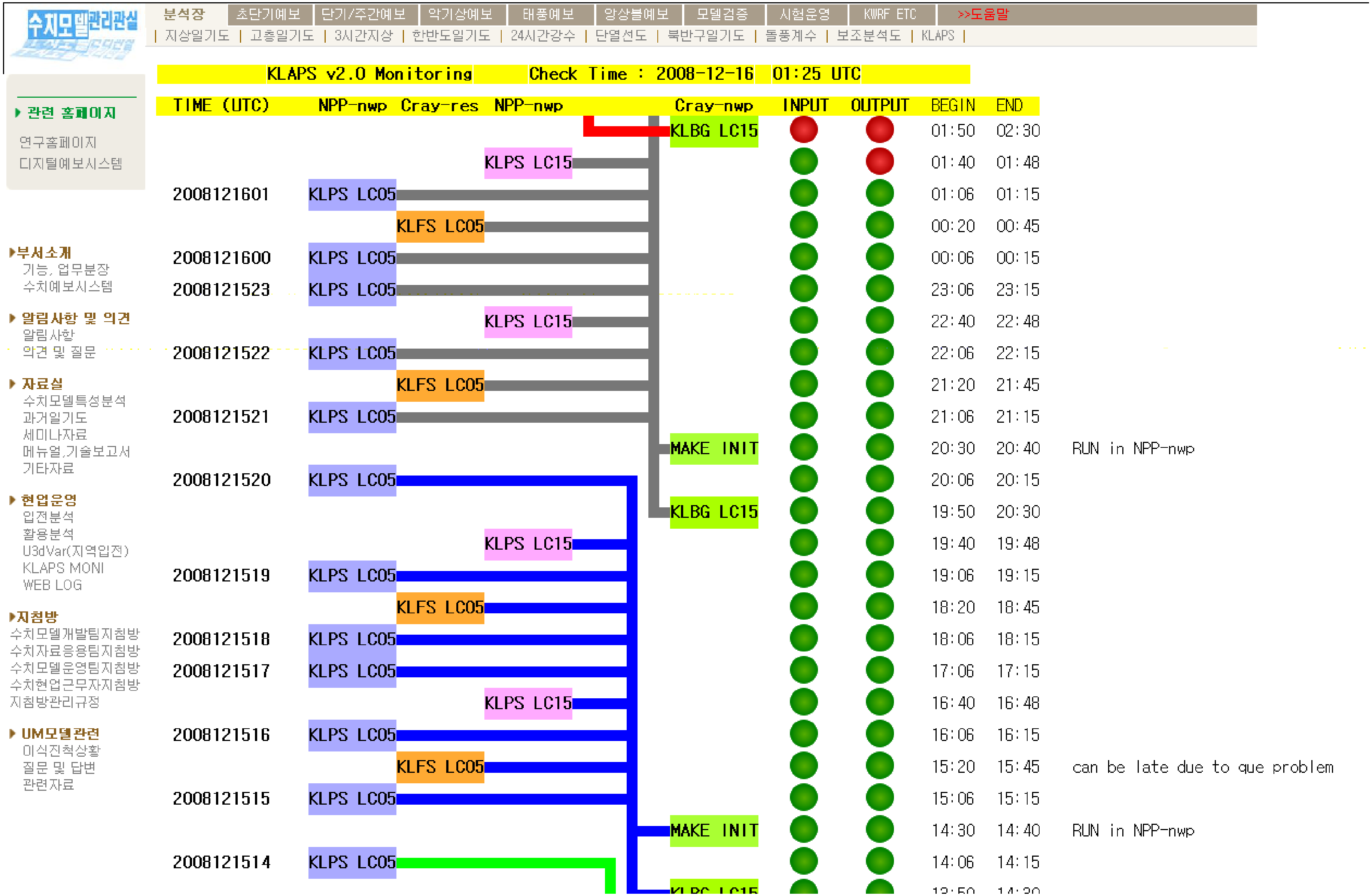
TMPA : rainfall estimates

WDM6 (WRF-double-moment 6-class cloud scheme) that predicts CCN, Nc, Nr will be released in WRF in April 2009 (Version 3.1)

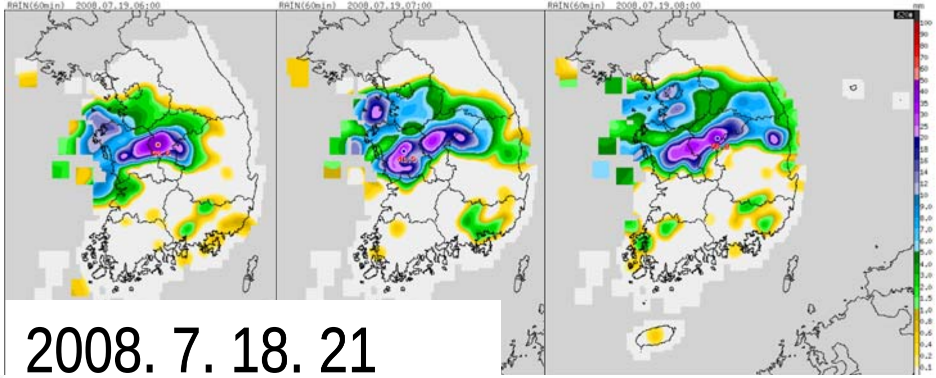
WSM6 : Hong and Lim (2006)

WDM6 : Lim and Hong (2009)

3 hourly forecast experients during JJA 2008
[Lee, Yong-Hee (KMA) and his colleagues]



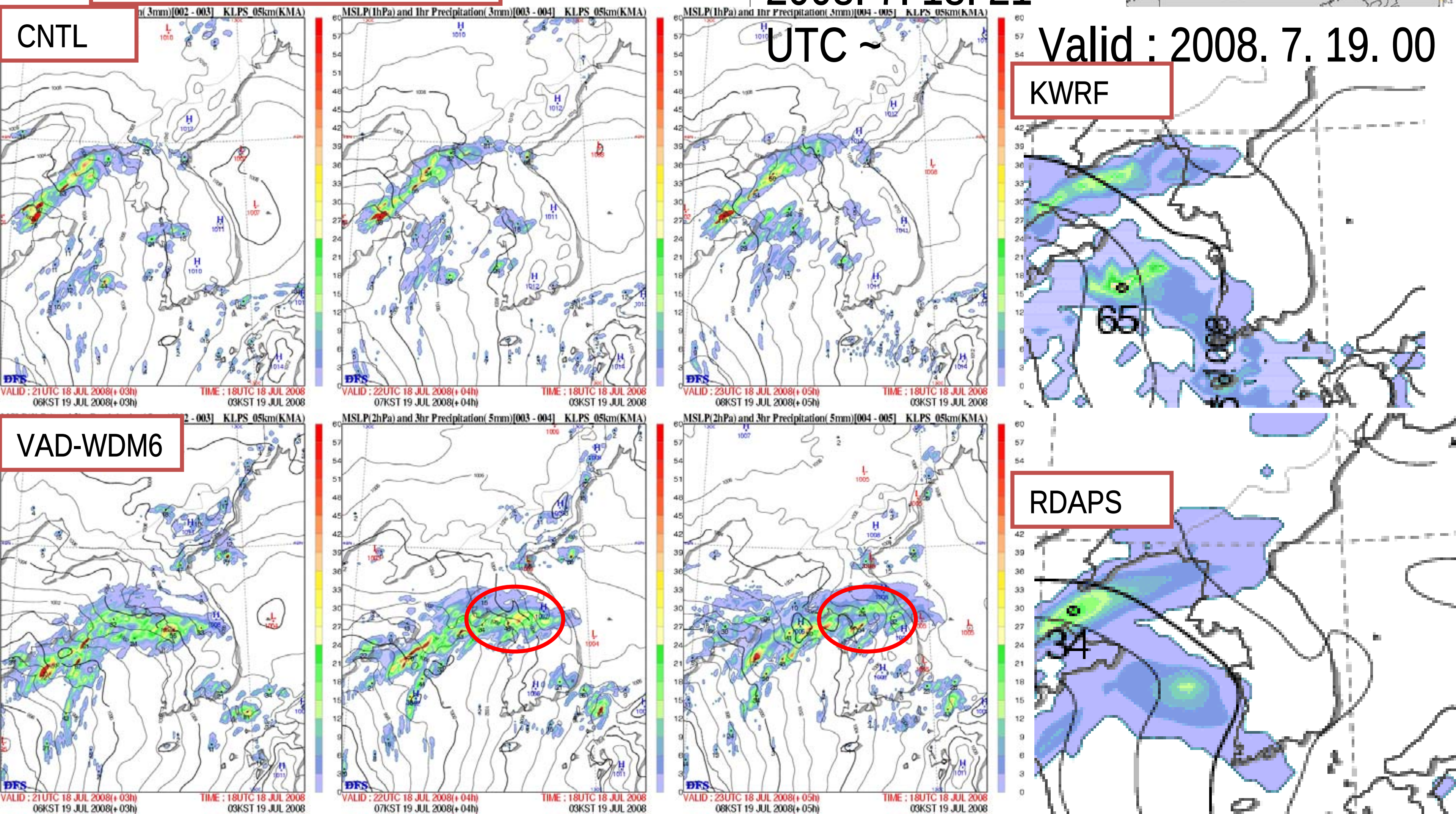
Precipitation (hourly)



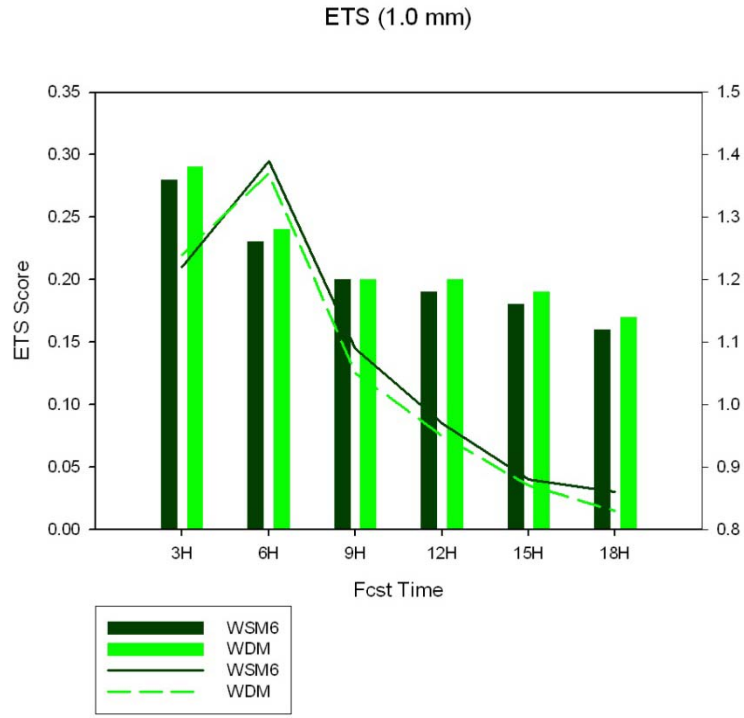
2008. 7. 18. 21 UTC ~

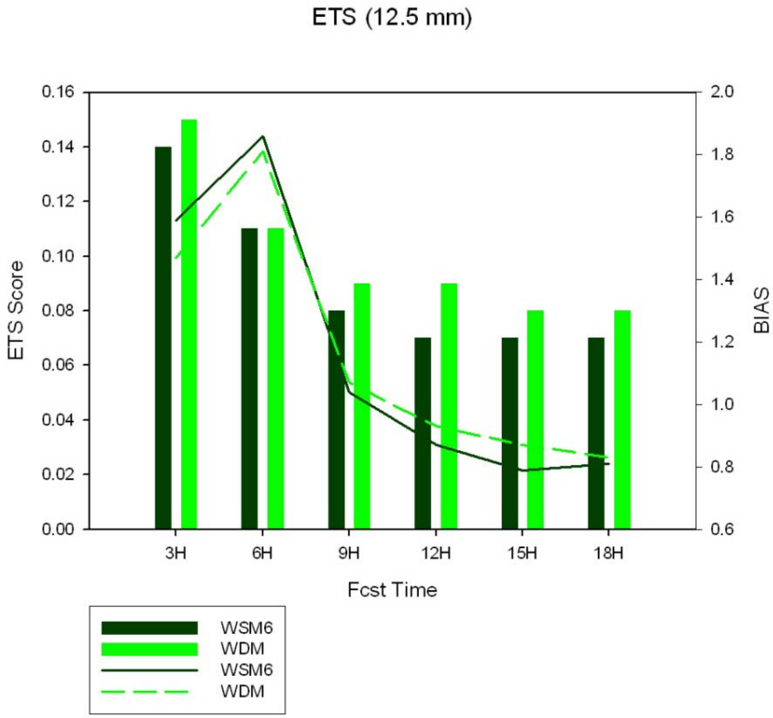
Valid : 2008. 7. 19. 00

2008. 7. 18. 18 UTC (3-5 fc)



Verification for JJA 2008 [8x92 = 726 case]

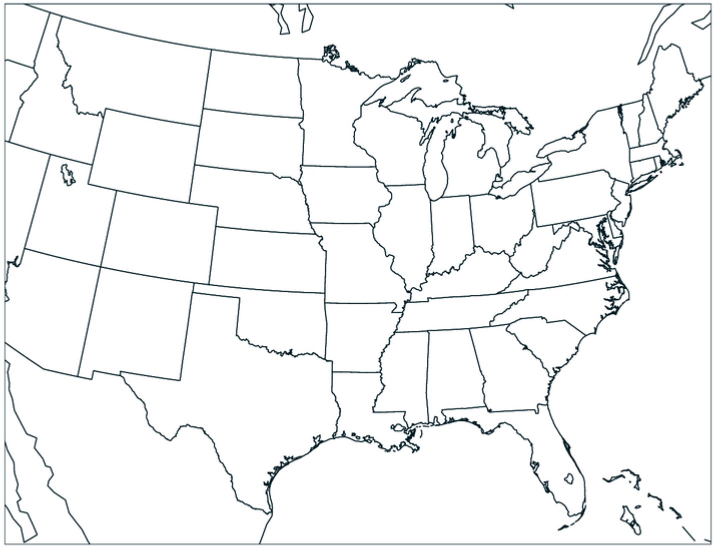




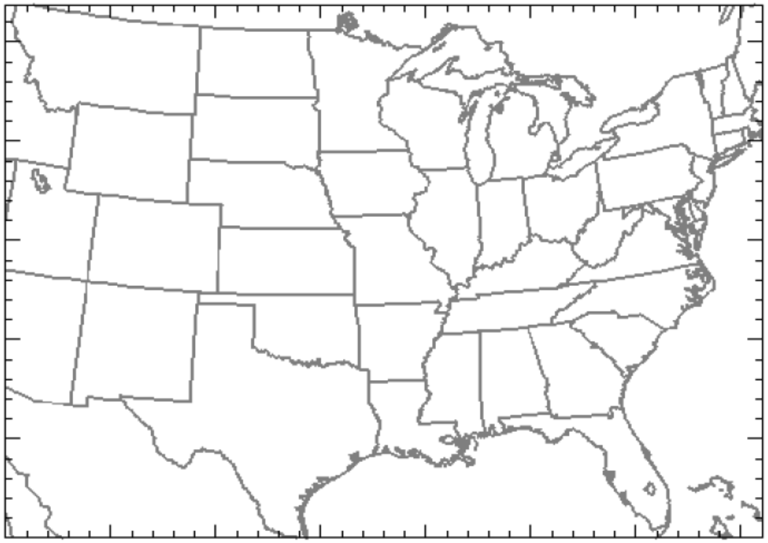
Reflectivity issue [from Jack Kain]

- 36h forecasts of WRF-ARW run daily at 00Z, Mon-Fri, from about April 15 – June 8, 2008.

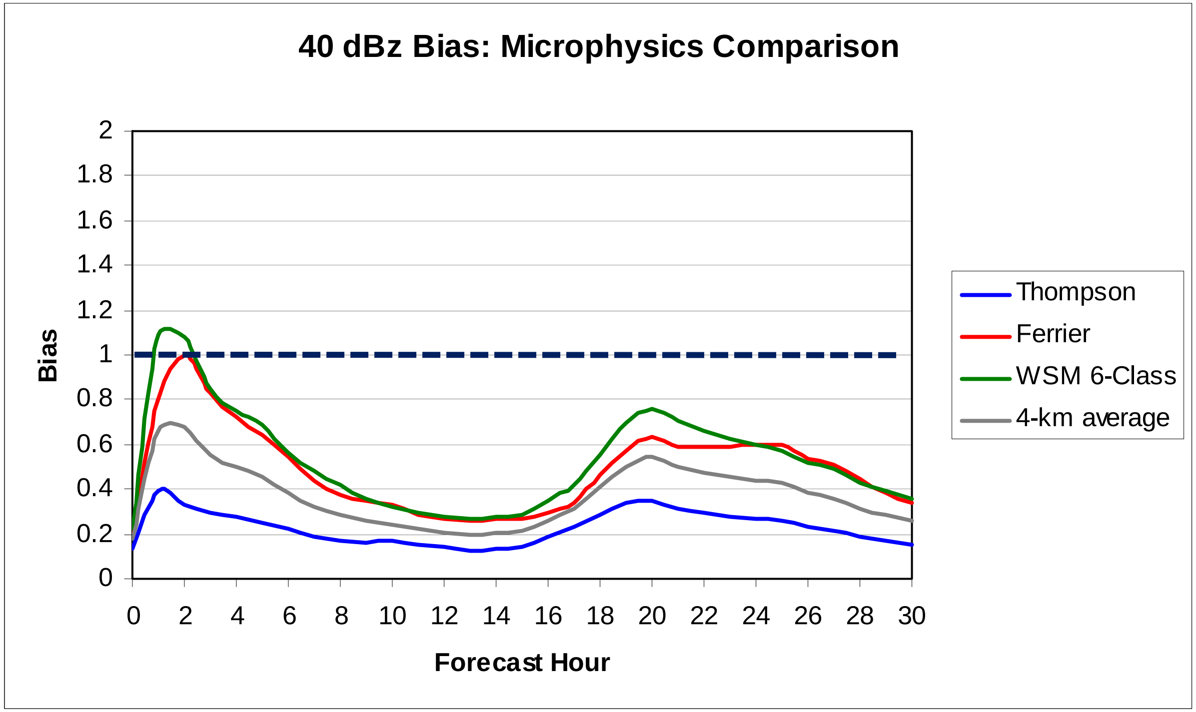
NSSL domain



CN, C0 domain

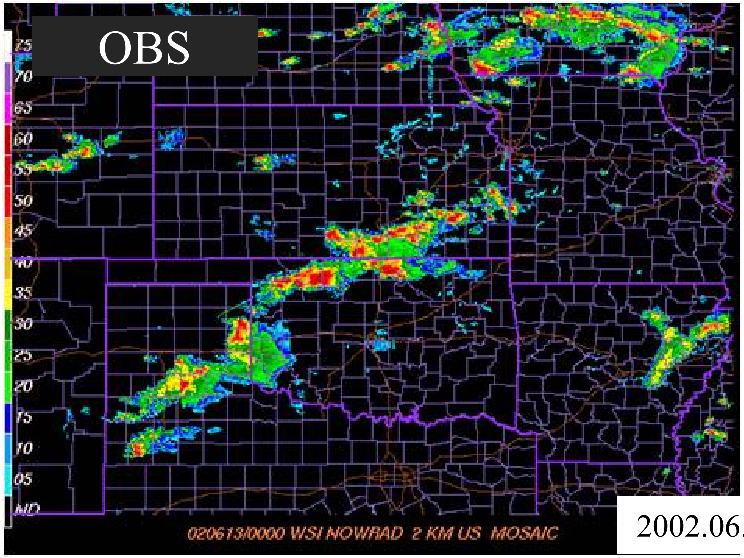


Simulated reflectivity bias as a function of time for a 10 day period in May 2008 based on individual members from the CAPS 10-member WRF-ARW ensemble (configurations listed on next slide). The curves below show the average value for all members that use the indicated microphysics scheme.

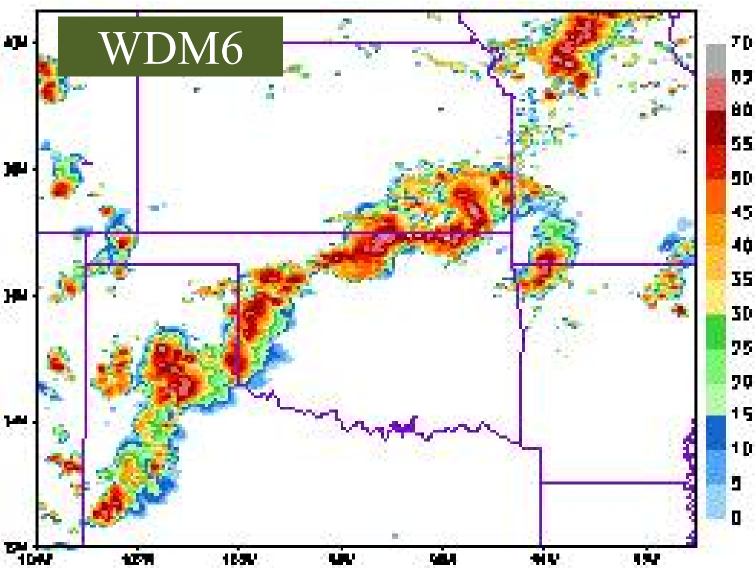


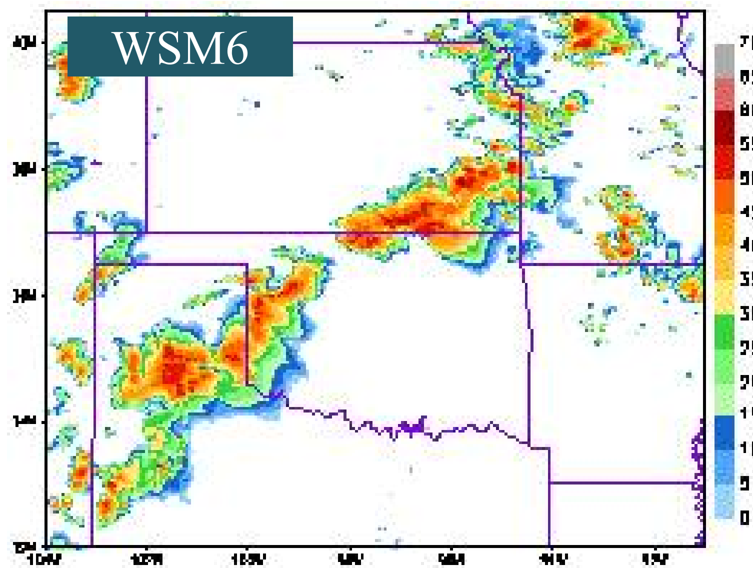
Systematic bias of weak reflectivity in the existing MPSs would be alleviated by the WDM scheme

IHOP CASE : Maximum Reflectivity (9, 3, 1 km – 24 hr fcst)

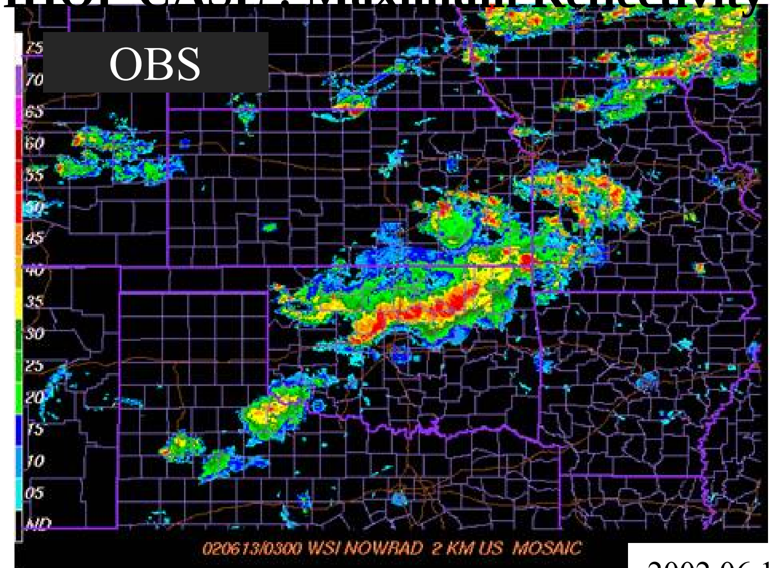


2002.06.13.00:00 UTC

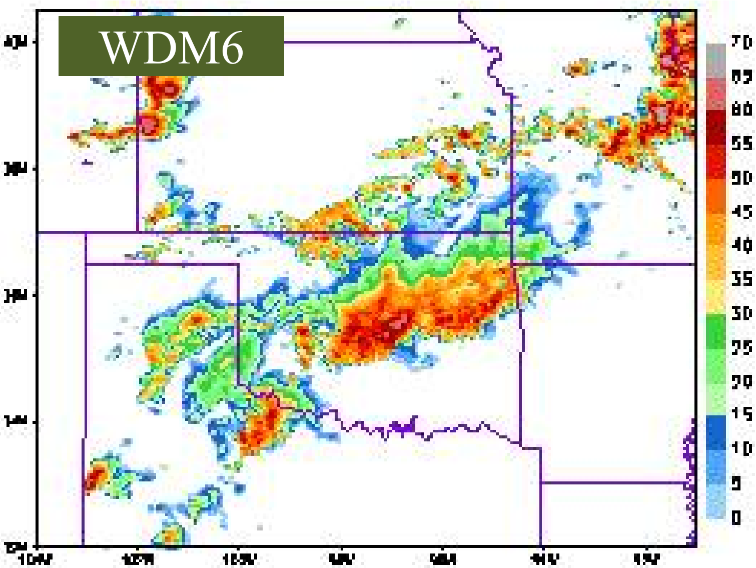


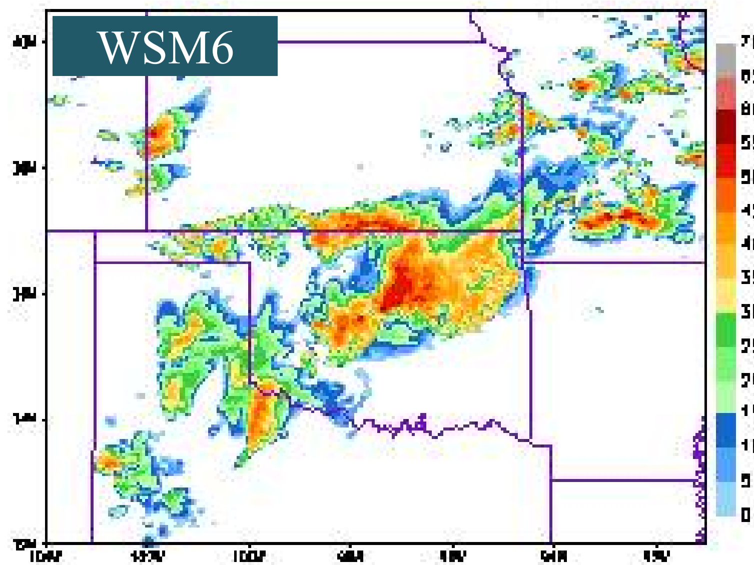


IHOP CASE : Maximum Reflectivity (9, 3, 1 km – 27 hr fcst)



2002.06.13.03:00 UTC





Systematic bias of isolated intense reflectivity in the WSM6 scheme would be alleviated by the WDM6 scheme

Comment

A semi-lagrangLan advection scheme for sedimentation of falling precipitation would be implemented (P2B.12)

WDM5 scheme performs similarly to WDM6, but the Twomey effects of CCN distribution are not properly simulated (P2B.11)

For those who use the WSM6 scheme, we suggest to test the WDM6 scheme.

WSM and WDM microphysics have been evaluated in the framework with the YSU PBL scheme.

Thanks for your attention !!!

Comment for YSU PBL

The lowest model level should not be too low since the first model level is assumed to be the surface layer in YSU (full sigma = 0.995, about 40 m, is recommended).

Less than 20 m is the ill-posed setup since it violates the similarity theory