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Numerical Simulation of a Hail Storm Event of April 2015 over Eastern China: Hailstone Size Forecast, Microphysical Budgets and Convection Initiation Mechanism

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Motivation

Because the lack of thorough observation within hailstorm, until now people still do not know well about the real dynamics and microphysics processes during the formation of the golf-sized hailstones. This leads to a large extent of blindness when it comes to hailstone size forecast.

Since 1960, operational numerical weather prediction(NWP) models have improved considerably due to increases in computer power and advanced treatment of physical processes. Currently models generally use bulk microphysics schemes (BMSs) to parameterize the effects of cloud microphysics. This allows us to see more details in the microphysical processes contributing to hailstone growth during the rapid growth stage.

Case overview

In the afternoon of April 28, 2015, severe hailstorm swept through almost the whole Jiangsu province, China, producing golf-ball sized hails that covered up the ground. The whole process with hail, strong winds and lightning lasted nearly seven hours.

Aim and Method

1) Based on ARPS and WRF model, several sensitivity runs were performed to explore the effects of the number of predicted moments in bulk microphysics schemes on the simulated results.

2) To investigate the hailstone forecast skill, we calculate maximum size of hailstones, ground accumulated total number and mass of hailstones.

3) In order to diagnose the contribution of different microphysical processes to hailstone growth, detailed budget analysis based on the source and sink terms are calculated.

4) To better understand the convection initiation and evolution mechanism of this long-lasting severe hailstorm, we conduct other sensitivity experiment.

Experiments set up

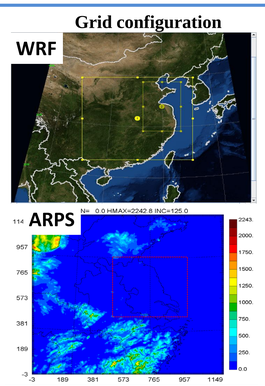
WRF 3.6.1

Domain (2-way nesting)	D01 :660 x 600 x 50 grid points . 3km horizontal D02: 979 x 1000 x50 . 1km
Initial field	FNL data，1 degree 6-hourly boundary conditions
Forecast period	2015.4.27:1200~28.1600UTC
Parameterization	Microphysics Schemes . HUJI spectral Bin scheme . Milbrandt and Yao(2005) - MY2 double moment . Morrison double moment . Lin et al.(1983) - LIN single moment . NSSL 1 mom . NSSL 2 mom

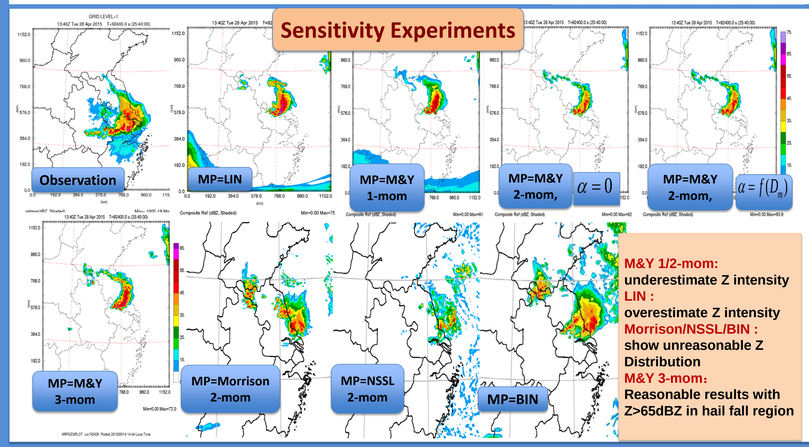
ARPS 5.3

Domain (1-way nesting)	D01 :403 x 403 x 53 grid points . 3km horizontal D02: 463 x 463 x 53 . 1km
Parameterization	Microphysics Schemes - LIN single moment - Milbrandt and Yao - single moment - double moment (a : fixed or diagnosed) - Triple moment

Grid configuration



Sensitivity Experiments



M&Y 1/2-mom: underestimate Z intensity
LIN : overestimate Z intensity
Morrison/NSSL/BIN : show unreasonable Z Distribution
M&Y 3-mom: Reasonable results with Z>65dBZ in hail fall region

Composite Reflectivity

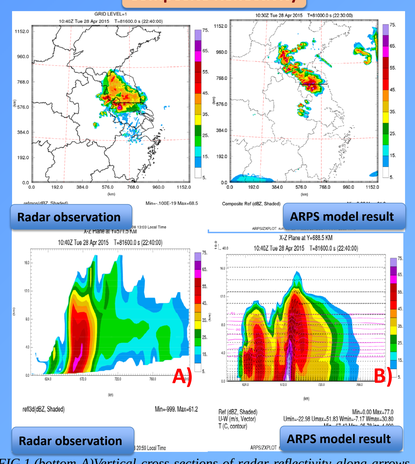


FIG.1.(bottom A)Vertical cross sections of radar reflectivity along arrows in (top A) the composites of maximum reflectivity from the Operational Radar at 1040 UTC 28 April 2015, and ARPS model results(B).

3-moments slice

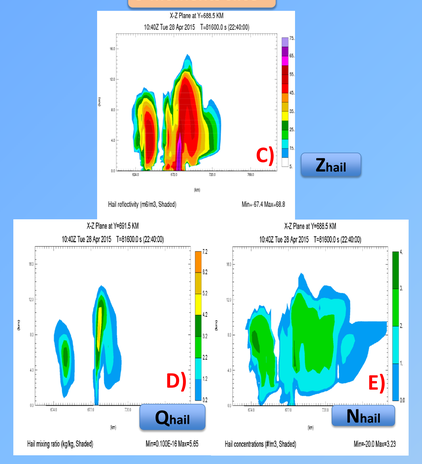


FIG.2.Vertical cross section of (C) reflectivity; (D) mass content; (E) number concentration of hail,

Comparing to the radar observations, FIG.1. shows that besides the location of storm is a little bit northeast than observation, the simulated storm reproduced several characteristics of the radar observation, such as the direction and speed of propagation, a bounded week echo region and a suspended overhang region.

Based on the predicted 3 moments, it can be seen that Zhail contributed substantially to Z total. From (E) we infer that the large number concentration of hail in the downwind direction is resulted from small size hailstones with small fall velocities which were transported to the downwind direction, the negligible Qhail in the downwind direction again proves it.

Hail Size Forecast

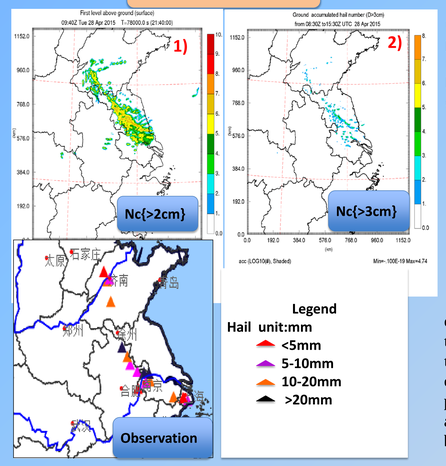


FIG.3.Top,ground accumulated hail number calculated based on the simulated result, form 0830 to 1530 UTC, 1)D>5mm,2)D>3cm;Bottom, observation of hail.

To identify the accumulated number of hail larger than a given size reaching the ground, we calculate the parameter Nc, given by the formula below, where $N_h\{D^*\}$ represents the total number concentration of hailstones larger than D^* and V is the terminal fall velocity at the surface for a given size hailstone.

$$N_h\{D^*\} = \int_{D^*}^{\infty} N(D)\,dD, V_h(D) = ra_h \times D^{bh} \times \exp(-f_h D)$$

$$R_h\{D^*\} = N_h\{D^*\} \times V_h(D^*)$$

$$Nc\{D^*\} = \sum_{T\min 0}^{T\min 1} R_h\{D^*\} * 60$$

$$a_h = 206.89, b_h = 0.6384, f_h = 0$$

The ground accumulated hail number distribution during seven hours(from 08:30 to 15:30UTC) shows that the number of hailstones with D larger than 2cm is about the order of 10^6 and the almost largest golf ball-sized ones with D larger than 3cm arrive at surface is about 10 per square meter. Such hail size distribution over a given area is consistent with the actual hail observation basically.

These exciting results indicate that the 3-moments bulk microphysics scheme has good skill in hail size forecast, owing to the full diagnose of parameters in the gamma distribution function.

Microphysical Budget Analysis

In order to investigate the physical reasons for the hailstone growth, the terms of hail mass content are extracted from the ARPS model and analyzed. We calculate the terms in a cuboid moving together with the hailstorm system.

$$\frac{dq_{lh}}{dt}_S = \left\langle \delta_{irh}\left(QCL_{ir} + QCL_{ri}\right) + \delta_{srh}\left(QCL_{sr} + QCL_{rs}\right) + \delta_{grh}\left(QCL_{gr} + QCL_{rg}\right) + QFZ_{rh} + QCN_{gh} + QCL_{ch} + QCL_{rh} + QCL_{th} + QCL_{sh} + QVD_{vh} - QML_{hr} \right\rangle$$

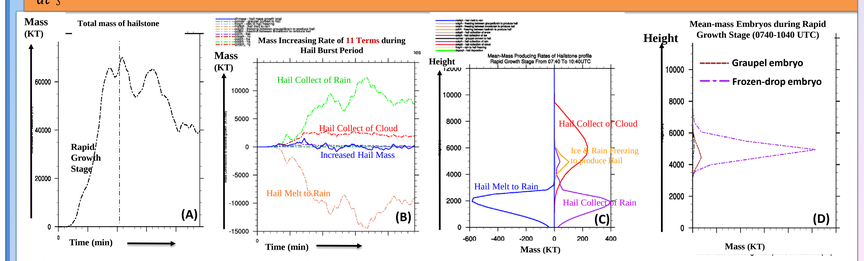
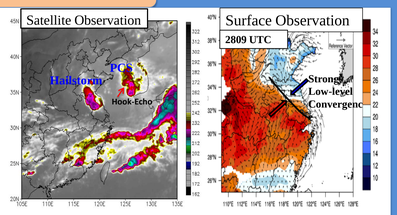


FIG.4.(A)Time sequence of total hail mass (0700~1500 UTC;(B) microphysical budget components contributed to hailstone growth; (C) profile of the microphysical budget components; (D)profile of hail embryos during rapid hailstone growth period

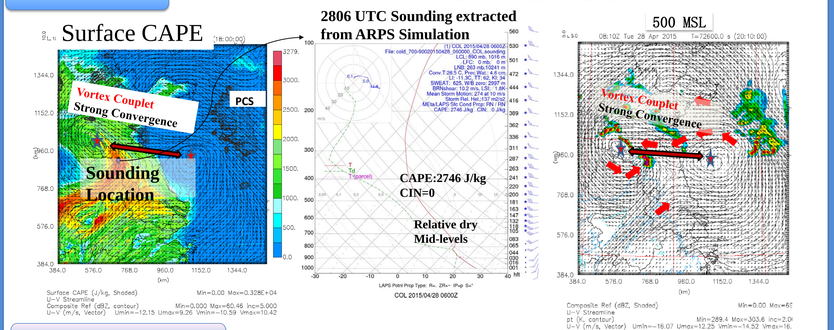
- **Rapid growth stage of hailstones from 07:40 to 10:40 UTC.**
- **Hail collect of cloud & hail collect of rain contribute most to the hailstone growth. Dominant sink of hailstone is melting to rain.**
- **Hail collect of cloud mainly happens nearly 6 km. Below the melting layer, hail collect of rain and hail melting to rain dominant. The maximum occurs at 2 km, maybe the height of averaged cloud base.**
- **Because of the relatively humid and maritime climatology, in this case hailstones mainly originate from frozen-drop embryos. The richest embryos zone is between 4-6 km.**

Convection Initiation Mechanism

We are surprised to find before the day hailstorm happened, another proceeding convective system(PCS) developed intensively and moved eastward to the sea, even with a hook-shaped echo appendage developed near the northern apex of a segment. There exists one strong low-level convergence line along east coast of China, and severe hailstorm burst out.

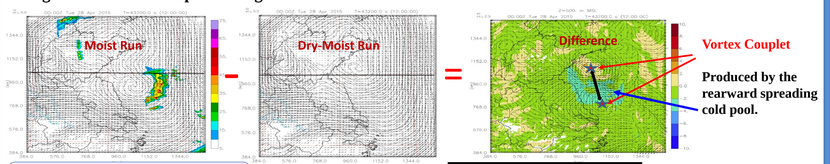


ARPS CNTR RUN

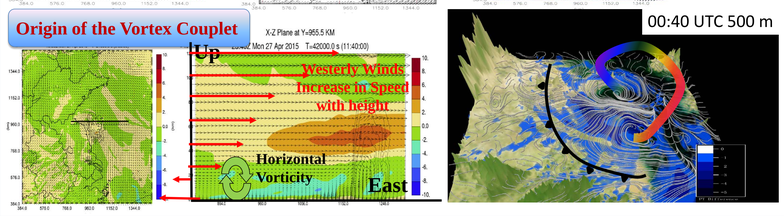


ARPS DRY-MOIST RUN

To explain the role of the proceeding convective system in the convection initiation of the hailstorm, we conduct another Dry-Moist sensitivity experiment – the same as CNTL, but with moist processes turned off throughout the life of the proceeding convection.



Origin of the Vortex Couplet



- **The rearward spreading cold pool, together with the positive vertical environmental shear, generated strong long-lived vortex couplet.**
- **The vortex couplet originated from tilting of the horizontal baroclinic vorticity produced by the cold pool.**

Conclusions:

- The ARPS with multi-moment MY schemes can predict the general evolution of the hailstorm better than with single-moment scheme, with the three-moment scheme performing the best.
- The MY three-moment scheme has certain skill in hail size forecasting. The predicted size and number concentration at ground appear consistent with limited observations.
- ➢ Due to the relatively humid coastal and maritime air mass in this case, hailstones mainly originate from frozen-drop embryos.
- ➢ Dominant sources contributing to hail growth are hail collection of rain and cloud, and the main sink is hail melting to rain.
- ◆ The rearward spreading cold pool, together with the positive vertical environmental shear, generated strong long-lived vortex couplet.
- ◆ The vortex couplet originated from tilting of the horizontal baroclinic vorticity produced by the cold pool.
- ◆ Strong low-level convergence between the vortex over Jiangsu province and the vortex circulation connected with the rearward spreading cold pool forced deep upwelling of moist air, which initiated the convective cells that evolved into a bow-shaped hailstorm.