Development of Bulk cloud microphysics schemes with prognostic hail in WRF

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Frequency of extreme precipitation increased based on observations.

However, most of the models produce light precipitation (<10 mm day\(^{-1}\)) more often than observed, too few heavy precipitation events and too little precipitation in heavy events (>10 mm day\(^{-1}\)) (IPCC, 2007).
• Both hail and/or graupel can occur in real weather events simultaneously, therefore a 4-ICE scheme (cloud ice, snow, graupel, and hail) is required for real time forecasts. * severe local thunderstorms, mid-latitude squall lines, and tornadoes

• However, most of microphysics schemes are 3-ICE (cloud ice, snow, and graupel). A few 3-ICE scheme have the option to switch graupel to hail.

• WSM6 show systematic deficiencies, such as too much light precipitation (Shi et al. 2007),

• WSM6 shows an excessive amount of graupel compared to snow (Lin and Colle 2009)

• Dudhia et al. (2008) alleviated the problem of excessive graupel, but this scheme has remained a wider area of light precipitation and lower heavy precipitation (Han et al. 2013)
Bulk cloud microphysics scheme with hail processes

- Governing equation of hail

\[
\frac{\partial Q_H}{\partial t} = \nabla \cdot (V \nabla Q_H) - \frac{Q_H}{\rho} \frac{\partial}{\partial z} (\rho V_H) + S_H
\]

- Advection
- Sedimentation
- Sink and source of hail

- The slope of the distribution of hail \((\lambda_H)\)

\[
\lambda_H = \left( \frac{\pi \rho_H n_{0H}}{\rho Q_H} \right)^{0.25}
\]

where, \(\rho_H\): the density of hail in kg/m³
\(\rho\): the density of air in kg/m³
\(n_{0H}\): intercept parameter in m-4

- The mass-weighted mean terminal velocity \((V_H)\)

\[
V_H = a_H D_H b_H \left( \frac{\rho_0}{\rho} \right)^{0.5}
\]

where, \(a_H, b_H\): empirical formula
\(D_H\): diameter of hail

WSM6

WSM7
Blue: cold process
Red: warm process
Black: both processes
Microphysics in WSM7 (Bae et al. 2018)

Blue: cold process
Red: warm process
Black: both processes

Processes related to hail
Experimental setup

- Model: WRF v3.7.1  
  (A reference model of KIM, Korean Integrated Model, Hong et al. 2018)

- [2D idealized squall-line test]

<table>
<thead>
<tr>
<th>time &amp; domain</th>
<th>unit</th>
<th>graupel</th>
<th>hail</th>
</tr>
</thead>
<tbody>
<tr>
<td>run hour</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 hr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time step</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 sec</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resolution</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 km, 601 point</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top ~ 20 km, 80 levels</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Terminal velocity      |      |         |      |
|                        |      |         |      |
| $a_x$                  |      |         |      |
| 330                    |      |         |      |
| $b_x$                  |      |         |      |
| 0.8                    |      |         |      |

- Name | Description

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>WSM6</td>
<td>Simulation with WSM6 (3-ICE)</td>
</tr>
<tr>
<td>WSM6_H</td>
<td>Simulation with WSM6 switched to hail (3-ICE)</td>
</tr>
<tr>
<td>WSM7</td>
<td>Simulation with the WSM7 (4-ICE)</td>
</tr>
</tbody>
</table>
The hovmöller plot of rainfall rate and total reflectivity from WSM6 and WSM7

WSM7 shows a weakened precipitation activities at the front of the leading edge.

Intensity of reflectivity is weaker with separate areas of moderate intensity in WSM7
Reflectivity is led by graupel (WSM6) and hail (WSM7)

For snow, intensity in the leading edge is weakened with time

Narrower trailing snow is due to enhanced accretion of snow by hail

Graupel evolves continuously
Mixing ratio of hydrometeors and process rate for WSM6 and WSM7
(average for 0-4 hr and 280-350 km)

- Differences in mixing ratios of hydrometeors
  1) Graupel decreases in WSM7, with the compensation of hail but its maximum at lower altitudes
  2) Weakened Pgacs increases snow aloft
  3) Rain decreases due to reduction of sum of qg and qh at the melting level, which is compensated by falling hail

- Main processes
  1) cold processes
     - WSM6: accretion related to snow
     - WSM7: accretion of rain by snow and graupel
  2) warm processes
     - WSM6: melting of graupel
     - WSM7: melting of hail
Impact of hail or graupel species: WSM6 vs. WSM6_H

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Graupel</th>
<th>Hail</th>
<th>Hail/ Graupel</th>
</tr>
</thead>
<tbody>
<tr>
<td>n0</td>
<td>m⁻⁴</td>
<td>4e6</td>
<td>4e4</td>
<td>1/100</td>
</tr>
<tr>
<td>ρ</td>
<td>kg/m³</td>
<td>500</td>
<td>912</td>
<td></td>
</tr>
<tr>
<td>λₚ</td>
<td>m⁻⁴</td>
<td>1583</td>
<td>545</td>
<td></td>
</tr>
<tr>
<td>1/λₚ</td>
<td></td>
<td>6.3e⁻⁴</td>
<td>1.8e⁻³</td>
<td>2.91</td>
</tr>
<tr>
<td>V</td>
<td>m s⁻¹</td>
<td>2.7</td>
<td>5.2</td>
<td></td>
</tr>
</tbody>
</table>

Process rate (Pr) = f(1/λ, n₀) → Pr ↓

* pgaci, pgacs = f(n0g or n0h)
pgaci: accretion of cloud ice by graupel or hail
pgacs: accretion of snow by graupel or hail

Decreased QG in WSM6 > Increased QH in WSM6_H

pgmIlt in WSM6 > phmIlt in WSM6_H
⇒ QR decreases around melting level.

intercept parameter (n₀) ↓
Slope parameter (λ) ↓
Comparison of time-series and PDFs of precipitations between WSM6 and WSM6_H (hail over graupel species)

- Intercepts parameter ($n_0$) ↓
- Slope parameter ($\lambda$) ↓
- Terminal velocity ($V$) ↑

- Density ($\rho_X$) ↑
- Slope parameter ($\lambda$) ↑
- Terminal velocity ($V$) ↓

Faster sedimentation
Enhance heavier precipitation
Impact of hail-related processes

Added hail processes

Because hail in WSM6_H is divided to graupel and hail in WSM7.

Owing to decreased QH, accretion of snow by hail is less likely to occur

Increased QS and QG lead to more aggregation with cloud water

QS ↑

QC ↓
Overall impact on vertical distribution is governed by the hail species itself (parameters), but with suppressed hail activities due to microphysics related to hail.
[3D real case]

- **Model:** WRF v3.7.1 (reference model of KIAPS)
  
<table>
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</tr>
<tr>
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</tr>
<tr>
<td>Time step</td>
</tr>
<tr>
<td>Resolution</td>
</tr>
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- **Experiment**

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<tr>
<td>WSM7</td>
<td>Simulation with the WSM7</td>
</tr>
</tbody>
</table>

10 UTC on 20 May 2011 (Tao et al. 2016)
WSM7 enhances convective activities in the leading edge of the squall line, whereas they are suppressed in the trailing stratiform region.
Overall impact is in line with that from 2D experiments, but a more robust increase of heavier precipitation.
The 24-hr accumulated precipitation for heavy rainfall case

Impact is significant at higher resolutions.
• WDM7 is also available

• Reference: Bae, Hong, and Tao (2018, Asia-Pac. J. Atmos. Sci.)

Recommendations, in particular, grid size less than 5 km

WSM6 $\Rightarrow$ WSM7, WDM6 $\Rightarrow$ WDM7

YSU PBL $\Rightarrow$ SHIN-HONG PBL
참고
HAIL 절편에 대한 민감도 실험
Hail의 절편에 대한 민감도 실험: Hovmöller plot and timeseries of precipitation rate

n0h: intercept parameter of hail

n0h이 커질수록
- hail의 크기가 작아짐
- slope parameter 증가

\[ \lambda = \left( \frac{\pi \rho n0h}{Q_h \rho} \right)^{0.25} \]

- process rate = \( f \left( \frac{1}{\lambda}, n0h \right) \)
  ➔ hail 관련 과정의 변화율 증가
  (∵ rslope의 변화정도
  \( << n0h \) 변화정도)

민감도 실험
- org: 4e4

<table>
<thead>
<tr>
<th>Parameter</th>
<th>n0h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large hail</td>
<td>1e4</td>
</tr>
<tr>
<td>Moderate</td>
<td>4e4</td>
</tr>
<tr>
<td>Small</td>
<td>1e5</td>
</tr>
<tr>
<td>GSFC</td>
<td>1e6</td>
</tr>
</tbody>
</table>
Hail의 절편에 대한 민감도 실험: timeseries of QS, QG, and QH

n0h: intercept parameter of hail

n0h이 커질수록
- hail의 크기가 큼
- slope parameter 증가

\[ \lambda = \left( \frac{\pi \rho_h n_0 h}{Q_h \rho} \right)^{0.25} \]

- process rate=\( f(\frac{1}{\lambda}, n0h) \)

\[ h \rightarrow \text{hail 관련 과정의 변화율 증가} \]
\[ (\because \text{rslope의 변화정도} \ll n0h \text{ 변화정도}) \]

민감도 실험
- org: 4e4

<table>
<thead>
<tr>
<th></th>
<th>n0h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>1e4</td>
</tr>
<tr>
<td>Middle</td>
<td>1e5</td>
</tr>
<tr>
<td>bottom</td>
<td>1e6</td>
</tr>
</tbody>
</table>

- n0h 증가함에 따라
snow, graupel \rightarrow hail로의 전환율 증가
hail 생성 위치 상승
대체적으로 강한 강수 증가
Hail의 절편에 대한 민감도 실험: 수상들의 수직분포

n0h 증가함에 따라,

Rain: 2-4 km의 QR 증가
Hail: QH 증가. 상층부에서 만들어지는 hail 증가
HAIL 밀도에 대한 분석
Density of hail (denh) ↑

Slope parameter ↑
(Nh 감소=N0h/lh)

Number-weighted-mean terminal velocity ↓

T<T0: phacw, phacr, phaci, phacs, phacg, phdep
T≥T0: phacw, Phmlt, phev, pheml
Process rate 비교

Hail density 증가 → accretion rate of X by hail (exception rain) 감소 → QH 감소

Phacg 감소 → QG 증가

같은 농도일 때,
Phacg > Phaci > Phacw > Phacs
* Phacs에서 vt2avg 적용하면 process rate 커짐
T = 280 K
Den = 1.0

Phevp = (rh - 1) * X
RH = 0.99
Qr = 0.1 g/kg

Phmlt = (T0c - T) * X
T = 280 K
Density of hail (denh) $\uparrow \rightarrow$ Slope parameter $\uparrow \rightarrow$ vt2h $\downarrow$

Accretion of x by hail $\downarrow$

T<T0

- QH $\downarrow$
- QC, QI, QS, QG $\uparrow$
- vt2i, vt2ave $\uparrow$
- QI $\downarrow$/QS, QG $\uparrow$
  - by psaci and pgaci
- QS $\uparrow$/QG $\uparrow$
  - by pracs
  - QH $\uparrow$ by phacs
  - QG $\uparrow$
  - by phacg

T>T0

melting $\downarrow$

T>T0

evaporation $\downarrow$

T<T0 RH<1

Deposition/sublimation $\downarrow$

T<T0 RH>1

Sedimentation $\downarrow$

QH $\downarrow$

강수 감소 이후 강수 증가

QC, QH $\uparrow$ QR $\downarrow$