Simulations of TWP-ICE deep convection using a new bulk ice microphysics scheme

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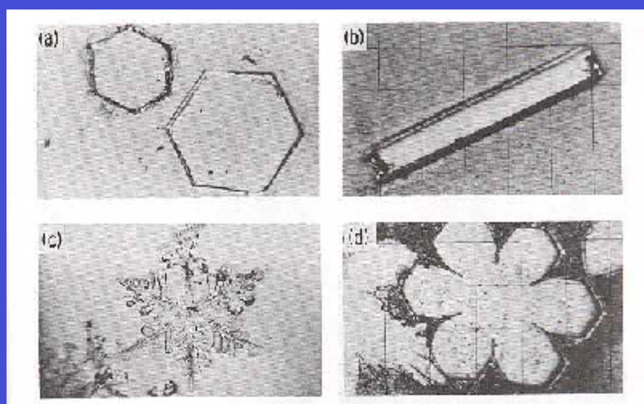
The treatment of ice microphysics has a large impact on model simulations, e.g., precipitation, through interactions with dynamics, radiation, etc…

…but is complicated by a wide range of particle characteristics.

Pristine ice crystals, grown by diffusion of water vapor



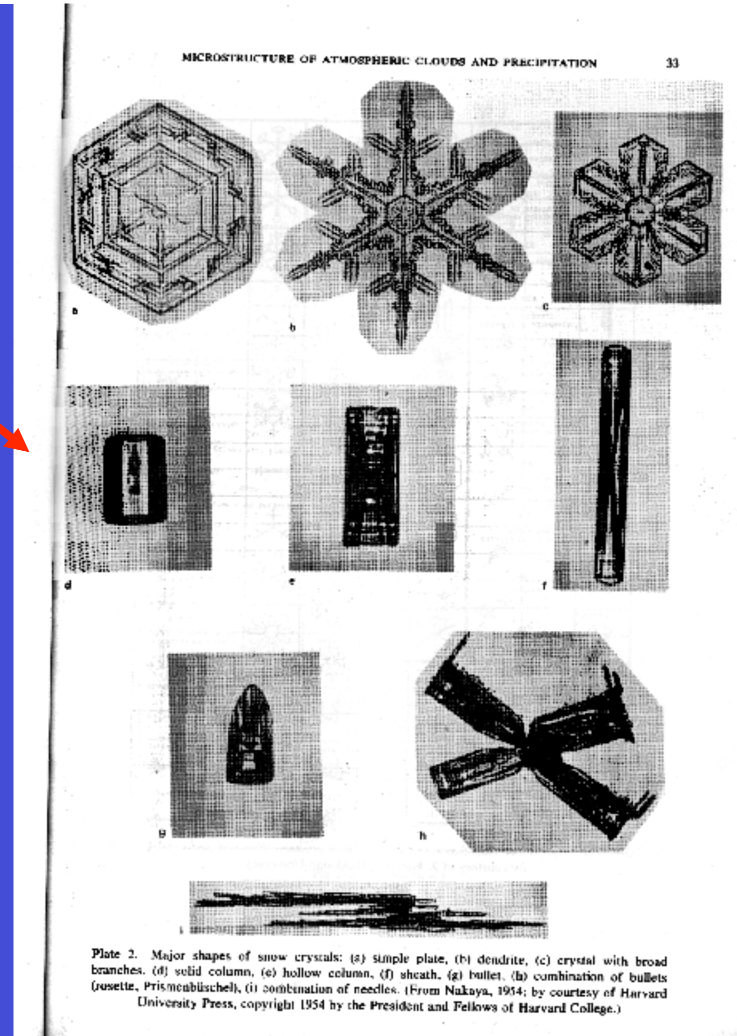
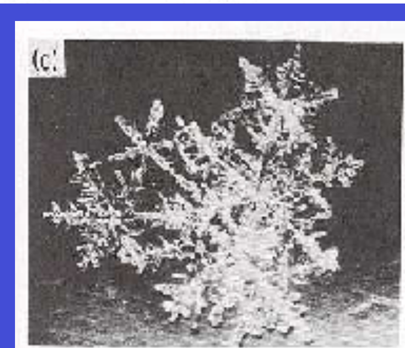


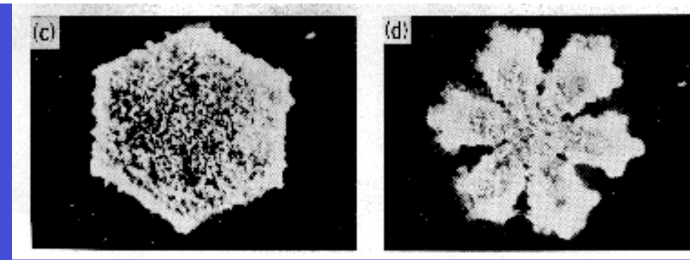
Plate 2. Major shapes of snow crystals: (a) simple plate, (b) dendrite, (c) crystal with broad branches, (d) solid column, (e) hollow column, (f) sheath, (g) bullet, (h) combination of bullets (rosette, Prismenbüschel), (i) combination of needles. (From Nakaya, 1954; by courtesy of Harvard University Press, copyright 1954 by the President and Fellows of Harvard College.)

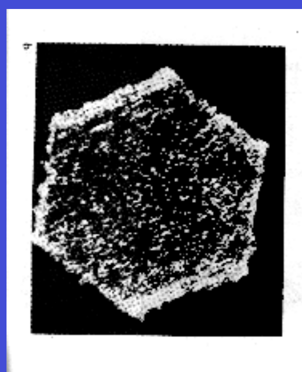
Snowflakes, grown by aggregation

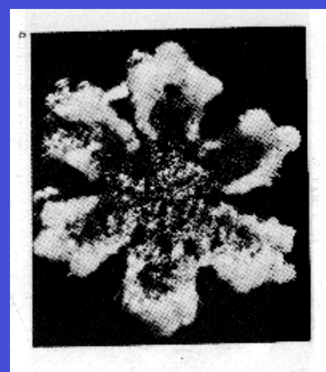


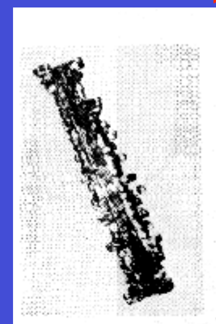
Pruppacher and Klett

Rimed ice crystals (accretion of supercooled cloud water)

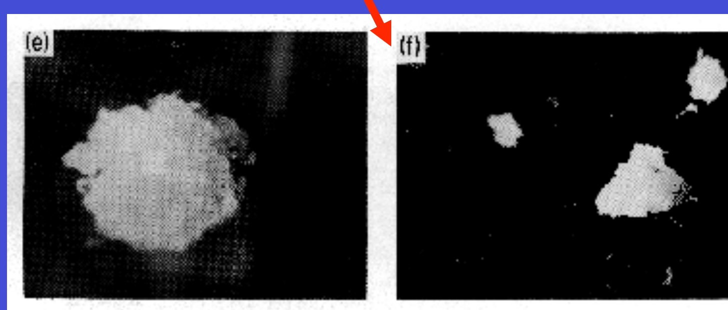


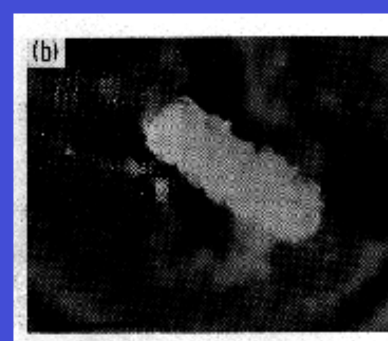






Graupel (heavily rimed ice crystals)





Most schemes used today include the logic of “cloud ice-snow-graupel/hail” to represent different size/shape particles.

Such a logic follows approaches proposed 20+ years ago (Rutledge and Hobbs, Lin et al.) that transplanted ideas from warm-rain microphysics into ice physics.

Rutledge and Hobbs, JAS 1984

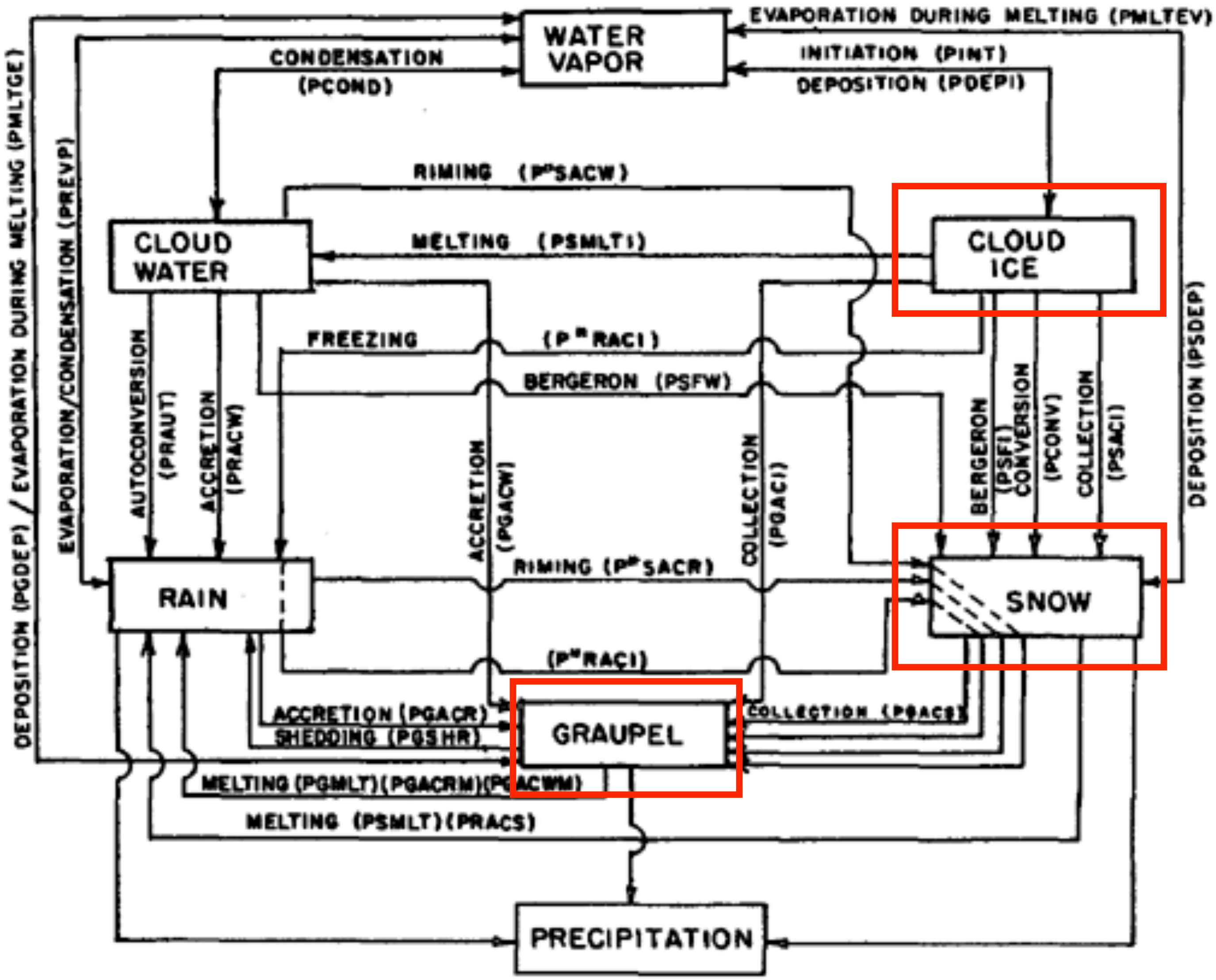


FIG. 1. Schematic depicting the cloud and precipitation processes included in the model for the study of narrow cold-frontal rainbands.

Most schemes used today include the logic of “cloud ice-snow-graupel/hail” to represent ice processes.

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Does it make sense?

Not really!

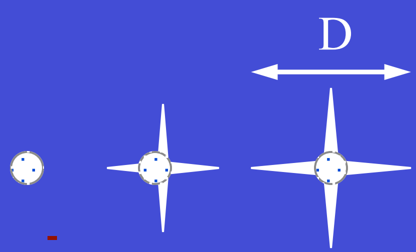
-For warm rain, clear separation does exist between cloud water and drizzle/rain, cloud water grows by diffusion of water vapor, drizzle/rain grows by collision/coalescence. For ice, the boundaries are not obvious and transitions from one category to another take place through a combination of diffusion, aggregation, or riming (accretion of liquid water) growth.

-The ice scheme should produce various types of ice (cloud ice, snow, graupel) just by the physics of particle growth; partitioning ice particles a priori into separate categories introduces unphysical “conversion rates” and involves “threshold behavior” for various parameters (e.g., sedimentation velocity).

Conceptual model of particle evolution during growth (similar to Heymsfield 1982)

Stage 1: Unrimed crystal

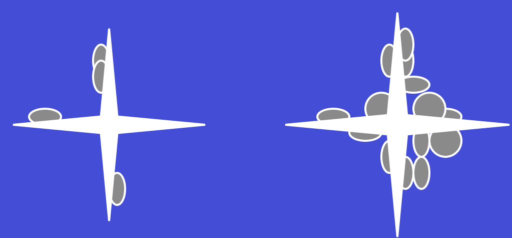
- Particle dimension D and mass increase by vapor deposition



- Vapor depositional growth

Stage 2: Partially-rimed crystal

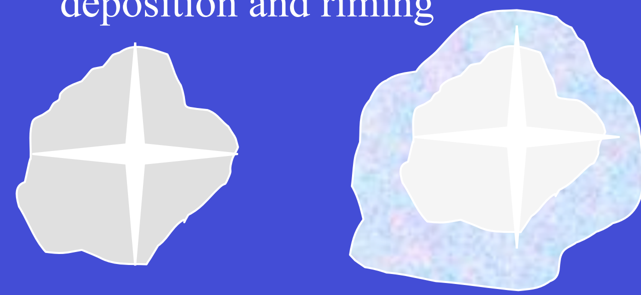
- Particle dimension increases by vapor deposition
- Mass increases by vapor deposition and riming



- Riming of crystal interstices
- Vapor depositional growth

Stage 3: Graupel

- Particle dimension increases by vapor deposition and riming
- Mass increases by vapor deposition and riming



- Complete filling-in of interstices with rime
- Further growth by riming and vapor deposition

Separate prediction of riming and vapor deposition mixing ratios allows for more realistic particle evolution during growth.

A new two-moment three-variable ice scheme: No separate categories for ice, instead growth history determines ice type

$$\frac{\partial N}{\partial t} + \frac{1}{\rho_a}\nabla \cdot [\rho_a(\mathbf{u} - V_N\mathbf{k})N] = \mathcal{F}_N$$

Number concentration of ice crystals, N

$$\frac{\partial q_{dep}}{\partial t} + \frac{1}{\rho_a}\nabla \cdot [\rho_a(\mathbf{u} - V_q\mathbf{k})q_{dep}] = \mathcal{F}_{q_{dep}}$$

Mixing ratio of ice grown by diffusion of water vapor, q_{dep}

$$\frac{\partial q_{rim}}{\partial t} + \frac{1}{\rho_a}\nabla \cdot [\rho_a(\mathbf{u} - V_q\mathbf{k})q_{rim}] = \mathcal{F}_{q_{rim}}$$

Mixing ratio of ice grown by riming (accretion of liquid water), q_{rim}

3 prognostic variables instead of 6 or more in the traditional approach!

Morrison and Grabowski 2008, JAS

The new scheme is tested for the Jan 18 – Feb 3, 2006, period of TWP-ICE.

- 2D version of EULAG (Smolarkiewicz and Margolin 1997), Dx = 1 km
- 97 vertical levels, stretched vertical coordinate
- Initial and forcing conditions same as TWP-ICE intercomparison for cloud resolving models (ARM variational analysis, Xie et al. 2009)

Microphysical sensitivity tests

Mass-size and projected area-size relationships for unrimed crystals

- Aggregates of unrimed assemblages of crystals (Baseline)
- Plate with sector branches (P1b)
- Heymsfield et al. (2007) (H07)

Conceptual model of particle evolution during growth (similar to Heymsfield 1982)

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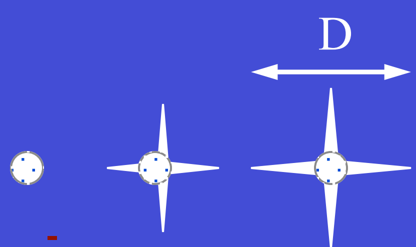

- Vapor depositional growth

Stage 2: Partially-rimed crystal

- Particle dimension increases by vapor deposition
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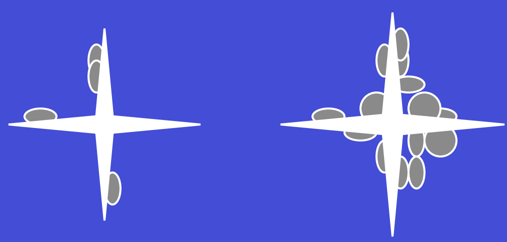

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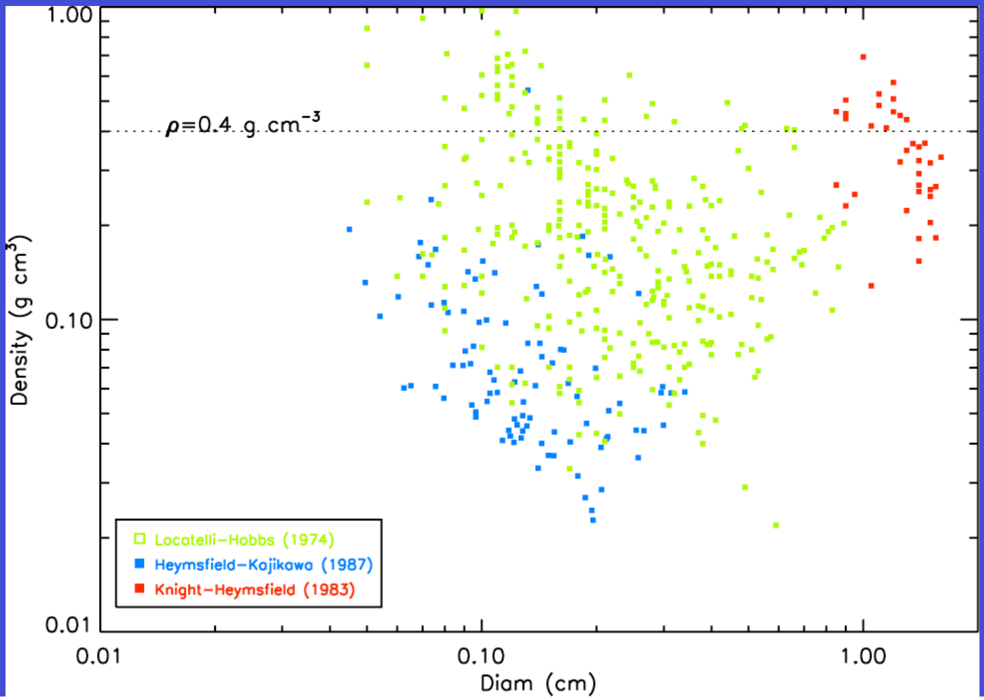
Mass-size and projected area-size relationships for fully rimed particles

- Graupel from Heymsfield and Kajikawa (1987) (Baseline)
- 3 x baseline graupel density (High density)
- Hail, spheres with bulk density of 0.8 g cm^{-3} (Hail)

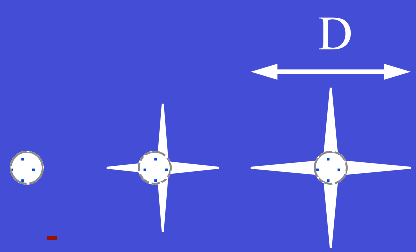


From A. Heymsfield

Conceptual model of particle evolution during growth (similar to Heymsfield 1982)

Stage 1: Unrimed crystal

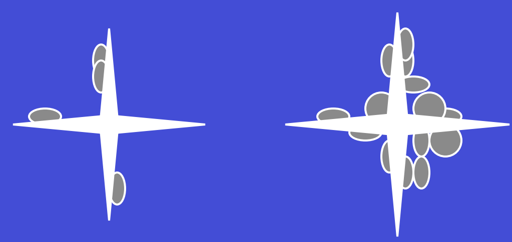
- Particle dimension D and mass increase by vapor deposition



- Vapor depositional growth

Stage 2: Partially-rimed crystal

- Particle dimension increases by vapor deposition
- Mass increases by vapor deposition and riming



- Riming of crystal interstices
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Stage 3: Graupel

- Particle dimension increases by vapor deposition and riming
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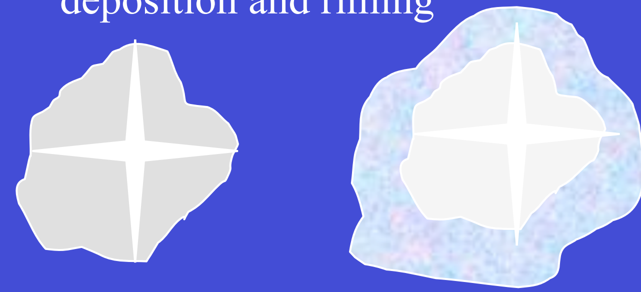

- Complete filling-in of interstices with rime
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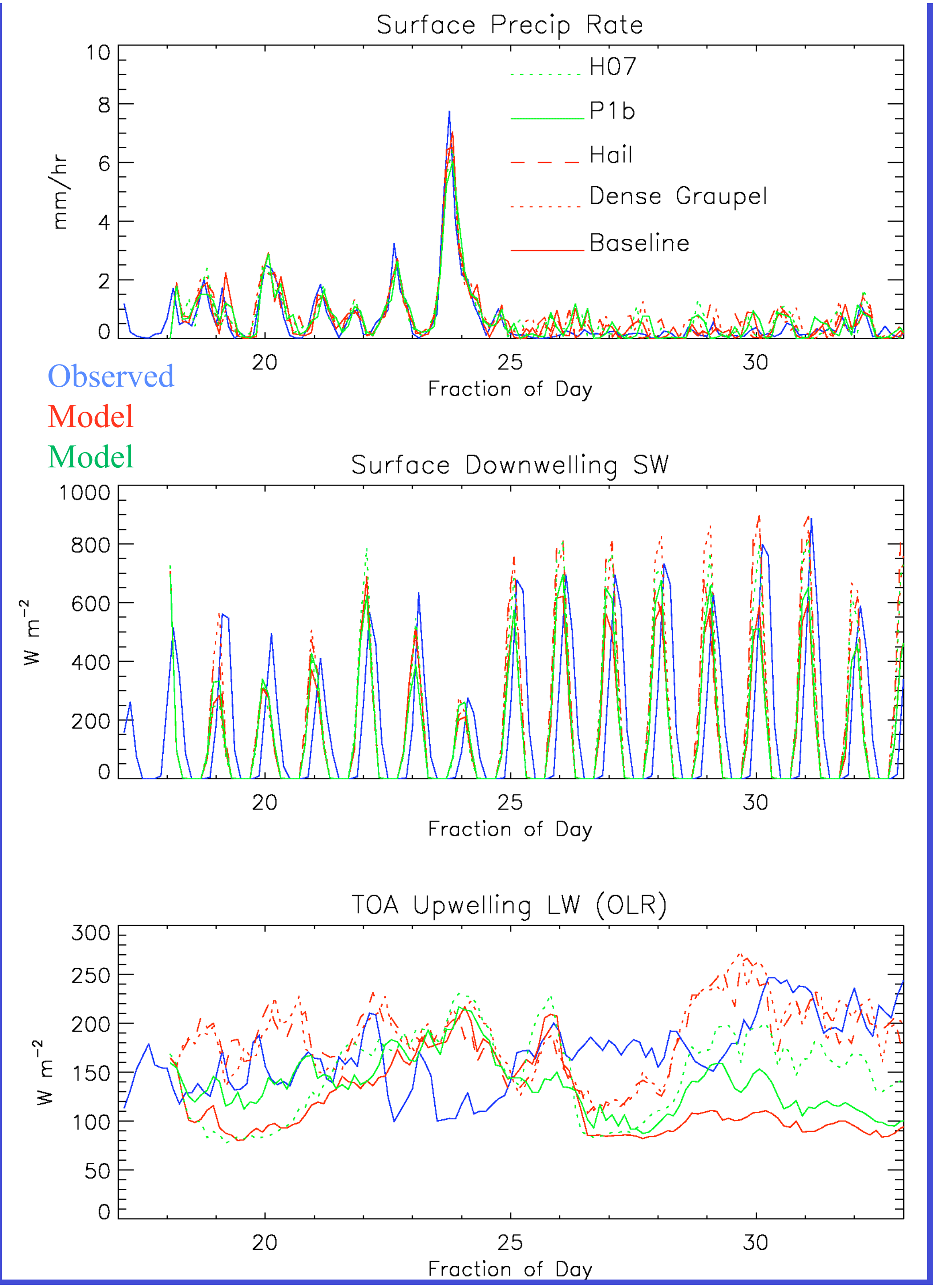
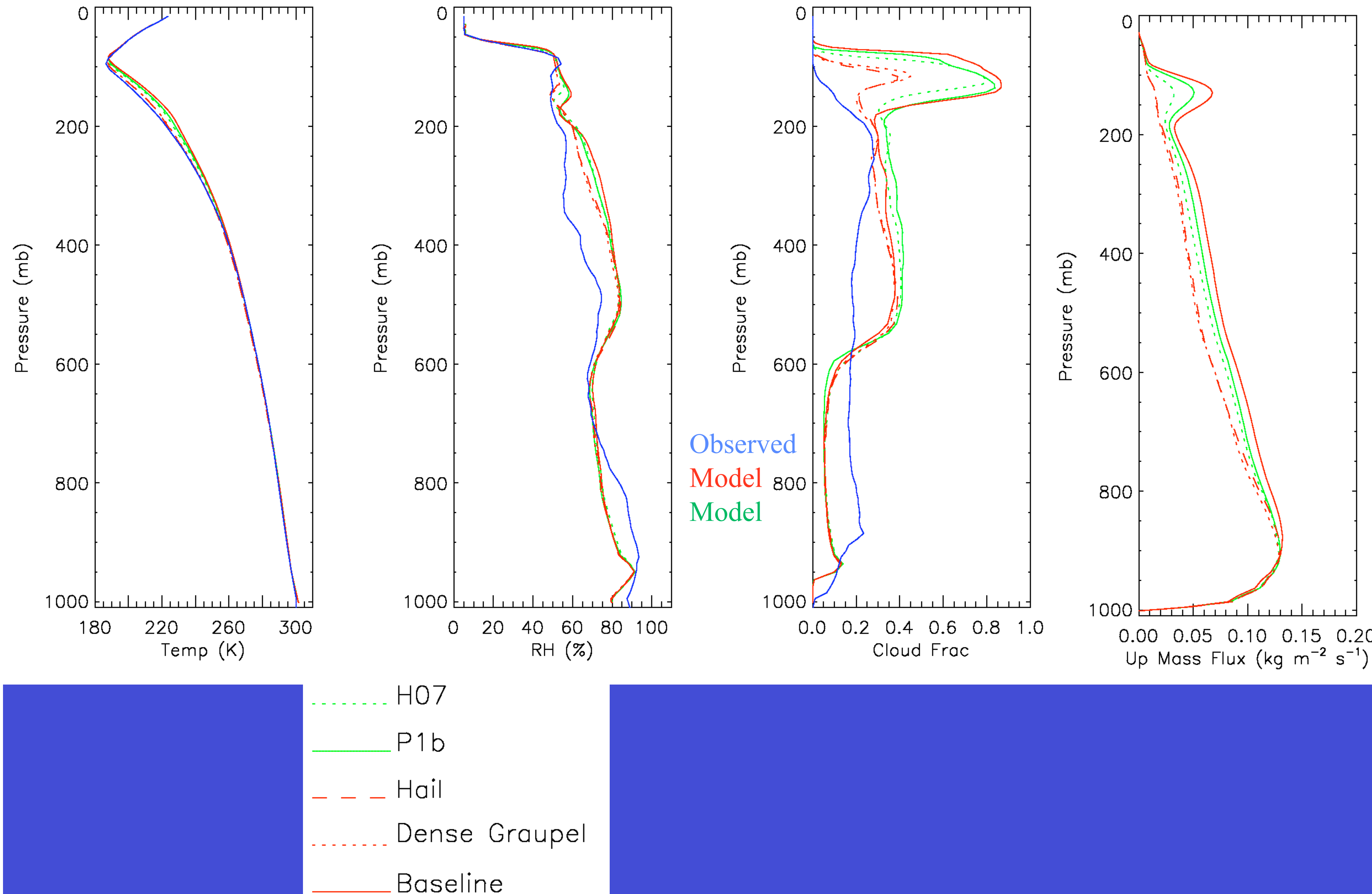
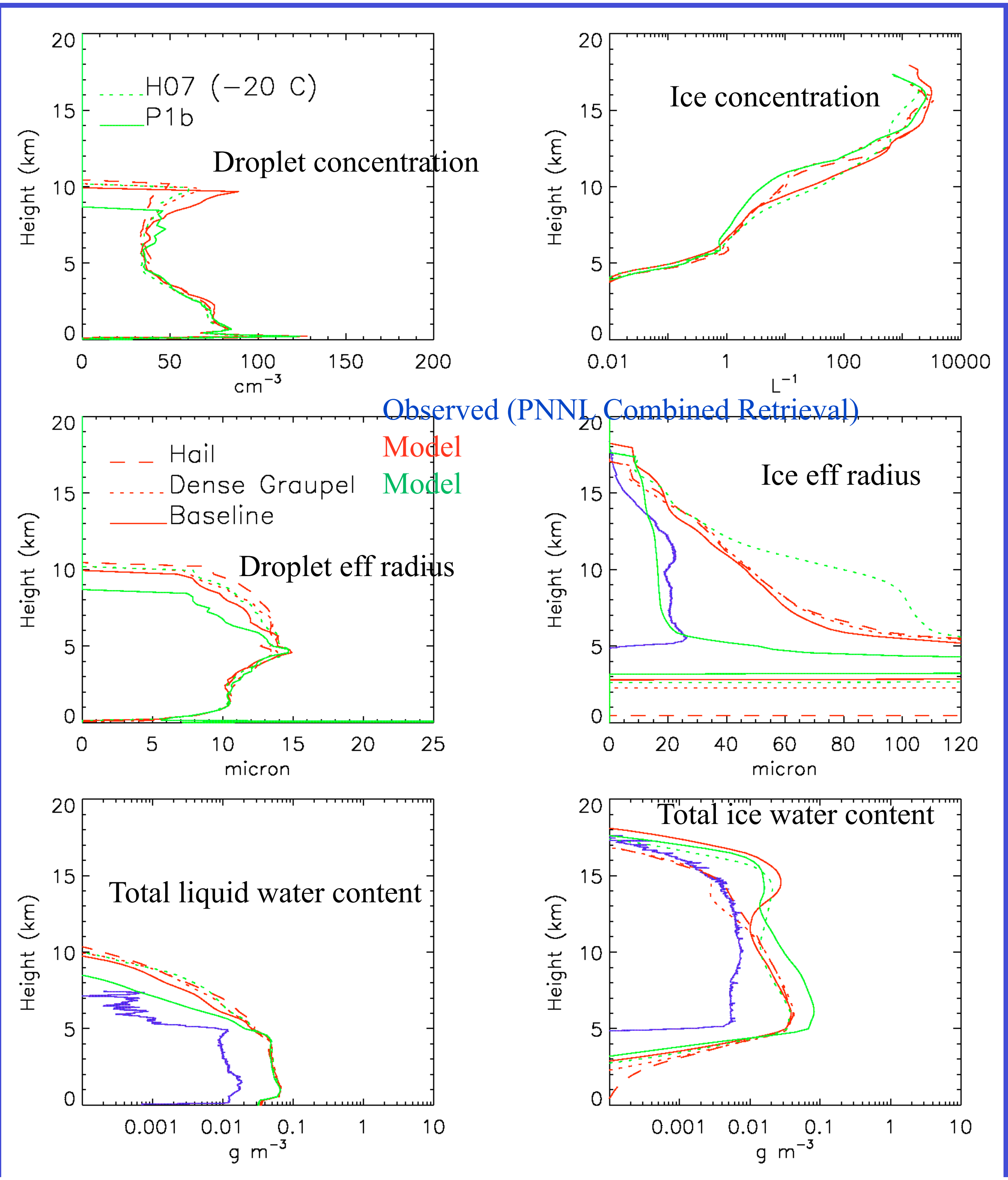
Separate prediction of riming and vapor deposition mixing ratios allows for more realistic particle evolution during growth.

Results


Surface Precip Rate
H07
P1b
Hail
Dense Graupel
Baseline
mm/hr
Fraction of Day
Observed
Model
Model
Surface Downwelling SW
W m^-2
Fraction of Day
TOA Upwelling LW (OLR)
W m^-2
Fraction of Day



Pressure (mb)
0
200
400
600
800
1000
180
220
260
300
Temp (K)
Pressure (mb)
0
200
400
600
800
1000
0
20
40
60
80
100
RH (%)
Observed
Model
Model
Pressure (mb)
0
200
400
600
800
1000
0.0
0.2
0.4
0.6
0.8
1.0
Cloud Frac
Pressure (mb)
0
200
400
600
800
1000
0.00
0.05
0.10
0.15
0.20
Up Mass Flux (kg m^{-2} s^{-1})
H07
P1b
Hail
Dense Graupel
Baseline



H07 (−20 C)
P1b
Droplet concentration
Height (km)
cm⁻³
Ice concentration
L⁻¹
Observed (PNNL Combined Retrieval)
Model
Model
Hail
Dense Graupel
Baseline
Droplet eff radius
micron
Ice eff radius
micron
Total liquid water content
g m⁻³
Total ice water content
g m⁻³

Summary

- A new microphysics scheme has been developed that predicts rime mass fraction and moves away from traditional approach of a priori categorization into different species (cloud ice, snow, graupel).

- Overall, preliminary results for TWP-ICE appear reasonable, with some notable biases relative to obs/retrievals (excessive high cloud fraction, too large ice and liquid water contents).

- Model exhibits some sensitivity to ice microphysics parameters tested, especially graupel density. Increased density leads to reduced ice water content at upper levels, reduced anvil coverage, and reduced mass flux. Results suggest need to better represent graupel density.

- Need to compare ice microphysical sensitivities w/ other model sensitivities (rain microphysical parameters, 2D vs. 3D, horizontal/vertical resolution, etc).