Key issues in contemporary cloud microphysics

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Overview

1. Cloud microphysical processes
2. Key issues in cloud microphysics
3. Potential paths forward

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Confronting the Challenge of Modeling Cloud and Precipitation Microphysics

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Key Points:

- Microphysics is an important component of weather and climate models, but its representation in current models is highly uncertain
- Two critical challenges are identified: representing cloud and precipitation particle populations and knowledge gaps in cloud physics
- A possible blueprint for addressing these challenges is proposed to accelerate progress in improving microphysics schemes

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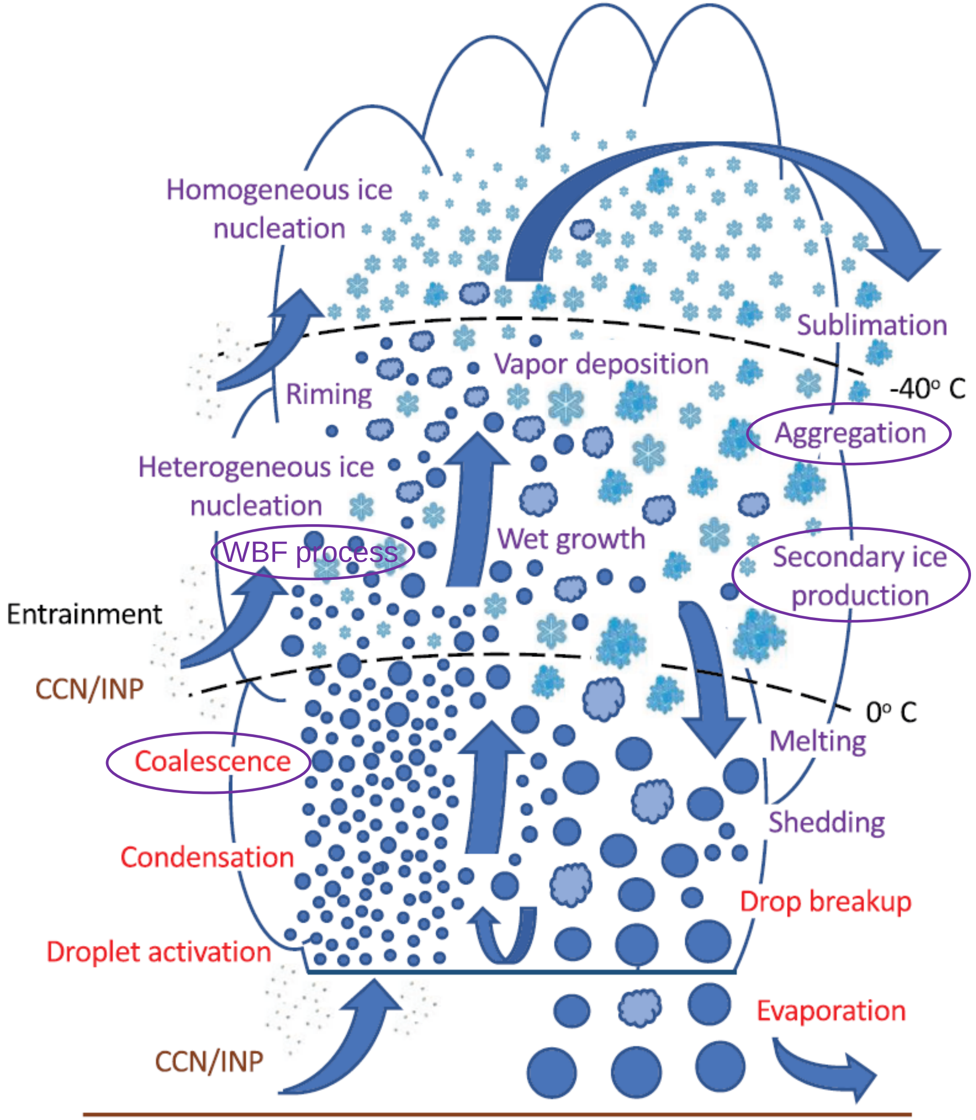
Abstract In the atmosphere, *microphysics* refers to the microscale processes that affect cloud and precipitation particles and is a key linkage among the various components of Earth's atmospheric water and energy cycles. The representation of microphysical processes in models continues to pose a major challenge leading to uncertainty in numerical weather forecasts and climate simulations. In this paper, the problem of treating microphysics in models is divided into two parts: (i) how to represent the population of

Basic cloud processes

1. Droplet spectra broadening
2. Collision-coalescence of small droplets
3. Coalescence coefficients of droplets
4. Collective growth of droplets
5. Collective growth of ice
6. Collective growth of cloud particles in mixed phase
7. Aggregation of ice, sticking efficiency



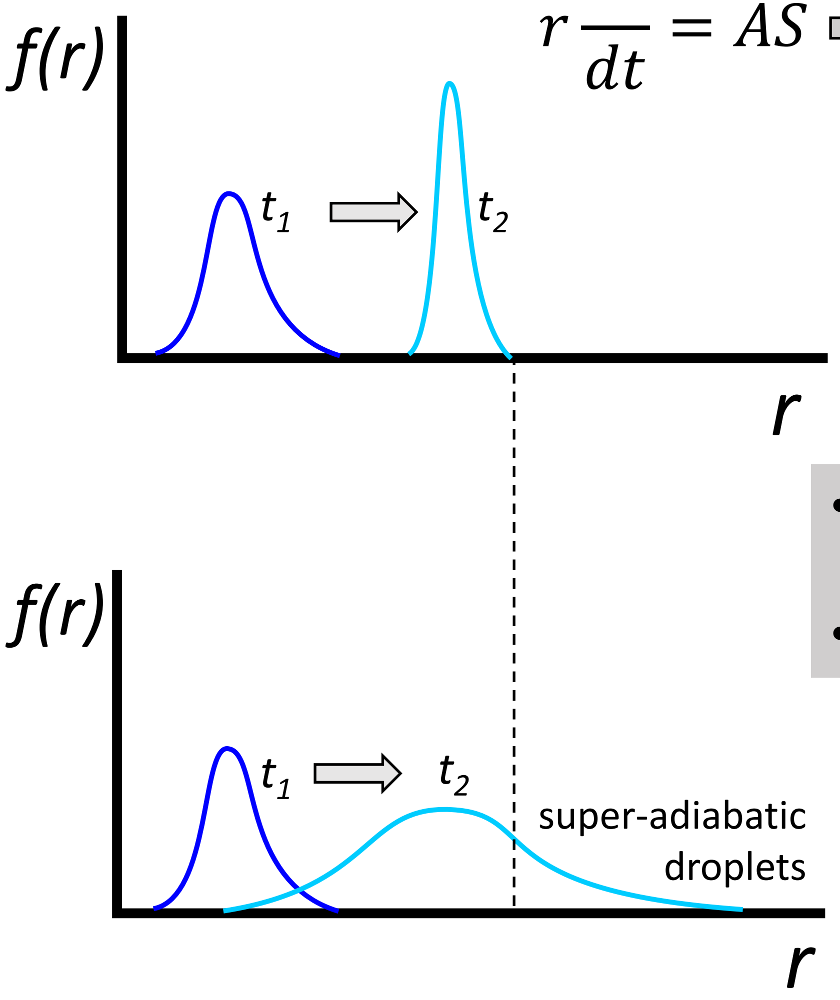
Morrison et al. 2020

Problem of droplet spectra broadening

$$r\frac{dr}{dt} = AS \Rightarrow \boxed{r \propto \sqrt{t}} \Rightarrow$$

Smaller droplets are growing faster than the larger ones.

Therefore, DSDs are expected narrowing during diffusional growth.



- Numerous in-situ measurements showed that the observed DSDs are *broader* than the theoretically predicted.
- Observed DSDs contain super-adiabatic droplets

Possible explanations: (a) broad CCN distribution, (b) stochastic effects, (c) entrainment and mixing, (d) Ostwald ripening, (e) collision-coalescence, etc.

No consensus has been achieved regarding the mechanisms responsible DSD broadening.

Collision-coalescence of small droplets (r<20μm)

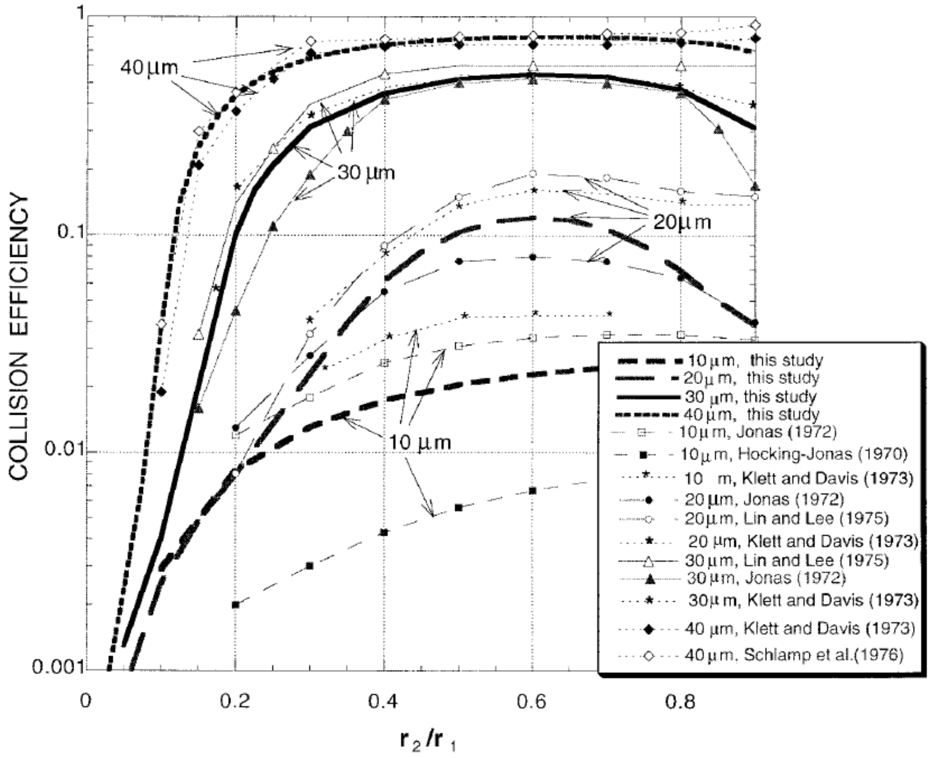


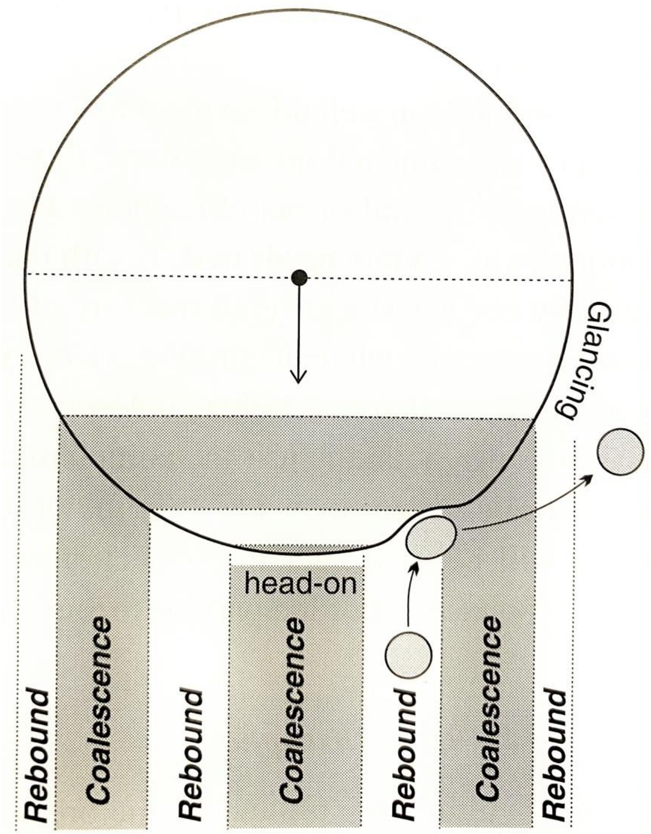
FIG. 5. Theoretical collision efficiencies of small spherical water droplets in calm air as a function of drop radii ratio (p ratio, see Pruppacher and Klett 1997) and of collector drop radius (given by the labels of each curve). For sake of comparison, the results of some earlier theoretical studies are presented as well.

Pinsky et al. JAS, 2001

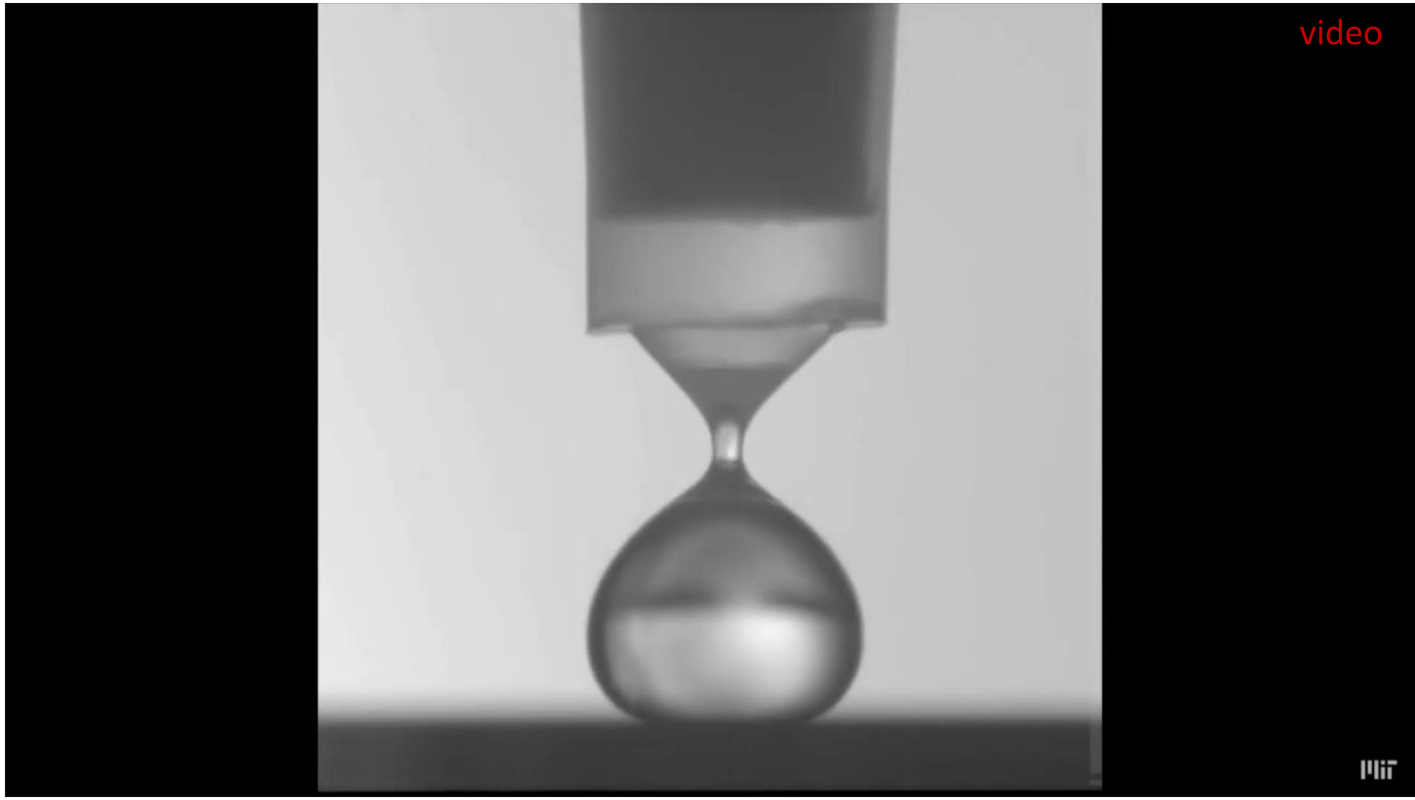
There is a good wealth of theoretical studies of collision-coalescence process for droplets r<20μm in still and turbulent environment.

However, there are a very few laboratory studies of collision-coalescence efficiencies for droplets with r<20μm.

Coalescence coefficients of droplets



Conceptual diagram of coalescence and rebound regions
(Jayaratne and Mason, Proc.Roy.Soc.,1964)

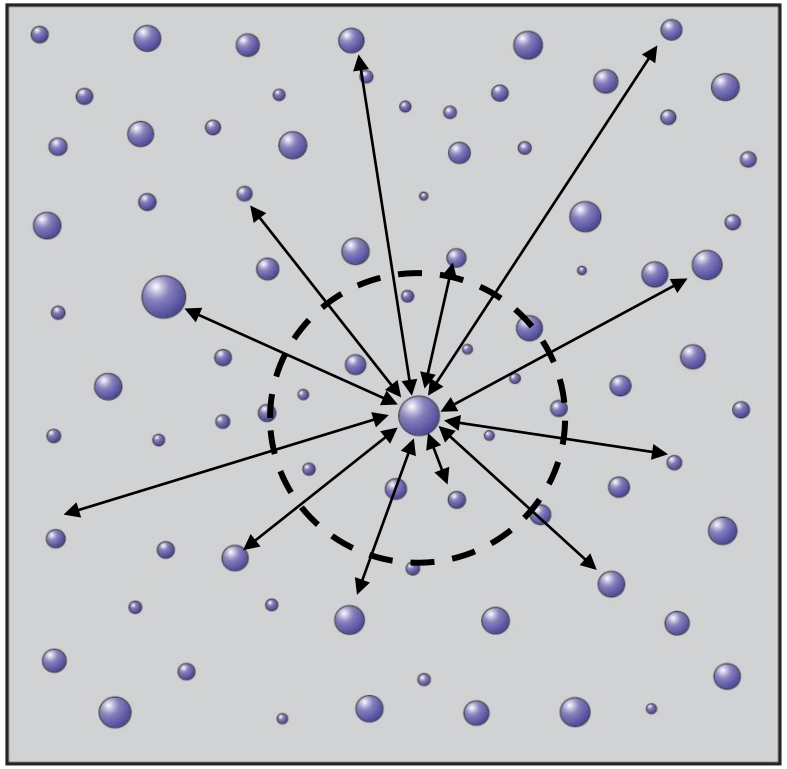


MIT video: https://www.youtube.com/watch?v=YlsGXk7jxDE

"Unfortunately, most of these experiments were not carried out under natural conditions. For proper simulations, both interacting drops should fall freely at relative velocities following from their size difference, or from wake capture effects. Only in this way can the flows controlling drop deformations and relative trajectories for close separations be represented accurately. For these reason, experiments with fixed large drops should be regarded as primarily exploratory and qualitative in nature"

Pruppacher and Klett, 1997 (p.595)

Collective growth of droplets



In the frame of regular condensation all droplets are interacting with each other

$$\frac{dS}{dt} = a_1 u_z - a_2 \frac{dq_w}{dt}$$ supersaturation (mass conservation)

$$\frac{dT}{dt} = -a_4 u_z + a_5 \frac{dq_w}{dt}$$ temperature (energy conservation)

$$a_i = a_i(P, T)$$

During diffusional growth, droplets affect local fields of *T* and *S*.

During *regular condensation*, at each time step *Δt,* fields of *T* and *S* are considered uniform across the domain.

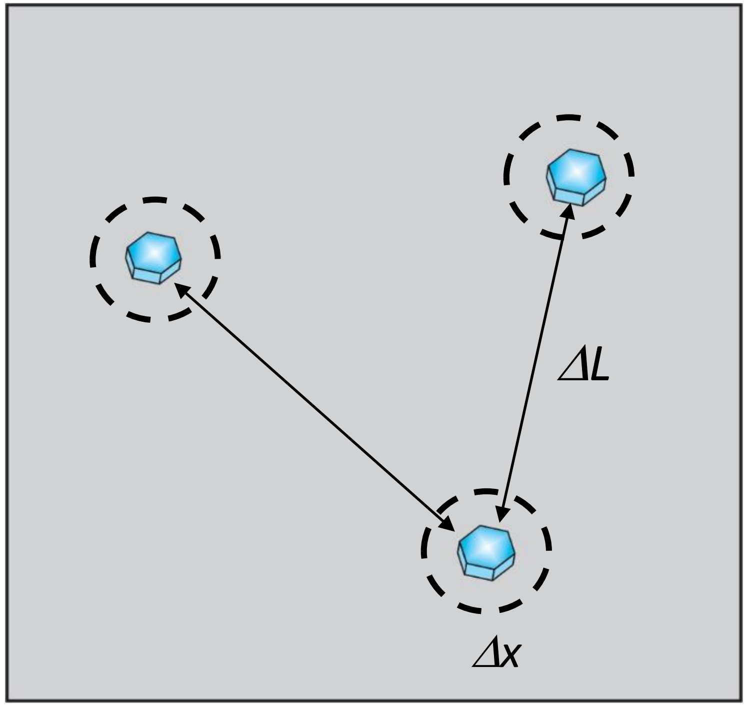
T and q_{vapor} mix within the modeling domain within the time step *Δt*

This results in an unrealistically high coeff. of turbulent diffusion $K_t \sim L^2/\Delta t$ ~10^4-10^8 m^2/s (typically K_t ~10^0-10^2 m^2/s)

It means that each particle affects all other particles in the domain.

There were no lab experiments on validation of the regular condensation concept in liquid clouds!

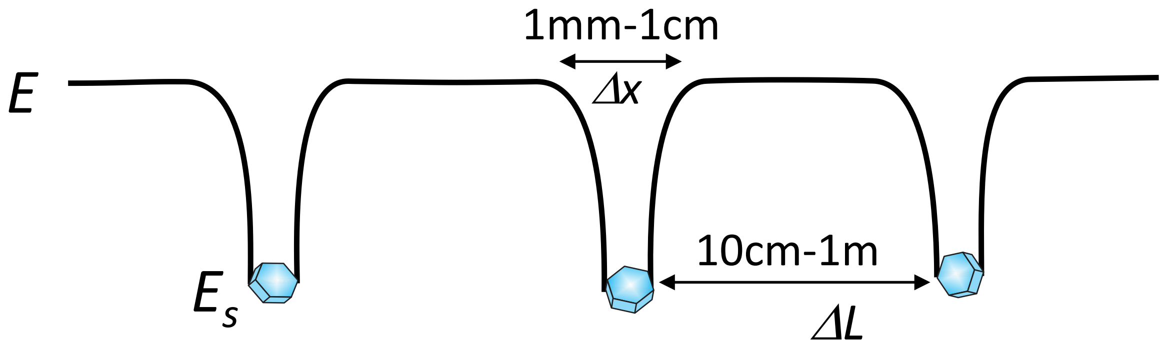
Collective growth of ice



Typical average distance between ice particles in ice clouds varies in the range 10cm< ΔL <1m

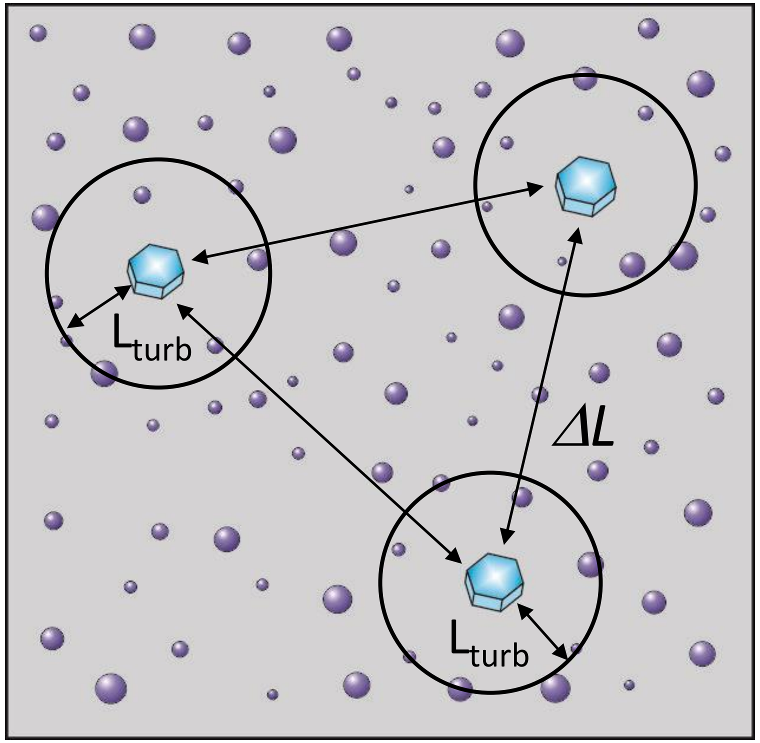
Interaction between ice particles in ice clouds is hindered by large distance between particles: $\Delta L >> \Delta x$

Is the regular condensation approximation applicable for ice clouds?



There were no lab experiments on validation of the regular condensation concept in ice clouds!

Collective growth of cloud particles in mixed phase clouds



$\Delta L \sim 10^{-1}$- $10^{0}m$ average distance between ice particles

$L_{turb} \sim (\tau^2 \varepsilon)^{\frac{1}{3}}$ spatial scale around ice affected by turbulent mixing

At time steps $\Delta t \sim 1s$, $L_{turb} < \Delta L$

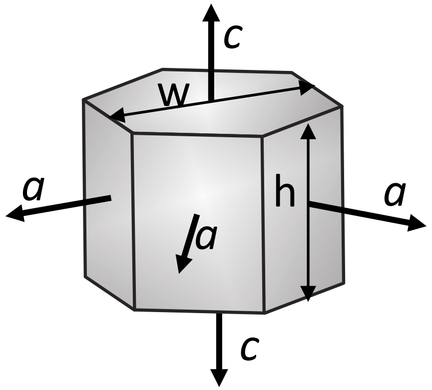
This results in the inhomogeneity of *S* and *T* fields inside mixed-phase parcels and the violation of the regular condensation assumption.

There were no lab experiments quantifying:

(a) partitioning rates of liquid and ice phases vs u_z (e.g. WBF process)
(b) glaciation time
(c) maintenance of mixed-phase

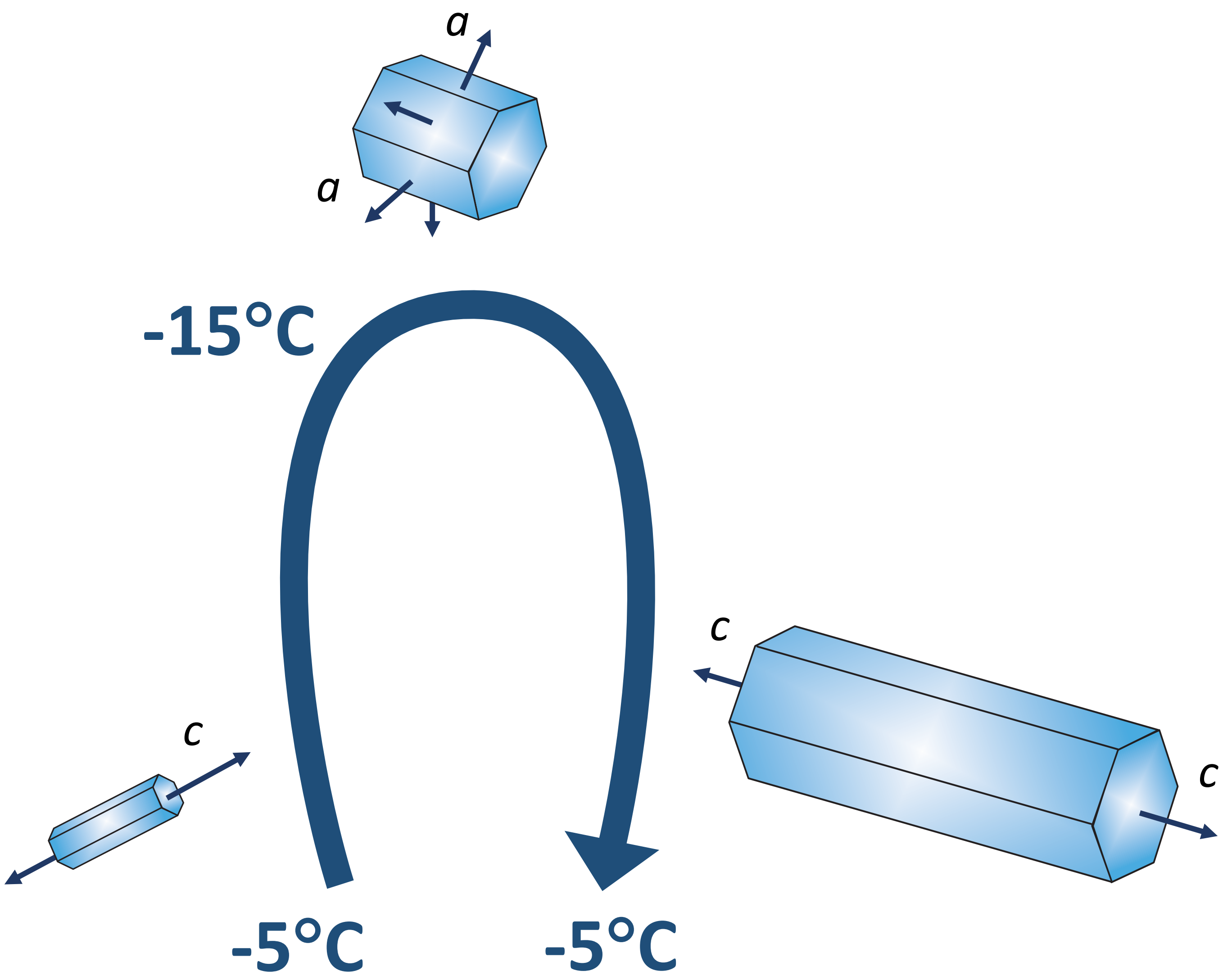
Growth and metamorphosis of ice particle shapes during cycling *T* and *S*

"Simple" cases of ice crystal shapes



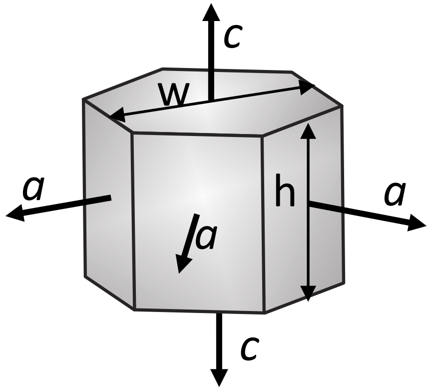
$$\frac{dm}{dt} = FCS_i$$

The adaptive habit prediction approach describes the metamorphosis of ice particles in terms of the growth rates along the *c* and *a* axes, i.e. $\frac{dh}{dt}$ and $\frac{dw}{dt}$ depending on *T* and *S* (Chen & Lamb, 1994)



Metamorphosis of ice particle shapes during cycling *T* and *S*

"Simple" cases of ice crystal shapes



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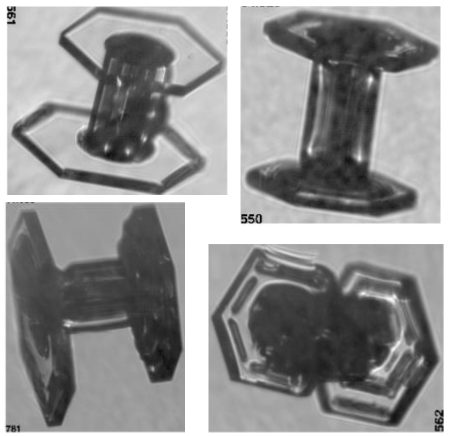
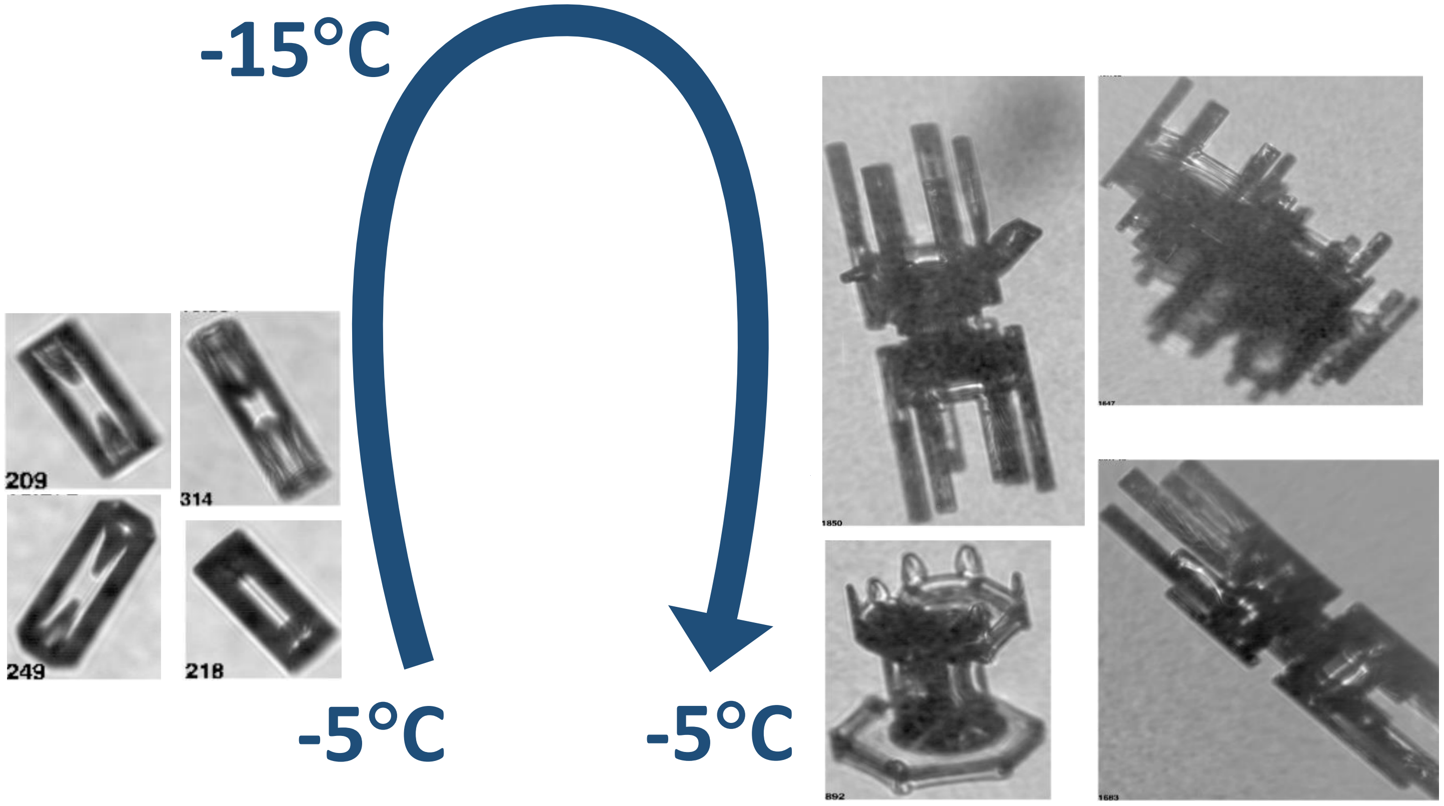


Metamorphosis of natural ice particles does not follow the adaptive habit approach



Workshop on laboratory facilities for cloud research, Beijing, 22 September 2021

Effect of the ice metamorphosis on the growth rate

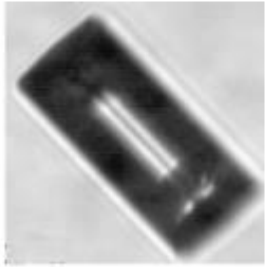
Numerous laboratory studies of ice growth were conducted in 1950s-80s (overview Pruppacher and Klett, 1997).

All lab studies were performed for steady-state conditions (*T*=const, *RH*=const) for basic ice crystal shapes (i.e. hexagonal plates, columns, dendrites).

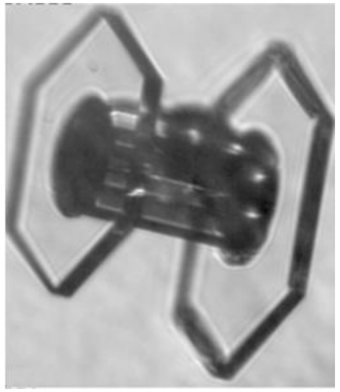
Summary work of Fukuta and Takahashi (1999) showed that isometric crystals follow Maxwellian growth $m \propto t^{\frac{3}{2}}$
However, for non-isometric particles the mass growth may be higher than $m \propto t^{1.9}$.

No lab studies have been done for changing *T* and *S* (exception: Bailey et al. AMS conf., 2002).

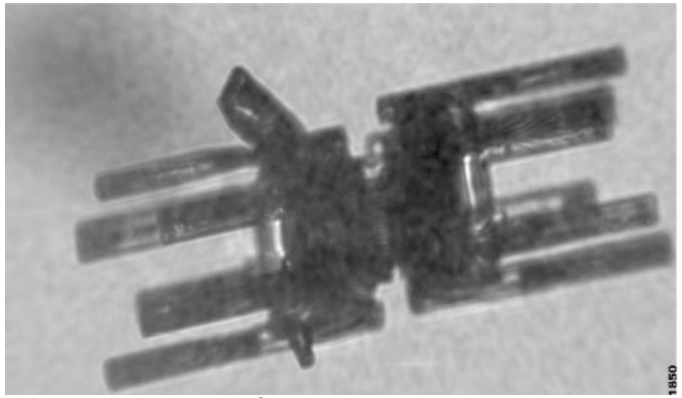
Specific case: How to describe $\frac{dm}{dt}$ of capped columns and X-crystals during cycling T and S?



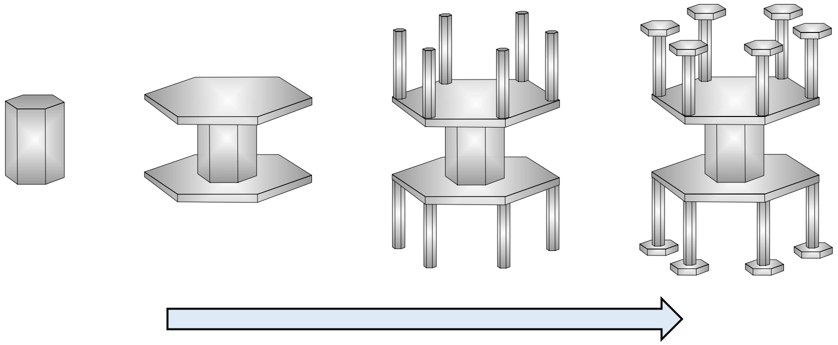
monocrystal



monocrystal



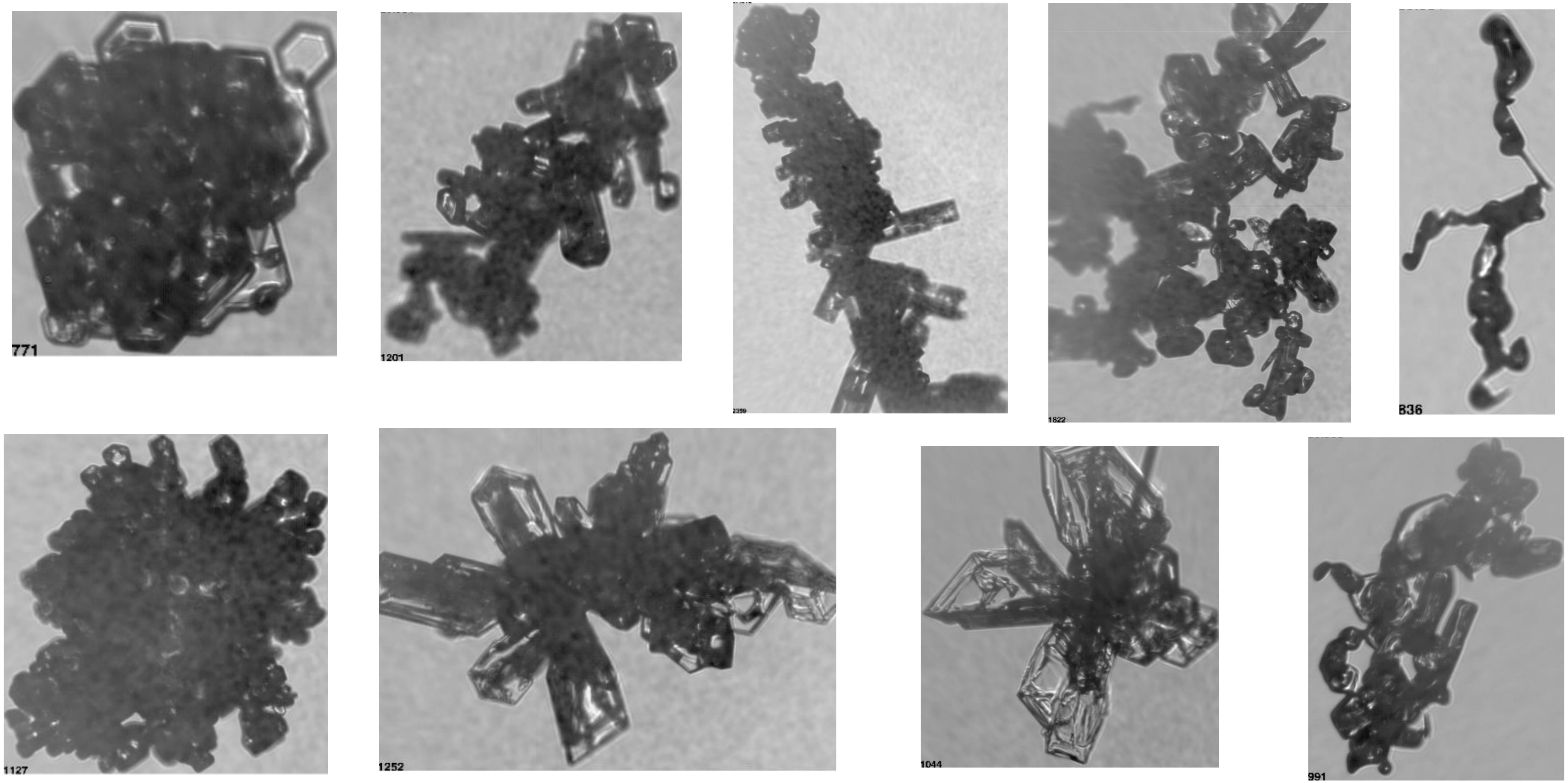
monocrystal



Growth progression

How to describe the diffusional growth of ice particles with intricate shapes?

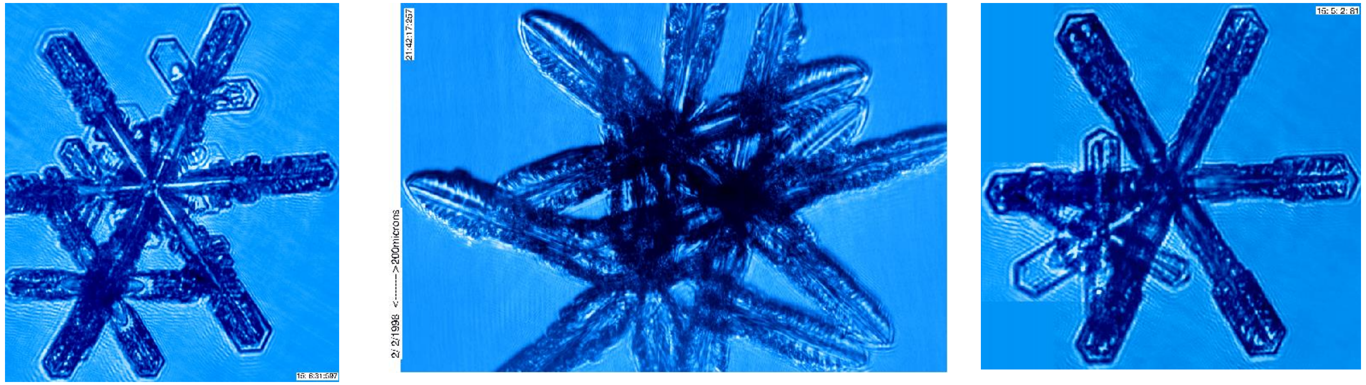
"Complex" shapes of ice particles ("typical" ice shapes)



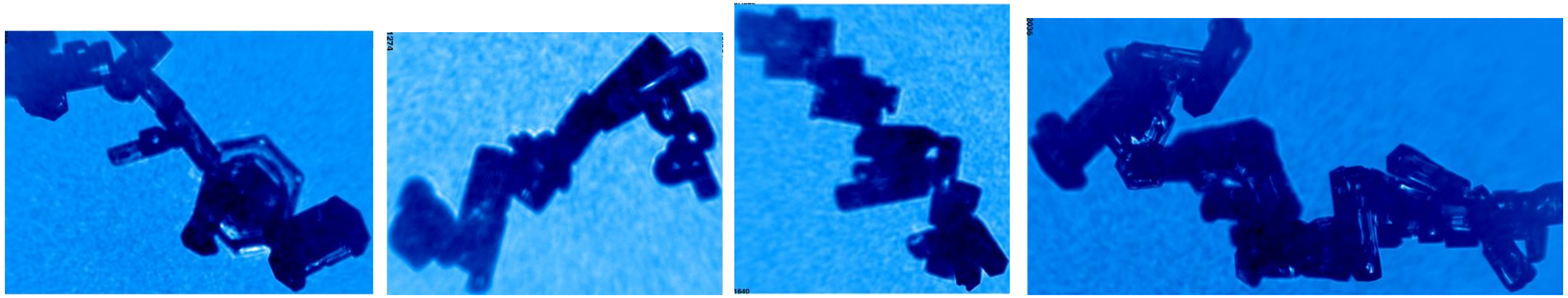
Recognized mechanisms of aggregation of ice particles

Adhesive quasi-liquid layer
on ice surface

Mechanical interlocking
of ice particles with spatially
developed shapes



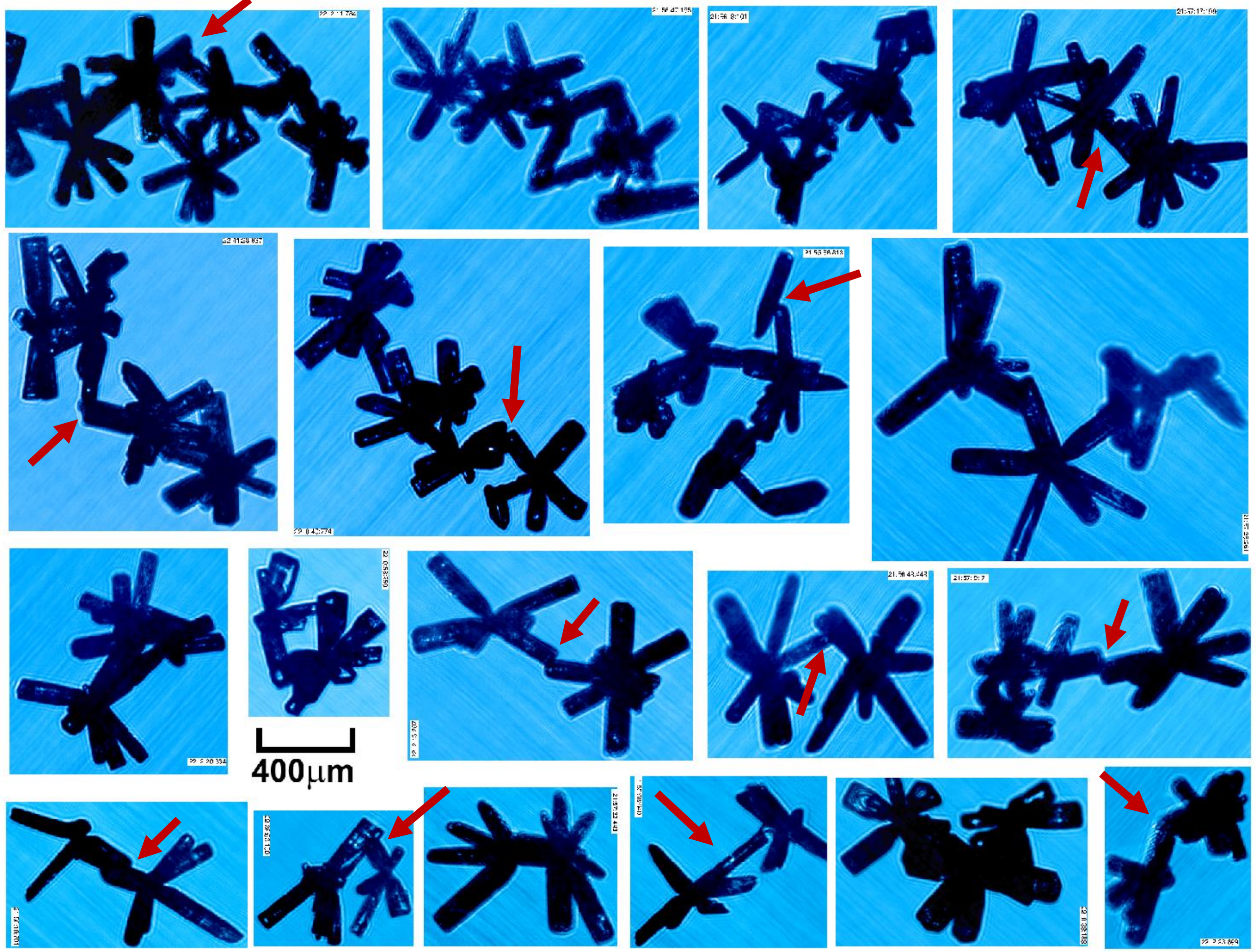
Electrostatic aggregation



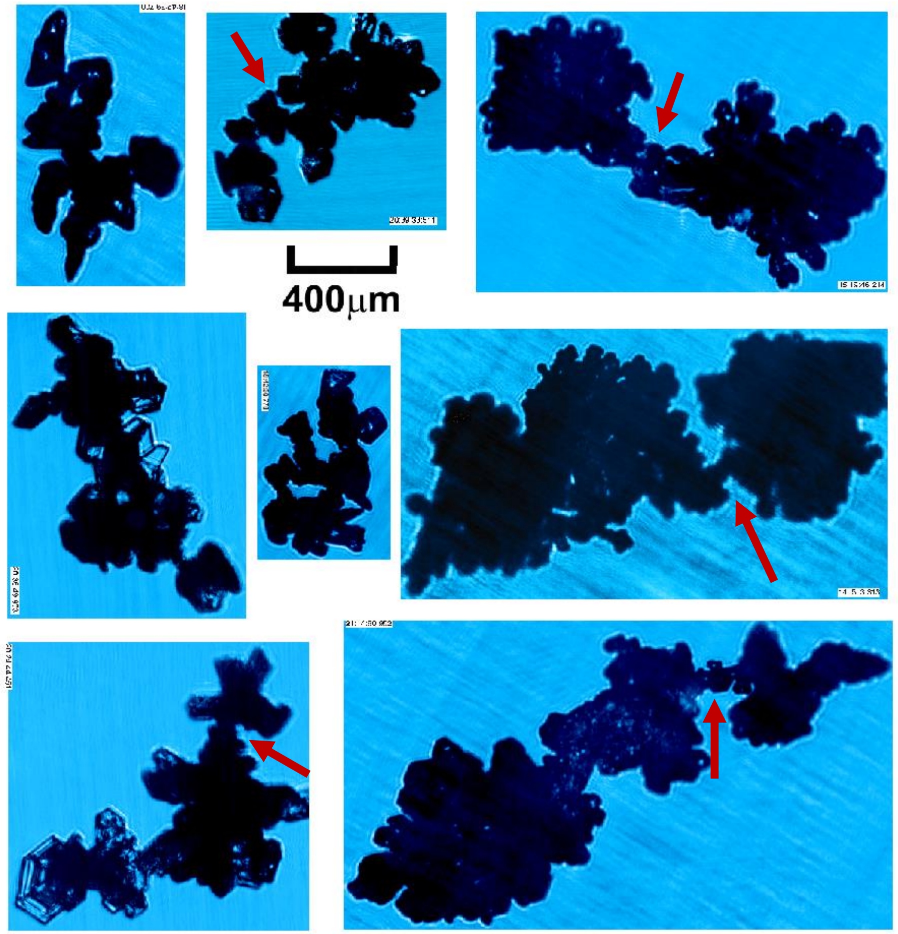
Saunders et al. 1975 (lab.)
Connolly et al. 2005 (observ.)
Stith et al. 2014 (observ.)
and others….

Linear aggregates

Inuvik, Canadian **Arctic**, Ci, T=-40C; FIRE-ACE, 1998



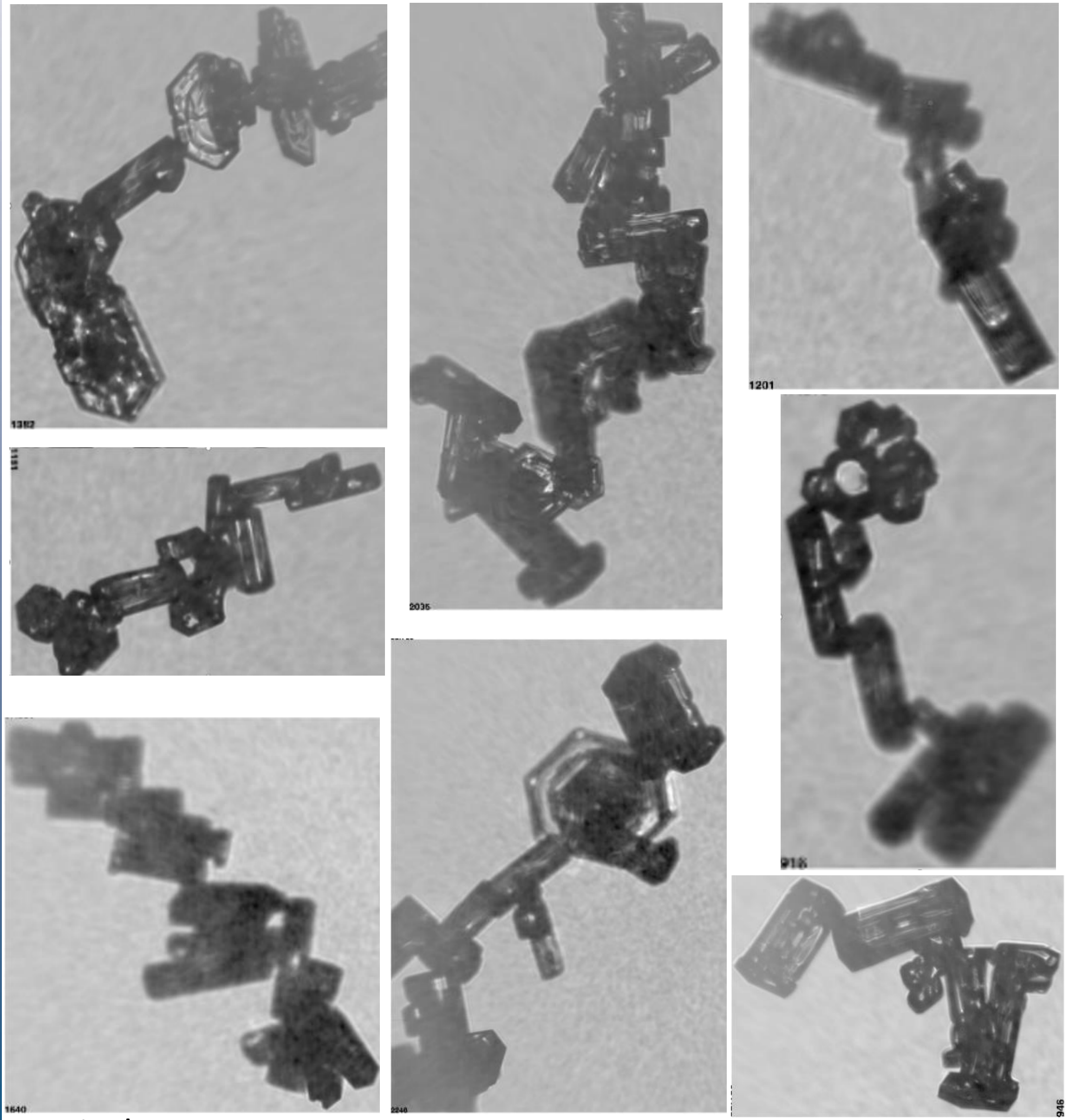
Ottawa, frontal Ns, AIRS, 13-Nov-2003



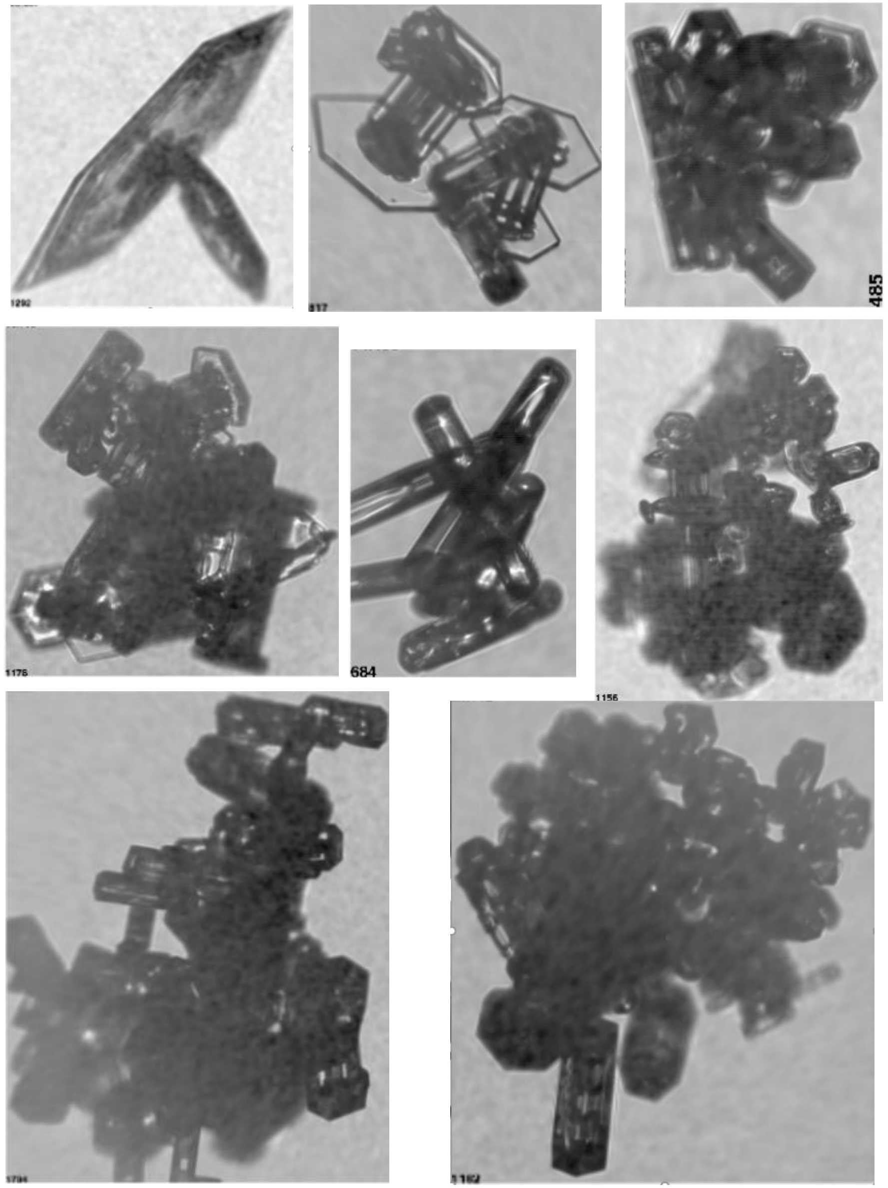
No clear evidence of mechanical interlocking and no QLL at -40C.
In many cases, ice crystals have a singular point of connection.
What is the source of the electric field in Arctic?

Two types of aggregates

Linear alignment

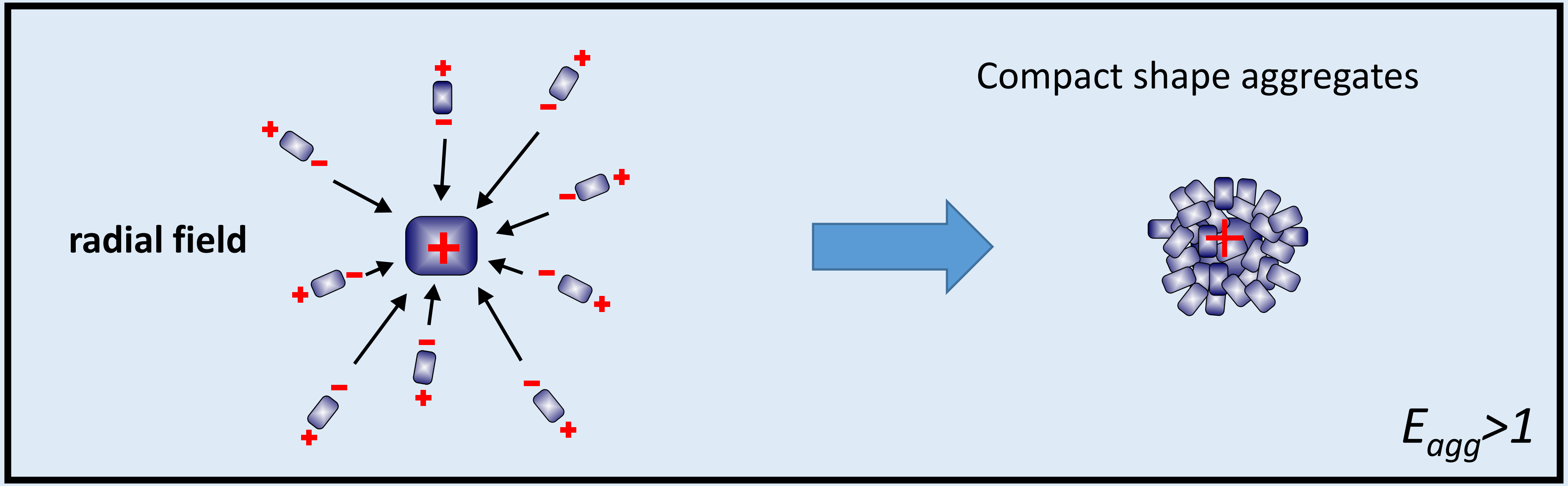


Compact shape

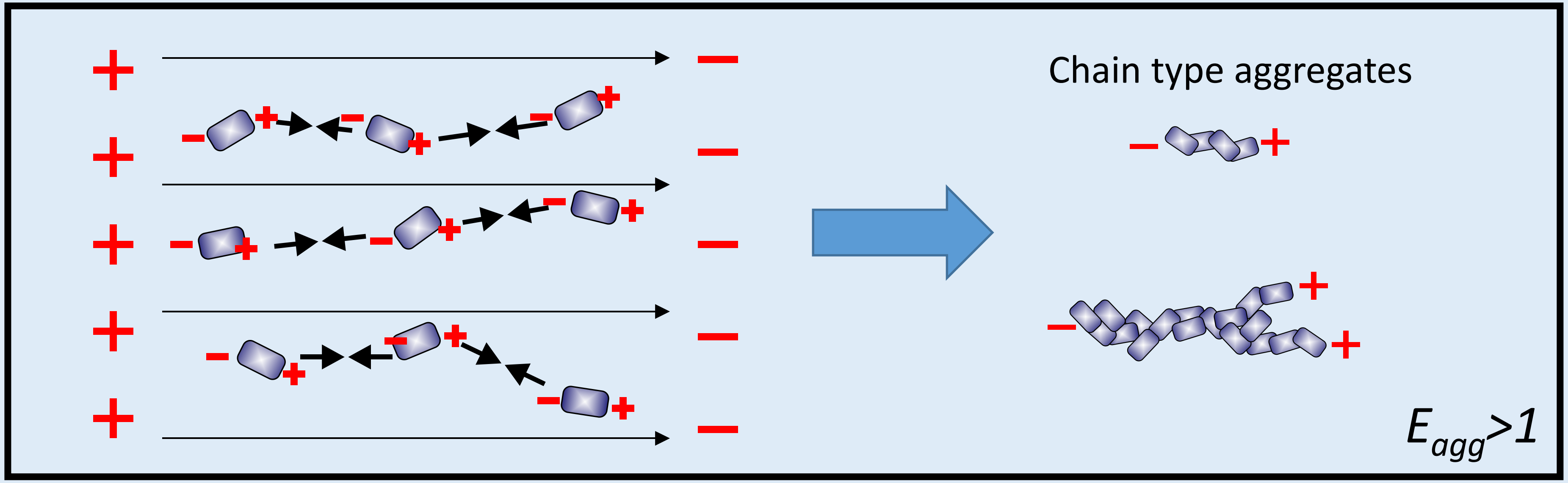


Tropical MCS

Expected shapes of ice aggregates



Local electric field



Large scale electric field

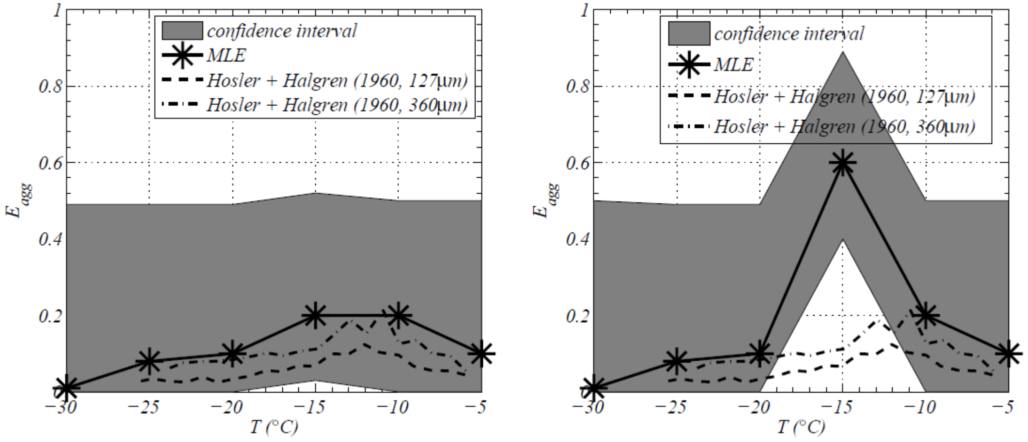
Korolev et al. (SAE, 2015)

Aggregation of ice particles

Lab studies of aggregation:

1. Hosler and Hallgren (1960); Hallgren and Hosler (1960)
2. Connolly et al. (2012)

-30C<T<-5C; 7μm<D<400μm



Connolly et al. 2012

In-situ studies of aggregation:

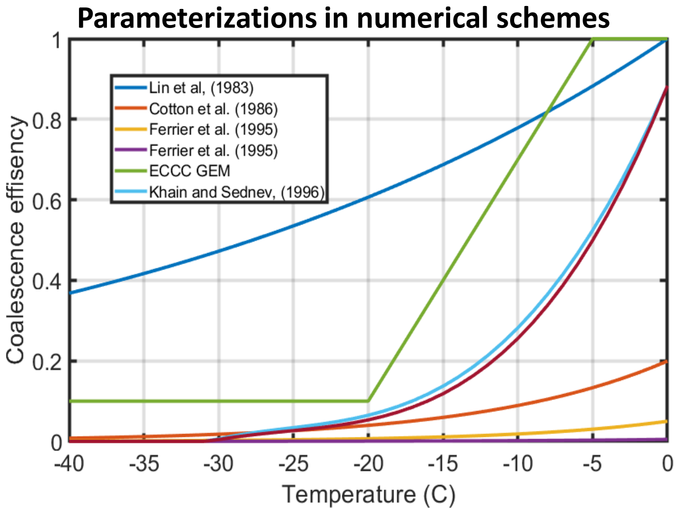
Numerous studies (e.g. Mitchel, 1996; Field et al. 2003, 2006; and many others)

Caveats: no history of ice particles, vertical sorting, recognition of aggr. etc.

Single variable parameterization $E_{agg}(T)$

Parameterizations:

Large variety of different parameterizations of aggregation efficiency $E_{agg}(T)$ are employed in cloud models and NWPs (overview in Khain and Pinsky, 2018).

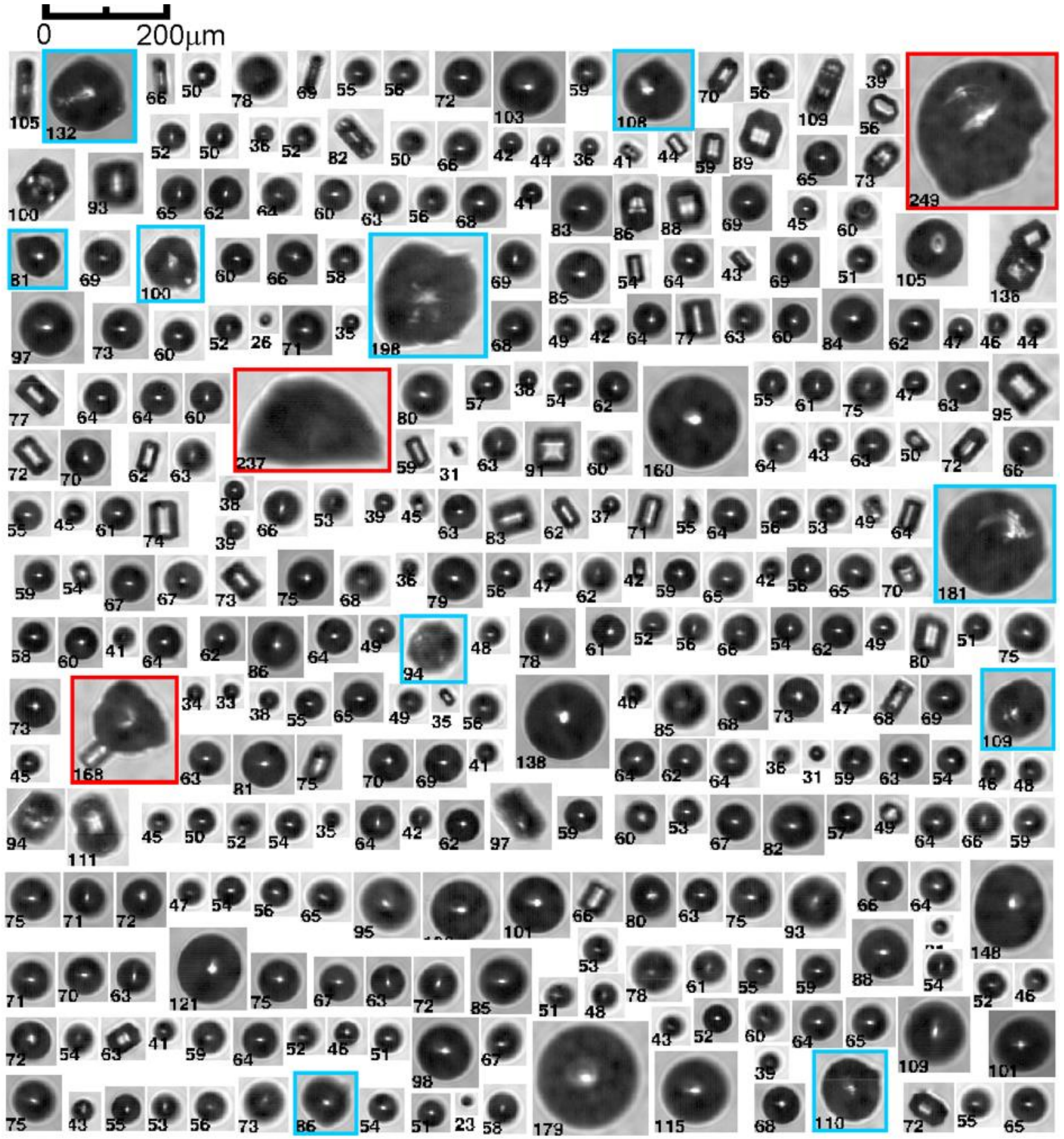


Effects of (a) particle shape, (b) particle size, (c) particle charge, (d) particle surface properties (e.g. liquid layer, surface roughness), (e) electric field, (f) humidity, (g) temperature on the ***sticking efficiency*** of ice crystals remain poorly understood or unexplored.

Secondary Ice Production

Secondary ice production is one of the fundamental cloud processes.

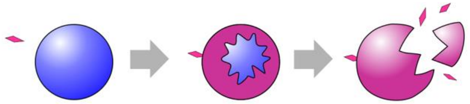
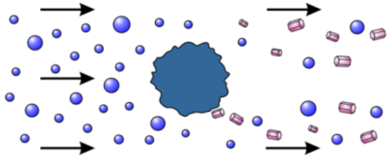
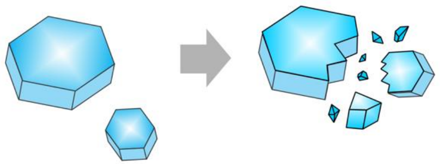
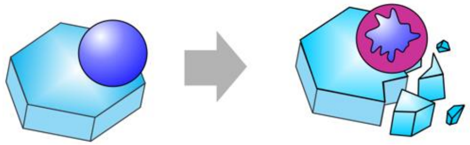
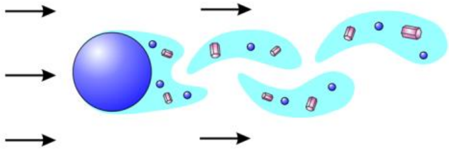
Along with the primary nucleation secondary ice production is one of the major sources of ice in clouds.



An example of explosive concentration of secondary ice particles at -5C in tropical MCS.

Korolev et al., 2020

Status of SIP laboratory studies

	description	mechanism	# Lab works	Lab studies quantification	# years	simulations
1		Droplet fragmentation during freezing	35	work-in-progress (ongoing)	69	early stage
2		Splintering during riming (HM process)	22	work-in-progress (ongoing)	61	yes physical mechanism is under debate
3		Fragmentation during ice-ice collision	2	work-in-progress (deeply hibernated)	49	early stage
4		Ice fragmentation during thermal shock	3	not attempted	53	no
5		Fragmentation during sublimation	9	work-in-progress (deeply hibernated)	47	early stage
6		Activation of INPs in transient supersaturation	5	not attempted	49	no

Other SIP mechanisms?

Korolev and Leisner, 2020

List of the key problems in cloud microphysics

1. Droplet spectra broadening
2. Collision-coalescence of small droplets ($D<40\mu m$)
3. Coalescence coefficients of droplets
4. Collective growth of droplets
5. Collective growth of ice
6. Collective growth of cloud particles in mixed phase
7. Aggregation of ice, sticking efficiency
8. Necessary and sufficient conditions for secondary ice productions (6 mechanisms)
9. Entrainment and mixing
10. Mechanisms of charge separation and electrification of clouds
11. Effects of the global and local electric fields on cloud microphysics
12. …

Way forward

Laboratory studies provide the only practical means of quantifying the rates of individual microphysical processes under controlled conditions.

Stage 1

a) Critical assessment and review of the past lab experiments of cloud processes.
b) Identification of weakness, gaps, missing points in each lab experiment.
c) Identification of the parameters the cloud process may depend on.
d) Workshops summarizing the status of knowledge, review papers (inventory of problems in cloud physics).

Stage 2

a) Design of a lab experiment and formulation of outcomes.
b) Identification of the suite of monitoring instrumentation.

Stage 3

a) Building laboratory installation.
b) Calibrations/tests of the lab installation.
c) Performing lab experiments.
d) Developing physically based parameterizations (ultimate goal)

Thank you

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