A Double-Moment Parameterization with In-Cloud Microphysical Processes for Use in Weather Forecasting

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A history of the MPS scheme development

Hong, Juang, and Zhao (1998, MWR) : NCEP cloud 2, 3, 5
--- Prognostic clouds with inner loops at 120s for cloud 3 and 5

Hong, Dudhia, and Chen (2004, MWR) : WSM3, WSM5, WSM6
--- Revised ice microphysics. No temperature dependency in Ni

Juang and Hong (2010, MWR) : Semi-Lagrangian sedimentation
--- Rectified a problem of Eulerian advection

Lim and Hong (2010, MWR) : WDM5, WDM6
--- Prognostic CCN, Nc, Nr

Bae, Hong, and Tao (2018, APJAS) : WSM7, WDM7 (+ hail)
--- for sub-kilo meter resolutions

Kim and Hong (2018, JAS) : Introduction of partial-cloudiness on microphysics
--- In-cloud microphysics for production terms

* GFDL MP (GFSV16) : Some ice microphysics adapted from Hong et al. (2004)

New MPS ???

WSM MPs were written in 2003 summer, in 2009 summer for WDM MPs

Development strategy

-----Take all the advantages of previous developments….(e.g, MPS step = 180s)

-----Adopt the findings in the literature (e.g., Lei et al. 2019, Grasso et al. 2014)

-----Bug fixed (e.g., melting of snow and graupel, evaporation of rain drops)

===☐ Code was re-written for readability and computational efficiency

Two major ingredients

1) In-cloud microphysics concept (Kim and Hong 2018, JAS)
2) Semi-Lagrangian sedimentation

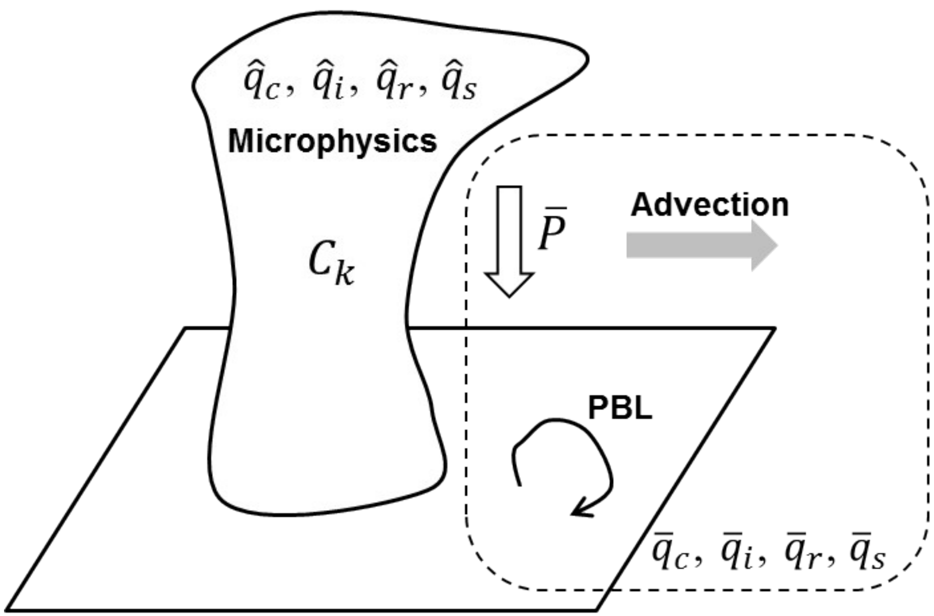
Name of the scheme : WDM62, NOAA, ESRL, PSL, or something else ?

===☐ tentatively, let us call "NEW or UFS MP"

Cloudiness in reality and in MPS schemes

Observation	33 %	98 %
Microphysics	100 %	100 %

In-cloud microphysics : Kim and Hong (2018, JAS) : Use the cloudiness in OBS

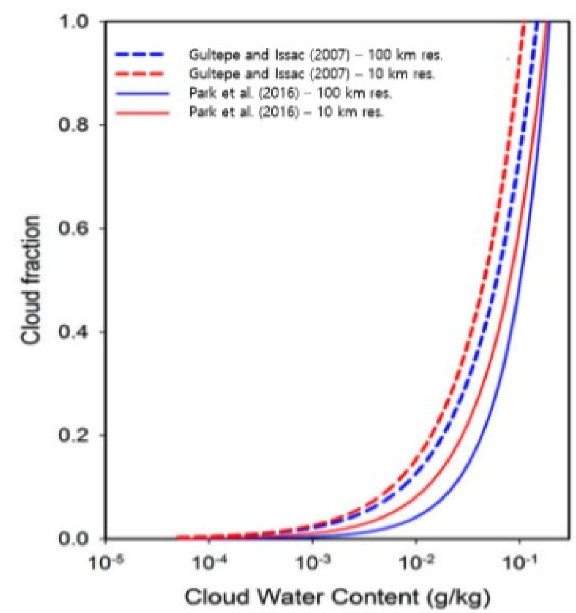


Microphysical processes	treated with **in-cloud scales**
Sedimentation Dynamical processes	treated with **grid-mean scale**
Cloudiness	Satellite observations Park et al. (2016, MWR)

$$\frac{\partial q_x}{\partial t} = f\,(q_c, q_i, q_r, q_s) \rightarrow \frac{\partial q_x}{\partial t} = f\,(q_c/C,\, q_i/C,\, q_r/C,\, q_s/C\,) \times C$$

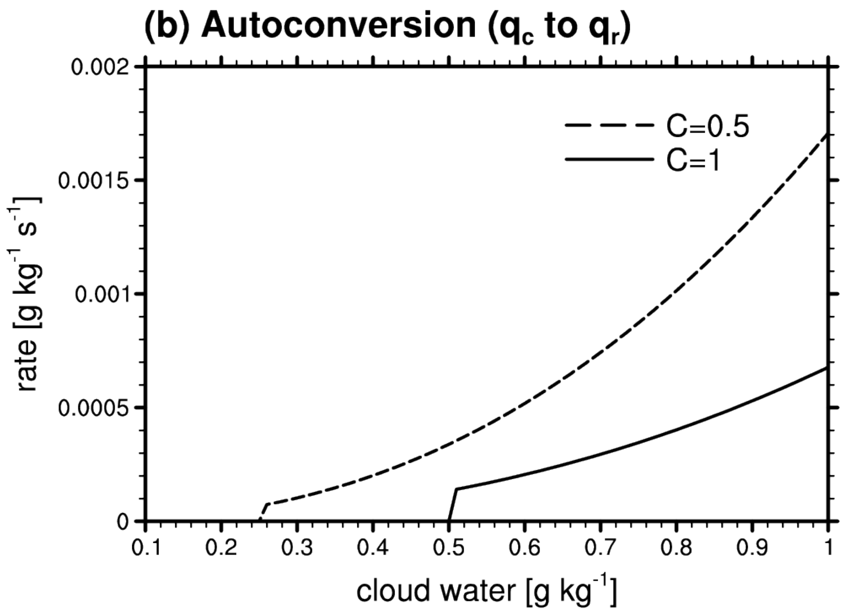
Input: in-cloud values

To get grid mean values



Cloudiness ranges between 0 and 1 whereas it is 1 in conventional MPS

In-cloud microphysics : Kim and Hong (2018, JAS) – Analytic solution



Analytic solution

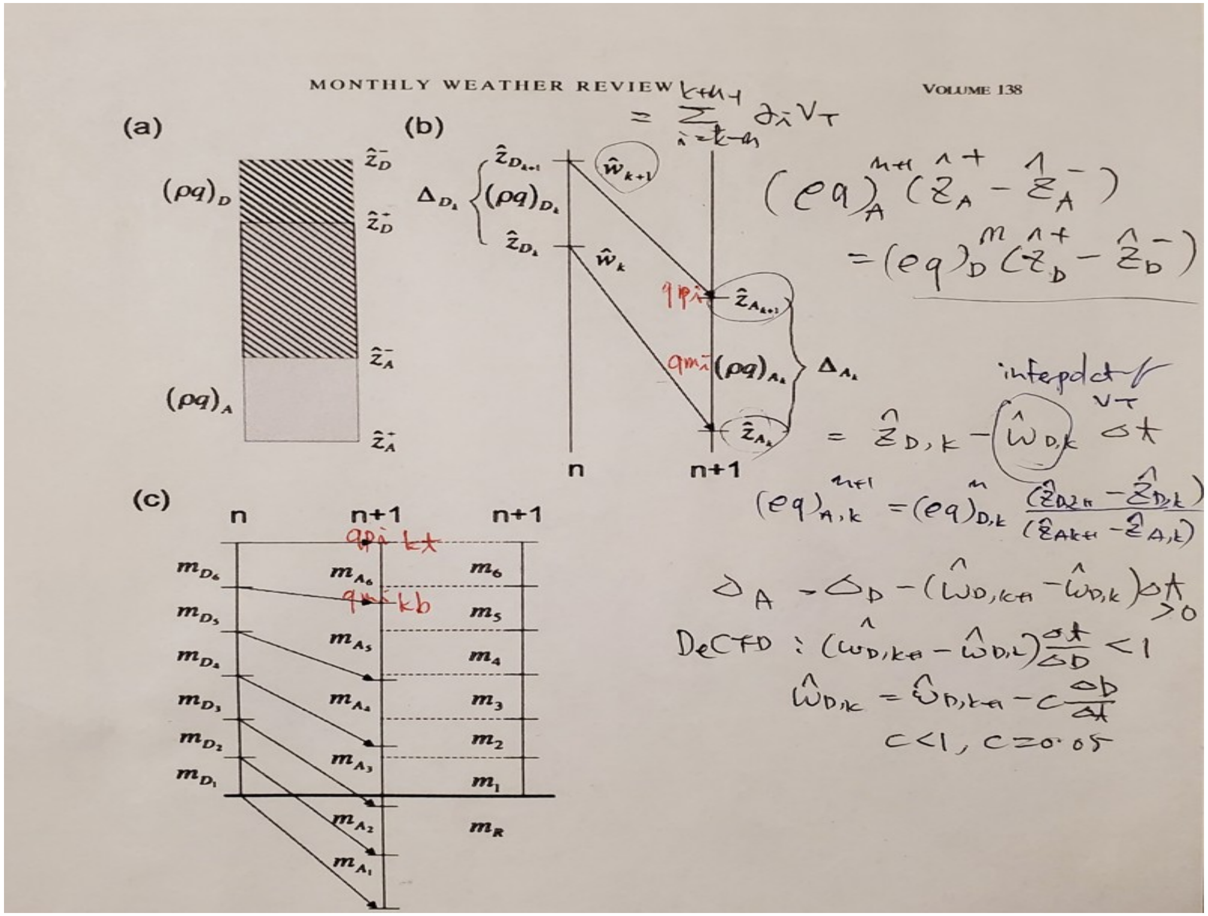
- Accretion – increased
- Autoconversion – increased
- Sublimation - decreased
- Snow melting - decreased

- For example, autoconversion rate is about doubled in C=0.5 as compared to C=1

Our method is much simpler (no cloud overlapping), but yet applies to all the source/sink terms.
It also implicitly represents the scale aware behavior
=□ Issue in develop In-cloud physics algorithm for a double-moment cloud microphysics

Juang and Hong (2010, MWR)

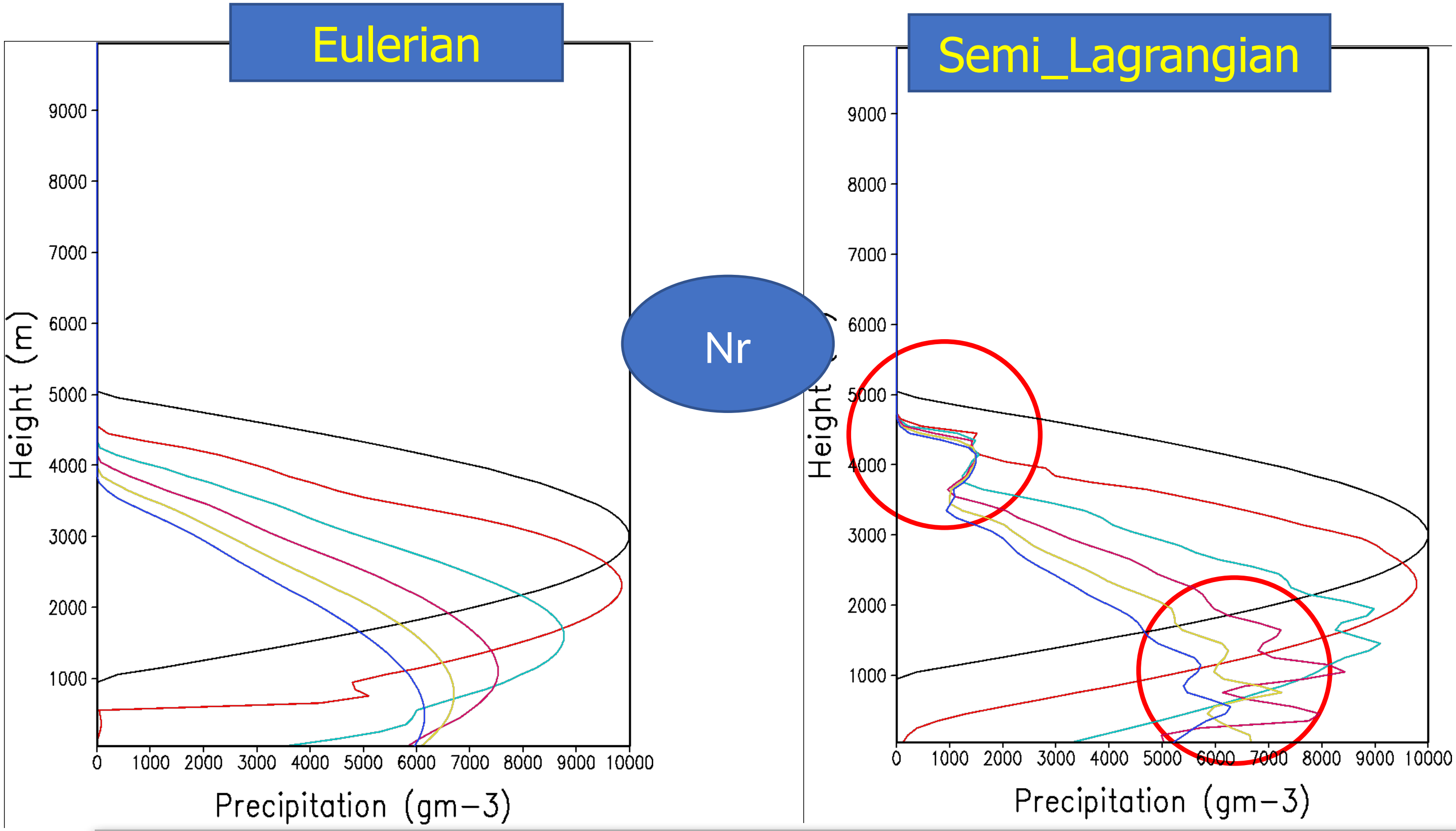
sedimentation : Monotonic mass conserving scheme



JH2010 sedimentation determines the arrival point using velocity at the top and bottom of a cloud cell

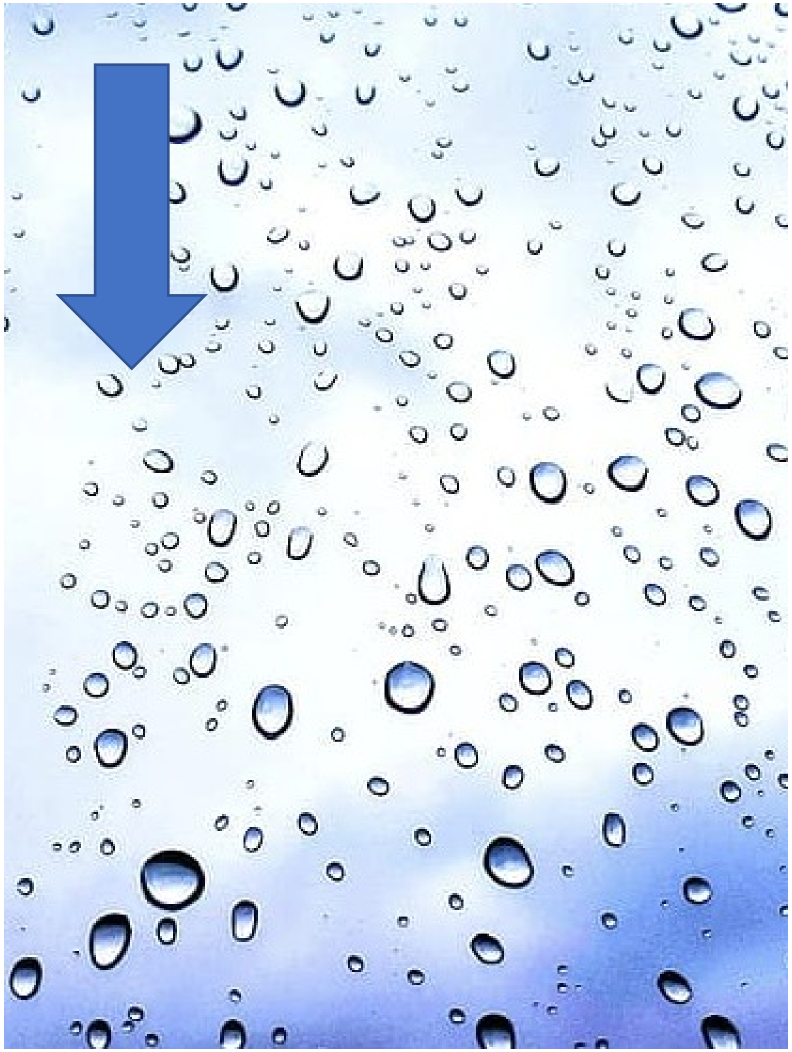
With the Deformation CFL condition, this method is numerically absolutely stable

Application for double moment (WDM6) :
Prof. Sunny Lim, 2009



Semi-Lagrangian scheme (JH2010) is not appropriate for double moment schemes : qr and Nr are advected by Eulerian scheme in WDM MP

Major issues in sedimentation of two-moment MPS



1. Size sorting of precipitation drop
: $V_n < V_r$ ($V_n = 0.47V_r$)
(n is # concentration of rain drop,
r = its mixing ratio)

: violates the CFL condition since Vt increases in sub-time steps

2. Depth of vertical layer decreases downward
: violates the CFL condition since nstep is computed before sedimentation

Eulerian advection could be unrealistic

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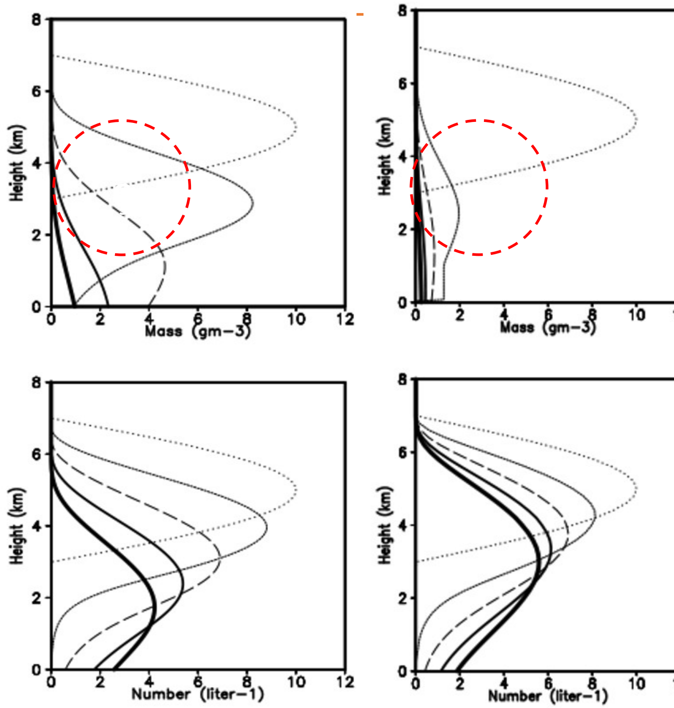
A semi-Lagrangian scheme for two moment MPS : One-D tests – sedimentation only

Name	Configuration	Maximum iteration #	Rainfall (mm)
BIN	Bin microphysics	N/A	24.96
EUL1	Eulerian scheme as in WDM6	185	5.49
EUL2	As in EUL1, but increased iteration	241	16.53
SEM1	Semi-Lagrangian scheme as in JH2010	1	18.86
SEM2	As in SEM1, but with modifications	1	18.87

- At t= 0, qr = 10 cos[pi (Zc-Z)/Zd] (g/kg)
- At t = 0, Nr = the same to qr (#/liter)
- dt = 180 sec, FH = 3600 sec,
- DZ = 10 m at k =1, increasing upward
- Contoured every



qr

Nr

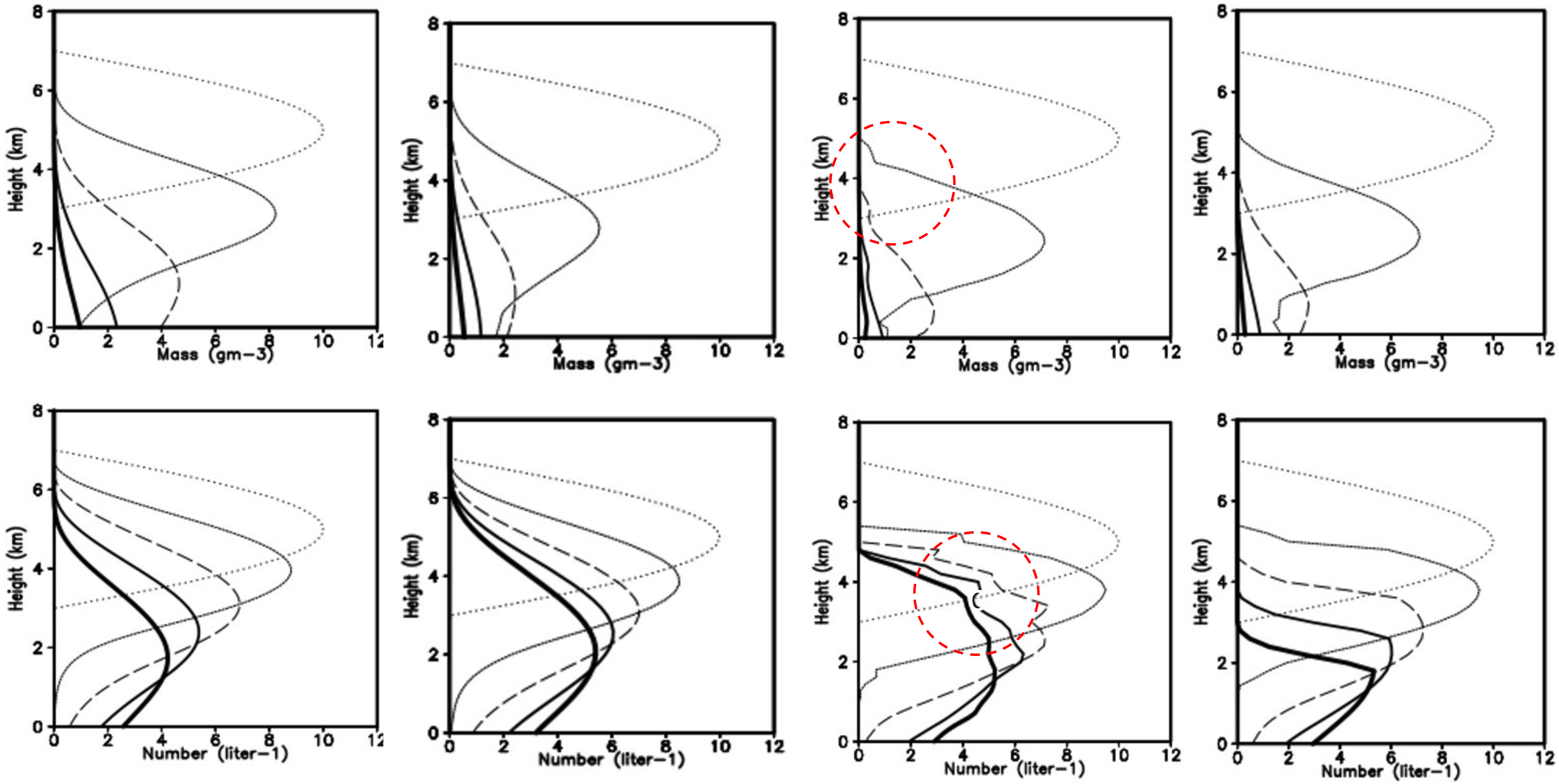
BIN

EUL1

Eulerian advection in WDM6 (EUL1) suffers from a noticeable deficit of mass even if the Vt is updated during sub-stepping (EUL1), which was good enough in single-moment scheme

A semi-Lagrangian scheme for two moment MPS :

One-D tests – sedimentation only



qr

Nr

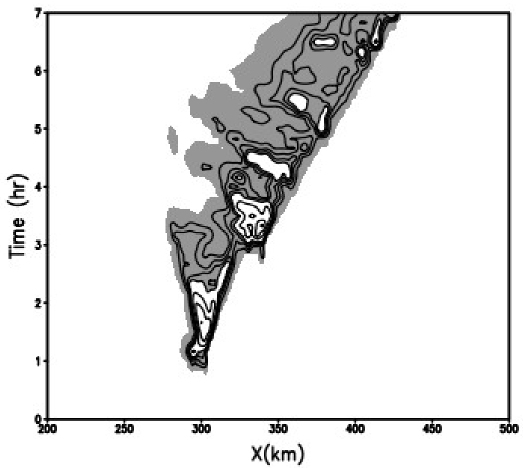
BIN | EUL2 | SEM1 | SEM2

EUL2 : The number of iteration is computed at the depth in the lowest model level… Iteration # =Max(Vt*delt/dz1). EUL2 with the maximum iteration at 241.

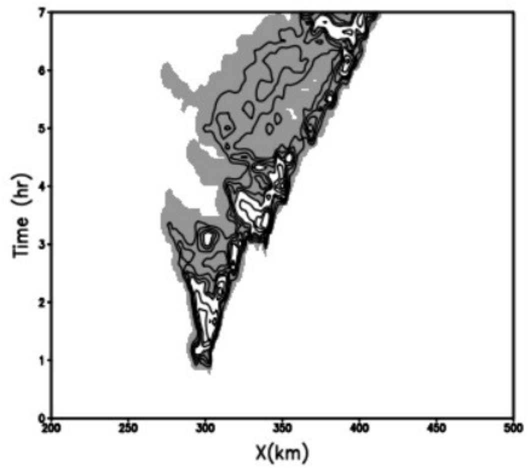
SEM2 : Considerations of constraints, radius constraints and smoothed Vt, produces realistic profiles of mass and number for falling precipitation…. (single loop)

2D Idealized Squall line tests (WRF): MPS only

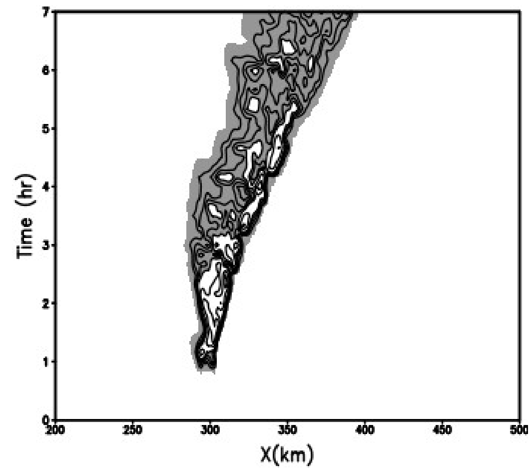
1 km 7hr forecast



WDM6



NEW1



NEW2

SFC Rain

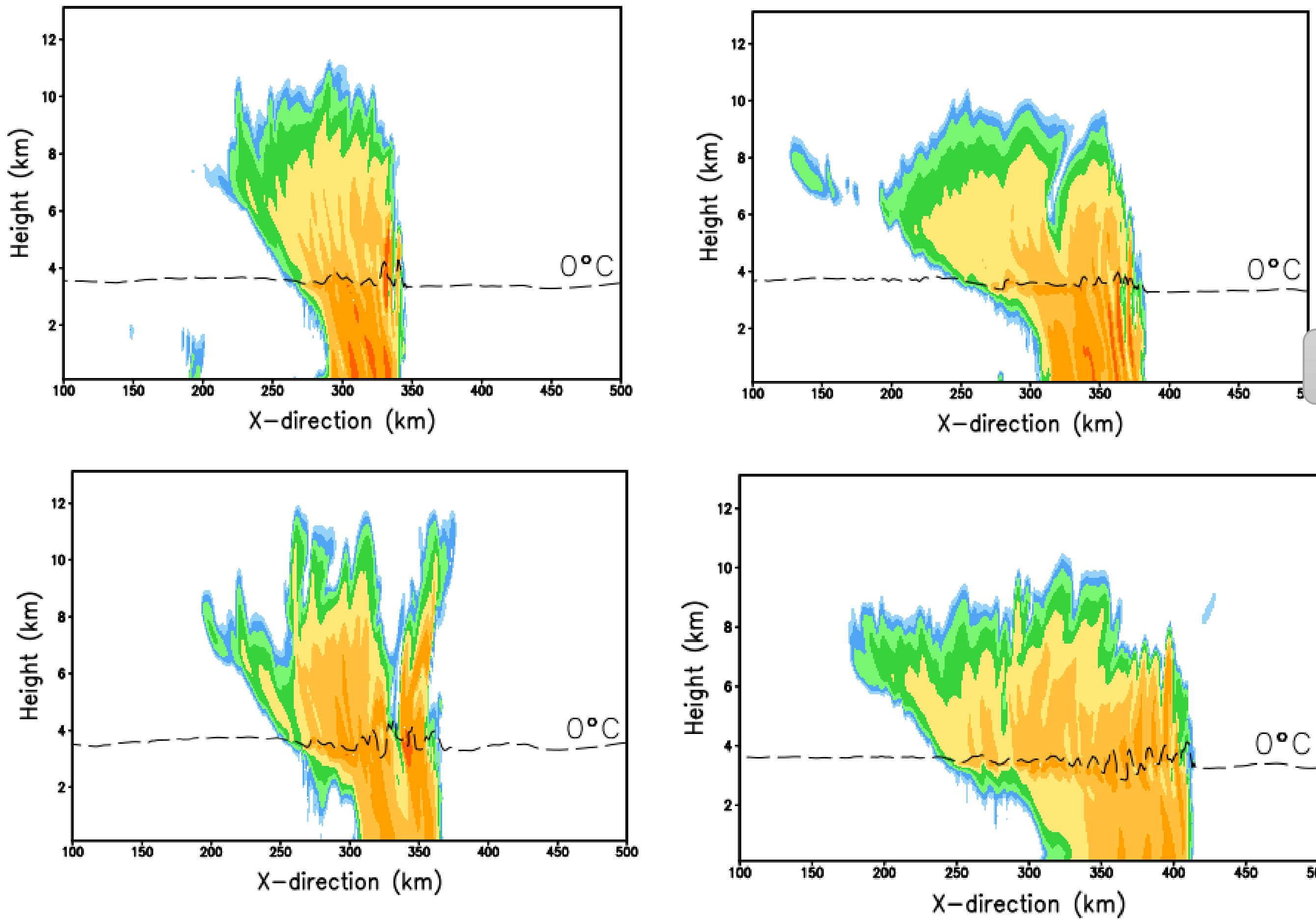
WDM6 : WRF version 4.2.1
NEW1 : All revisions other than In-cloud microphysics
NEW2 : NEW1 plus In-Cloud microphysics

2D Idealized Squall line tests (WRF):

Reflectivity

At 4hr

At 6hr



NEW2

WD~70km

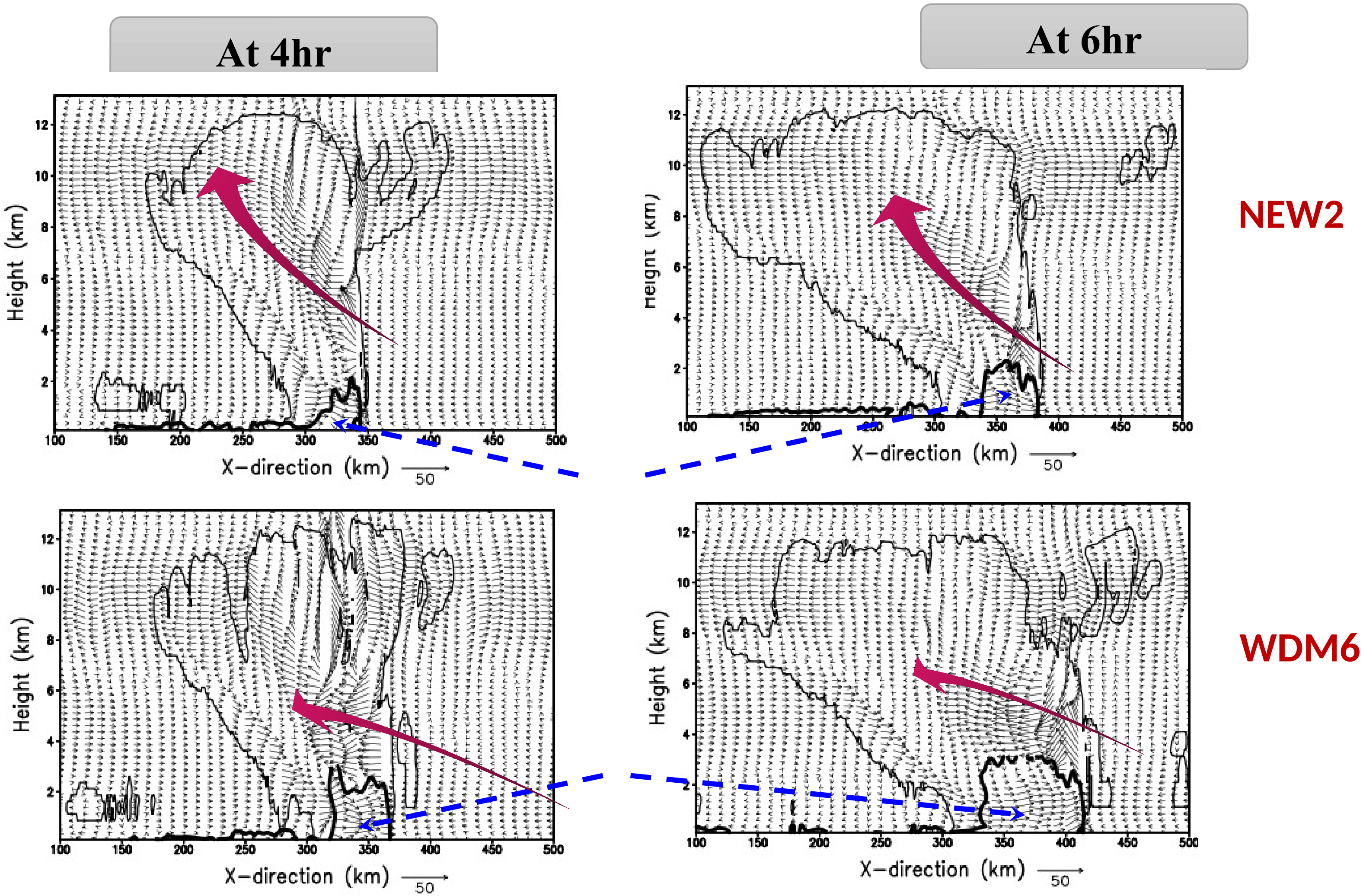
WDM6

WD~100km

NEW MPS produces stronger convective activities with smaller horizontal width

2D Idealized Squall line tests (WRF):

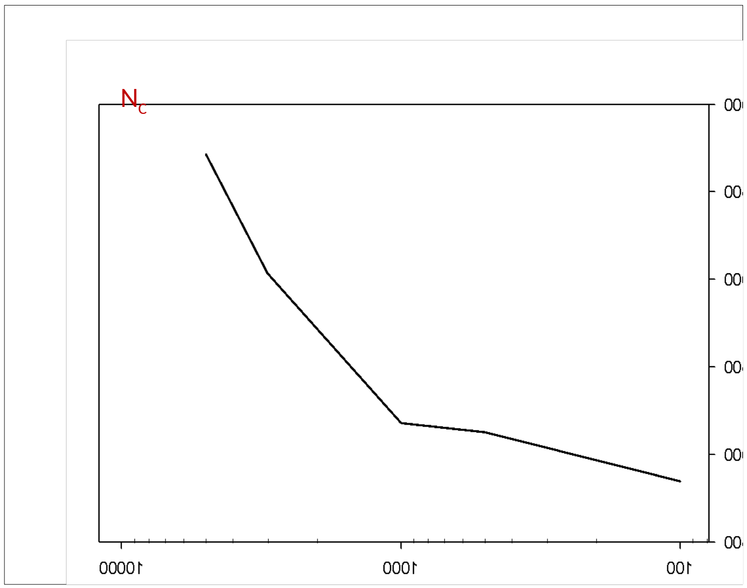
Storm structure

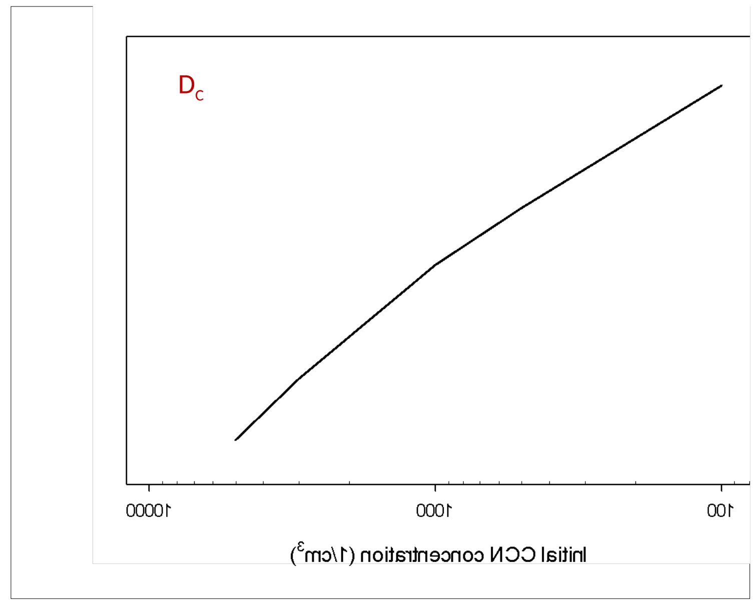


NEW MPS produces realistic FTR and RTF jets, along with cold pool near surface and outflow at the top

2D Idealized Squall line tests (WRF): MPS only

Aerosol effects (100, 500, 1000, 3000, 5000)



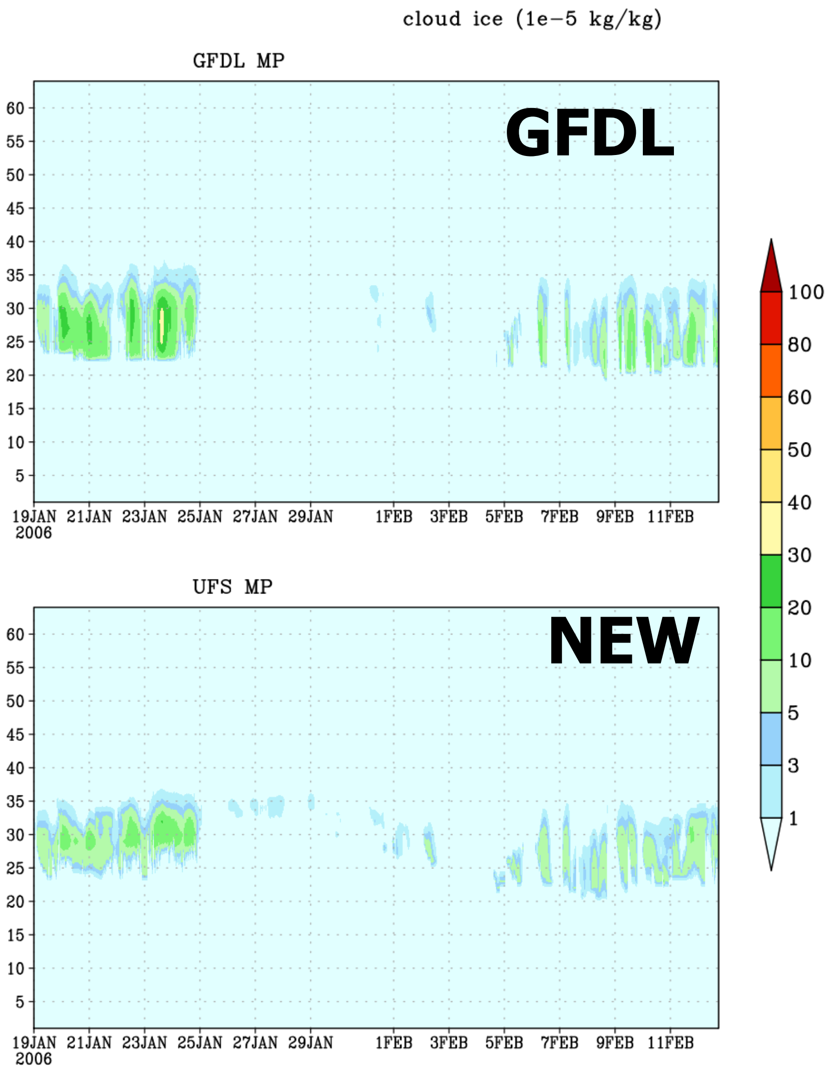


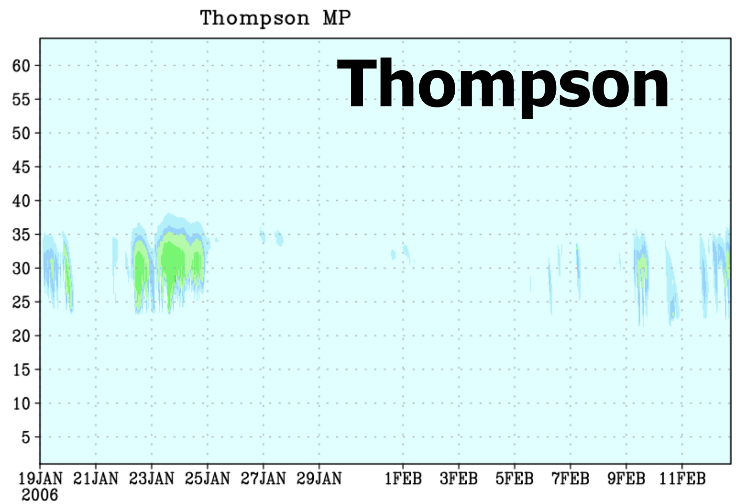
- ✔ Aerosol effects (2nd indirect) are reasonably reproduced

- ✔ As compared to WDM6 (Lim and Hong 2010), volume averaged
- Nc increases (Dc decreases, 14 micro → 7 micro)
- Nr decreases (Dr increases, 0.2 mm → 0.7 mm)

==→ complies with airborne observation Lei et al. (2019)

Single Column Tests : qi (ice)





Cloud ice is smaller than GFDL but greater than Thompson

Snow is smaller than Thompson but greater than GFDL

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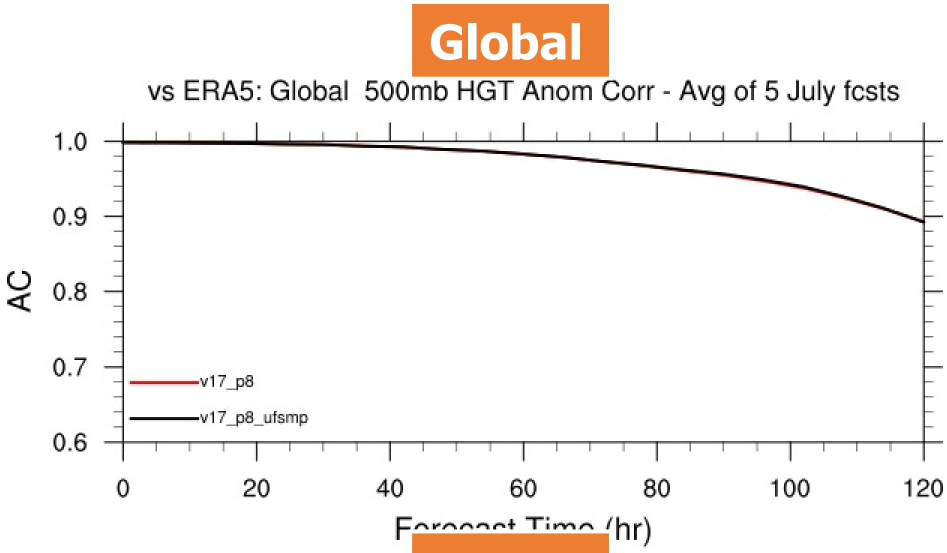
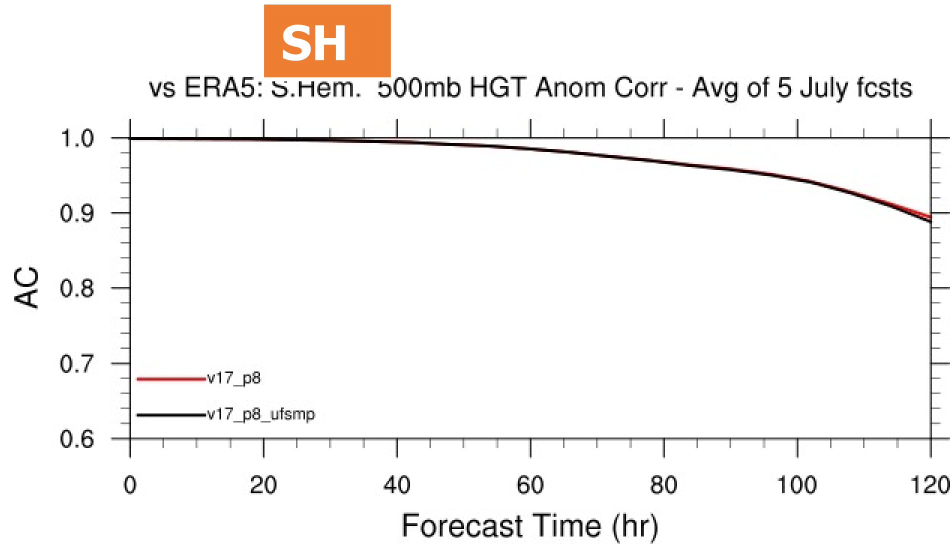
C768 (~13km) UFS run :

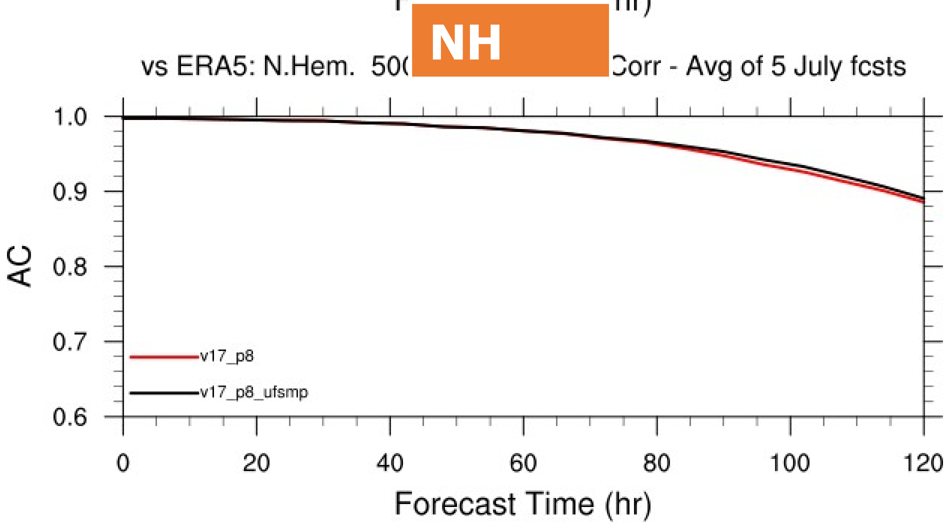
NEW MP : New Microphysics (v4.6.4) with other GFSv17 p8 physics
(CCN is initialized with 100 /cc) plus Aerosol-aware CCN
from Kang et al. 2019
(CCN is initialized with GOCART aerosol, by Haiqin Li)

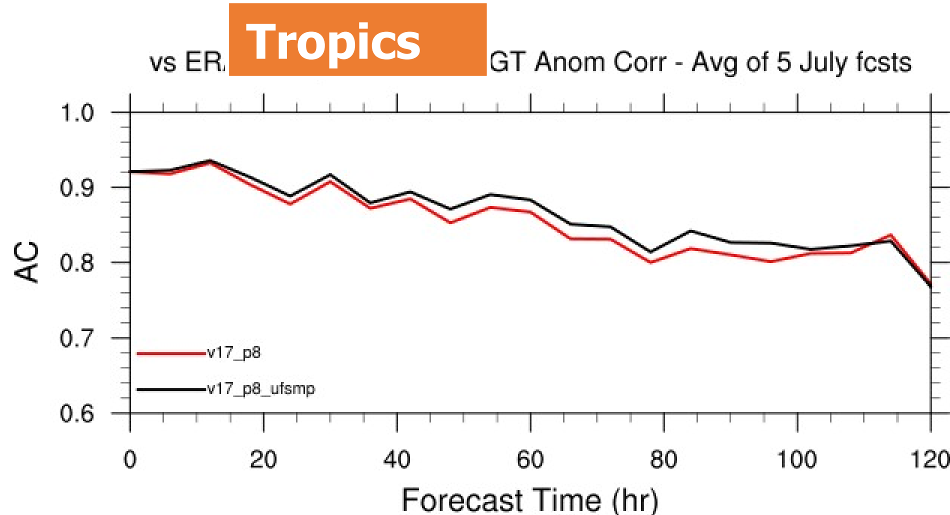
IC=2020120100
Horizontal resolution: C768 (~13km)
Vertical resolution: 127 layers
Time step: 150s
Integration length: 120hrs

500 ACC : Red (p8) Black (NEW) - July 2021

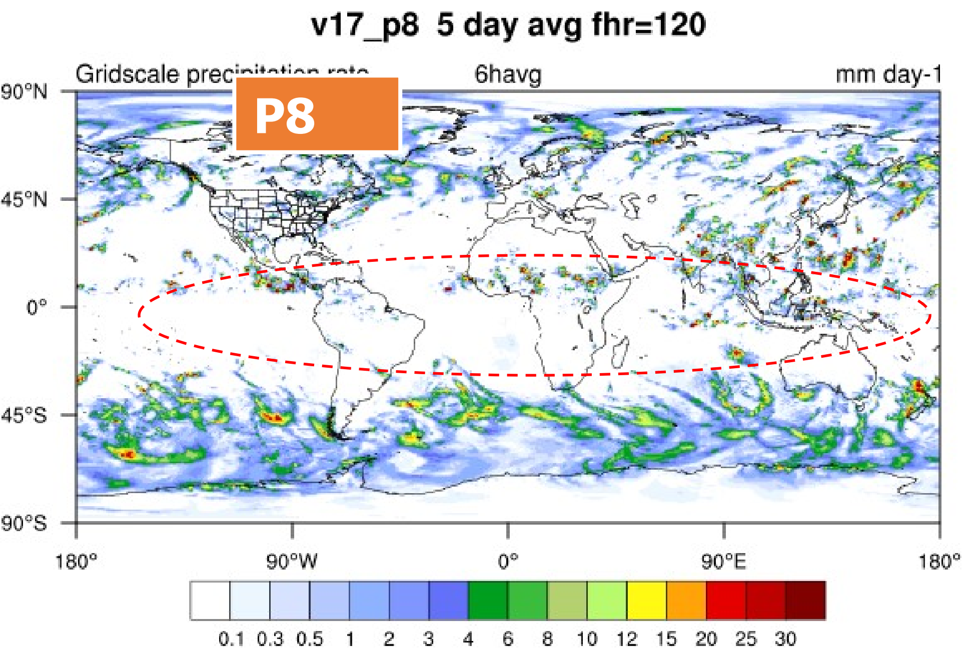


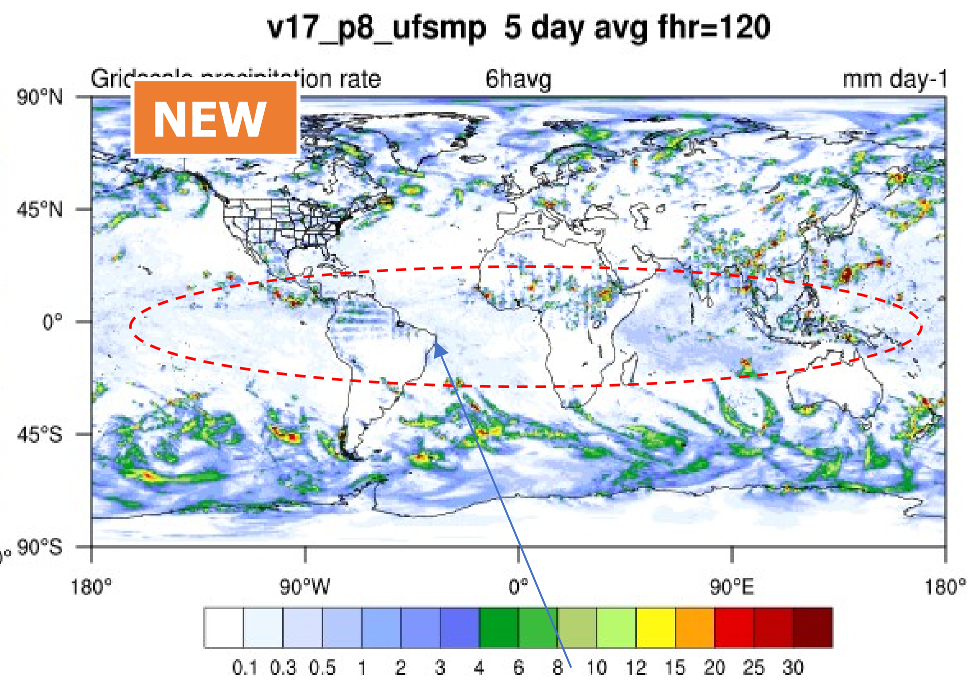






On-going issue : GRIDSCALE (MPS) PRECIP: July 2021





Enhanced light precipitation over tropical ocean and un-realistic distribution of rainfall over tropical land

=? Apparent deficiency of in-cloud MPS in NWP resolutions with larger time step (dt = 150s in GFS, 13km)

=? *All production terms need to be examined…*

C768 (~13km) UFS run : (wall clock time)

	Number concentration variables (additional 3D prognostic variables)	Wall-clock time (s)
GFDL MP	N/A	6628
Thompson MP	Ice number concentration (Ni) Rain water number concentration (Nr)	7384 (11.4% more)
NEW MP	Cloud droplet number concentration (Nc) Rain water number concentration (Nr) Cloud Condensation Nuclei (CCN)	6949 (4.8% more)

♥ NEW MP is *under development …!!!*

Remarks….

A new MPS scheme (presumably, UFS MP) is underdevelopment, along with promising preliminary evaluation results

The scheme is to be shared on UFS public domain in 2024, with the goal to be a candidate in UFSv18

Major to do list in 2023 :

- Examine the source for instability (one of 6 cases was crashed)
- Re-examine the concept of in-cloud processes for NWP resolutions
- Revise all the production terms accordingly
- Add INP data input to improve ice-microphysics, in particular, mixed clouds
- Modify ice-microphysics to improve clouds radiative forcing
- Revise semi-Lagrangian advection to improve numerical accuracy
- Prepare the codes to UFS protocol on public domain

Single Column Tests : CCPP

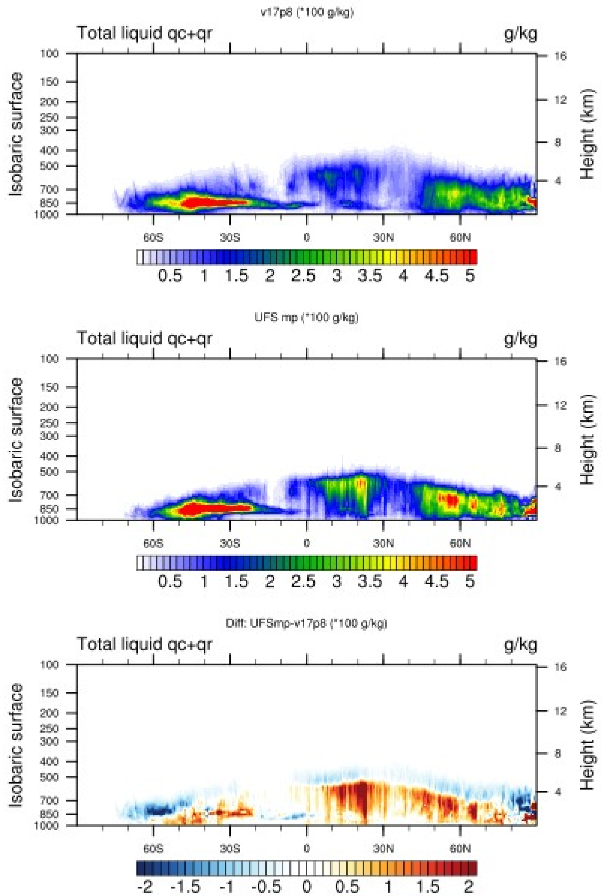
GFDL MP: GFDL Microphysics with other GFSv16 physics
Thompson MP: Thompson Microphysics with other GFSv16 physics
NEW MP: New Microphysics with other GFSv16 physics

Test Case: TWP-ICE
Vertical resolution: 64 layers
Time step: 600s

C768 (~13km) UFS run :

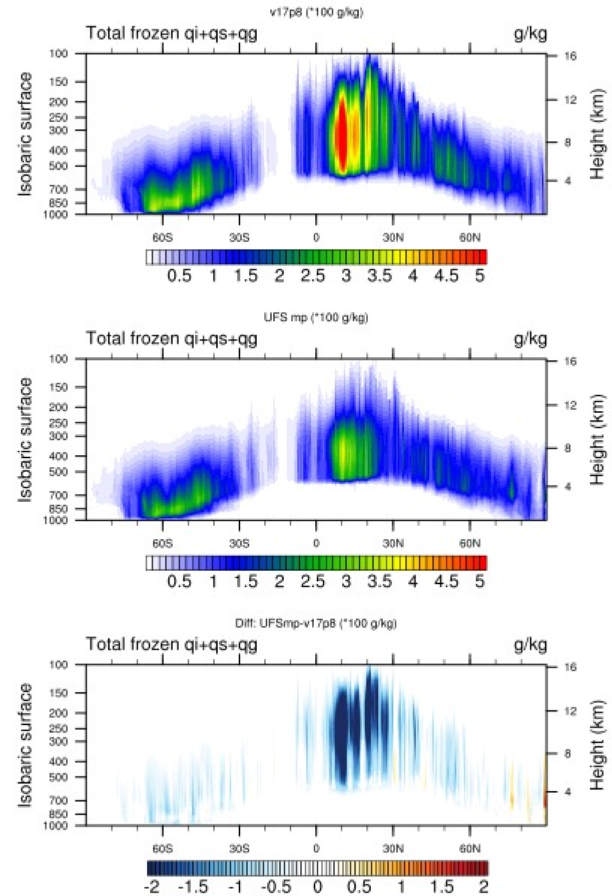
Liquid - increases

Total liquid (qc+qr) mixing ratio averaged over 5 cases for fcst hr 120



Ice - decreases

Total frozen (qi+qs+qg) mixing ratio averaged over 5 cases for fcst hr 120



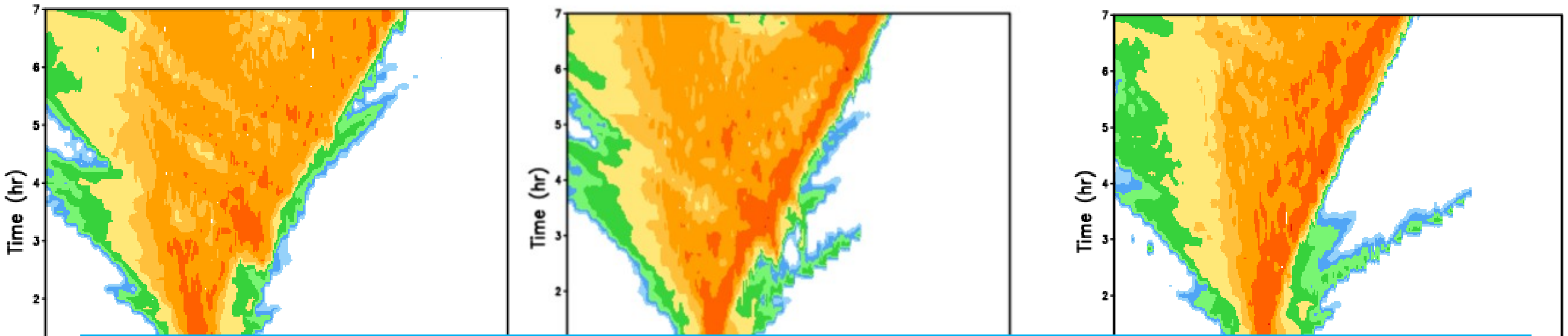
P8

NEW

NEW minus P8

2D Idealized Squall line tests (WRF): MPS only

1 km 7hr forecast

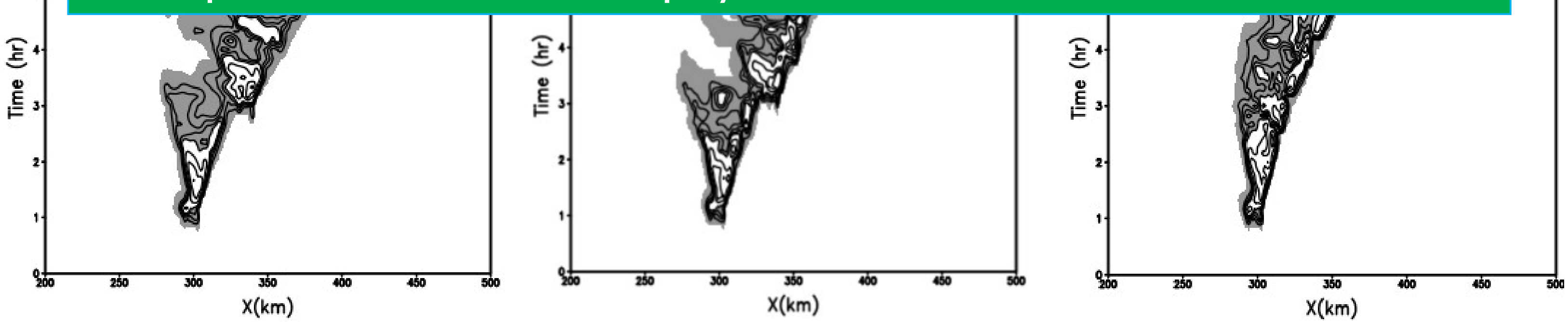


Reflectivity

NEW1 - WDM6 : Convection at leading edge is enhanced

NEW2 - NEW1 : Squall width is narrowed

=> Impact of in-cloud microphysics is dominant



Rain

WDM6 | NEW1 | NEW2