Ice multiplication in clouds: modeling new processes

VAUGHAN PHILLIPS

DEPT OF PHYSICAL GEOGRAPHY AND ECO. SCIENCE, LUND UNIVERSITY, 25 OCT 2017

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E. WILLIAMS	MIT, USA
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A. DETWILER	South Dakata School of Mines and Tech., USA

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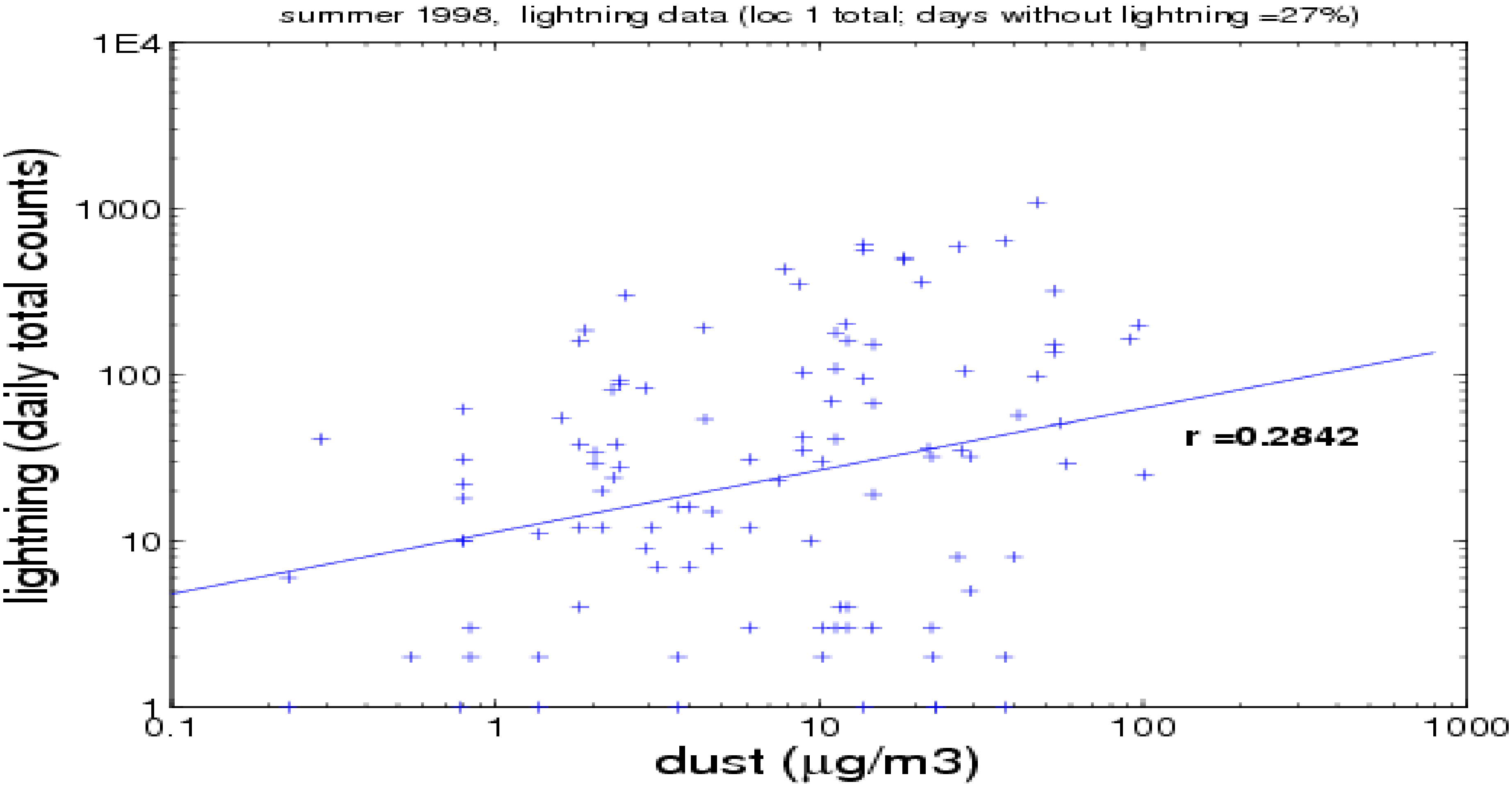
Outline

- Overview
- Theory of Microphysics of Ice-ice Collisions
  - Breakup
- Numerical Simulations of Multiplication and Lightning
- Conclusions and Future Directions

- **Overview**

Daily observations of lightning and dust near Miami



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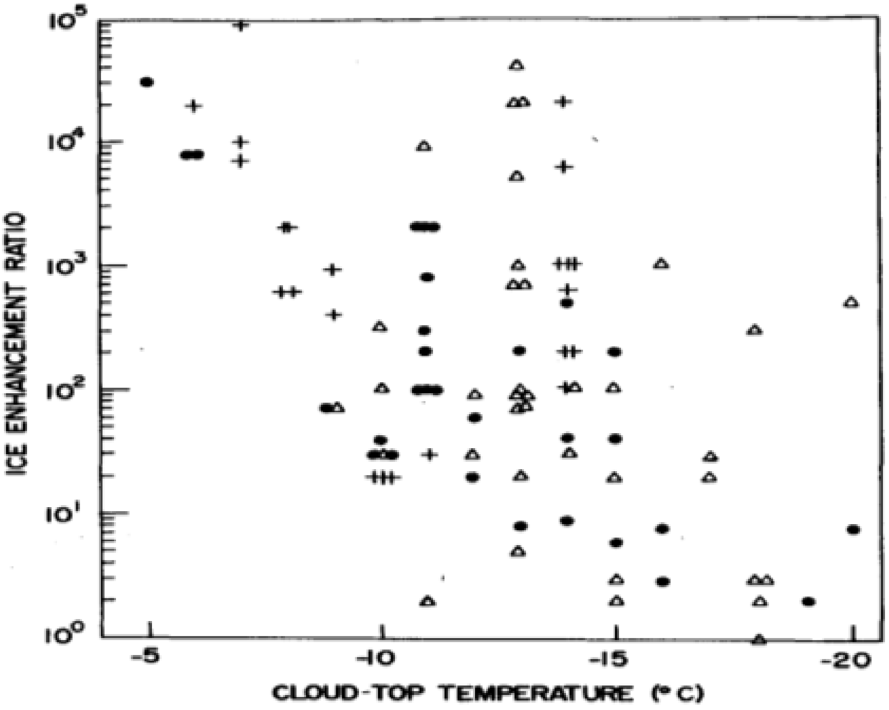
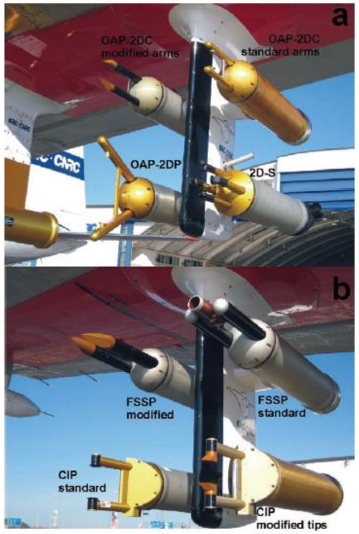
Problem: if lightning is due to charge separated in ice-ice collisions, why the lack of correlation to dust, a key ice nucleus (IN) ?

Ice multiplication seen in aircraft data



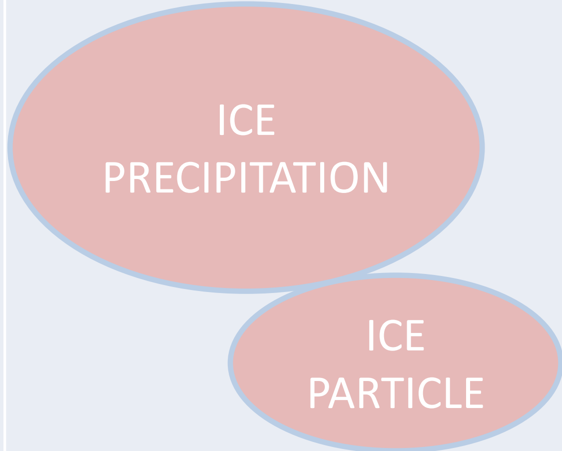
- Discrepancy between active ice nuclei and ice concentrations, if cloud is precipitating



IE ratio = ratio of total to primary ice concentrations

field observations of many deep Cu (Hobbs *et al.* 1980)

H-M PROCESS OF RIME-SPLINTERING	SHATTERING DURING RAINDROP-FREEZING	MECHANICAL FRAGMENTATION IN ICE-ICE COLLISIONS
ICE PRECIPITATIO N	SUPERCOOLE D RAINDROP	ICE PRECIPITATION ICE PARTICLE
-3 to -8 ^{o}C, humidity near water saturation	0 to -35 ^{o}C, humidity near water saturation	any sub-zero temperature, any humidity (water

H-M PROCESS OF RIME-SPLINTERING	SHATTERING DURING RAINDROP-FREEZING	MECHANICAL FRAGMENTATION IN ICE-ICE COLLISIONS
		
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		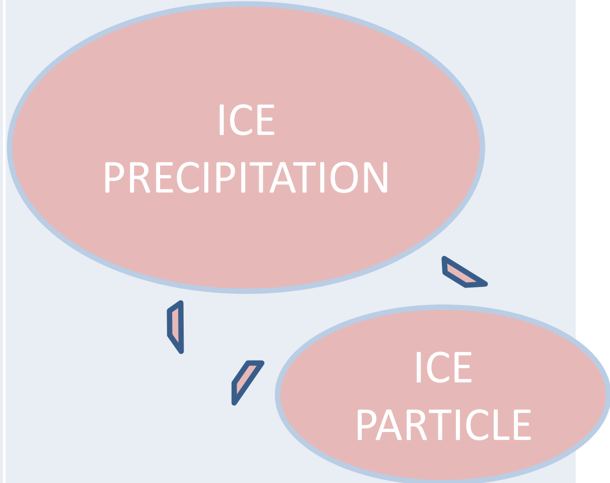
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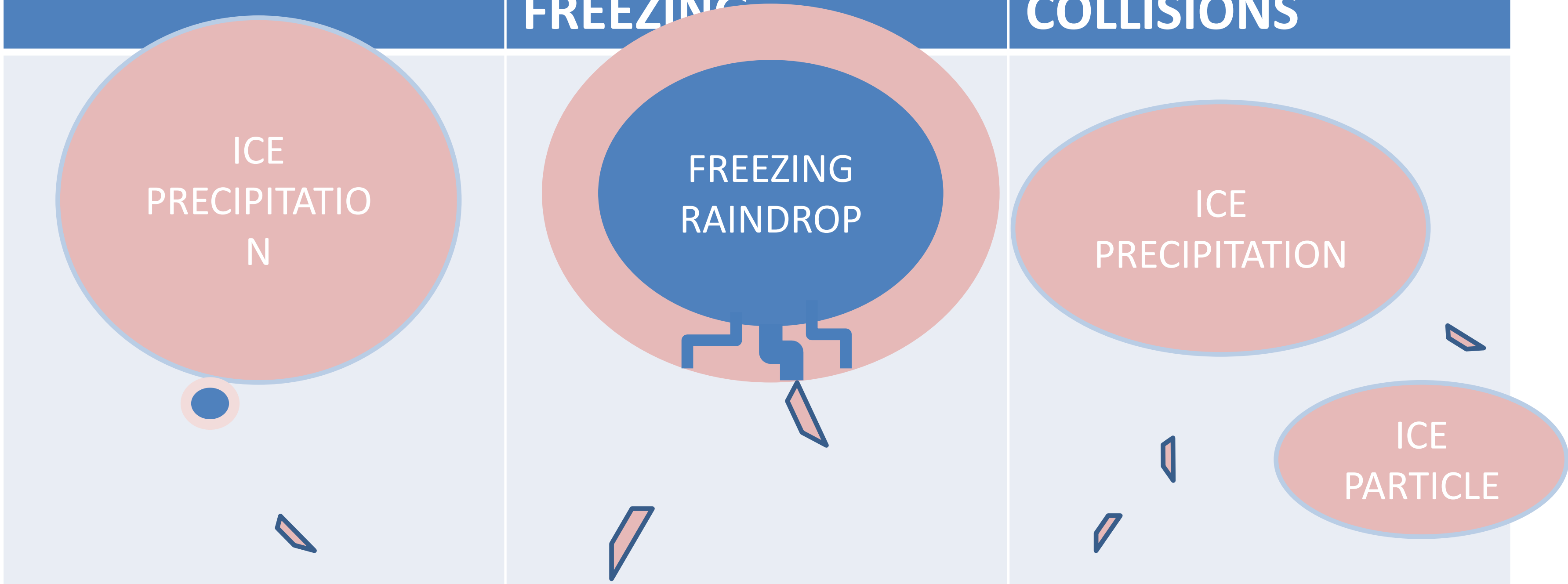
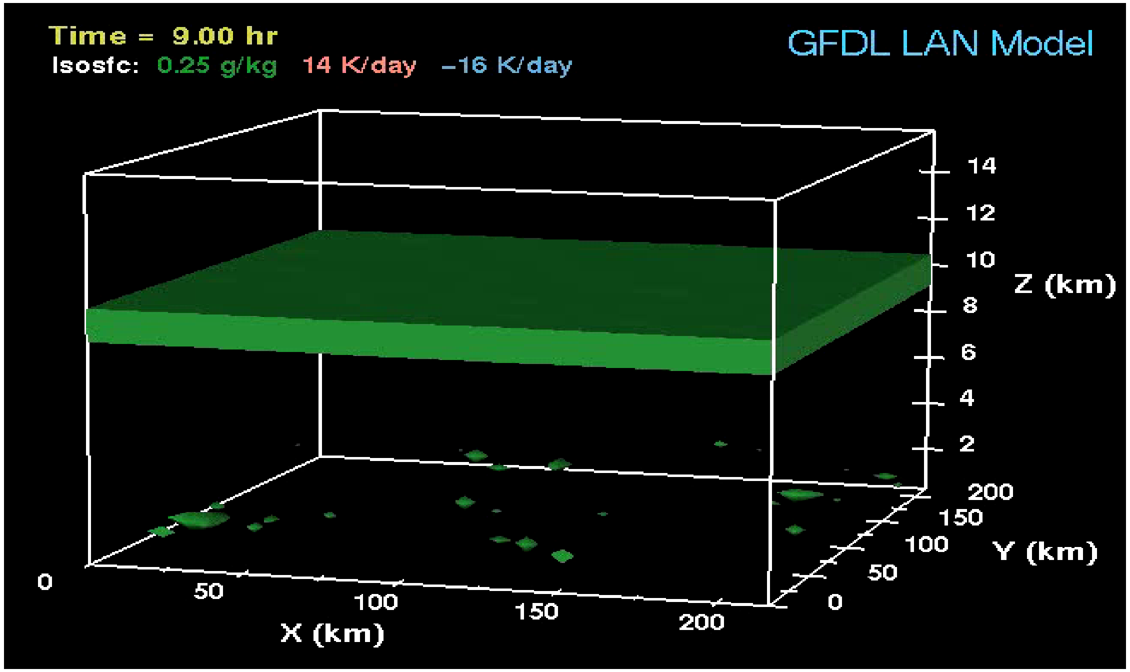
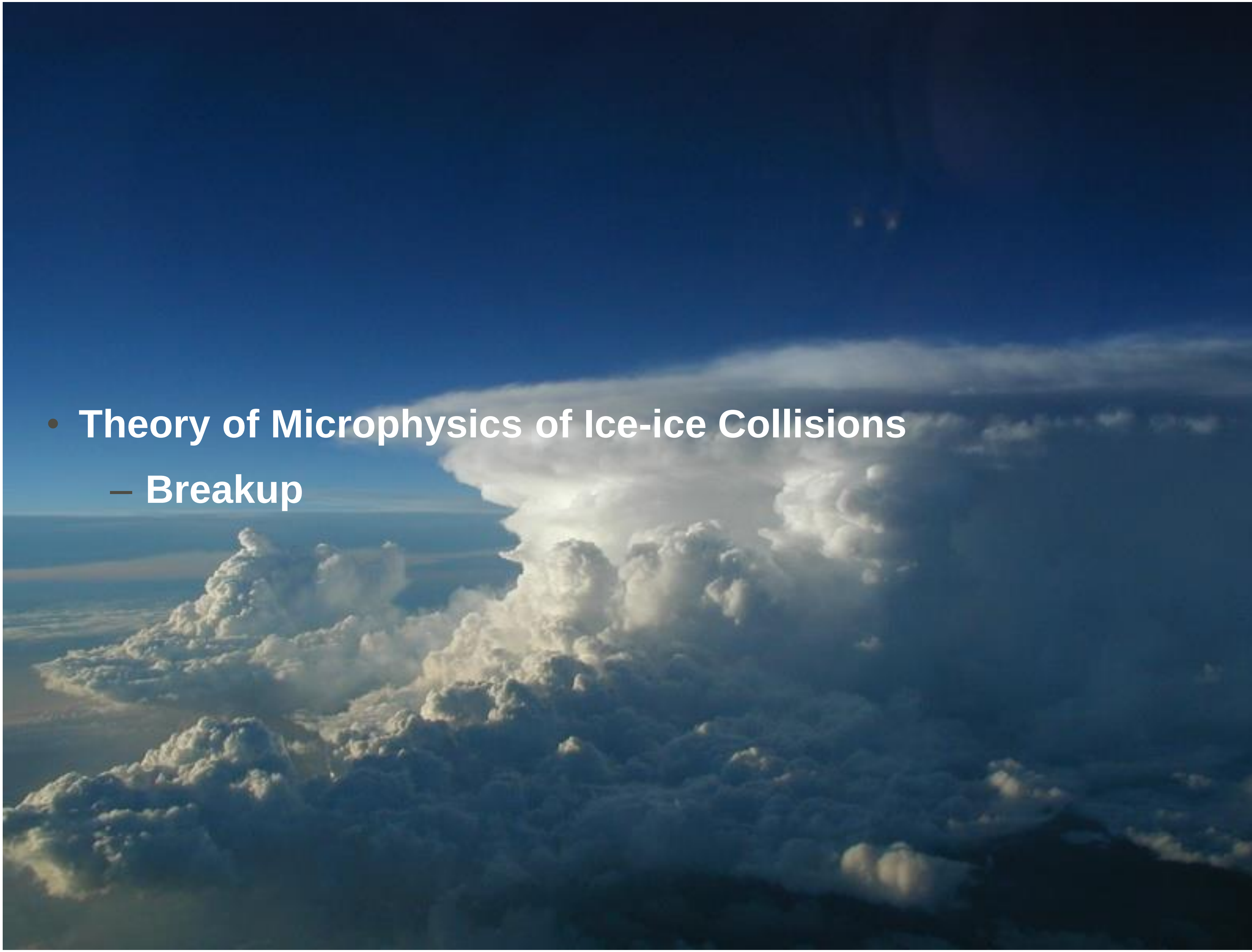


-3 to -8 °C, humidity near water saturation	0 to -35 °C, humidity near water saturation	any sub-zero temperature, any humidity (water

Approach: create formulations for aspects of ice-ice collisions, such as fragmentation
- numerical modeling to explain lightning observations





- **Theory of Microphysics of Ice-ice Collisions**
  - **Breakup**

New theory of fragmentation

- Conservation of energy for collision of 2 particles:

$$\overbrace{K_0}^{\substack{collision\\ kinetic\ energy\\ before\\ collision}} = \underbrace{K_1}_{\substack{final\\ collision\\ kinetic\ energy}} + \underbrace{\Delta S}_{\substack{work\ done\\ to\ separate\\ particles}} + \overbrace{K_{th}}^{\substack{energy\ lost\\ as\ heatand\ noise}}$$

W_{crit} = *work done to break a branch of length,* w

PDFs of W_{crit} or $w \approx c_3 W_{crit}^{\gamma}$

$$g \propto W_{crit}^{\gamma-1} \exp\left(-\left[\frac{W_{crit}}{W_0}\right]^{\gamma}\right)$$

$$p(w) = \lambda \exp(-\lambda w)$$

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New theory (cont.)

- A fraction, c_2, of energy dissipated is available for breaking branches, $\delta K_{th} = c_2 K_{th} \approx c_2 K_0 (1 - q^2)$.
- Branches broken per collision:

$$N = \alpha A(T,D,\chi)\ \mathrm{P}\left(W_{crit} \leq \frac{\delta K_{th}}{N_{contact}}\right) = \alpha A(T,D,\chi)\ \mathrm{P}(w \leq w_0)$$

$$w_0 = c_3 \left(\frac{\delta K_{th}}{N_{contact}}\right)^{\gamma} = c_3 \left(\frac{c_2 K_0 (1-q^2)}{N_{contact}}\right)^{\gamma} = c_3 \left(\frac{c_2 K_0 (1-q^2)}{n_{branch} \alpha c_1}\right)^{\gamma} = \beta(T,D,\chi) \left(\frac{K_c}{\alpha}\right)^{\gamma}$$

$$\Rightarrow \quad \boxed{N \propto 1 - \exp\left(-\left[\frac{BK_0}{\alpha A(T,D,\chi)}\right]^{\gamma}\right)}$$

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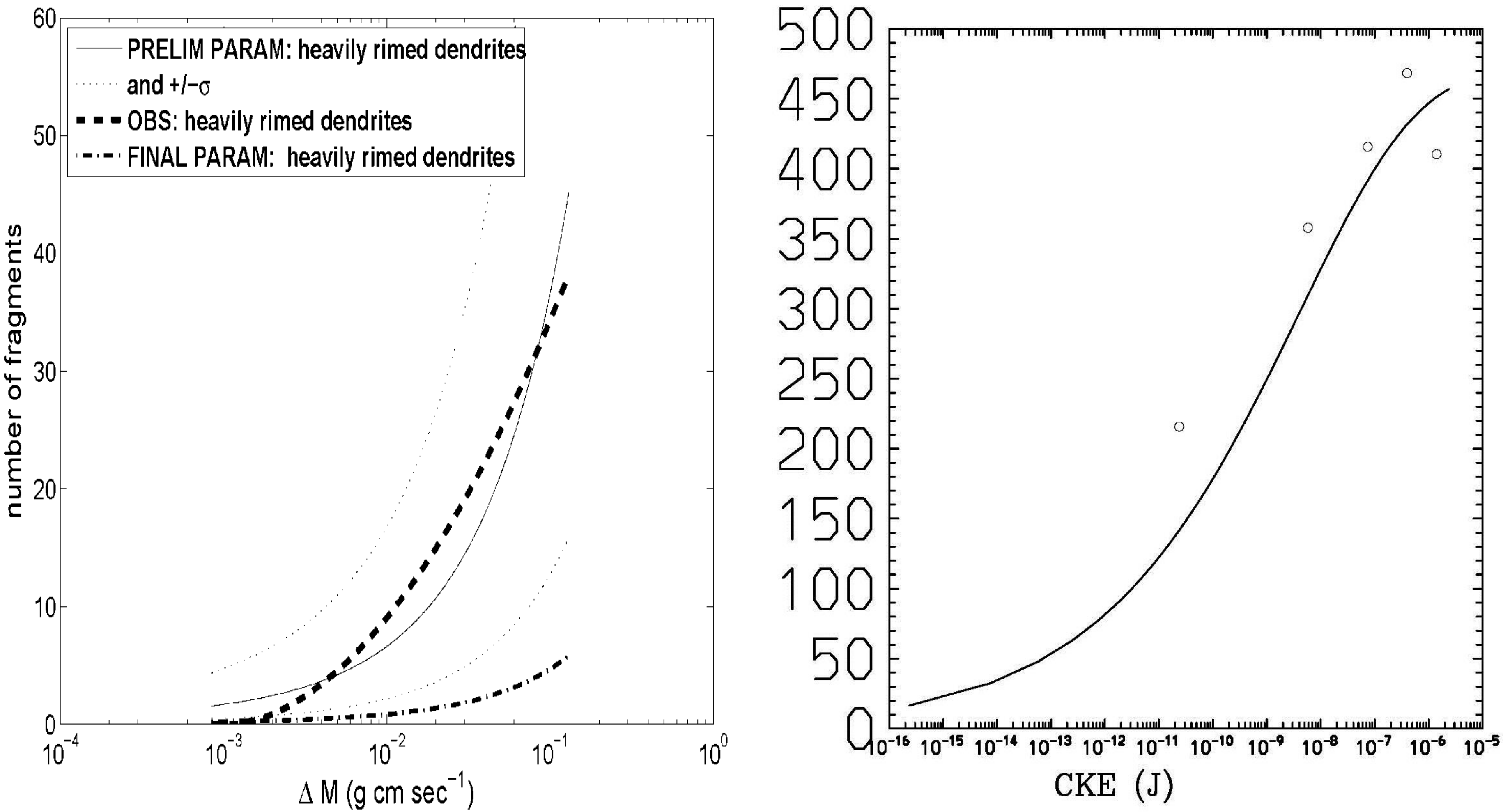
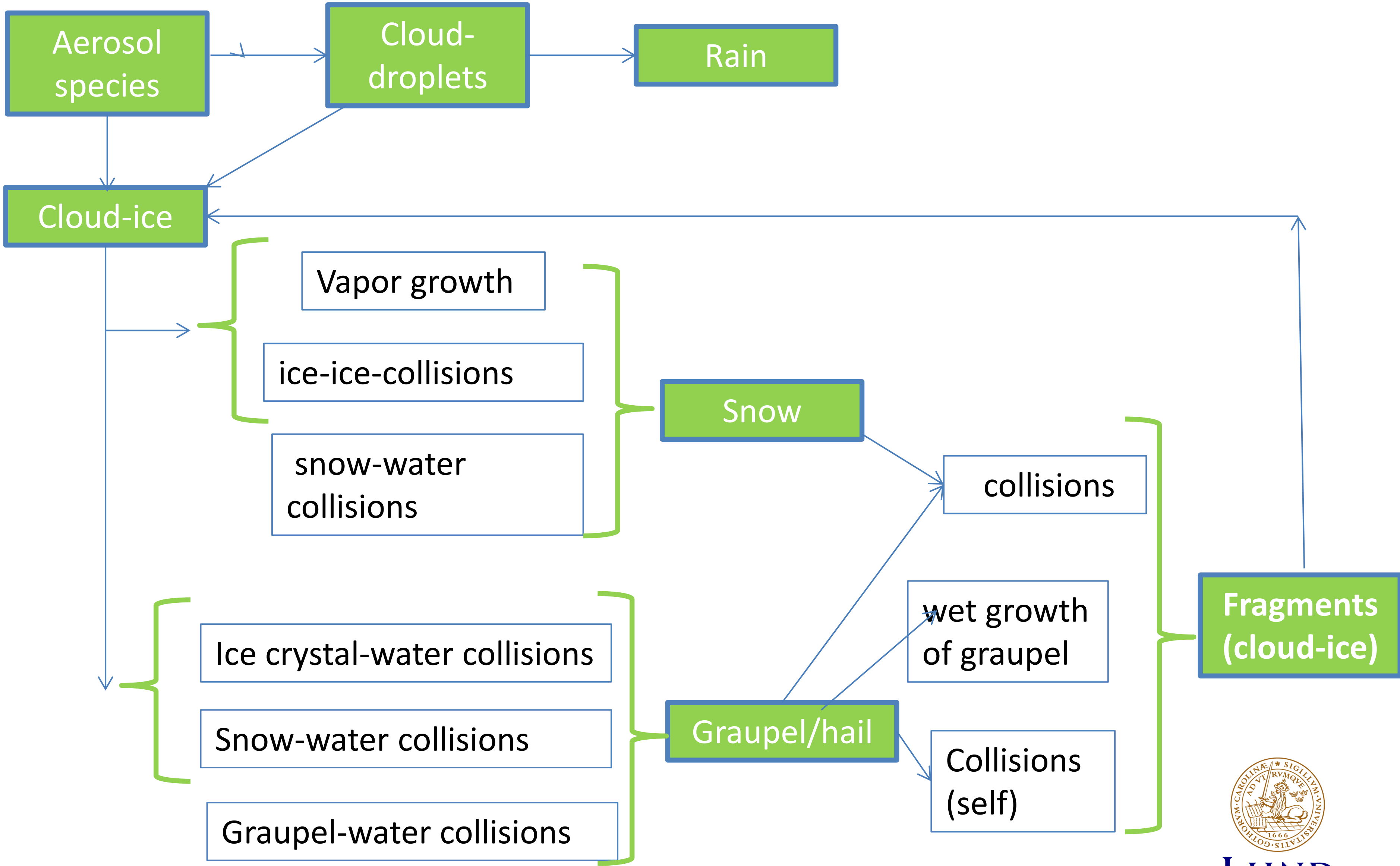
Formulation fitted to published observations of breakup
(graupel-snow, graupel-graupel, hail-hail)



Phillips et al. (2017a, JAS)

- **Numerical Simulations of Multiplication and Lightning**

Transformation of hydrometeors in aerosol-cloud model:

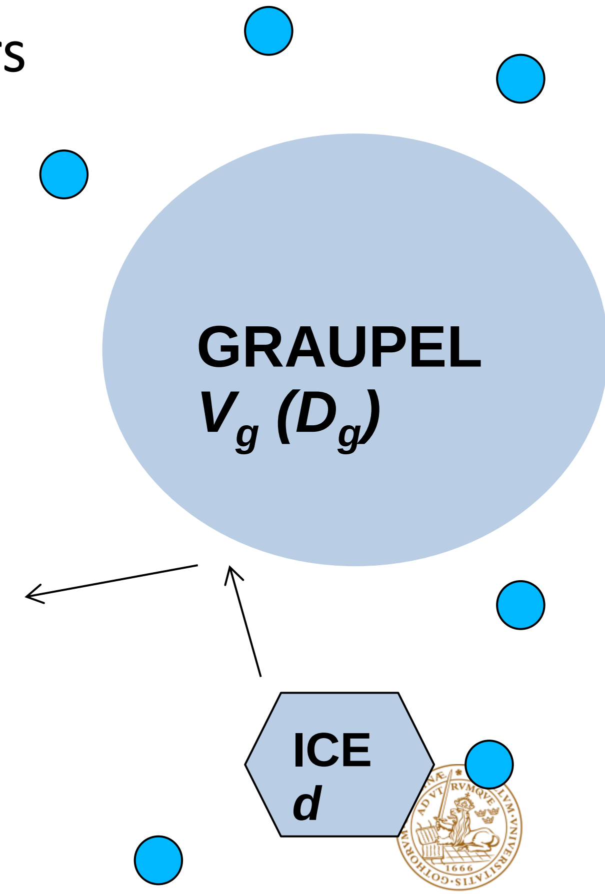


Phillips et al. (2007, 2009, 2014, 2015, 2017b JAS): Kudzotsa et al. (2016, QJRMS)

Non-inductive charge separation:

Empirical formulae (Brooks *et al*. 1997; Saunders and Peck 1998):

$RAR = EW \times V_g$ ⇒ sign of charge transferred, when compared with $RAR_{crit}(T)$



Charge transferred per ice-ice collision:

$Q = B\, d^a\, V^b\, q$ (Keith and Saunders 1989)

Model validation for STEPS (US High Plains, summer 2000): aerosol-cloud model and HUCM

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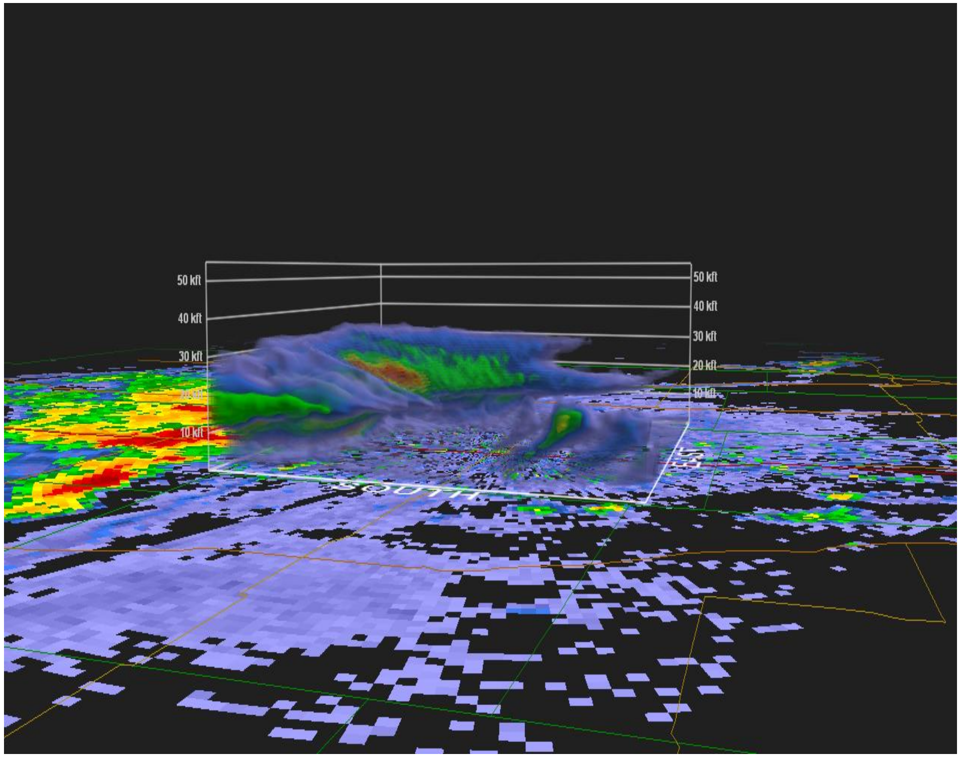
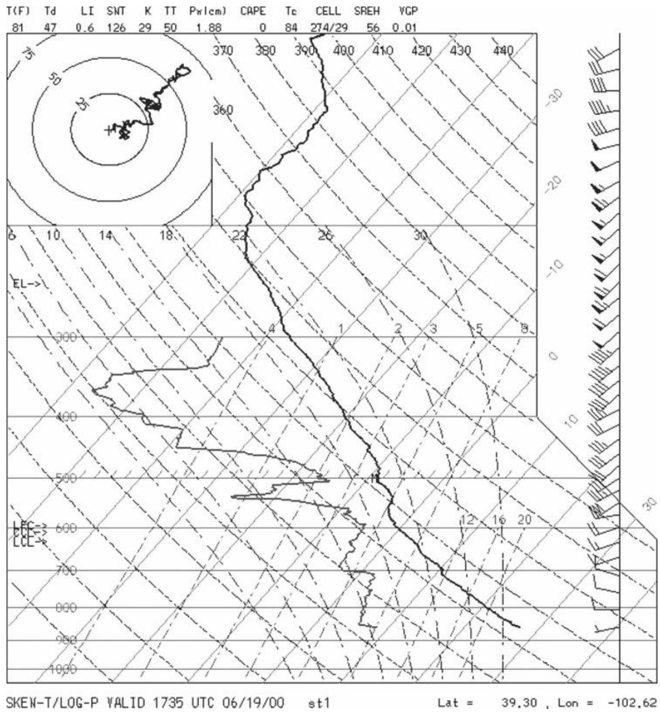
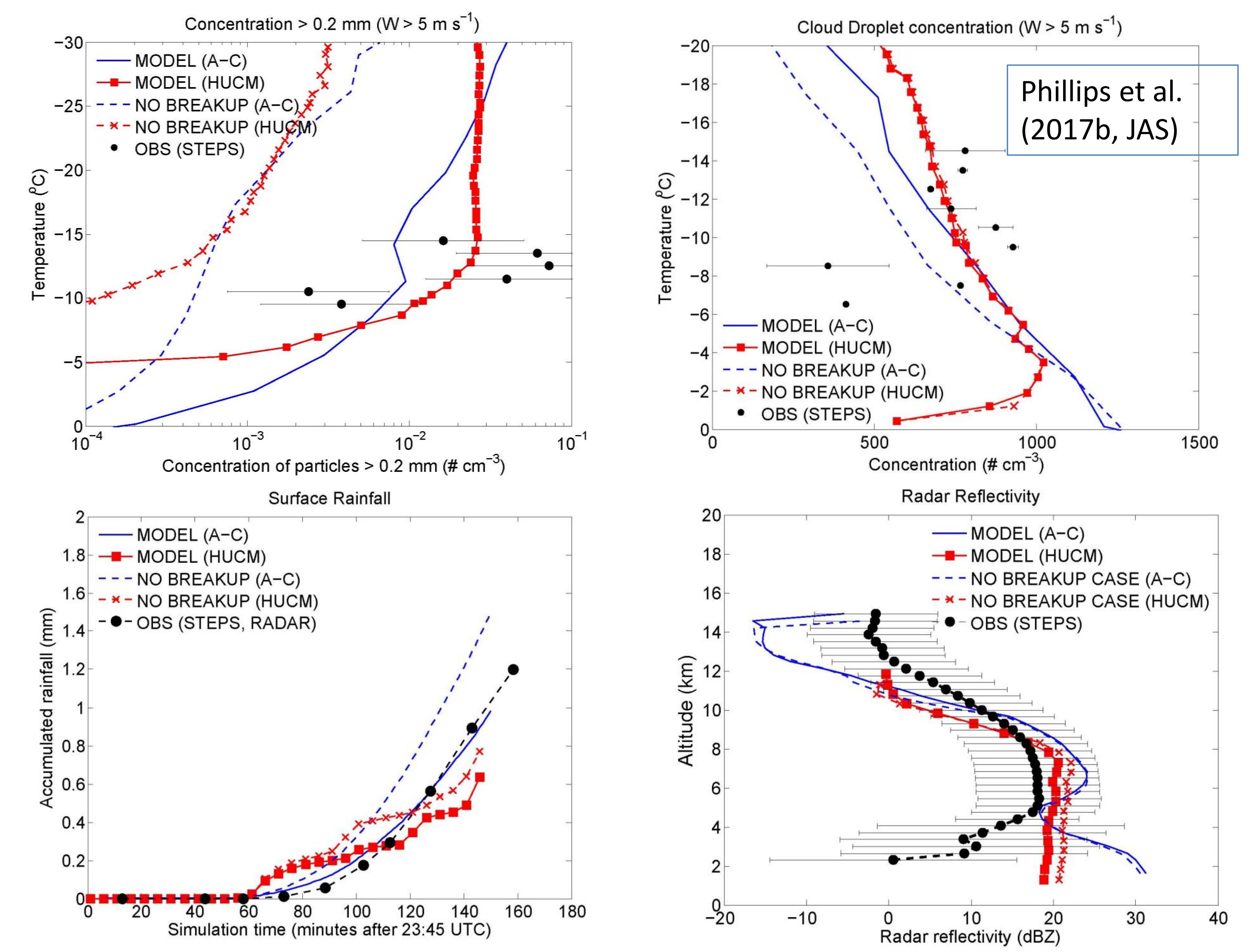
Cold-based convection near Kansas/Colorado border, summer 2000







Concentration > 0.2 mm (W > 5 m s^{-1})
MODEL (A−C)
MODEL (HUCM)
NO BREAKUP (A−C)
NO BREAKUP (HUCM)
OBS (STEPS)
Temperature (^{o}C)
Concentration of particles > 0.2 mm (# cm^{-3})
Cloud Droplet concentration (W > 5 m s^{-1})
Phillips et al. (2017b, JAS)
MODEL (A−C)
MODEL (HUCM)
NO BREAKUP (A−C)
NO BREAKUP (HUCM)
OBS (STEPS)
Temperature (^{o}C)
Concentration (# cm^{-3})
Surface Rainfall
MODEL (A−C)
MODEL (HUCM)
NO BREAKUP (A−C)
NO BREAKUP (HUCM)
OBS (STEPS, RADAR)
Accumulated rainfall (mm)
Simulation time (minutes after 23:45 UTC)
Radar Reflectivity
MODEL (A−C)
MODEL (HUCM)
NO BREAKUP CASE (A−C)
NO BREAKUP CASE (HUCM)
OBS (STEPS)
Altitude (km)
Radar reflectivity (dBZ)

Role of breakup

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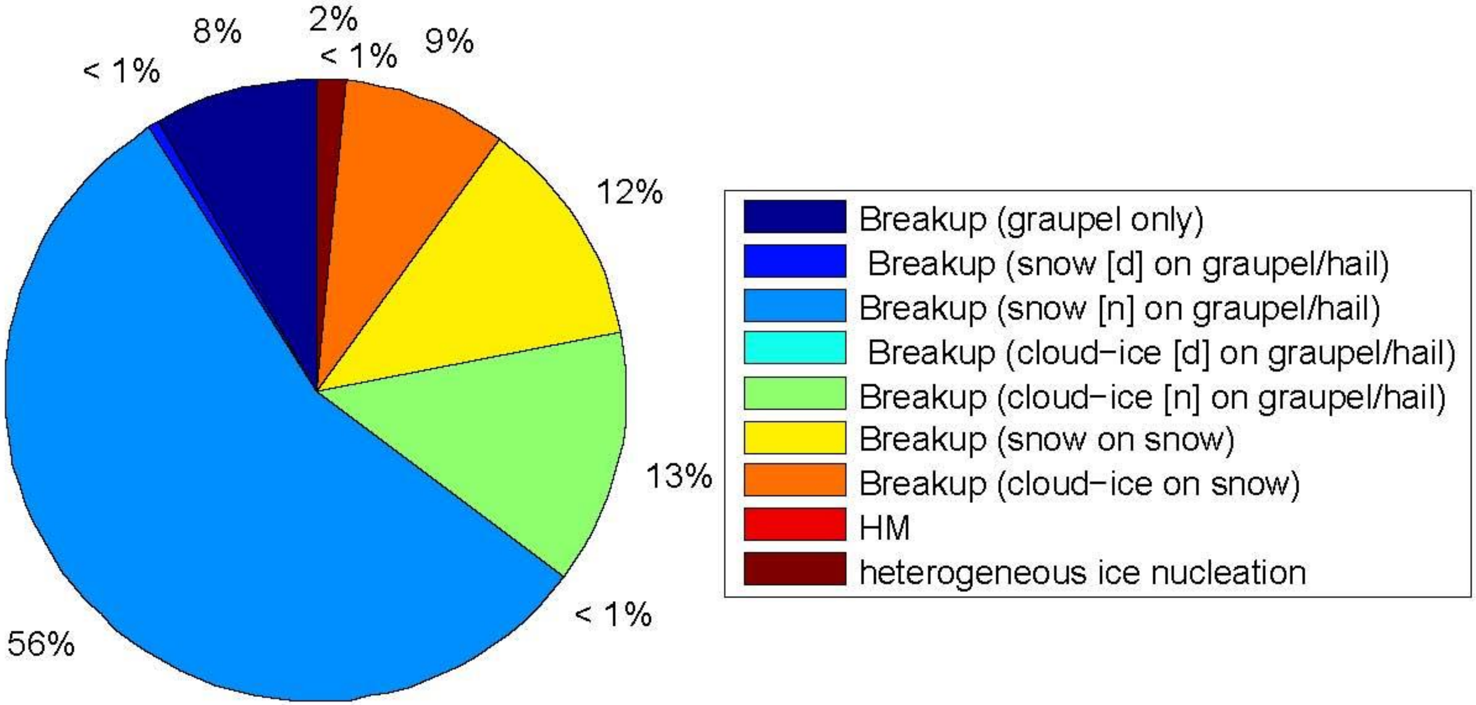
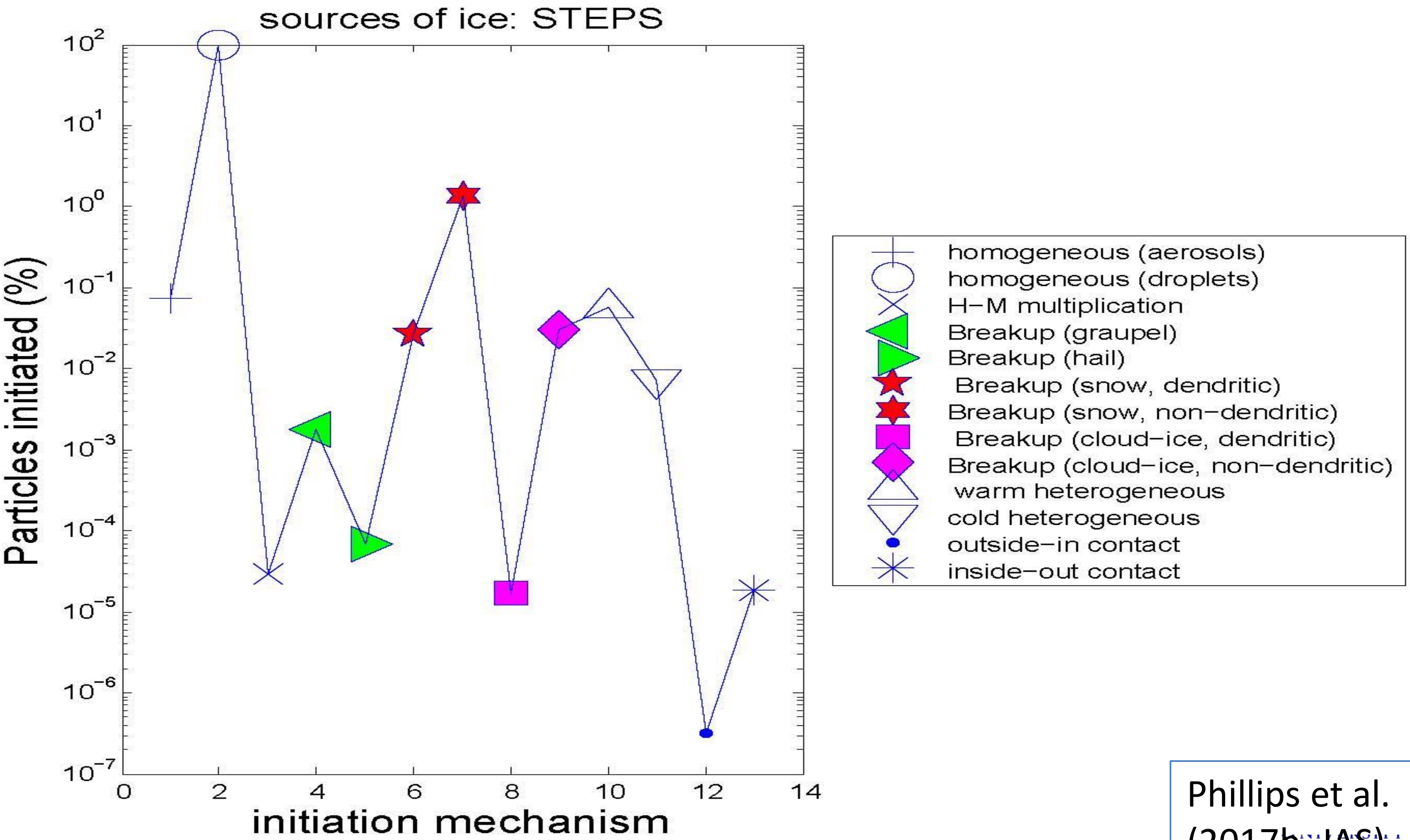
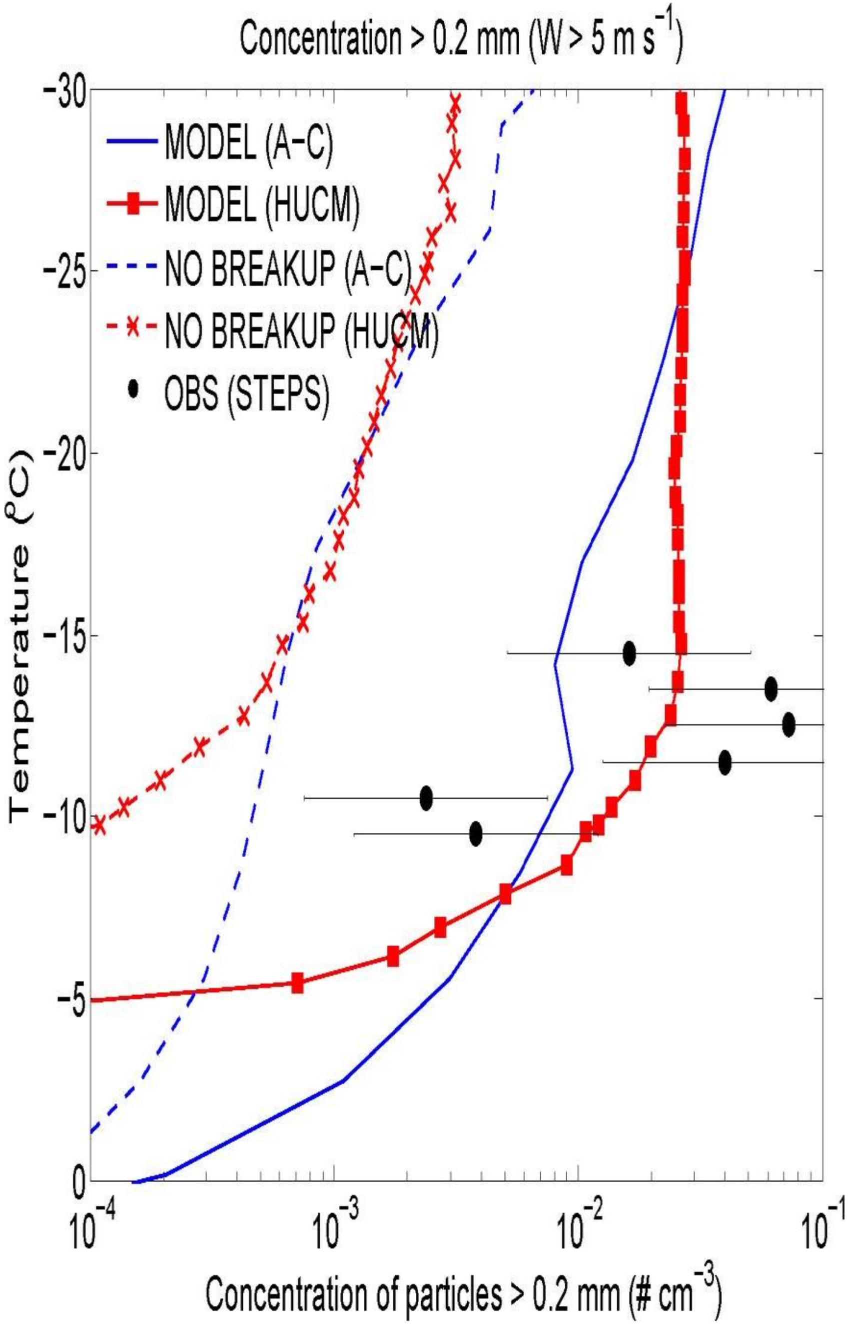
Simulated sources of ice: aerosol−cloud model

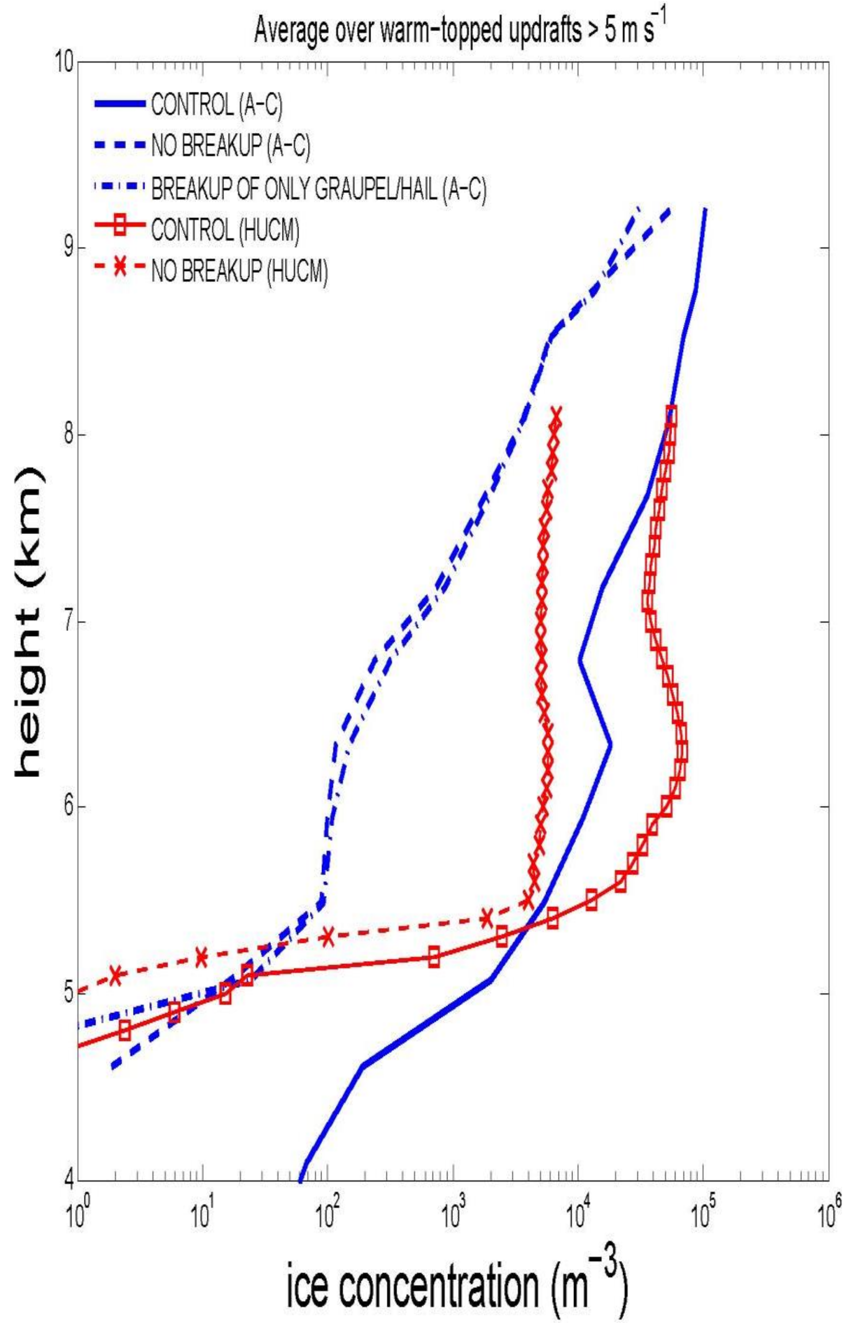


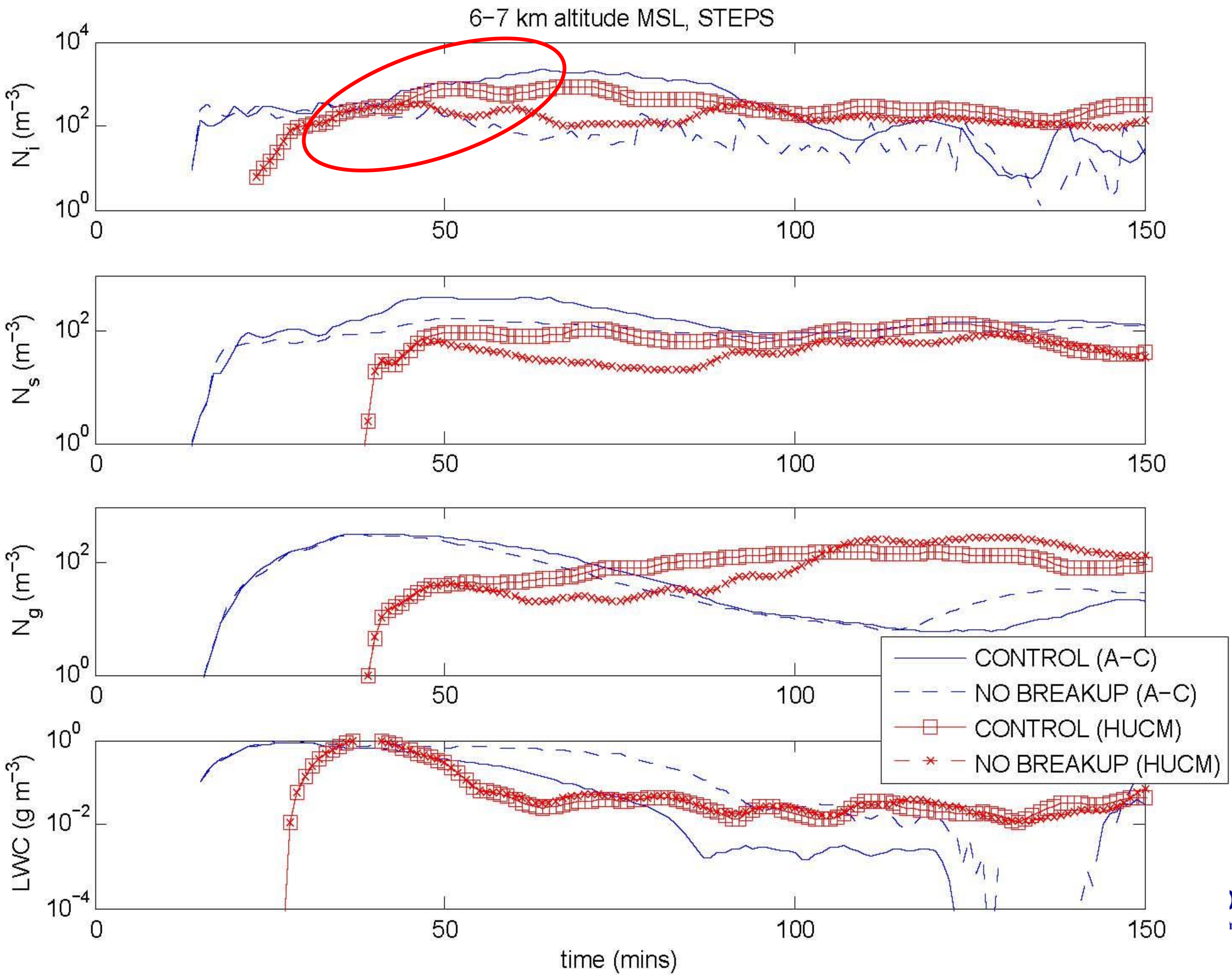
Budget: initiation of ice in aerosol-cloud model



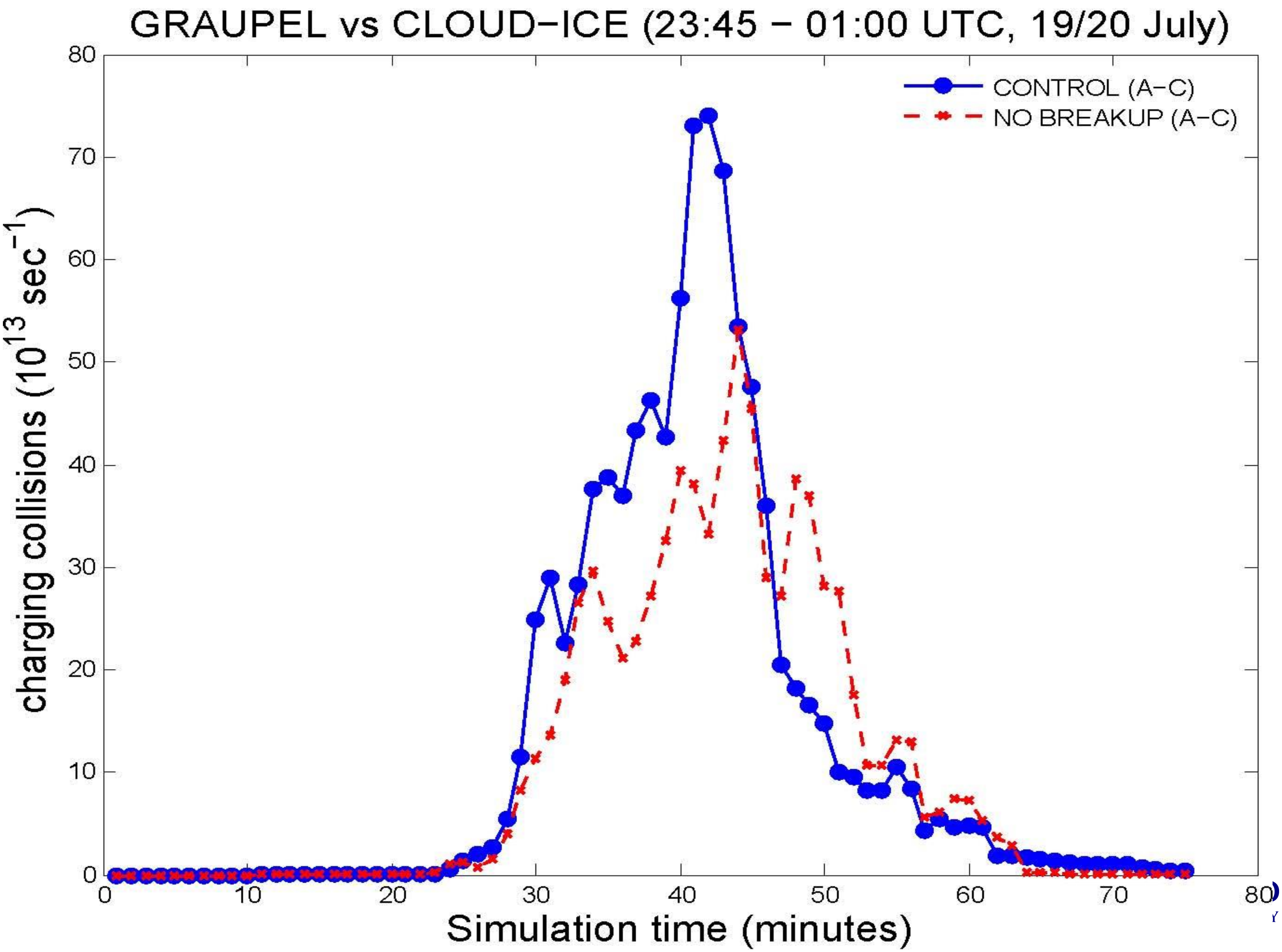
Phillips et al. (2017b, JAS)


Concentration > 0.2 mm (W > 5 m s^{-1})
MODEL (A-C)
MODEL (HUCM)
NO BREAKUP (A-C)
NO BREAKUP (HUCM)
OBS (STEPS)
Temperature (°C)
Concentration of particles > 0.2 mm (# cm^{-3})

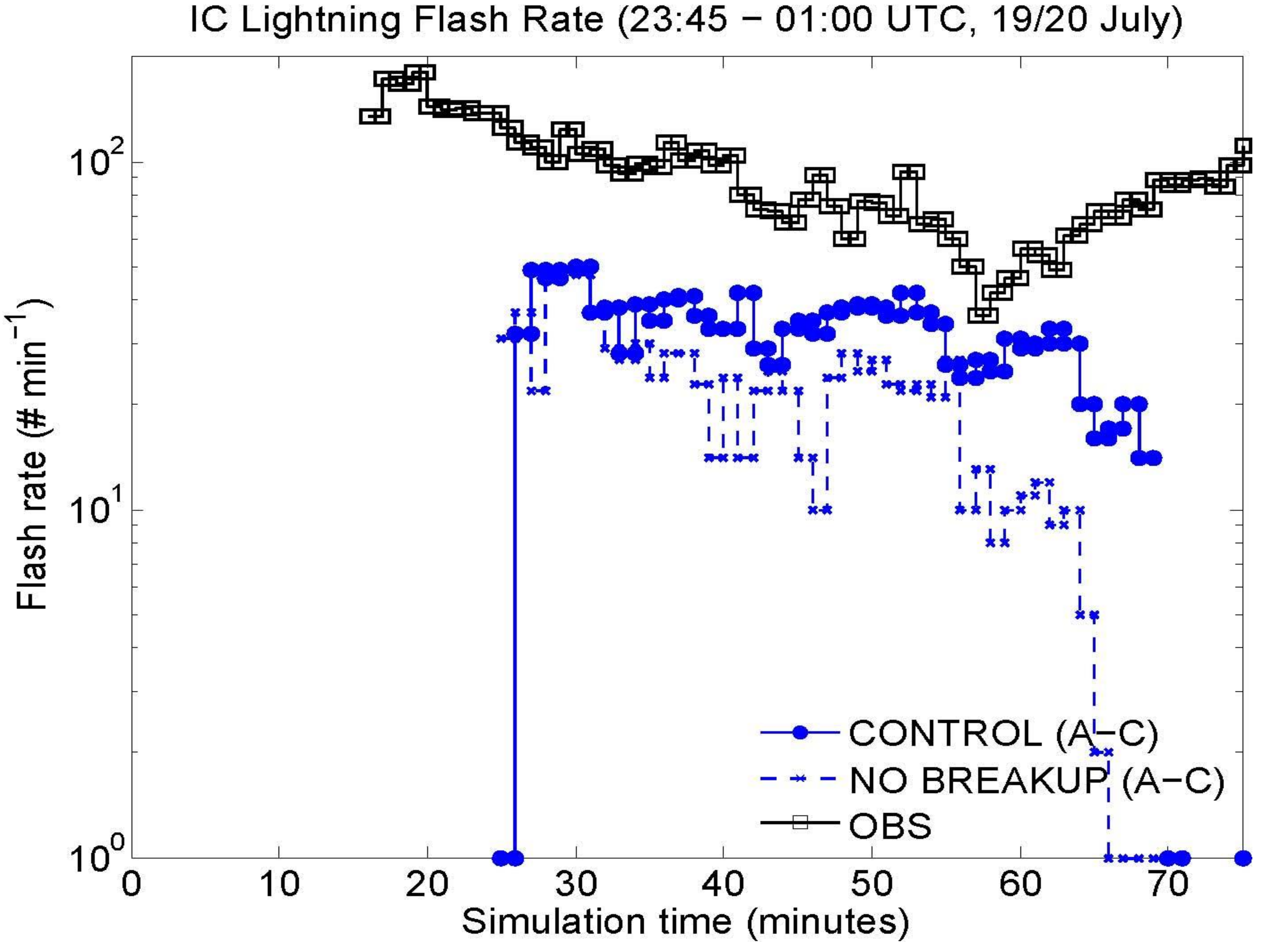

Average over warm-topped updrafts > 5 m s^{-1}
CONTROL (A-C)
NO BREAKUP (A-C)
BREAKUP OF ONLY GRAUPEL/HAIL (A-C)
CONTROL (HUCM)
NO BREAKUP (HUCM)
height (km)
ice concentration (m^{-3})



6−7 km altitude MSL, STEPS
N_i (m^{-3})
N_s (m^{-3})
N_g (m^{-3})
LWC (g m^{-3})
time (mins)
CONTROL (A−C)
NO BREAKUP (A−C)
CONTROL (HUCM)
NO BREAKUP (HUCM)



GRAUPEL vs CLOUD−ICE (23:45 − 01:00 UTC, 19/20 July)
CONTROL (A−C)
NO BREAKUP (A−C)
charging collisions (10^{13} sec^{-1})
Simulation time (minutes)
0
10
20
30
40
50
60
70
80



IC Lightning Flash Rate (23:45 − 01:00 UTC, 19/20 July)
Flash rate (# min^{-1})
10^2
10^1
10^0
0
10
20
30
40
50
60
70
Simulation time (minutes)
CONTROL (A−C)
NO BREAKUP (A−C)
OBS

Conclusions and Future Directions

Summary

- Theories created for breakup
  - Reproduces published lab data successfully

- Only with breakup represented can aircraft observations be predicted correctly

- Explosive multiplication by breakup in snow-graupel collisions produces most crystals, unless top of cloud is colder than -36 ^{o}C
  - Graupel, snow and cloud-ice altered
  - Breakup boosts lightning, especially intra-cloud (IC) lightning

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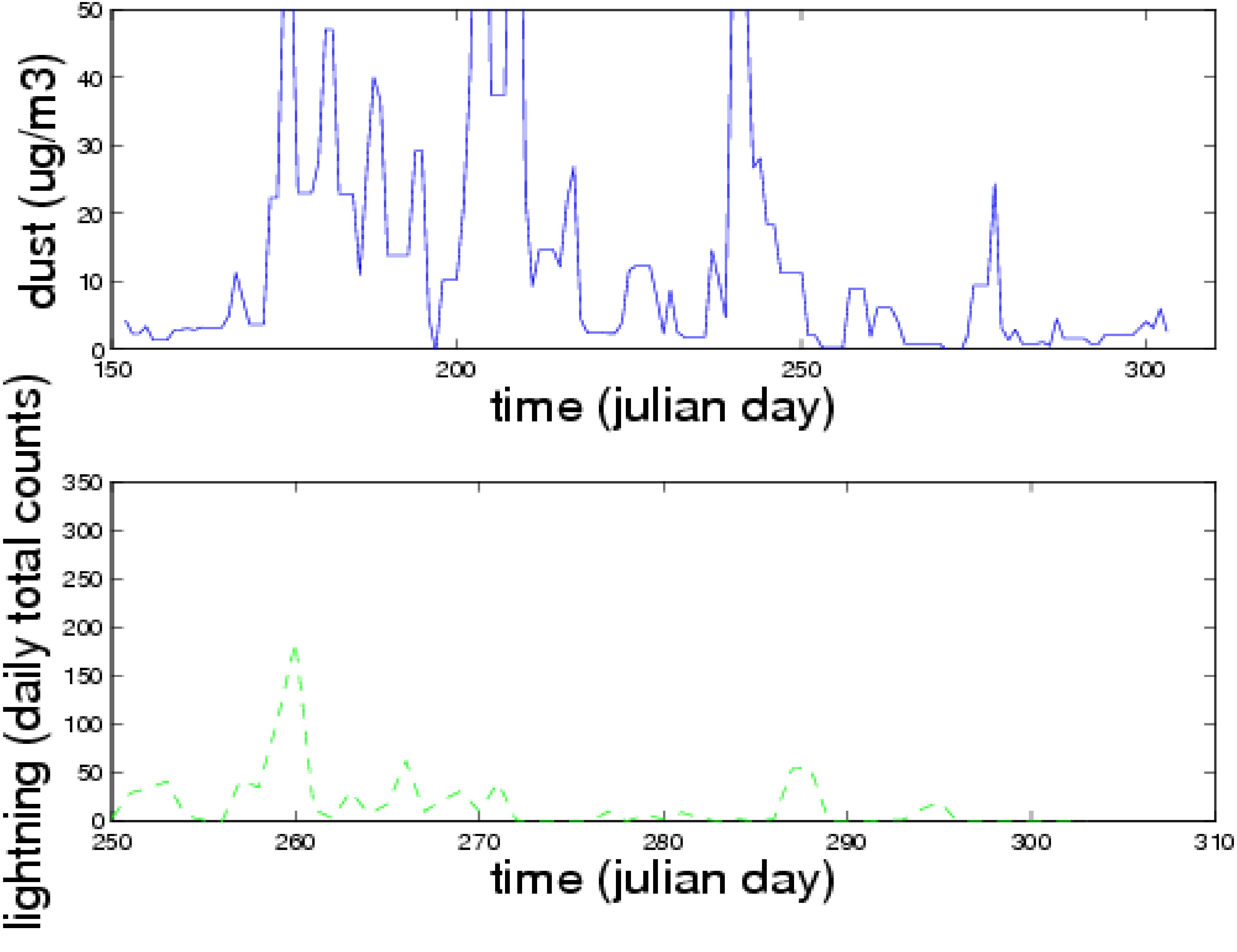
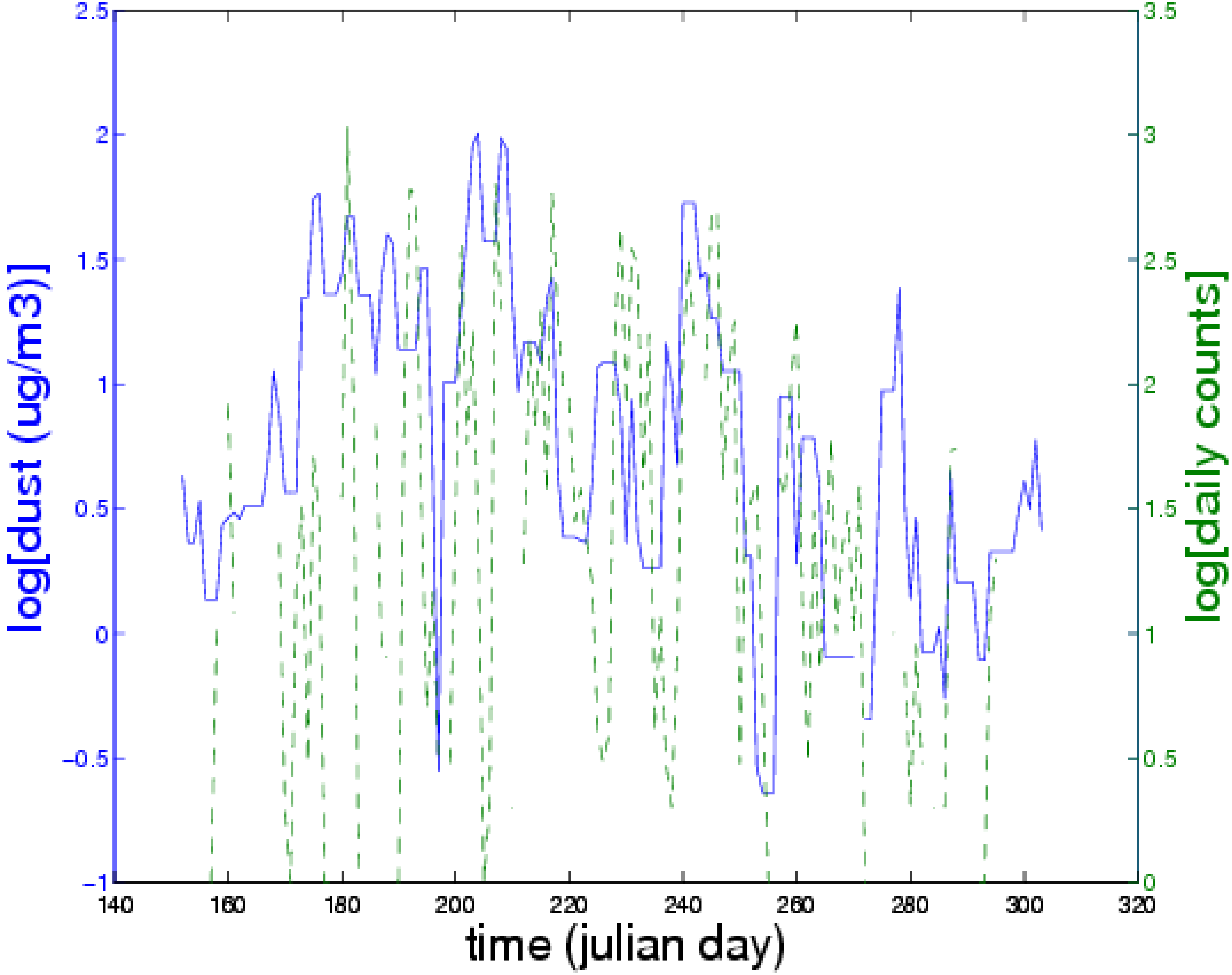

dust (ug/m3)
0
10
20
30
40
50
150
200
250
300
time (julian day)
lightning (daily total counts)
0
50
100
150
200
250
300
350
250
260
270
280
290
300
310
time (julian day)



log[dust (ug/m3)]
log[daily counts]
time (julian day)
2.5
2
1.5
1
0.5
0
−0.5
−1
3.5
3
2.5
2
1.5
1
0.5
0
140
160
180
200
220
240
260
280
300
320

Role of sticking efficiency

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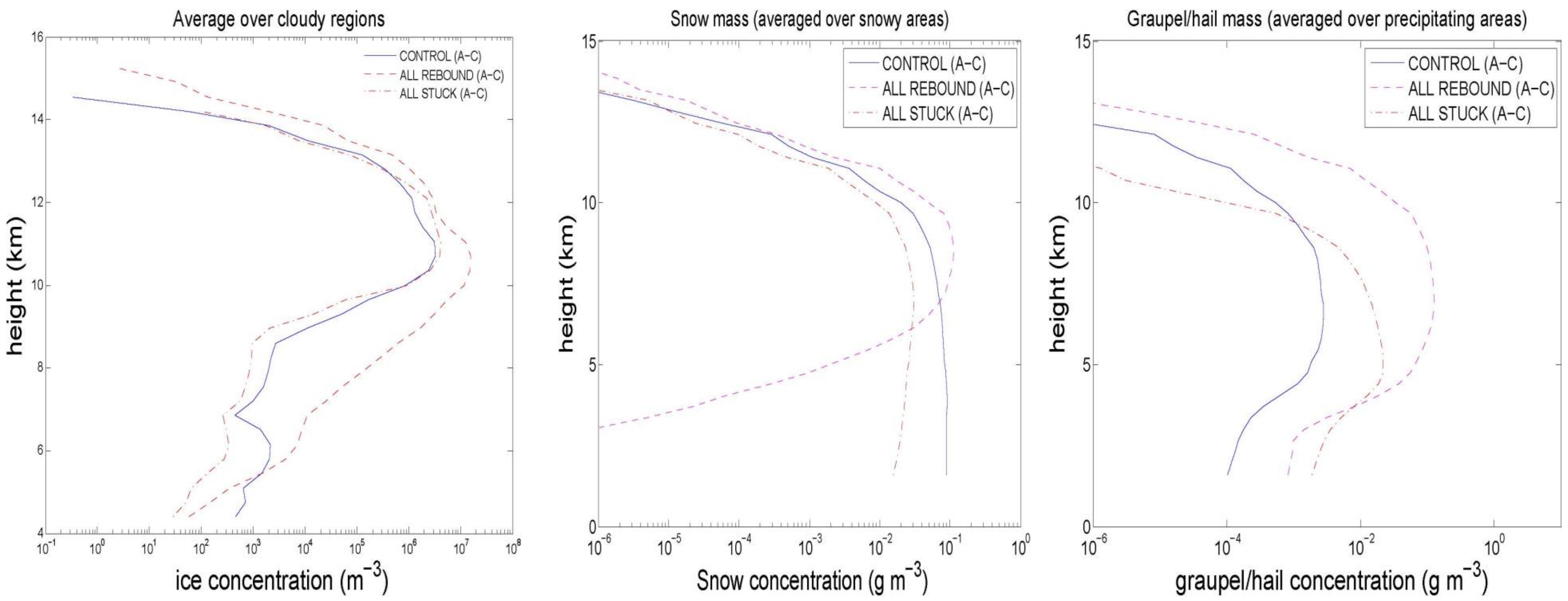
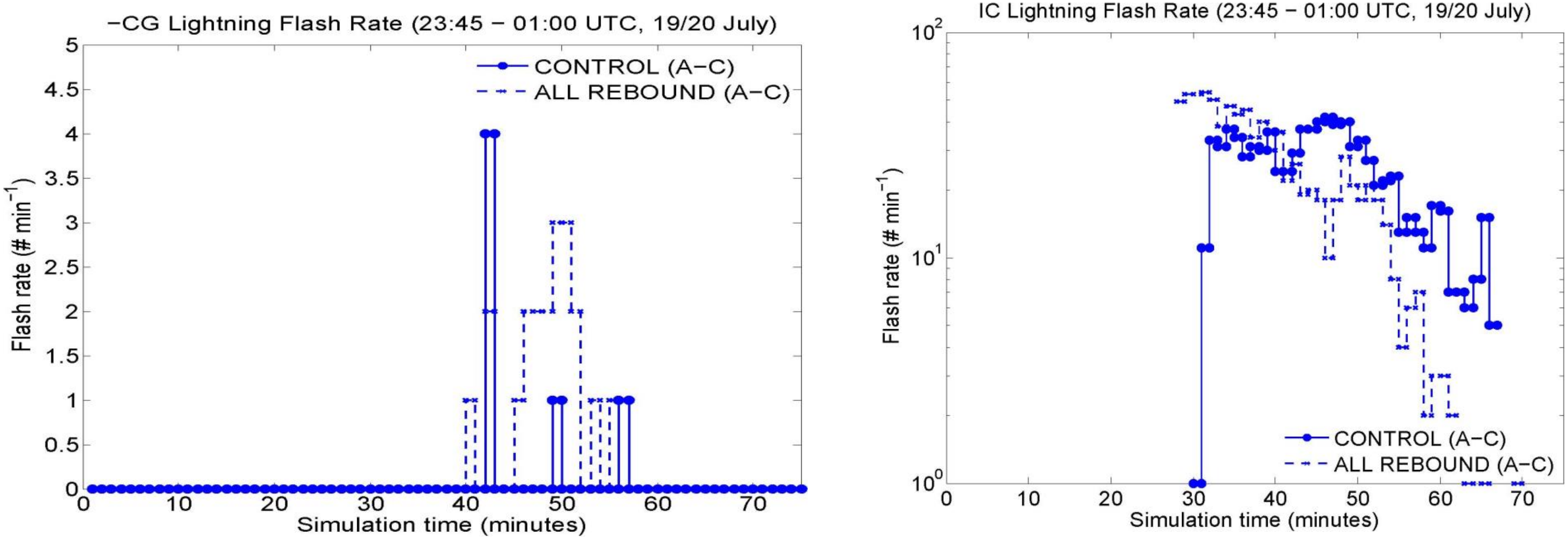
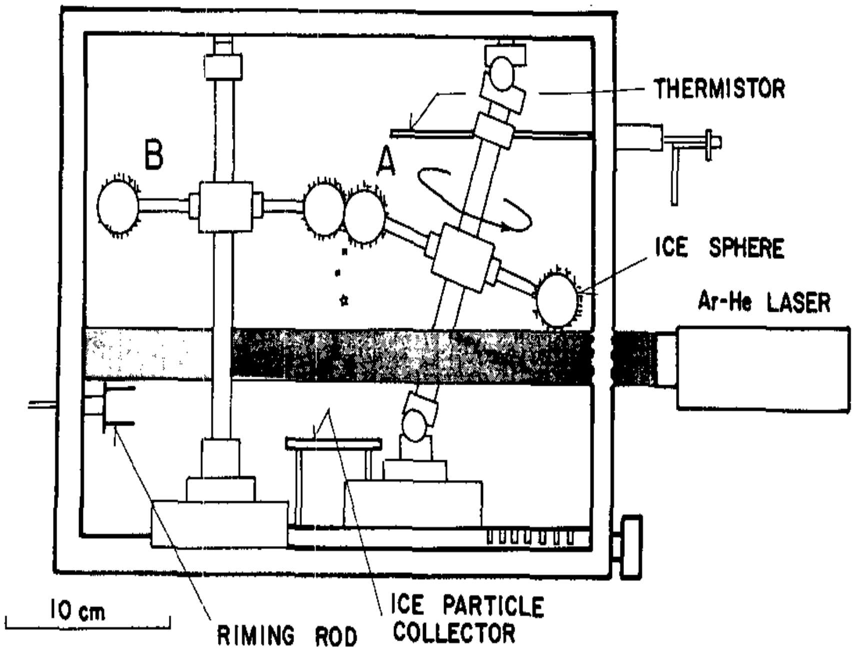
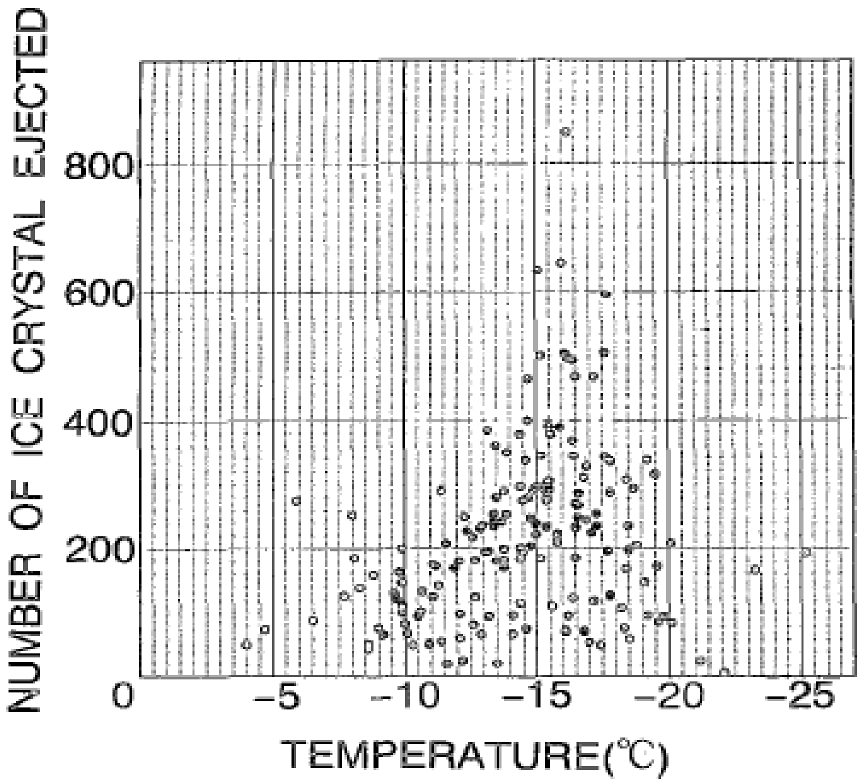

Average over cloudy regions
CONTROL (A−C)
ALL REBOUND (A−C)
ALL STUCK (A−C)
height (km)
ice concentration (m^{-3})
Snow mass (averaged over snowy areas)
CONTROL (A−C)
ALL REBOUND (A−C)
ALL STUCK (A−C)
height (km)
Snow concentration (g m^{-3})
Graupel/hail mass (averaged over precipitating areas)
CONTROL (A−C)
ALL REBOUND (A−C)
ALL STUCK (A−C)
height (km)
graupel/hail concentration (g m^{-3})


−CG Lightning Flash Rate (23:45 − 01:00 UTC, 19/20 July)
CONTROL (A−C)
ALL REBOUND (A−C)
Flash rate (# min^{-1})
Simulation time (minutes)
IC Lightning Flash Rate (23:45 − 01:00 UTC, 19/20 July)
CONTROL (A−C)
ALL REBOUND (A−C)
Flash rate (# min^{-1})
Simulation time (minutes)

Mechanical fragmentation in hail-hail collisions studied by Takahashi et al. (1995)





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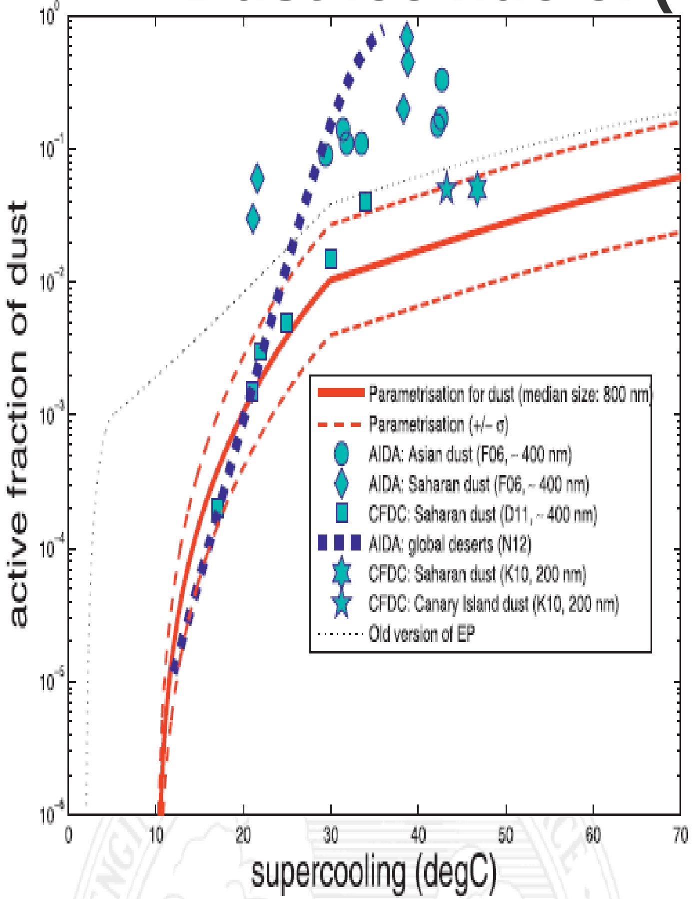
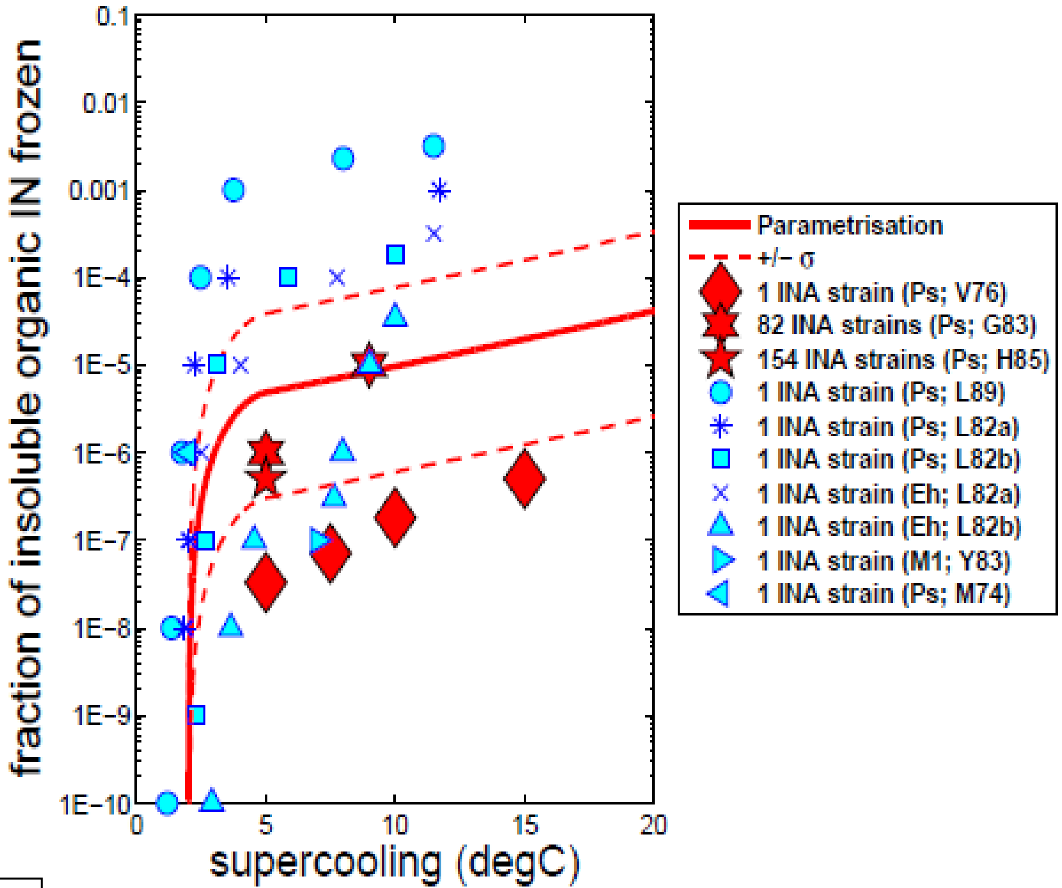
Phillips heterogeneous ice nucleation scheme ('empirical parameterization') based on coincident field observations of aerosol and ice nuclei (IN)

Dust ice nuclei (IN)



PBAP IN



Phillips et al. (2008, 2013, JAS)

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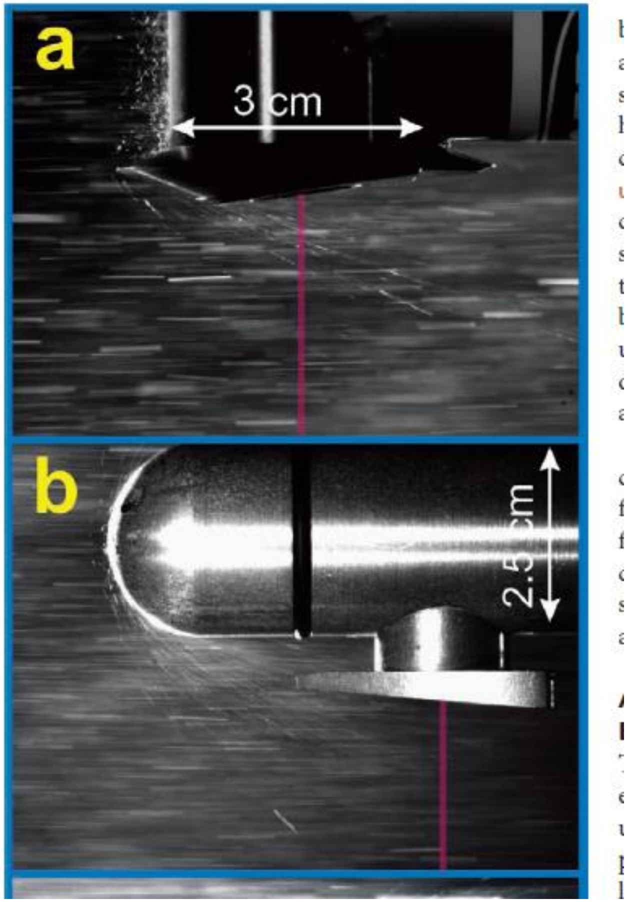
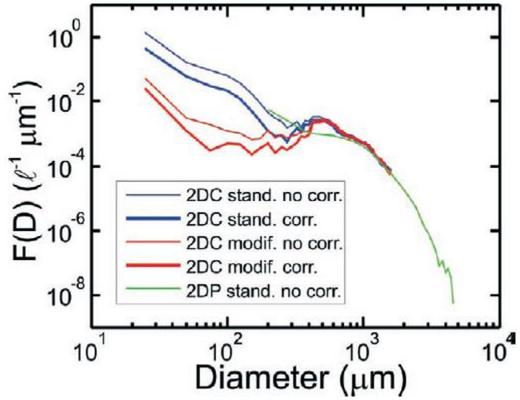
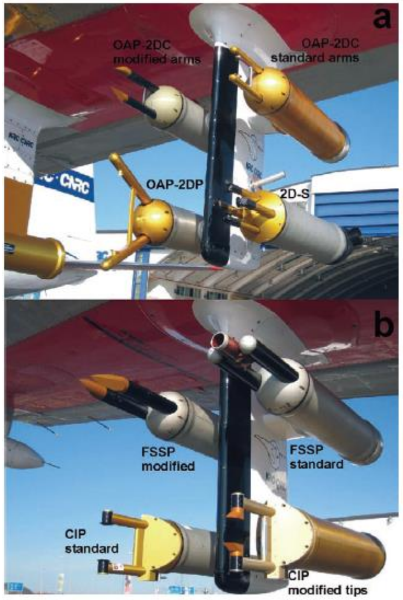
Measurement problems for aircraft observations of clouds (Korolev et al. 2011)







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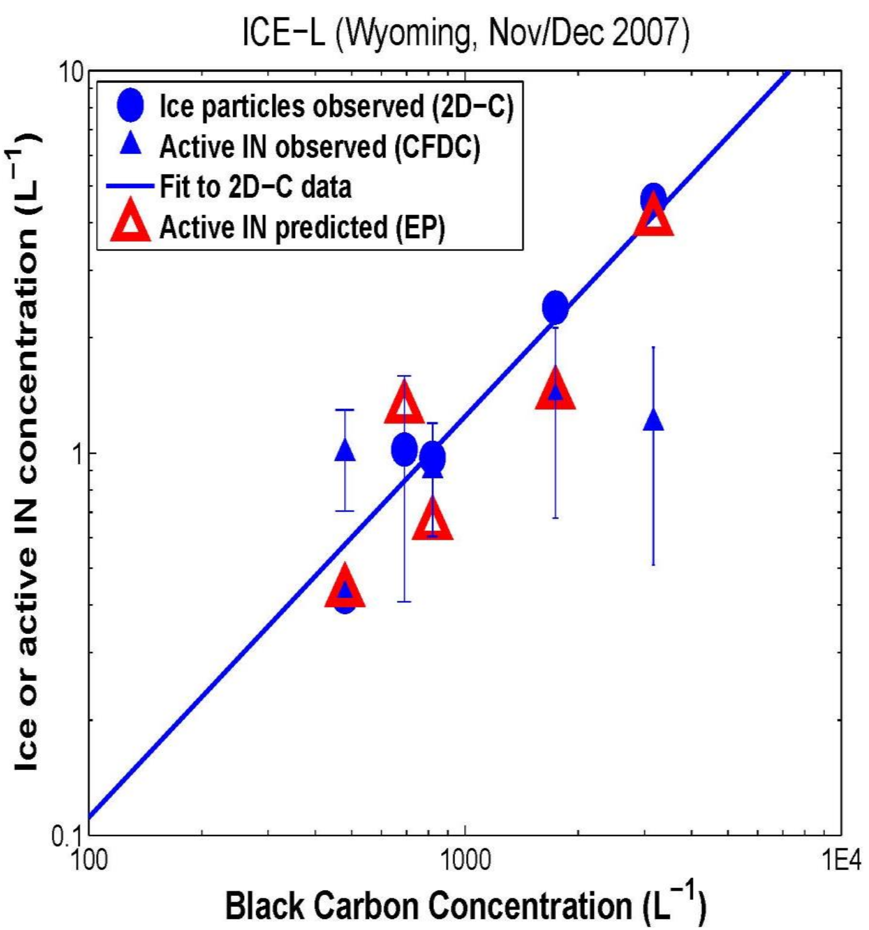
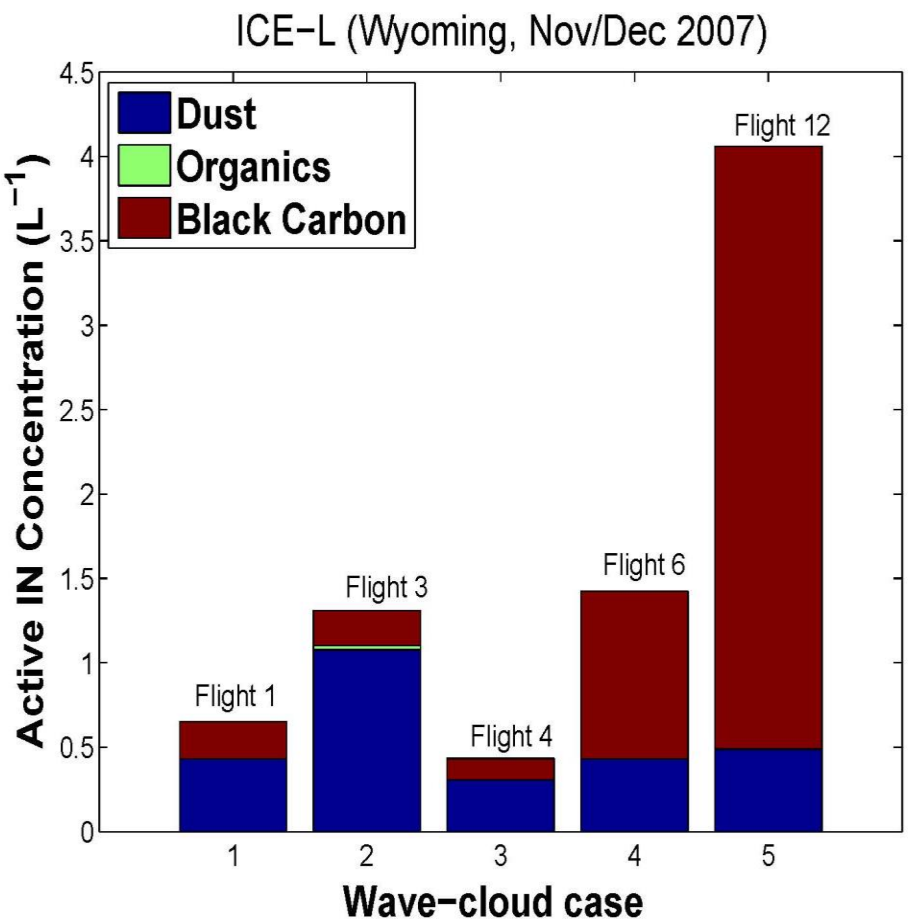
Yet lab studies show evidence of ice multiplication by fragmentation

- Irrespective of whether aircraft observations of IE ratio are reliable, cloud models must represent the fragmentation observed in the laboratory if they are to be accurate...
- Challenge: only a few lab studies have been done about each multiplication process
- Solution: for any fragmentation process, create a theory and fit it to the data from published experiments ...

EP ice nucleation scheme validated off-line for thin wave-clouds near -30 °C observed by aircraft





Phillips et al. (2008, 2013)

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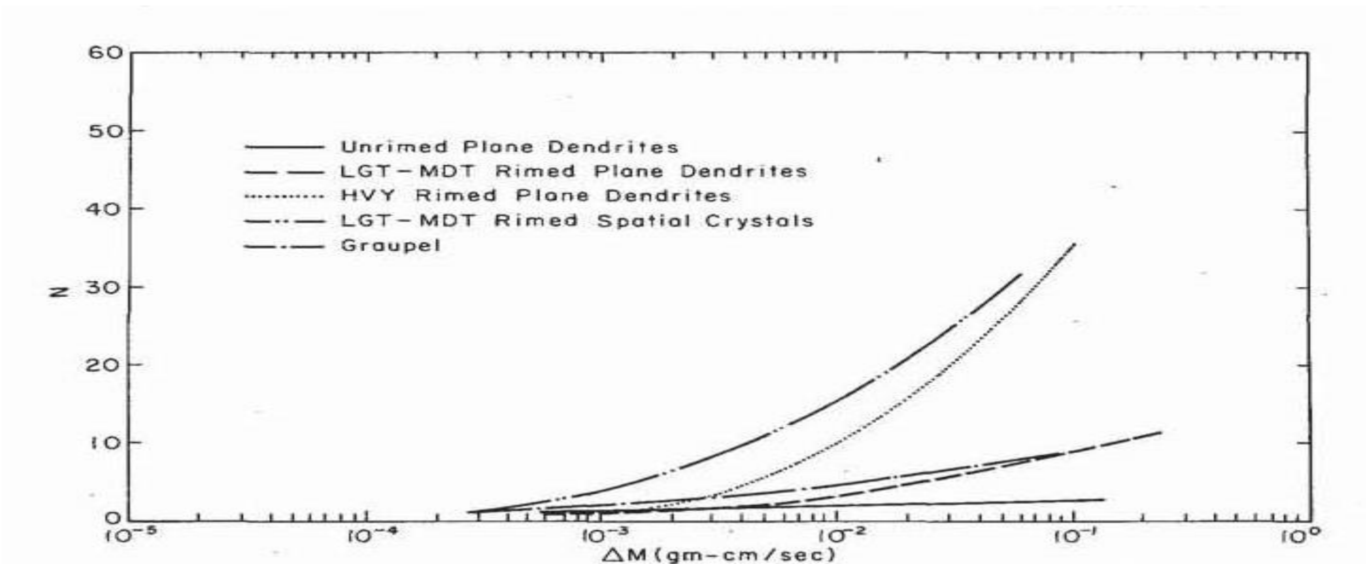
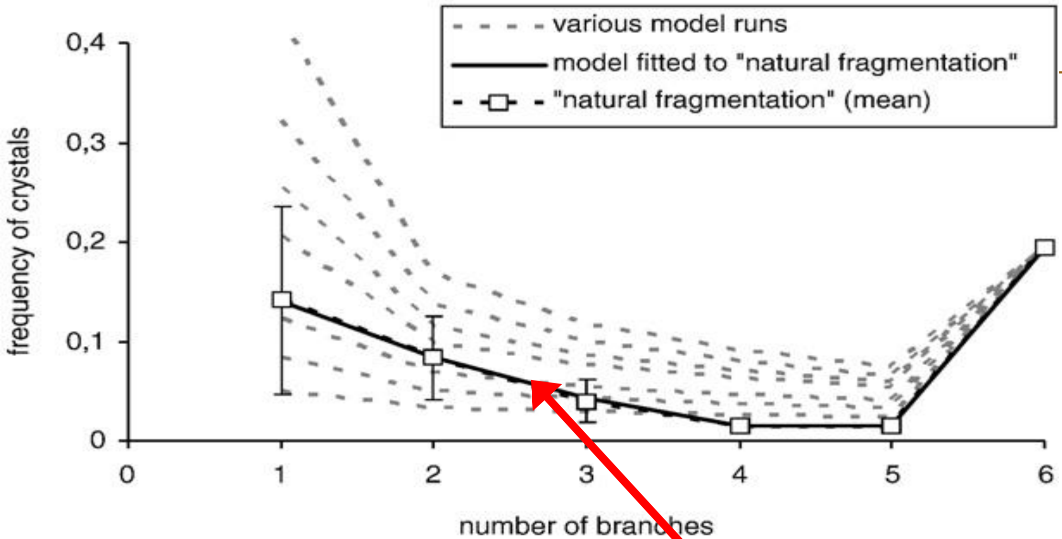
- **History of studies of multiplication**

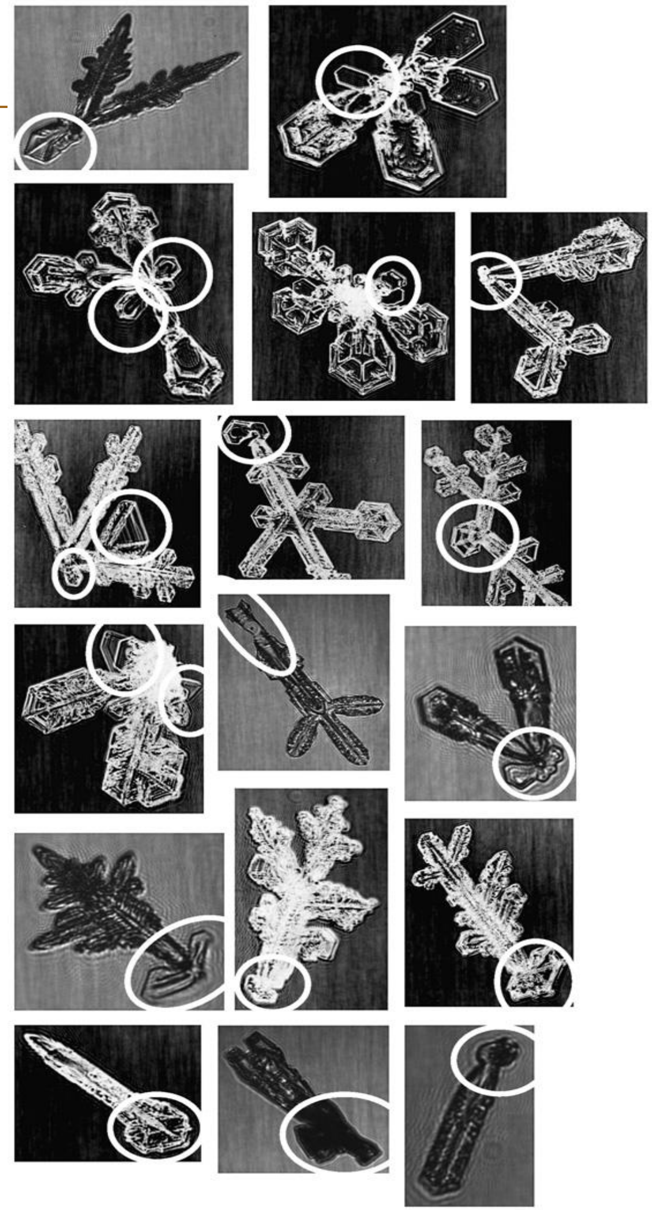
Ice multiplication

- Rime-splintering (Hallett-Mossop 1974) requires droplets > 24 um between -3 and -8 degC, so is absent in some (e.g. polar) clouds
- Raindrop-freezing only generates a few splinters per drop
- However, mechanical fragmentation may occur:-
  - Lab experiments by Vardiman (1978) with crystals impacting a plate:-



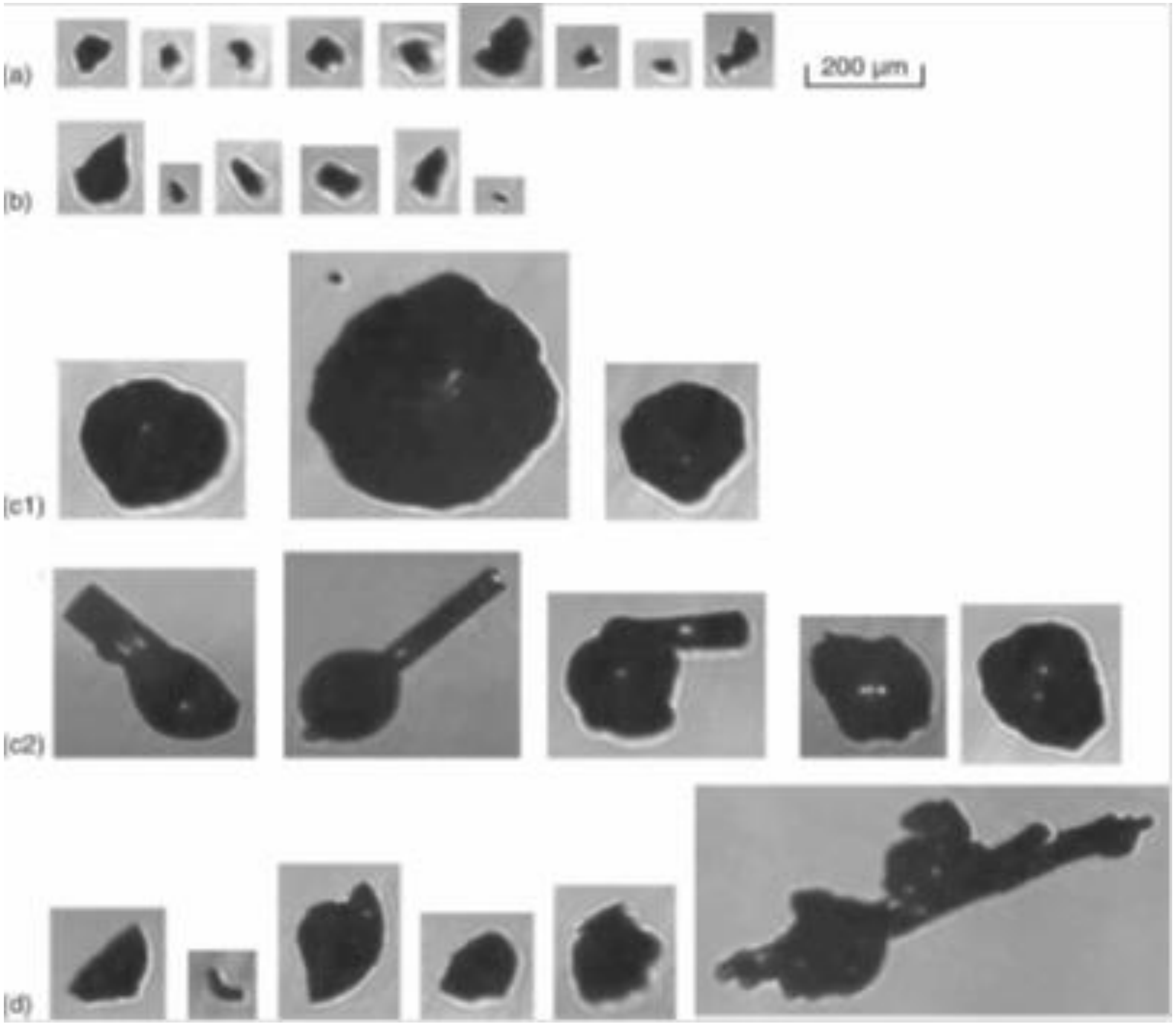
Aircraft observations of Arctic polar clouds (Schwarzenboeck 2009):



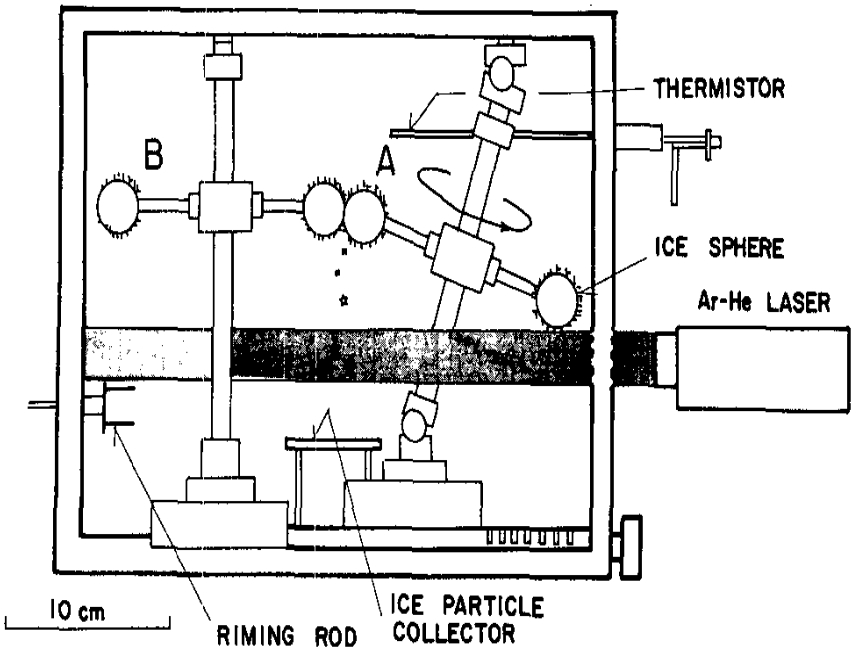


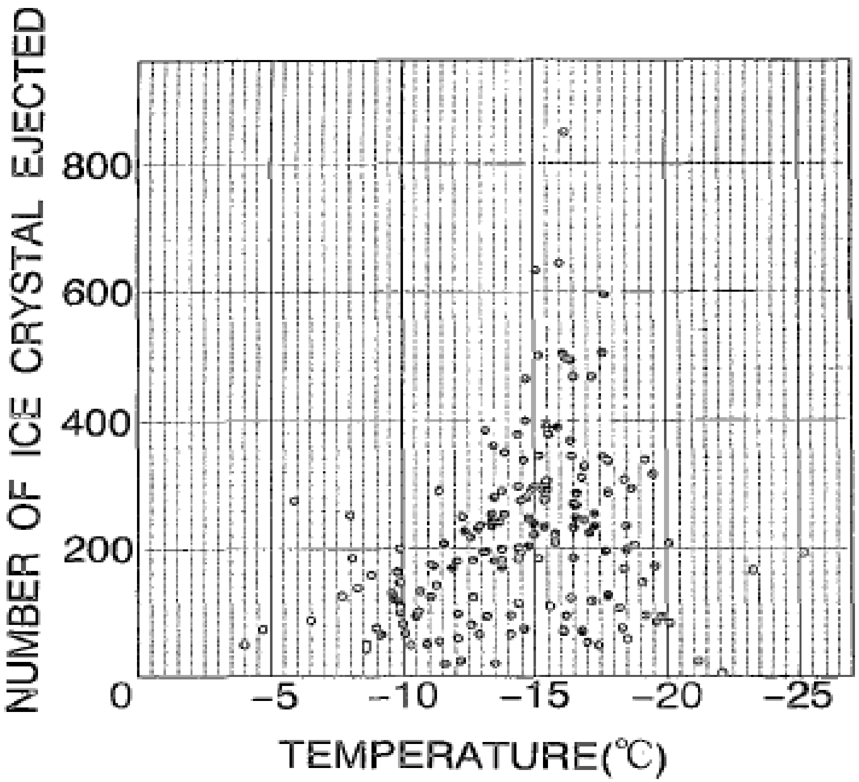
- 80% of all analysed crystals were fragmented,
- Of these fragmented ones:-
  - over 20% were naturally fragmented, either mechanically or during sublimation in ice-only cloud
  - up to 80% may have been artificially fragmented on impact with the probe or plane

Shattering during raindrop-freezing: Washington mixed-phase stratiform cloud (Rangno 2008)



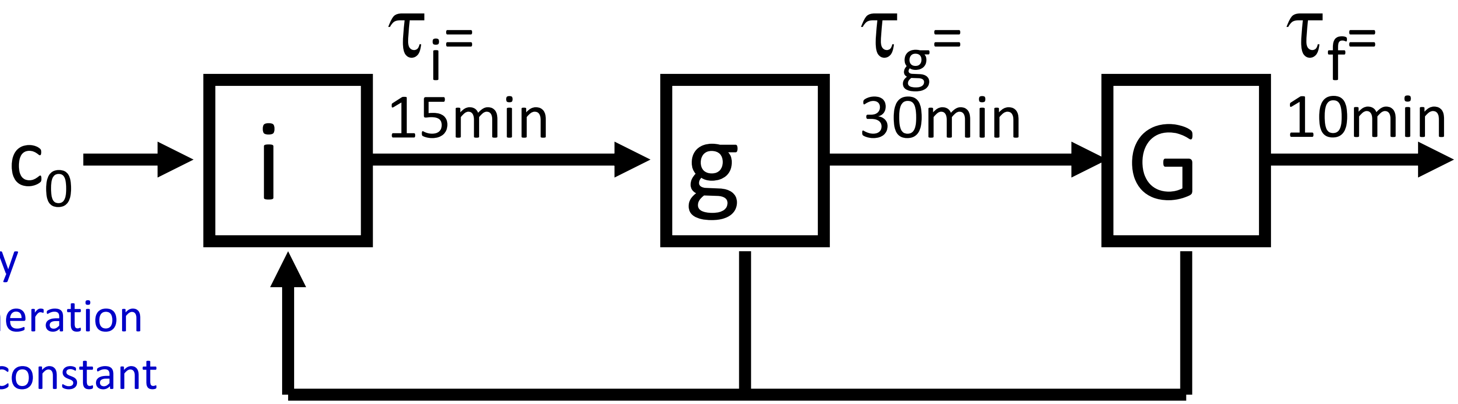
Mechanical fragmentation in graupel-graupel collisions studied by Takahashi et al. (1995)





Organisation of ice multiplication by dynamics in 0-D analytical model

ice crystal (i), small graupel (g), large graupel (G)



primary
ice generation
rate = constant

Mechanical break-up in ice+ice collisions

~ α ~

nondimensional parameter
(ice–multiplication efficiency):

$$\tilde{c} = 4 c_0 \tilde{\alpha} \tau_f \tau_g,$$

Increase with vertical velocity

Yano and Phillips (2011, *JAS*)

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relaxation model analysis :

nondimensionalization:

$n_i^* = (\tilde{\alpha}\tau_f\tau_g/\tau_i)n_i,\ n_g^* = \tilde{\alpha}\tau_f n_g,\ n_G^* = \tilde{\alpha}\tau_g n_G$

nondimensional set of equations:

$$\tau_i \dot{n}_i = \tilde{c}/4 - n_i + n_g n_G,$$

$$\tau_g \dot{n}_g = n_i - n_g,$$

$$\tau_f \dot{n}_G = n_g - n_G$$

nondimensional parameter

(ice–multiplication efficiency):

$$\tilde{c} = 4c_0\tilde{\alpha}\tau_f\tau_g,$$

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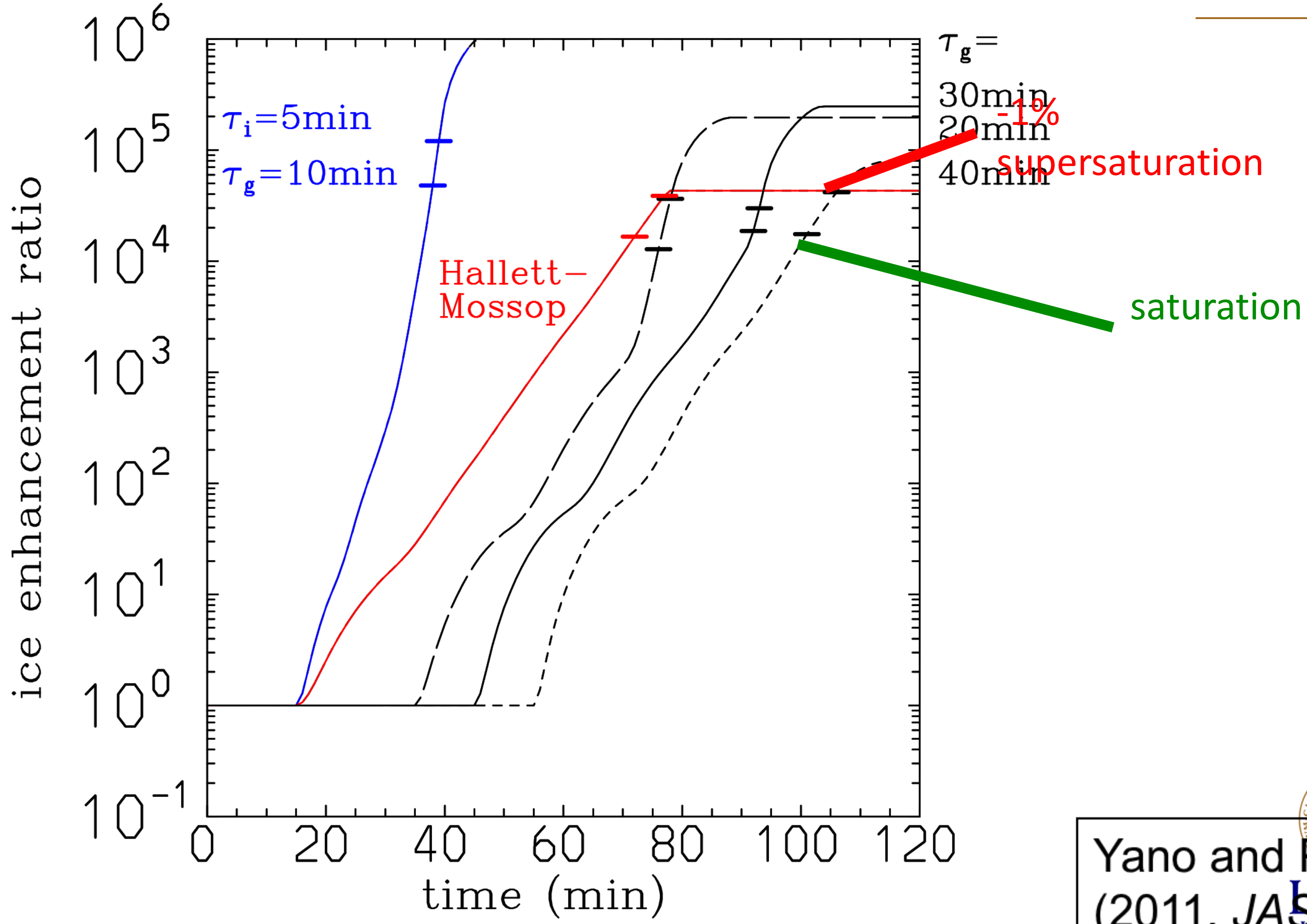
lag model analysis : water-vapor depletetion (Korolev and Mazin 2007):

Ice Enhancement Ratio: $IE = n_i/n_i^*$



Yano and Phillips (2011, *JAS*)

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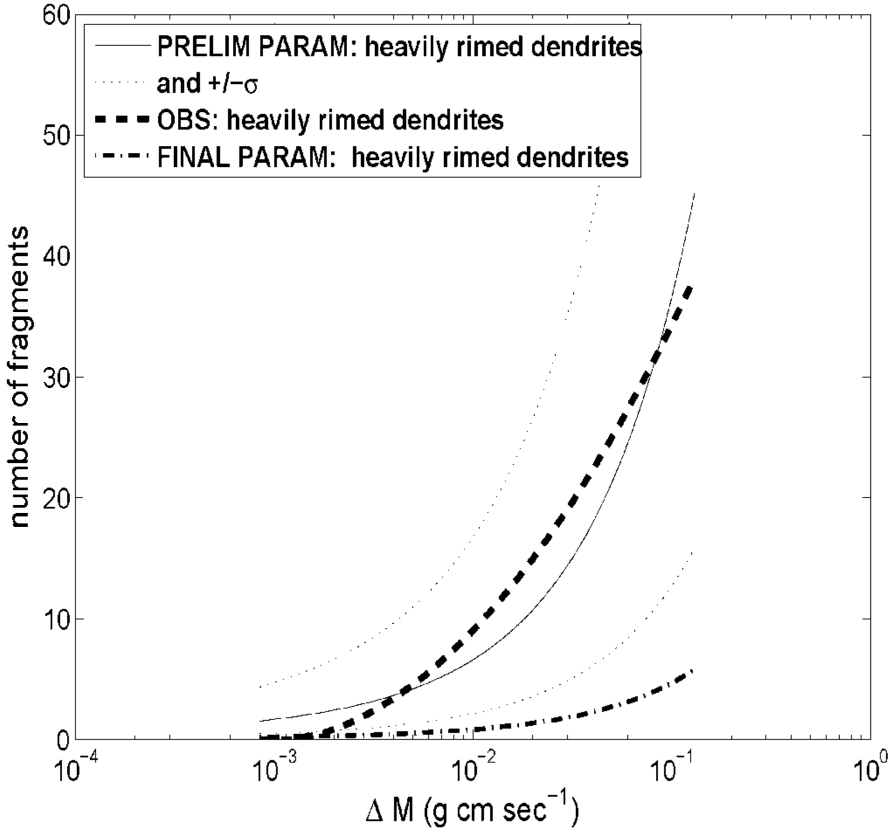
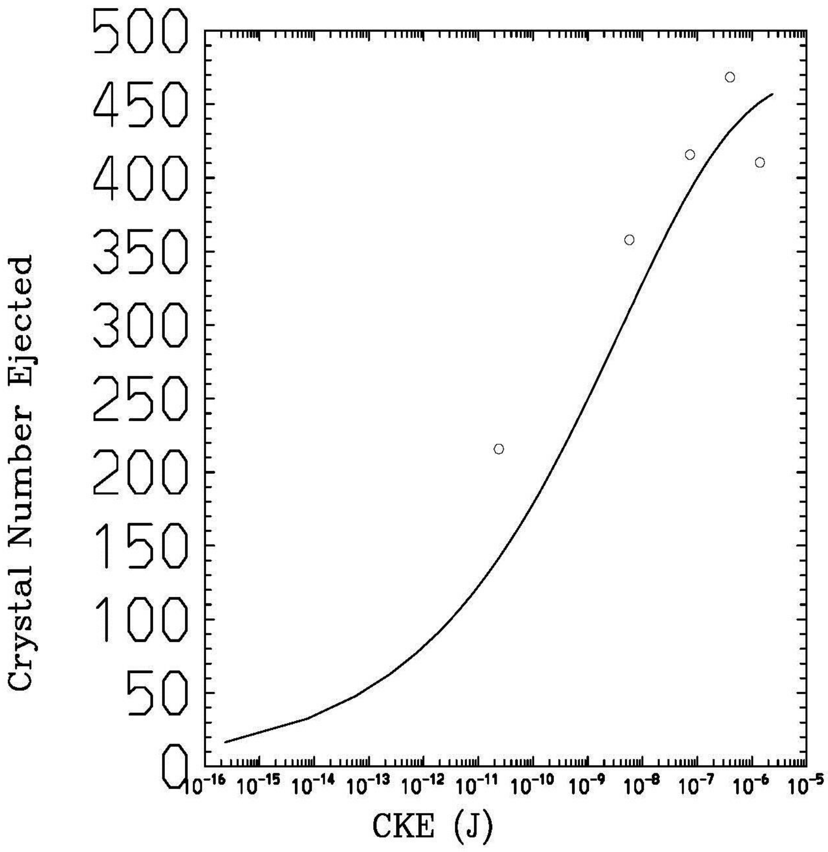
- **New theory of fragmentation**

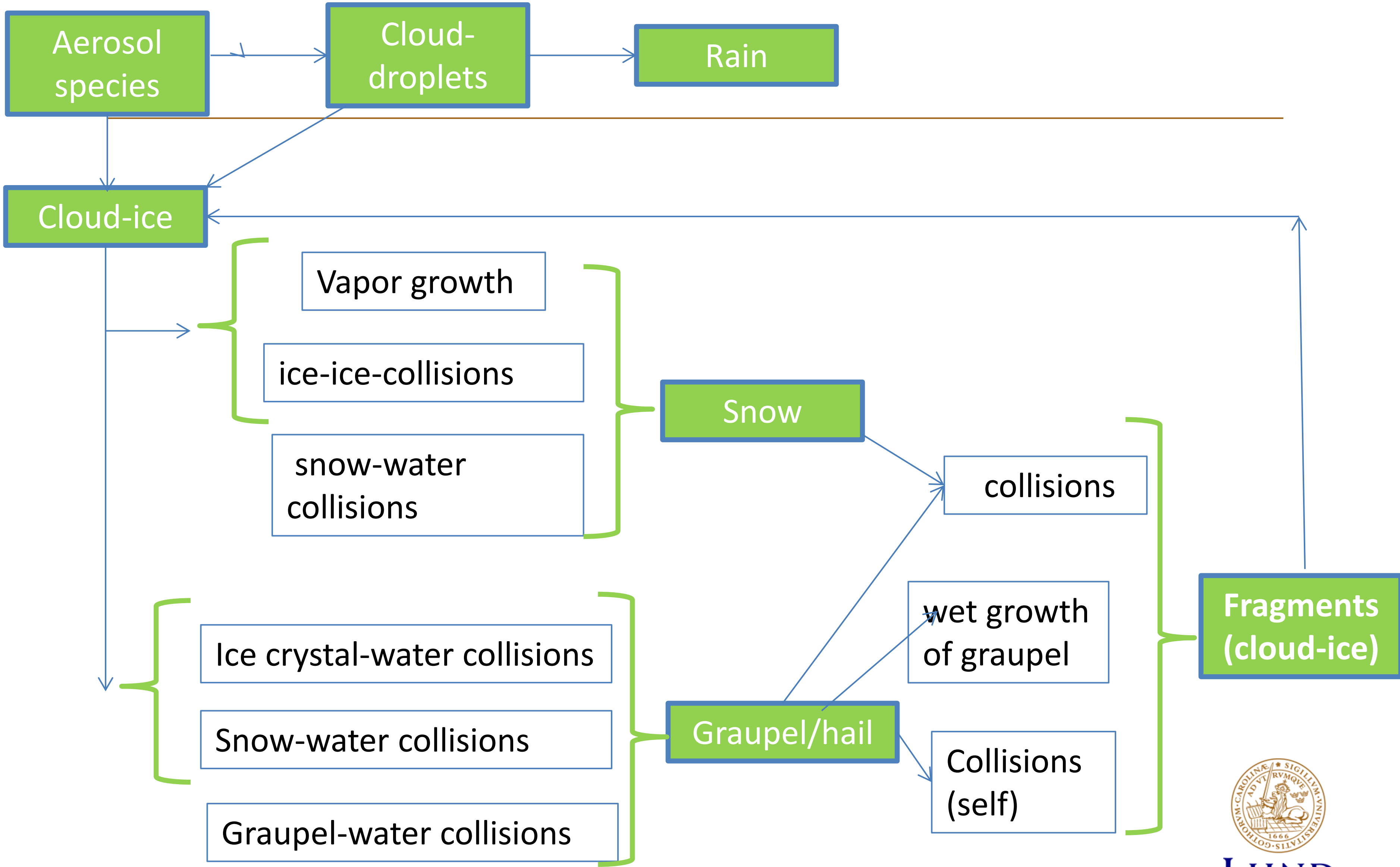
Fit theory to experimental data





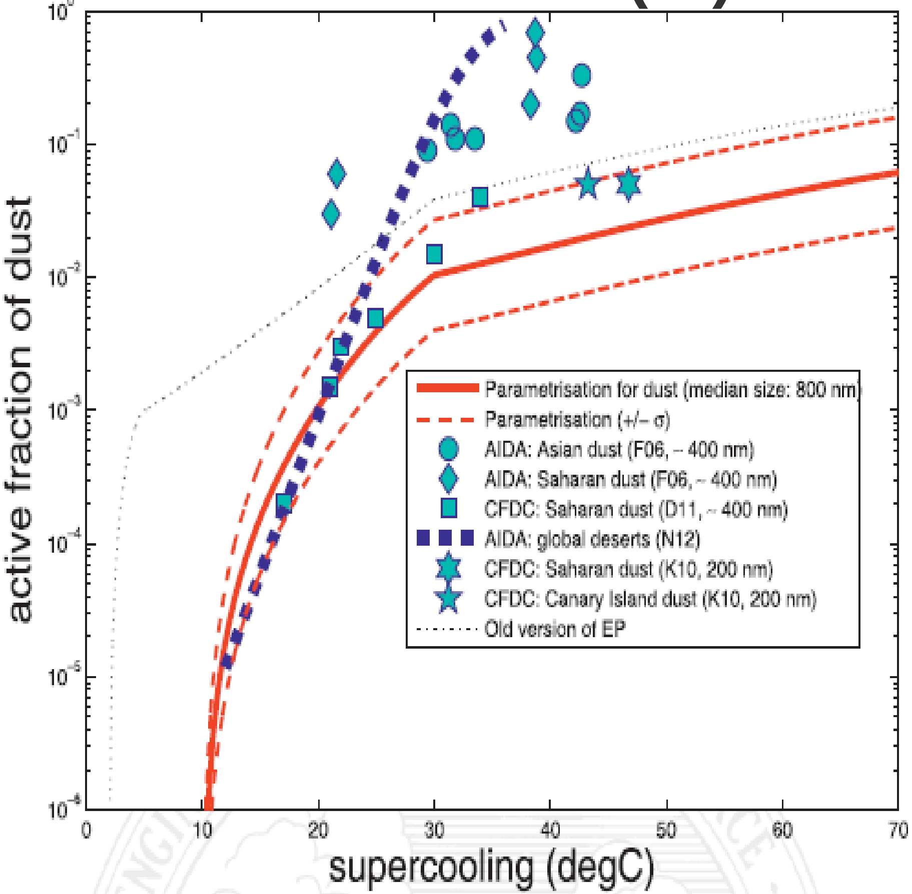
- Full simulations of cold-based convective storm
  - Role of fragmentation and explosive multiplication

Transformation of hydrometeors in aerosol-cloud model:

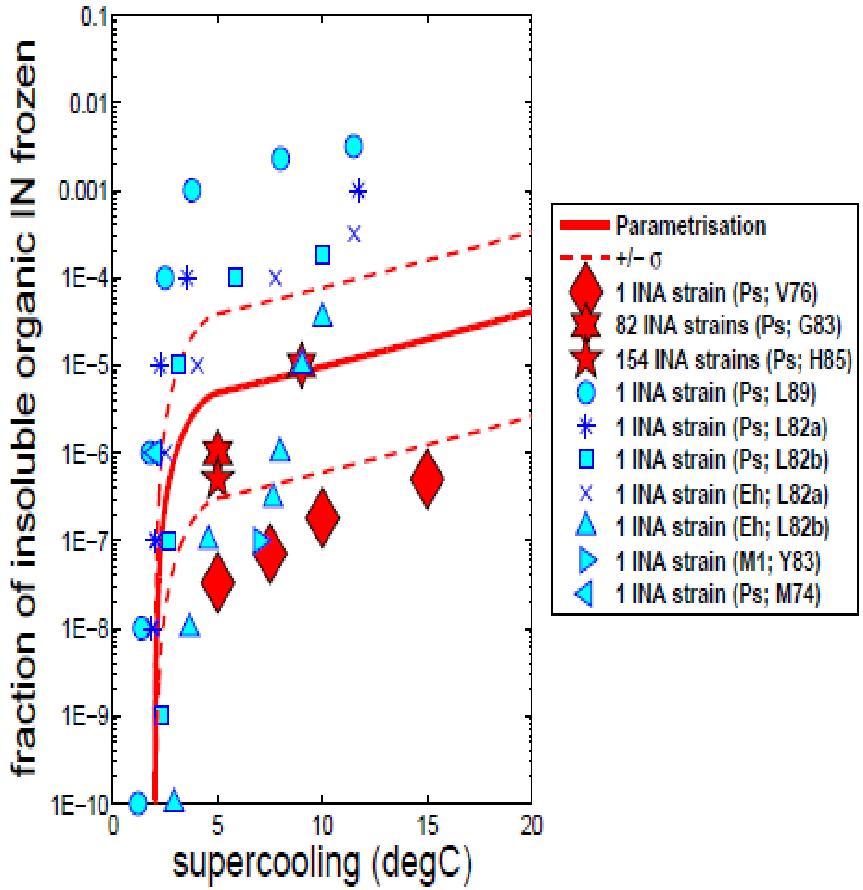


Phillips heterogeneous ice nucleation scheme ('empirical parameterization') based on coincident field observations of aerosol and ice nuclei (IN)

Dust ice nuclei (IN)



PBAP IN



Phillips et al. (2008, 2013, JAS)

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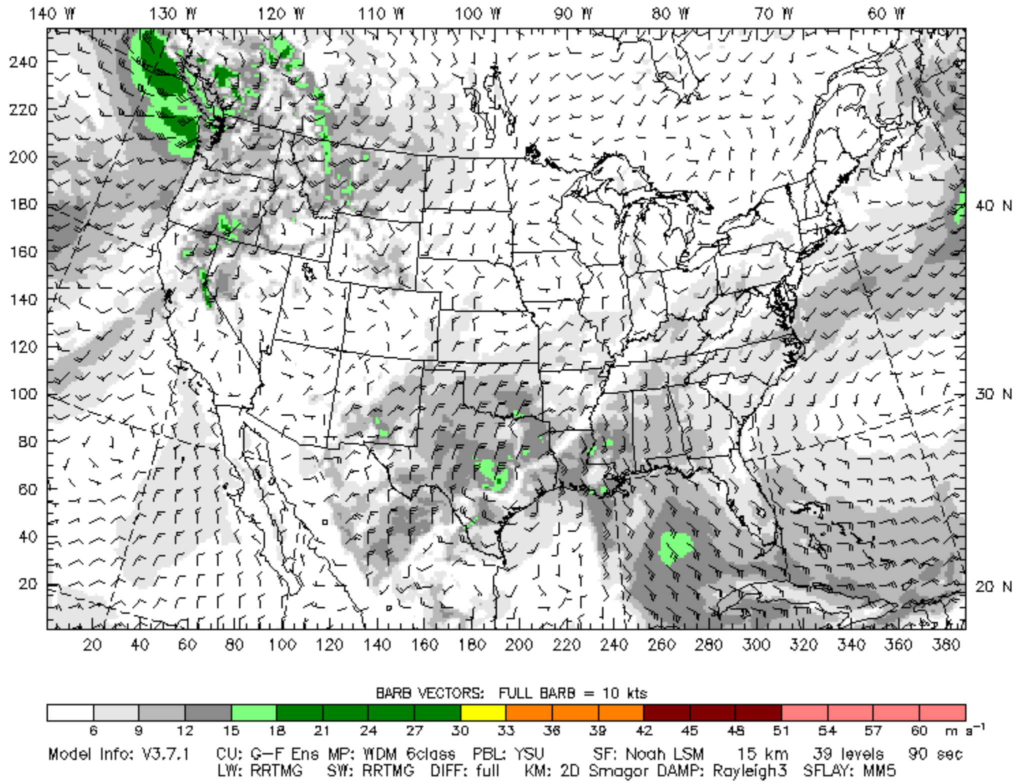
Phillips heterogeneous ice nucleation scheme implemented in leading weather forecasting model of USA (‘WRF’, NCAR):

WRF THE WEATHER RESEARCH & FORECASTING MODEL



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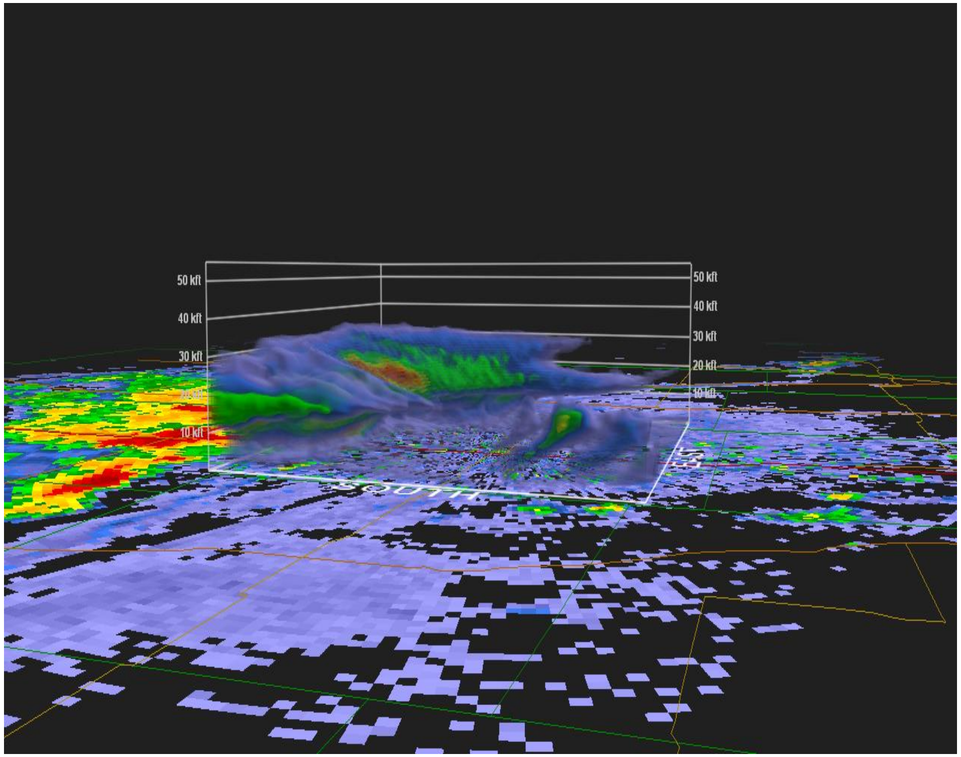
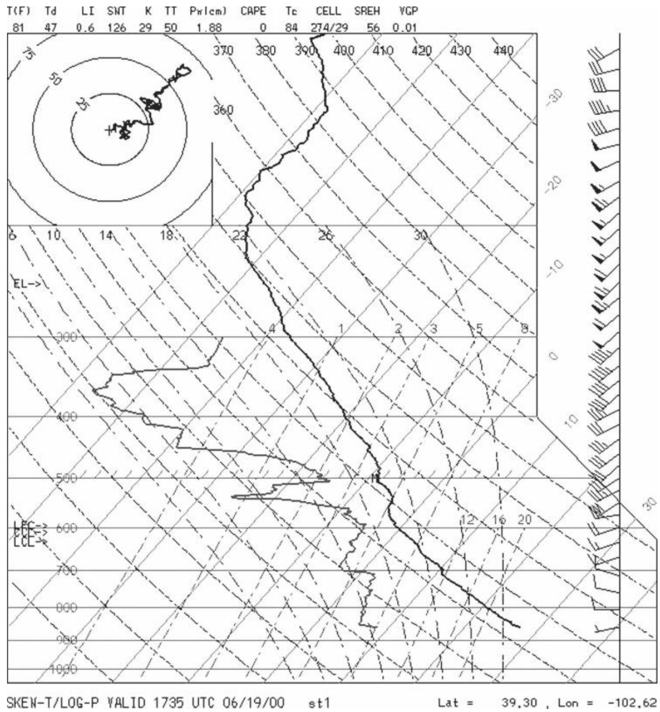
Cold-based convection near Kansas/Colorado border, summer 2000





Phillips et al. (2007, 2009, 2014, 2015 JAS): Kudzotsa et al. (2016)

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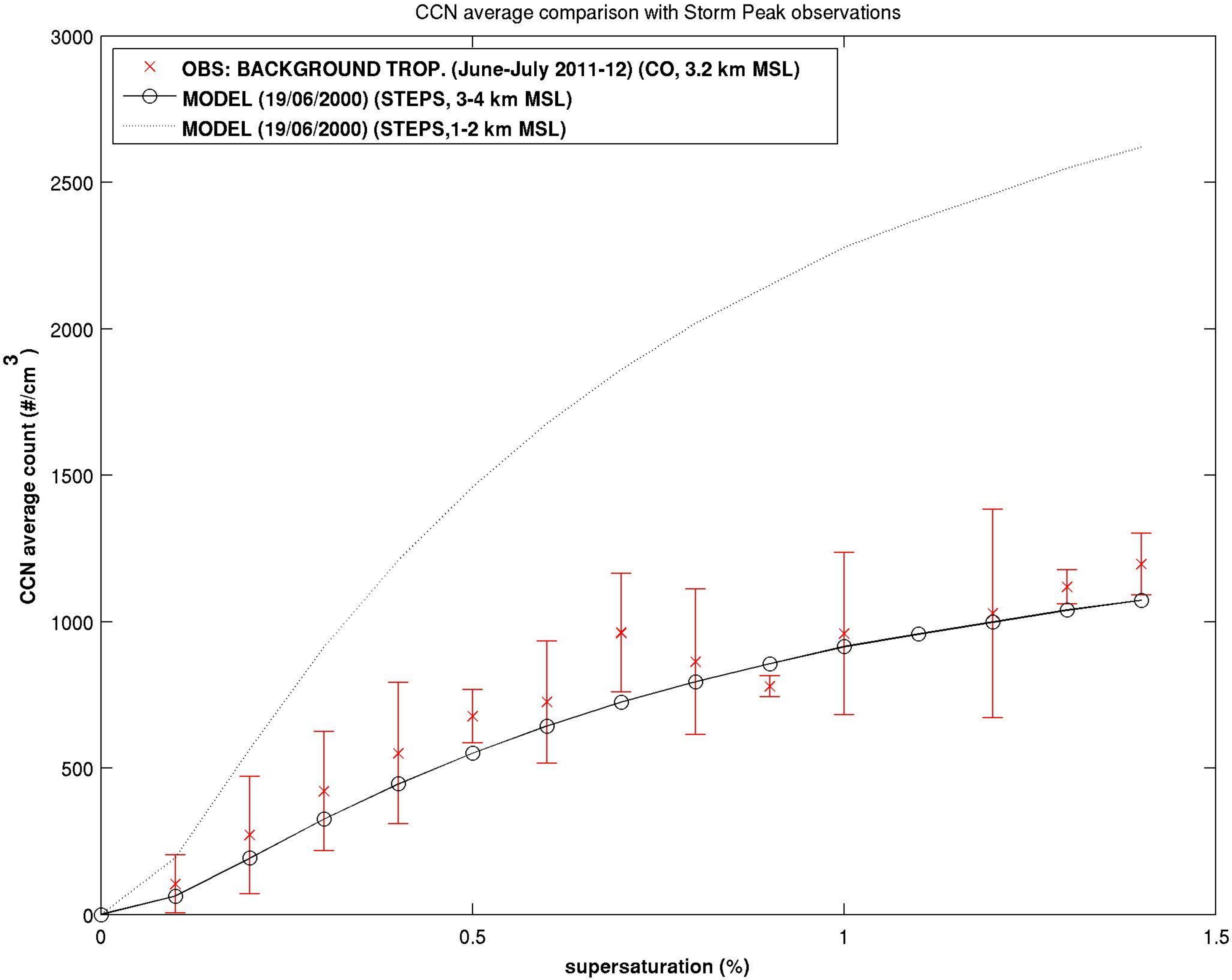
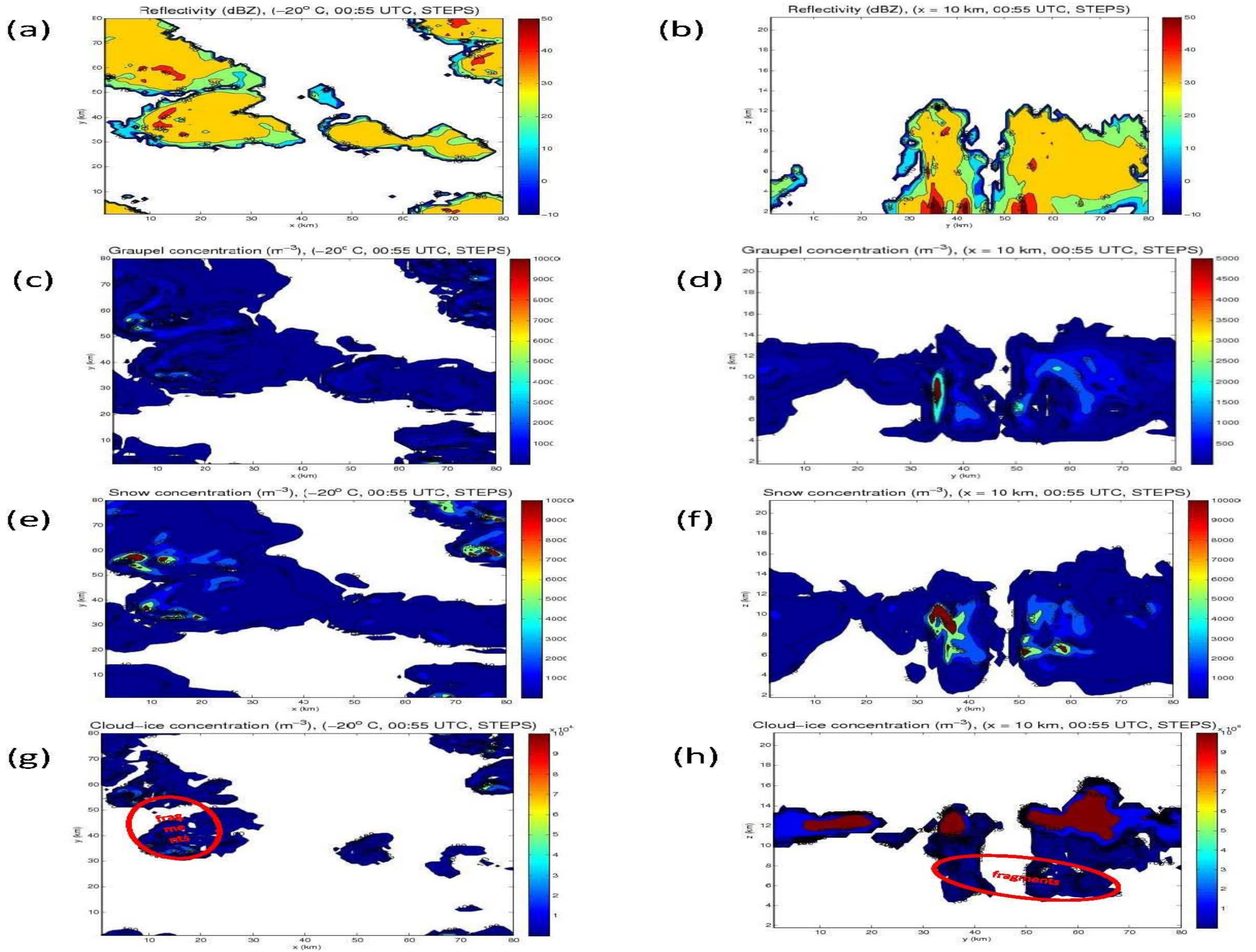
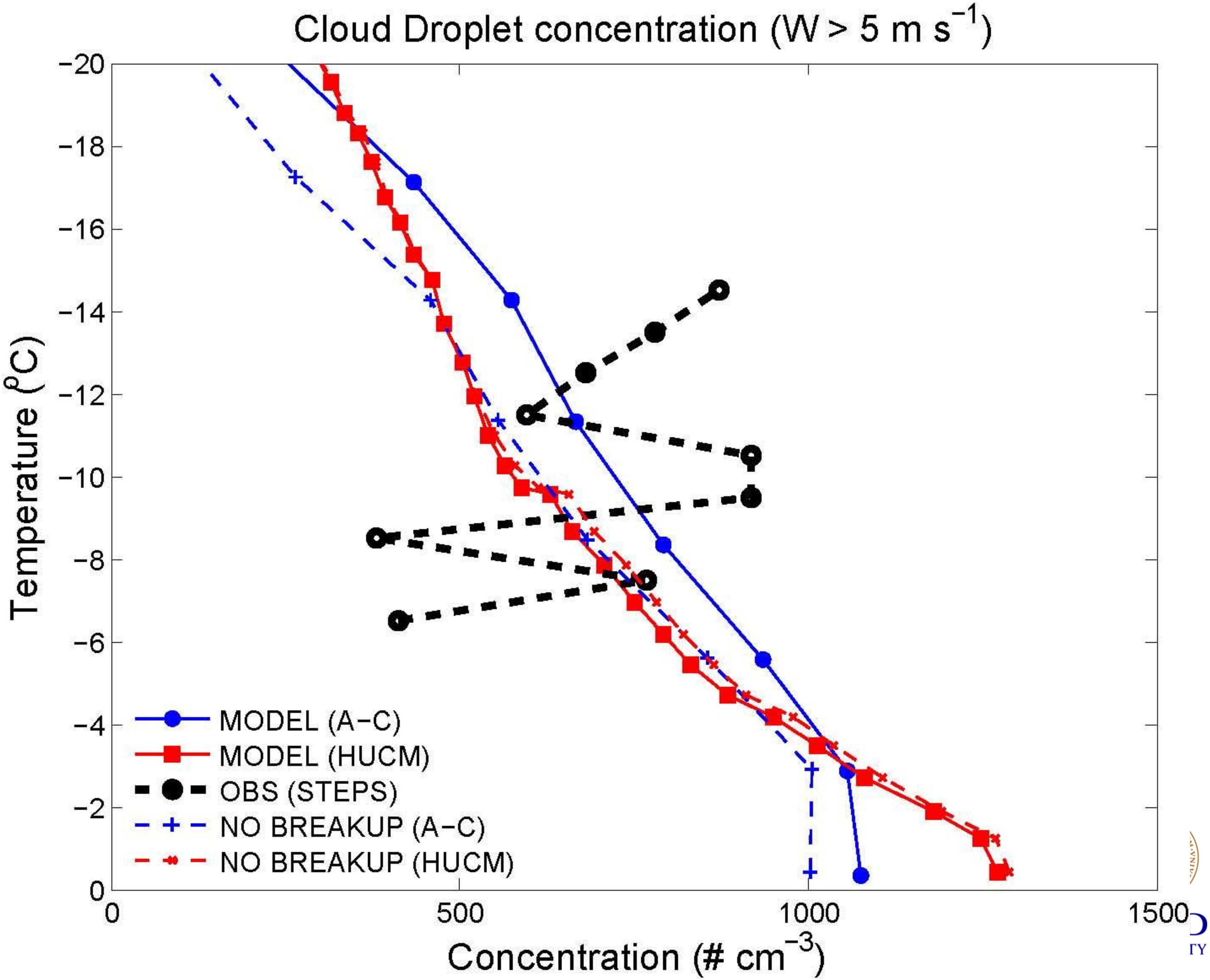


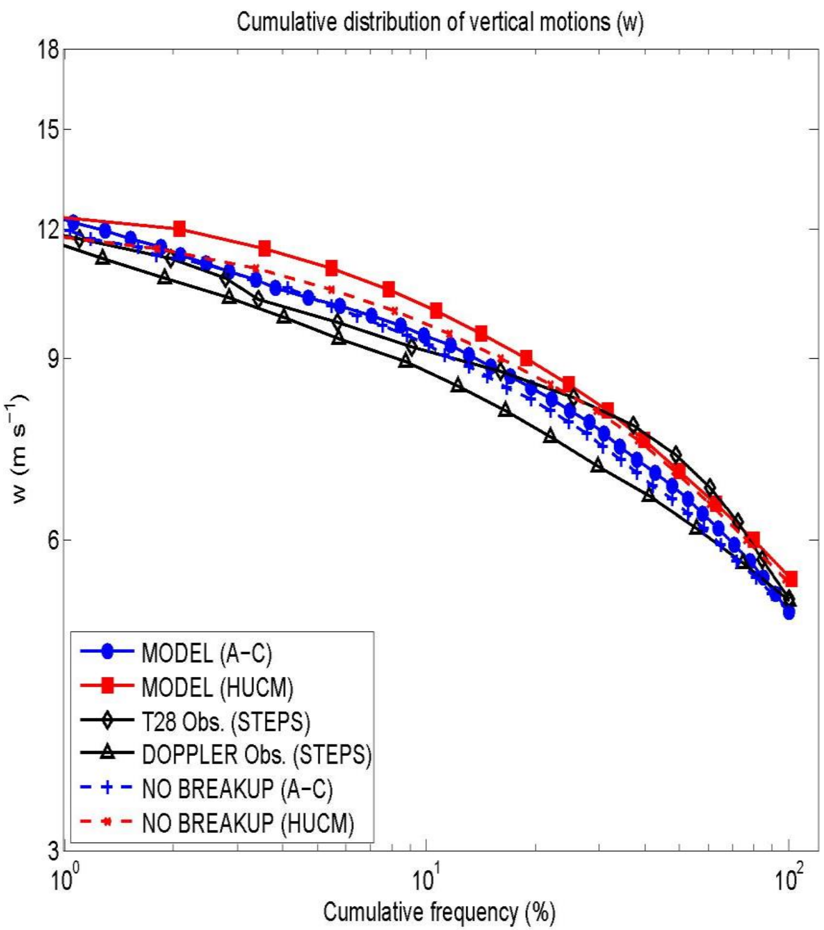
CCN average comparison with Storm Peak observations
OBS: BACKGROUND TROP. (June-July 2011-12) (CO, 3.2 km MSL)
MODEL (19/06/2000) (STEPS, 3-4 km MSL)
MODEL (19/06/2000) (STEPS,1-2 km MSL)
CCN average count (#/cm^3)
supersaturation (%)
0
500
1000
1500
2000
2500
3000
0
0.5
1
1.5

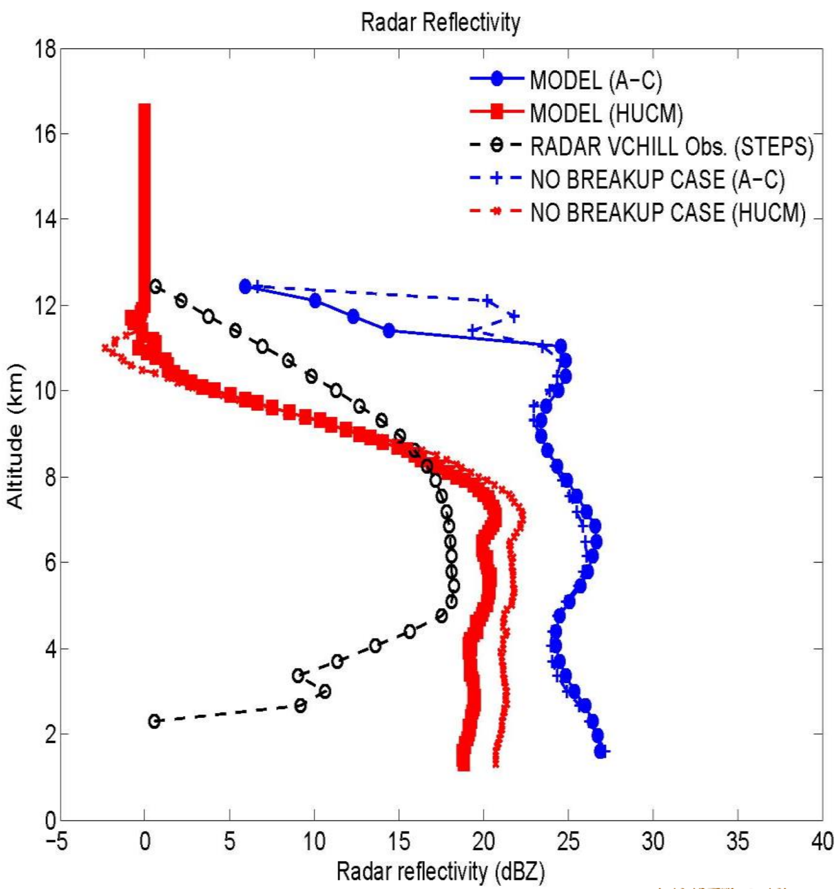


(a)
Reflectivity (dBZ), (−20° C, 00:55 UTC, STEPS)
(b)
Reflectivity (dBZ), (x = 10 km, 00:55 UTC, STEPS)
(c)
Graupel concentration (m⁻³), (−20° C, 00:55 UTC, STEPS)
(d)
Graupel concentration (m⁻³), (x = 10 km, 00:55 UTC, STEPS)
(e)
Snow concentration (m⁻³), (−20° C, 00:55 UTC, STEPS)
(f)
Snow concentration (m⁻³), (x = 10 km, 00:55 UTC, STEPS)
(g)
Cloud-ice concentration (m⁻³), (−20° C, 00:55 UTC, STEPS)
fragments
(h)
Cloud-ice concentration (m⁻³), (x = 10 km, 00:55 UTC, STEPS)
fragments
x (km)
y (km)
z (km)


Cloud Droplet concentration (W > 5 m s−1)
Temperature (°C)
Concentration (# cm−3)
−20
−18
−16
−14
−12
−10
−8
−6
−4
−2
0
500
1000
1500
MODEL (A−C)
MODEL (HUCM)
OBS (STEPS)
NO BREAKUP (A−C)
NO BREAKUP (HUCM)

Ascent and radar reflectivity





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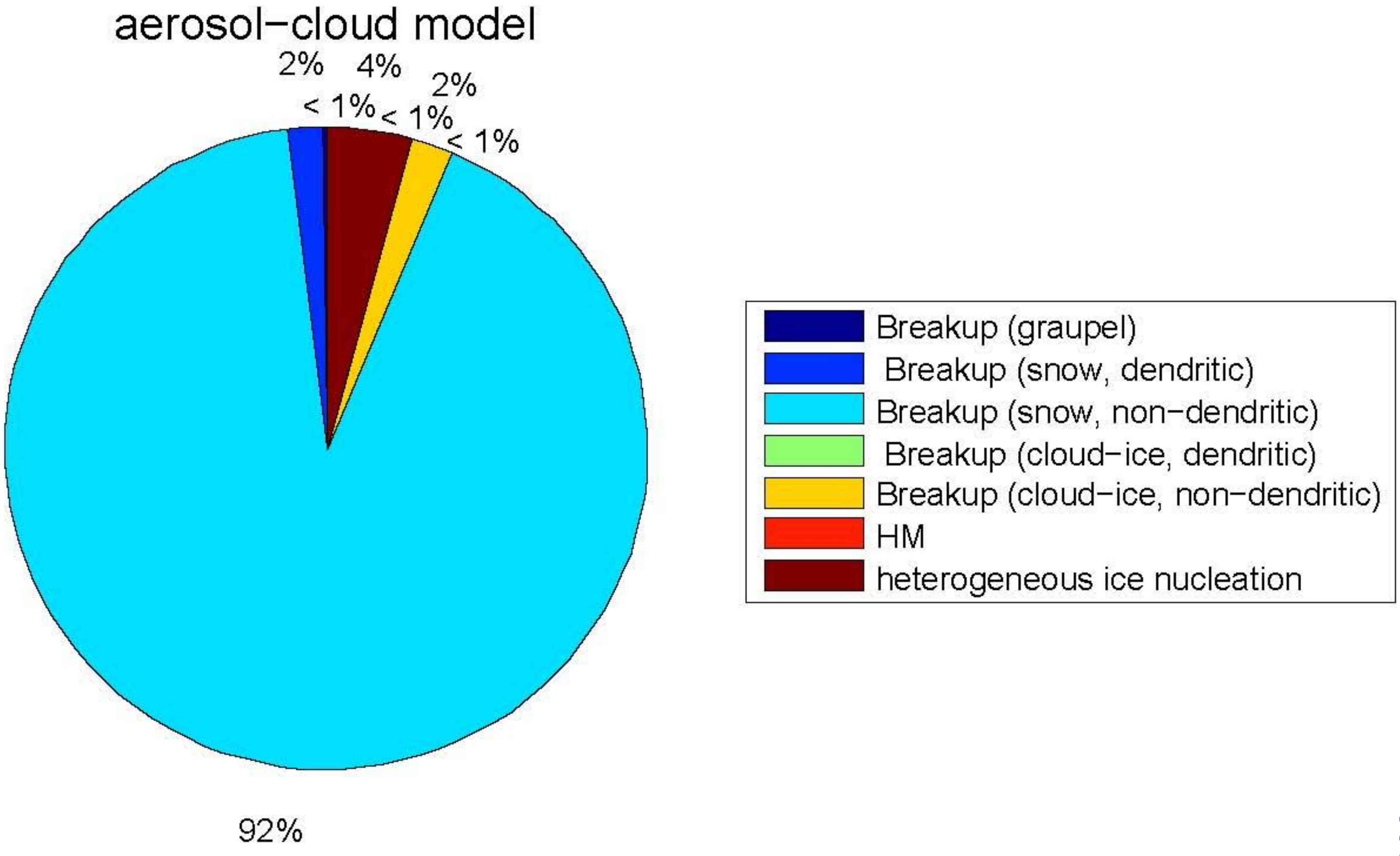
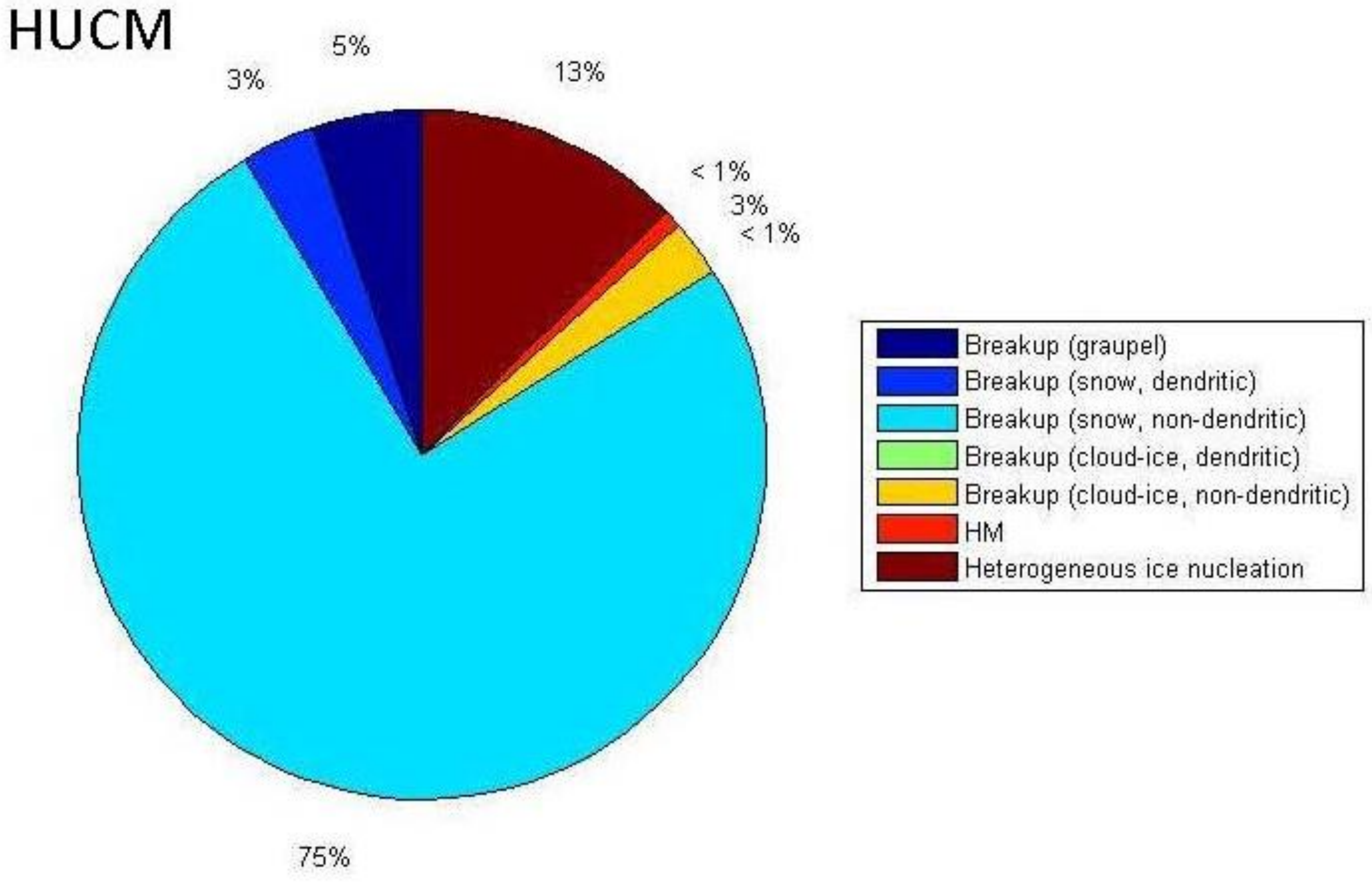
Budget: initiation of ice in aerosol-cloud model



Budget: initiation of ice in aerosol-cloud model



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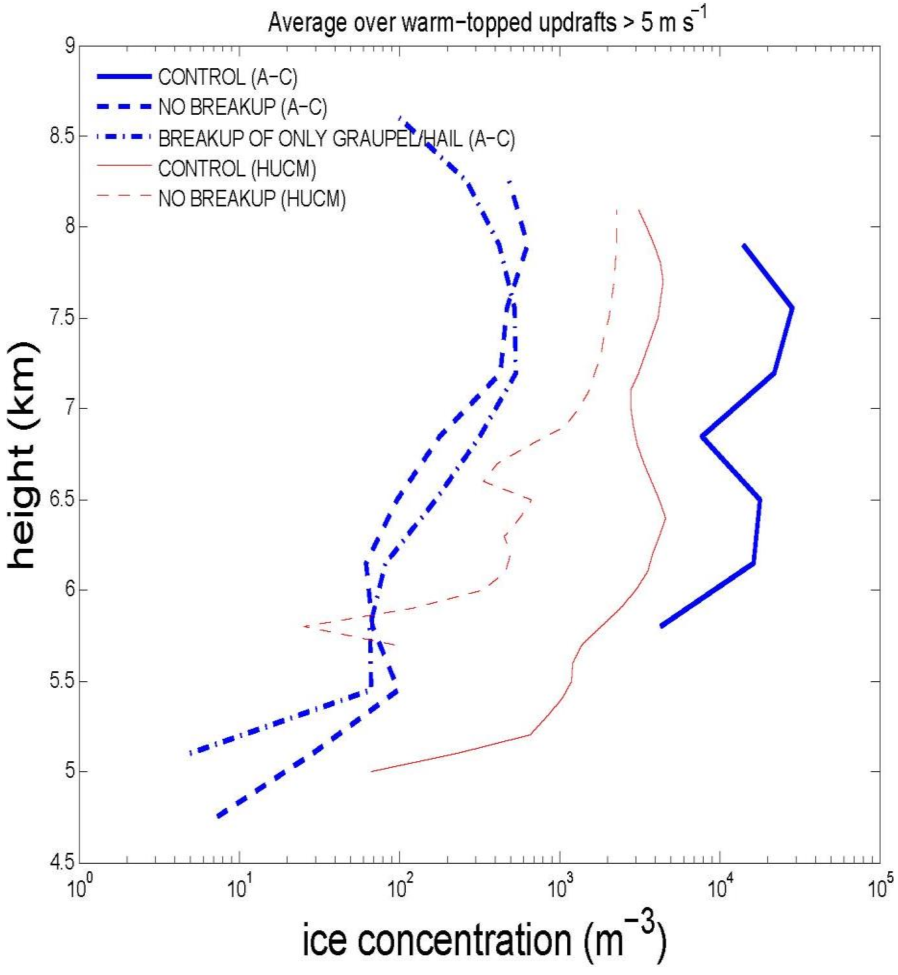
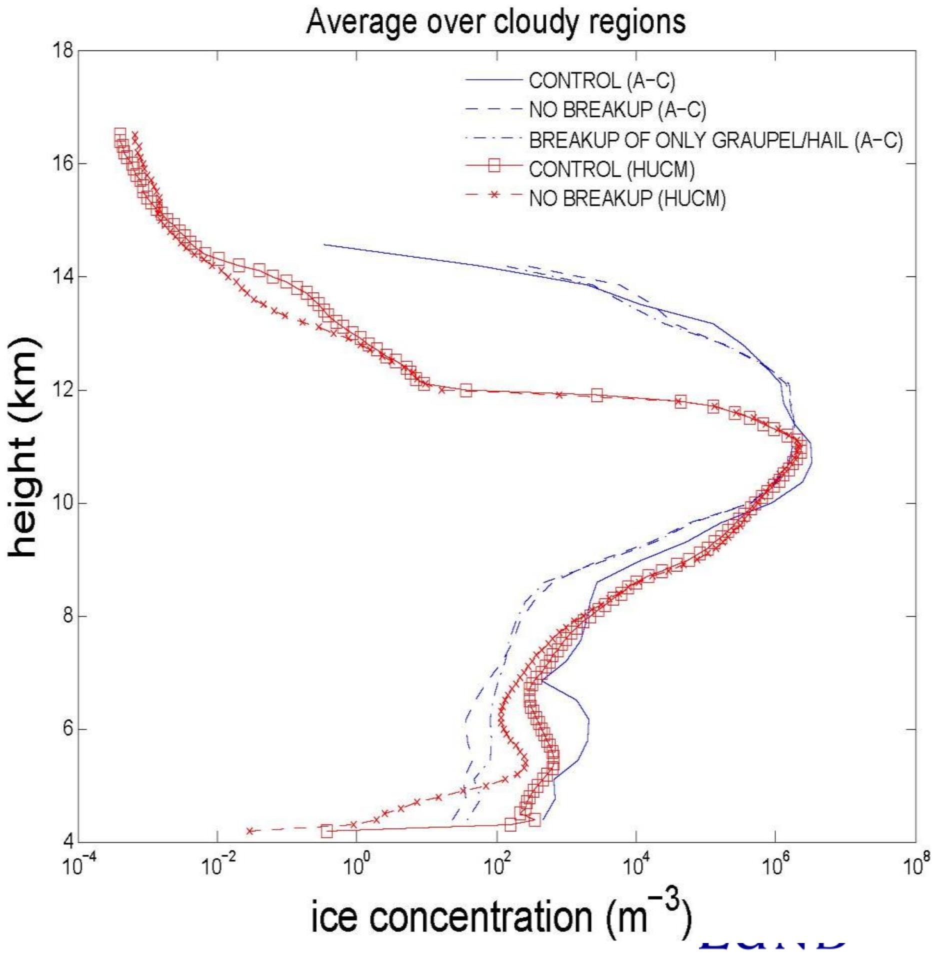
Ice concentrations





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• Conclusions and future directions

Summary

- Explosive multiplication produces most of the crystals in the storm, unless the top of the cloud gets above the -36 degC level.
- Full modeling support for the 0D analytical theory of multiplication
- Need to treat mechanical fragmentation if fundamental questions about cloud interactions with aerosol, radation and lightning are to be tackled.