Coupling of CCN and INP in cloud systems important to climate: Uncertainties and implications

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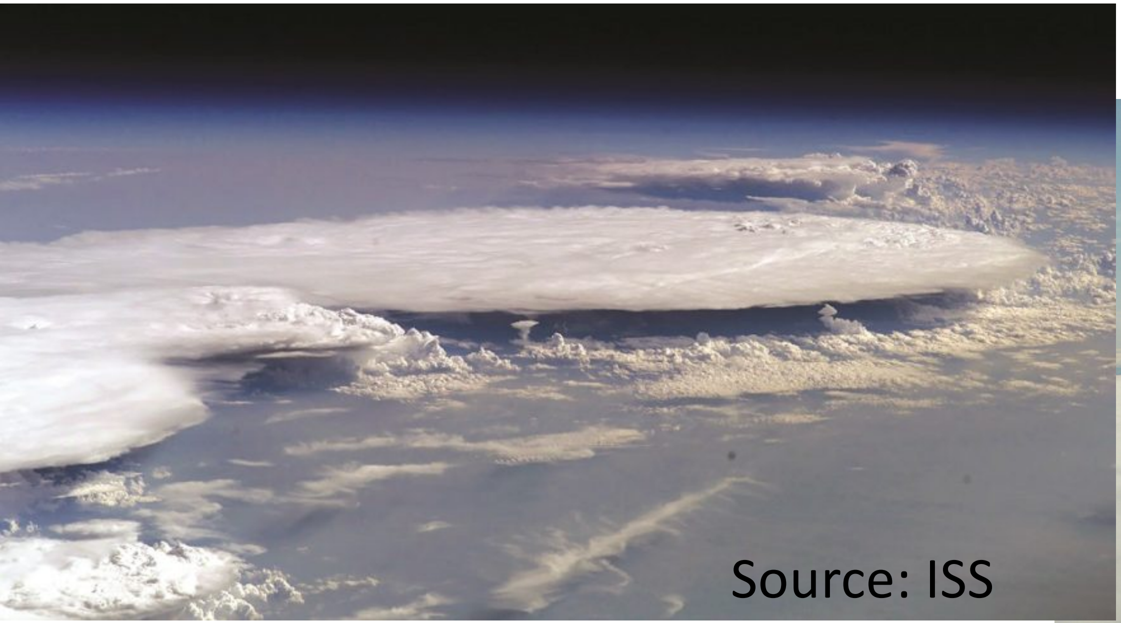
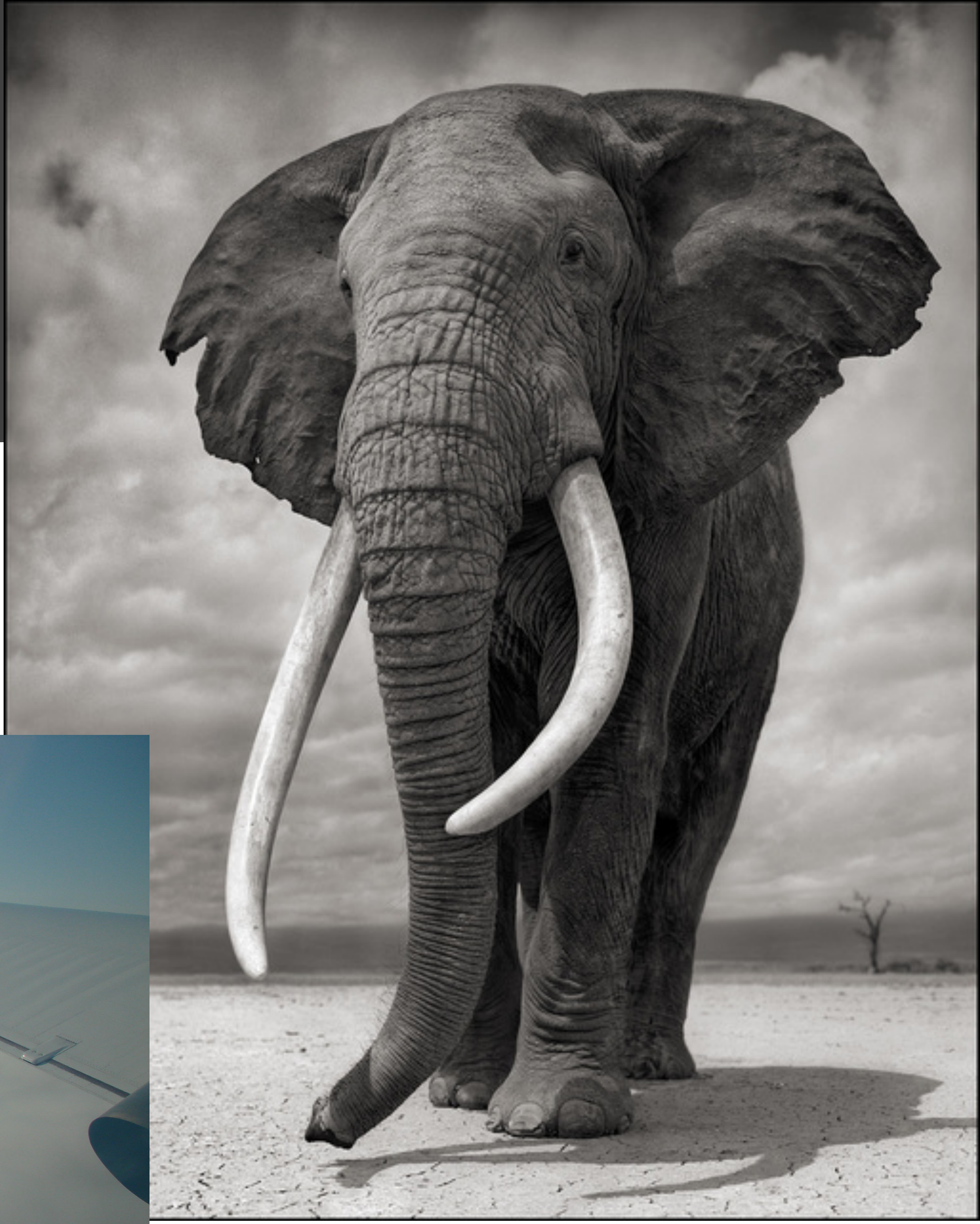

Source: ISS


Source: Walter Strapp



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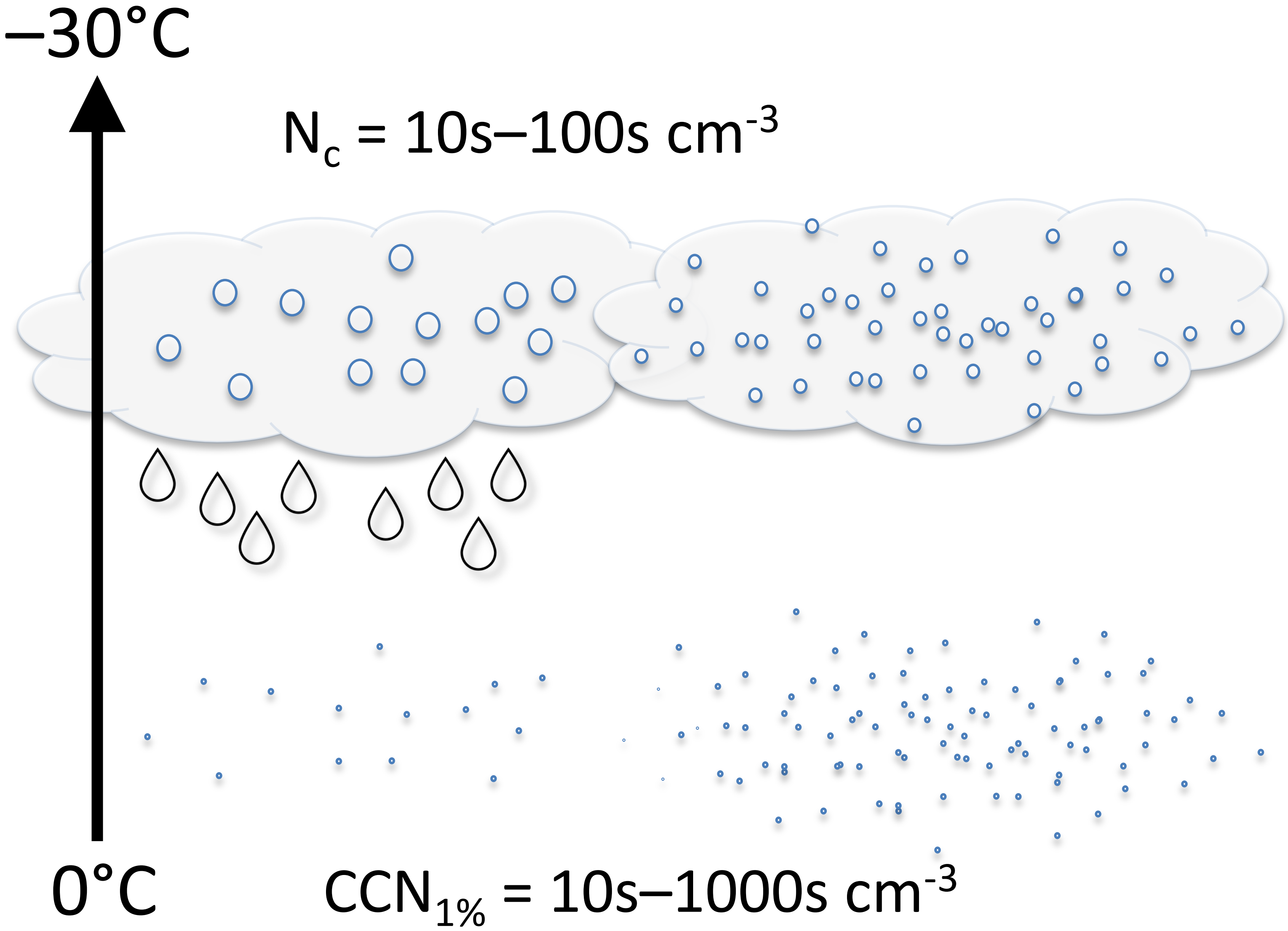
CCN and INP • climate system

- elephants in our living room
  - persistent evidence of efficient ice formation mechanisms that are not represented in most atmospheric models, poorly established [e.g., Koenig and Murray JAM 1976; Field et al. AMS 2017]
  - huge uncertainties in *in situ* measurements (ground truth)
    - ice crystal number concentrations (now ≈2X for D > ≈100 µm)
    - ice-nucleating particle (INP) concentrations (now ≈10X)

A world without INP (usual CCN)

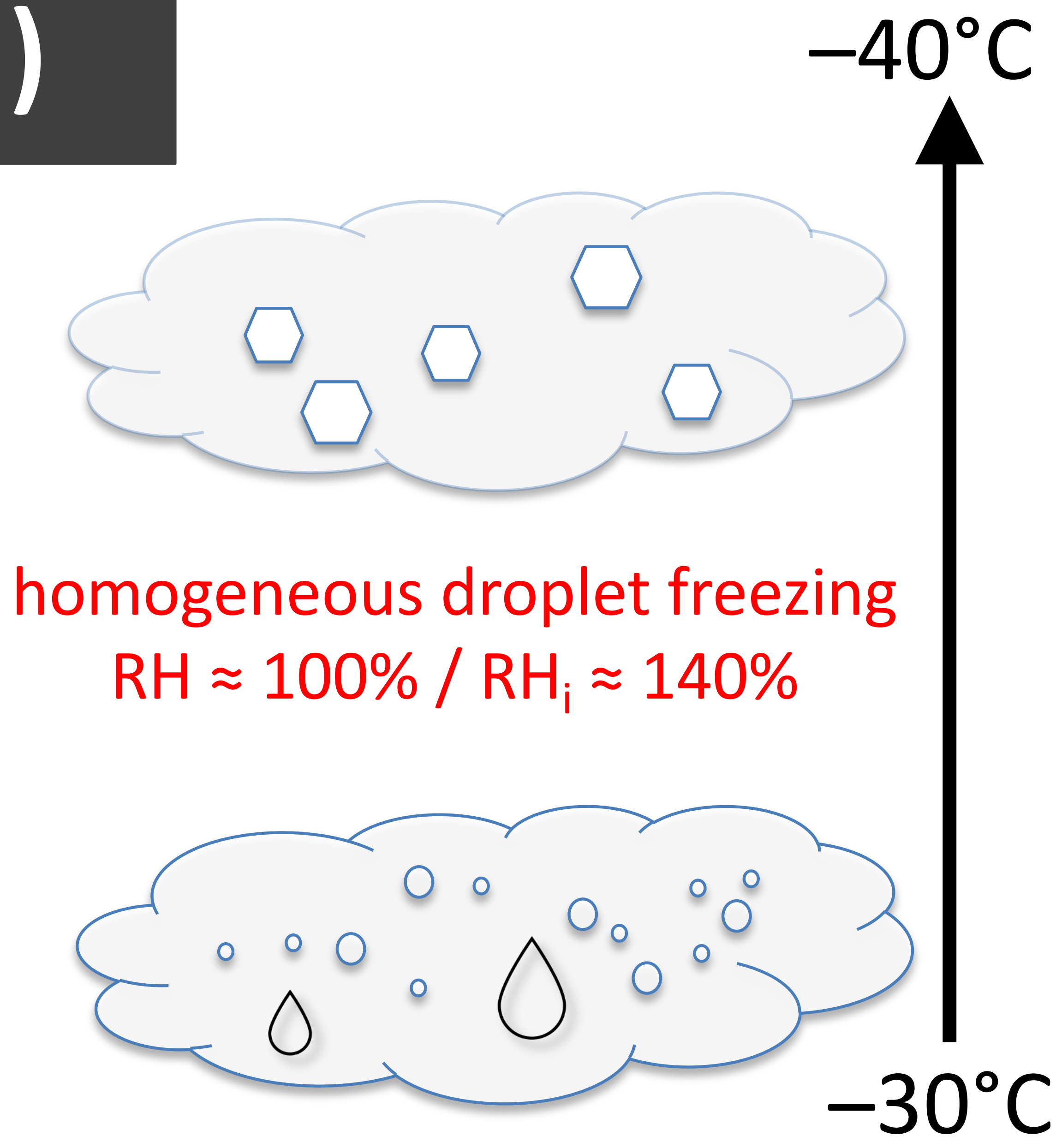


–30°C

N_c = 10s–100s cm^{-3}

0°C

$CCN_{1\%}$ = 10s–1000s cm^{-3}



–40°C

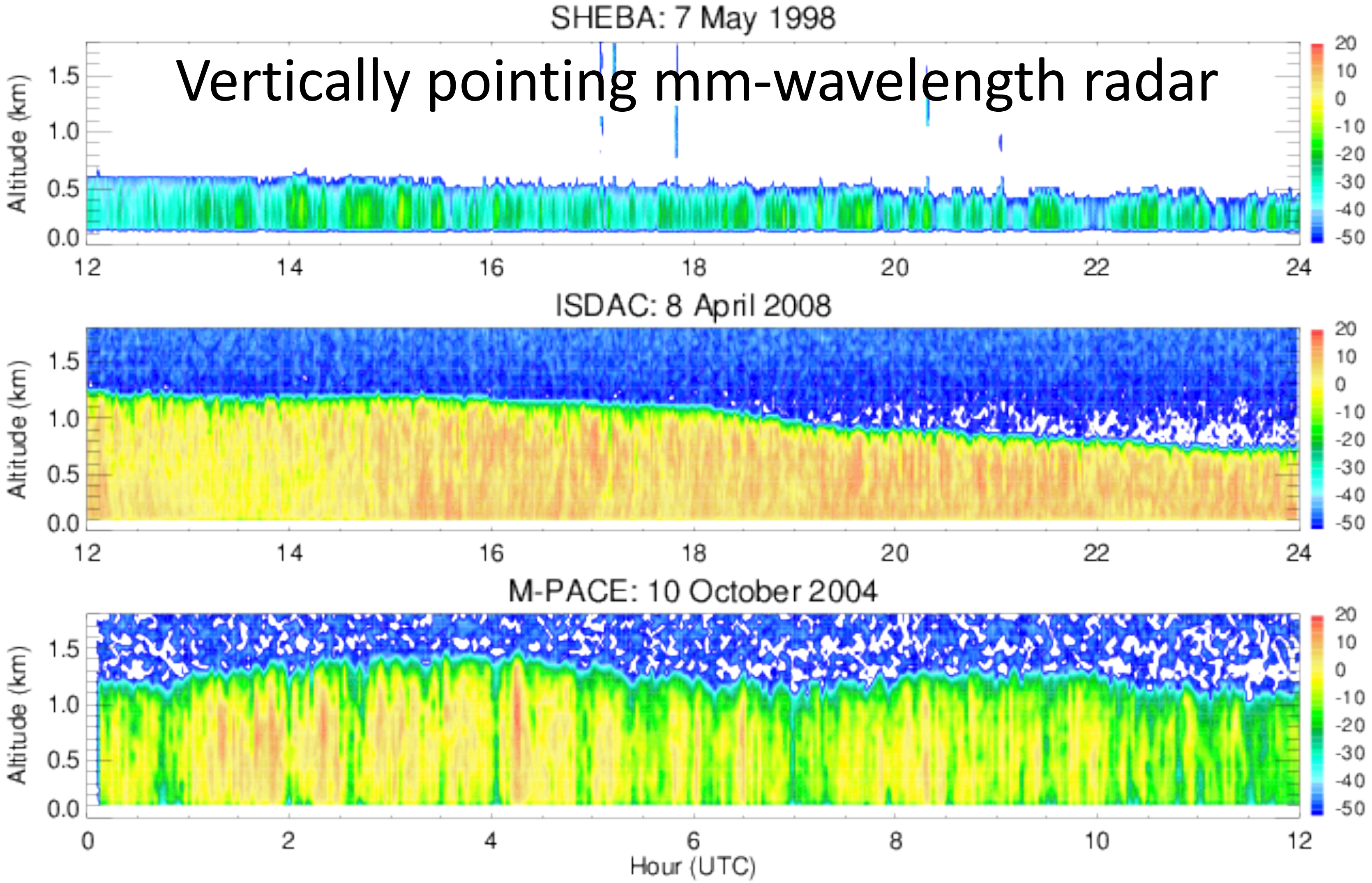
homogeneous droplet freezing

RH ≈ 100% / RH_i ≈ 140%

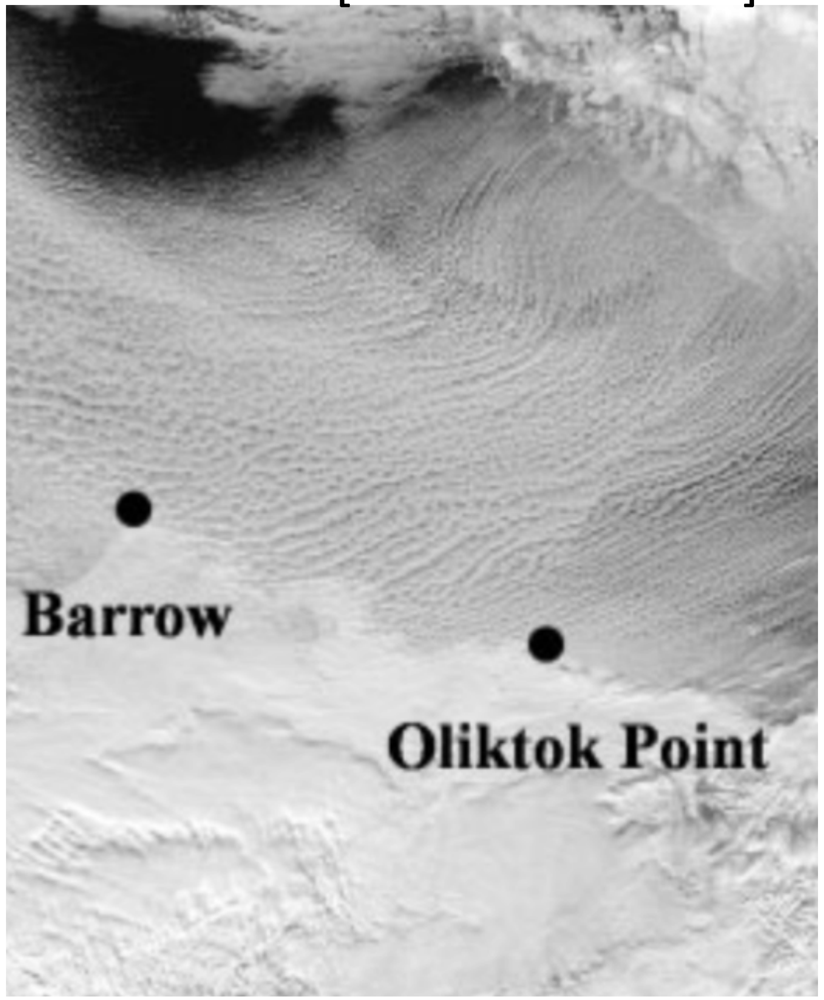
–30°C

–15°C < cloud top temperatures < –20°C

- continuously precipitating ice



M-PACE [Klein et al. 2009]

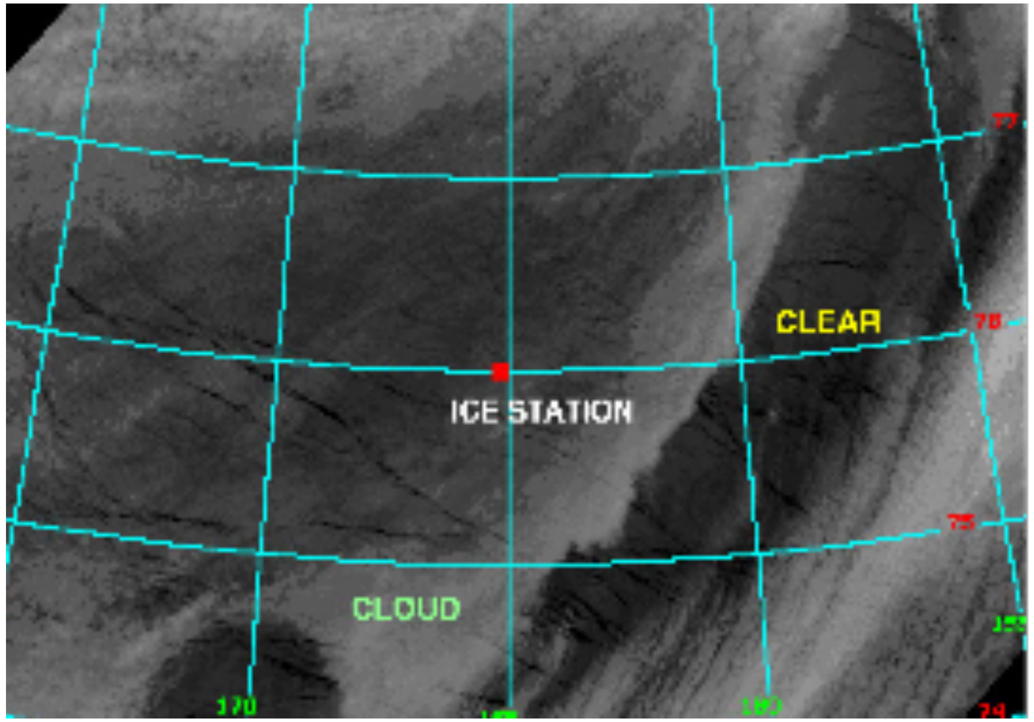


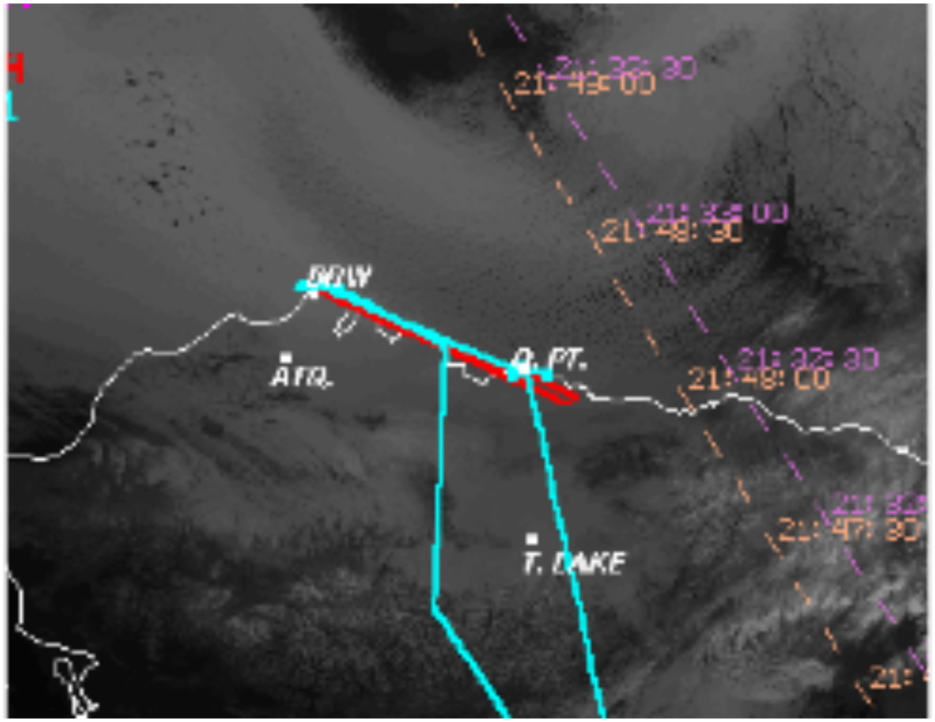
Fridlind and Ackerman [Ch. 7 in *Mixed-Phase Clouds: Observations and Modeling*, Ed. C. Andronache, 2018]

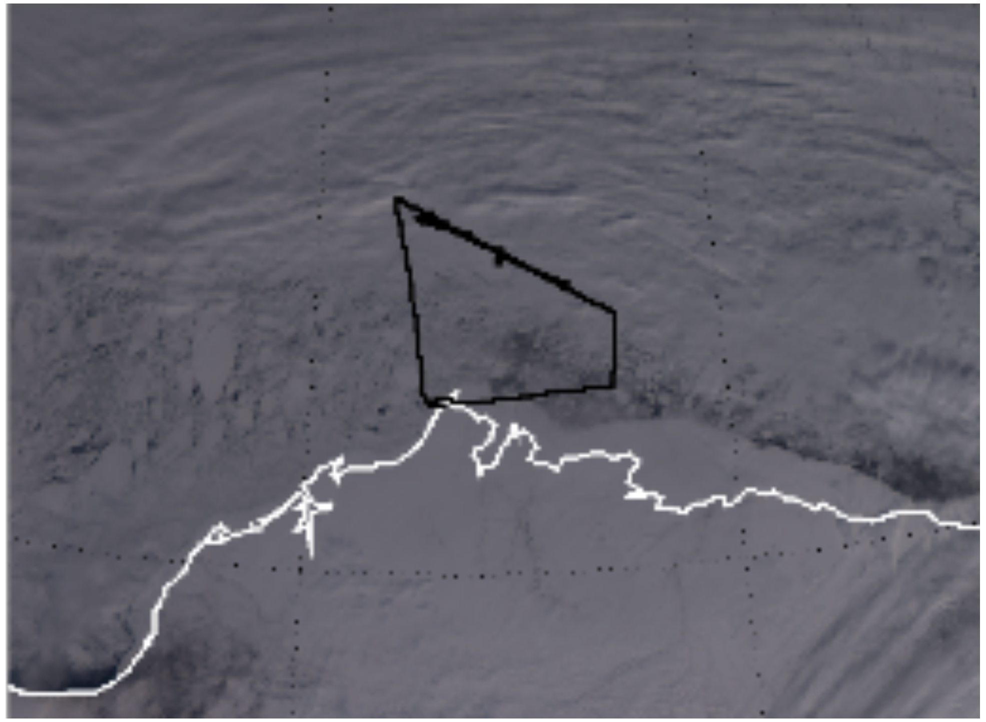
LES model intercomparison studies

~5X uncertainty

Field Campaign	Observation Period (UTC)	Cloud Top Height (m)	Cloud Temp. (C)		Path ($g\ m^{-2}$)		Conc. (cm^{-3})	
			Top	Base	Liquid	Ice	Drops	Ice
SHEBA	7 May 1998	500	−20°	−18°	5–20	0.2–1	200	∼0.0005
M-PACE	9–10 Oct. 2004	1000	−16°	−9°	110–210	8–30	40	∼0.01
ISDAC	26 April 2008	800	−15°	−11°	10–40	2–6	200	∼0.001

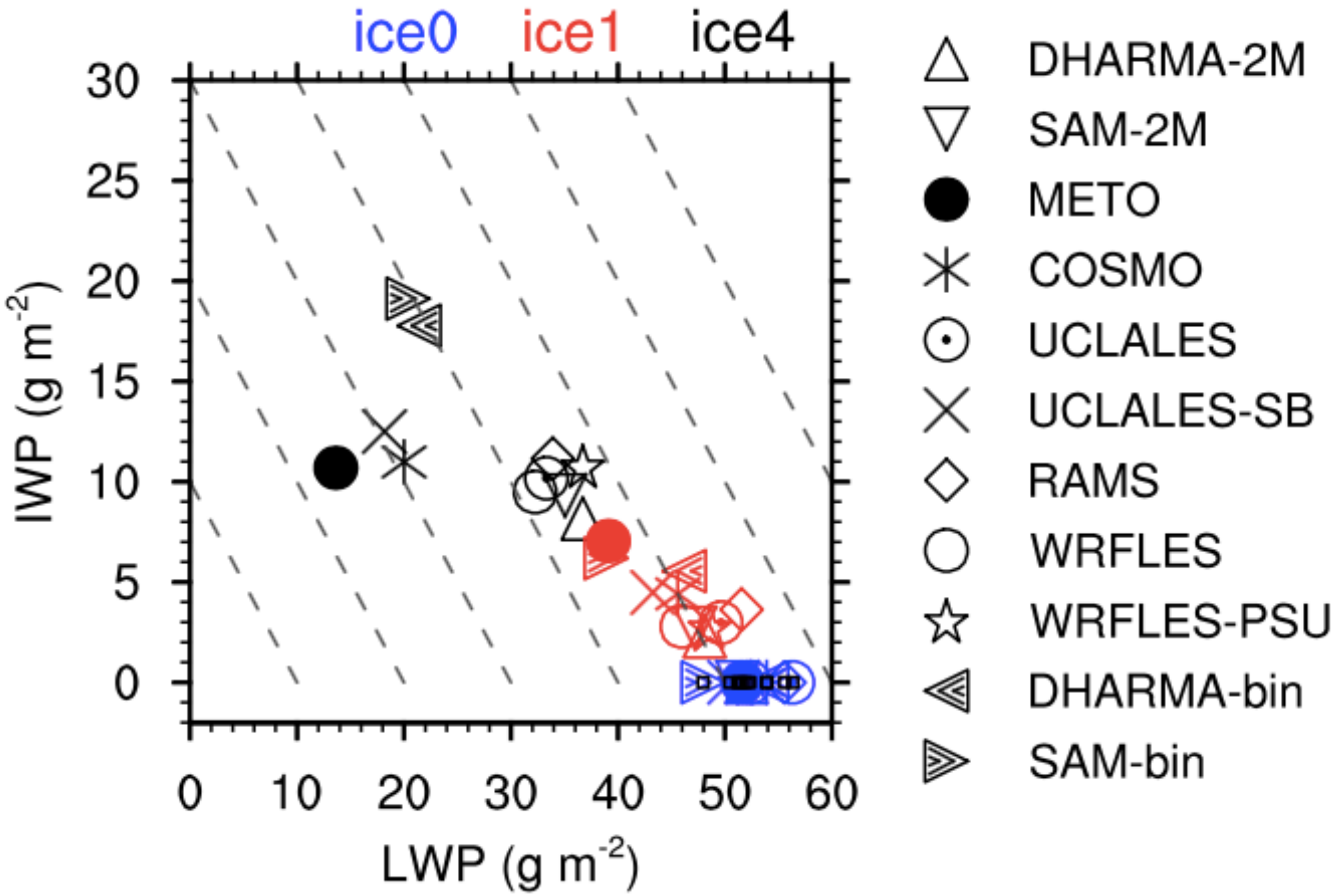






Fridlind and Ackerman [Ch. 7 in *Mixed-Phase Clouds: Observations and Modeling*, Ed. C. Andronache, 2018]

ISDAC intercomparison

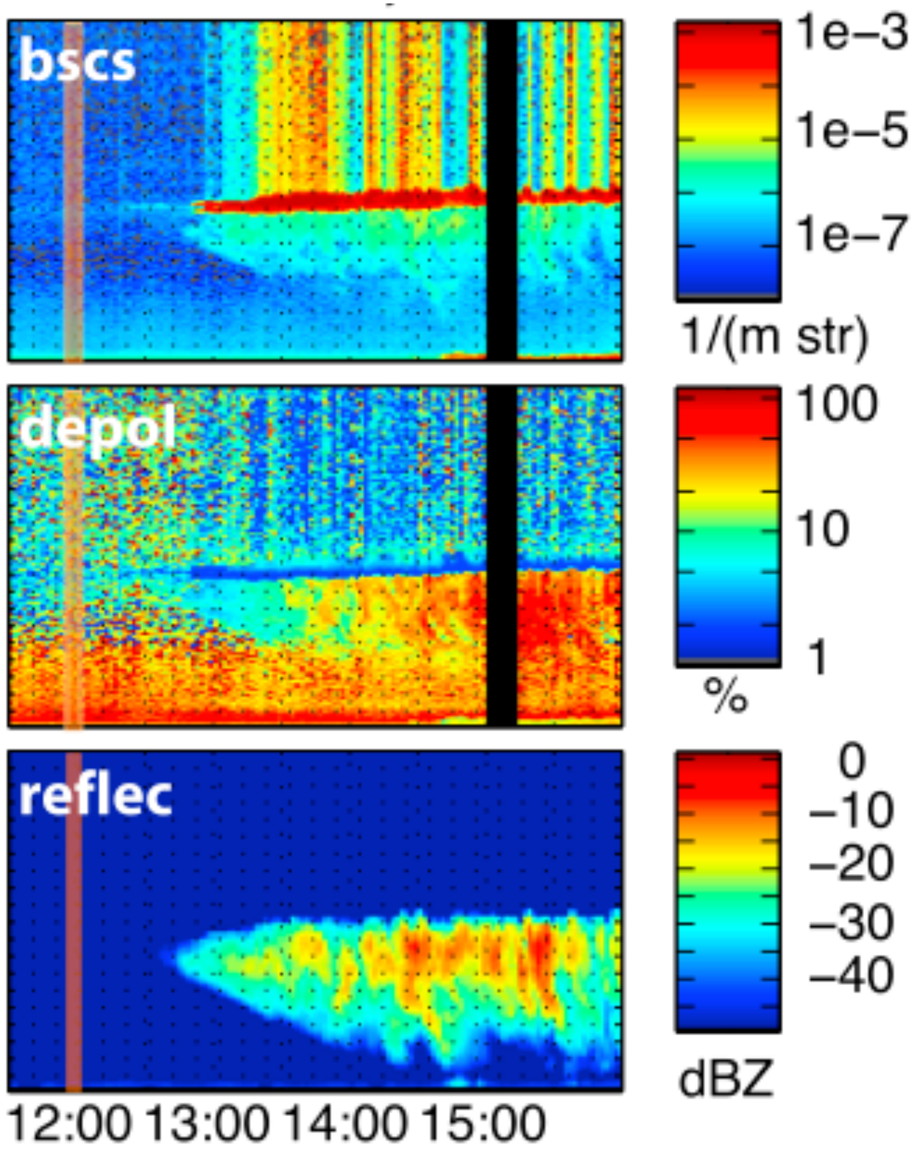


Ovchinnikov et al. [2014]

~~persistence~~
~~remarkable?~~

- when N_i and ice properties are specified, large-eddy simulation models perform well
- but what maintains N_i?

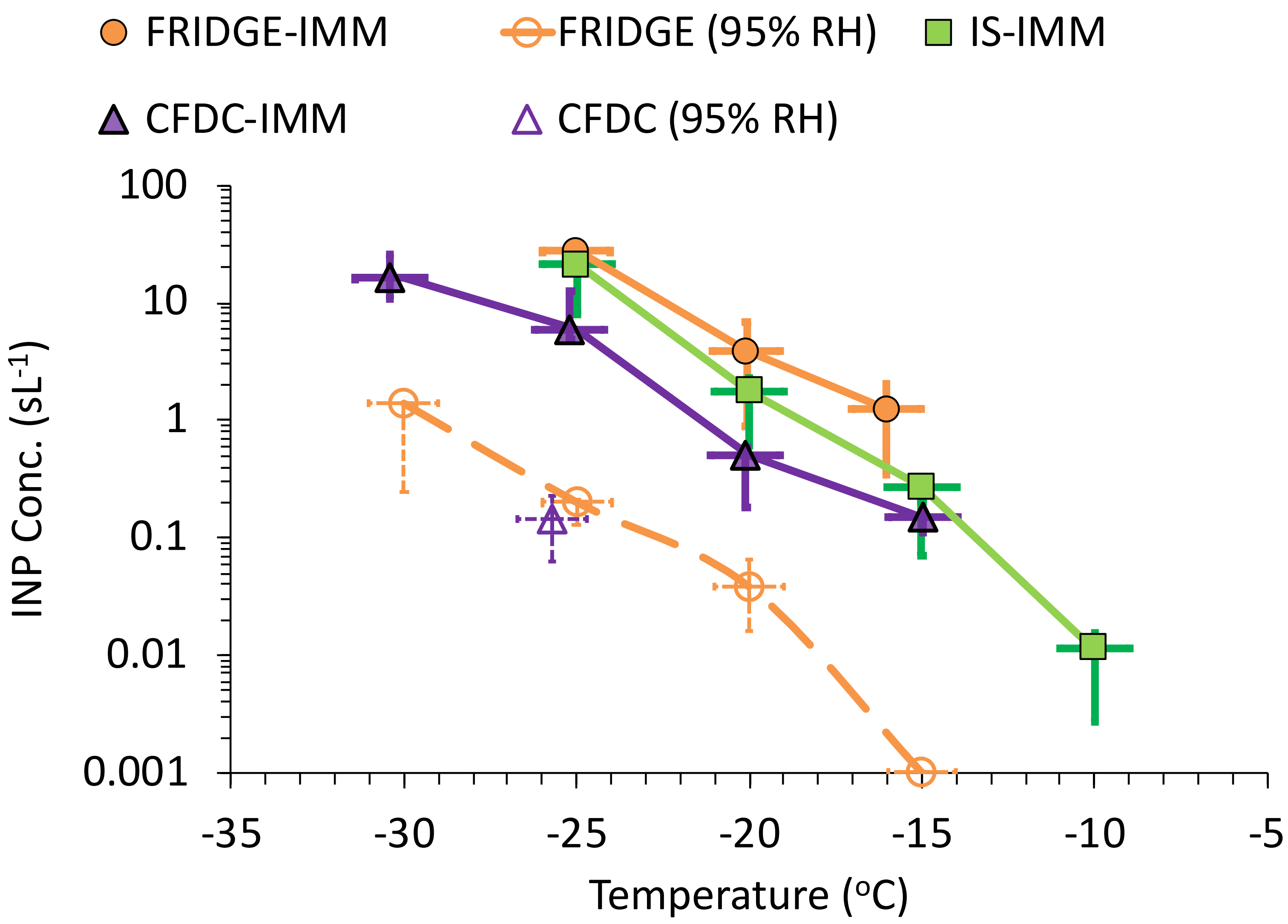
Primary ice formation follows drop formation



liquid cloud (lidar)

ice precip (radar)

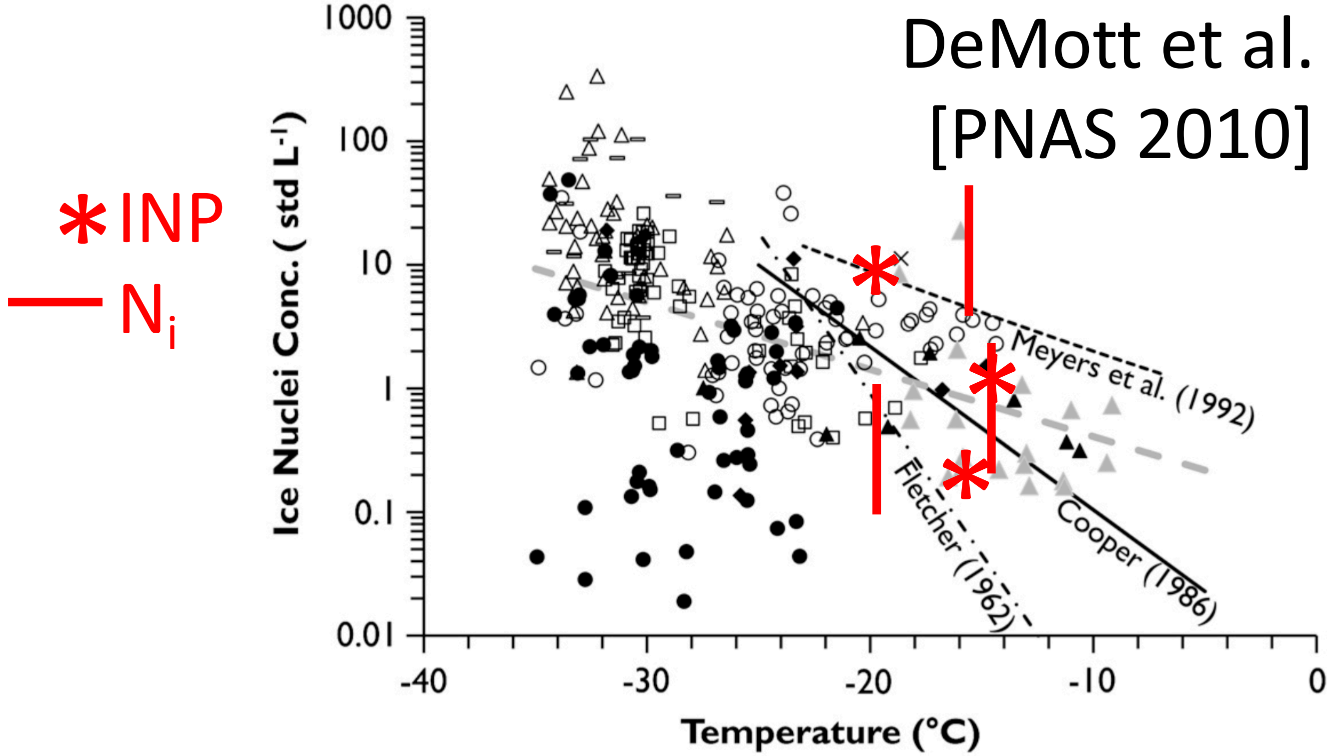
de Boer et al. [2011]



Courtesy of Paul DeMott and FIN-03 team

Primary ice nucleation

- contact too slow [Fridlind et al. 2007]
- immersion INP = dominant path for primary ice formation



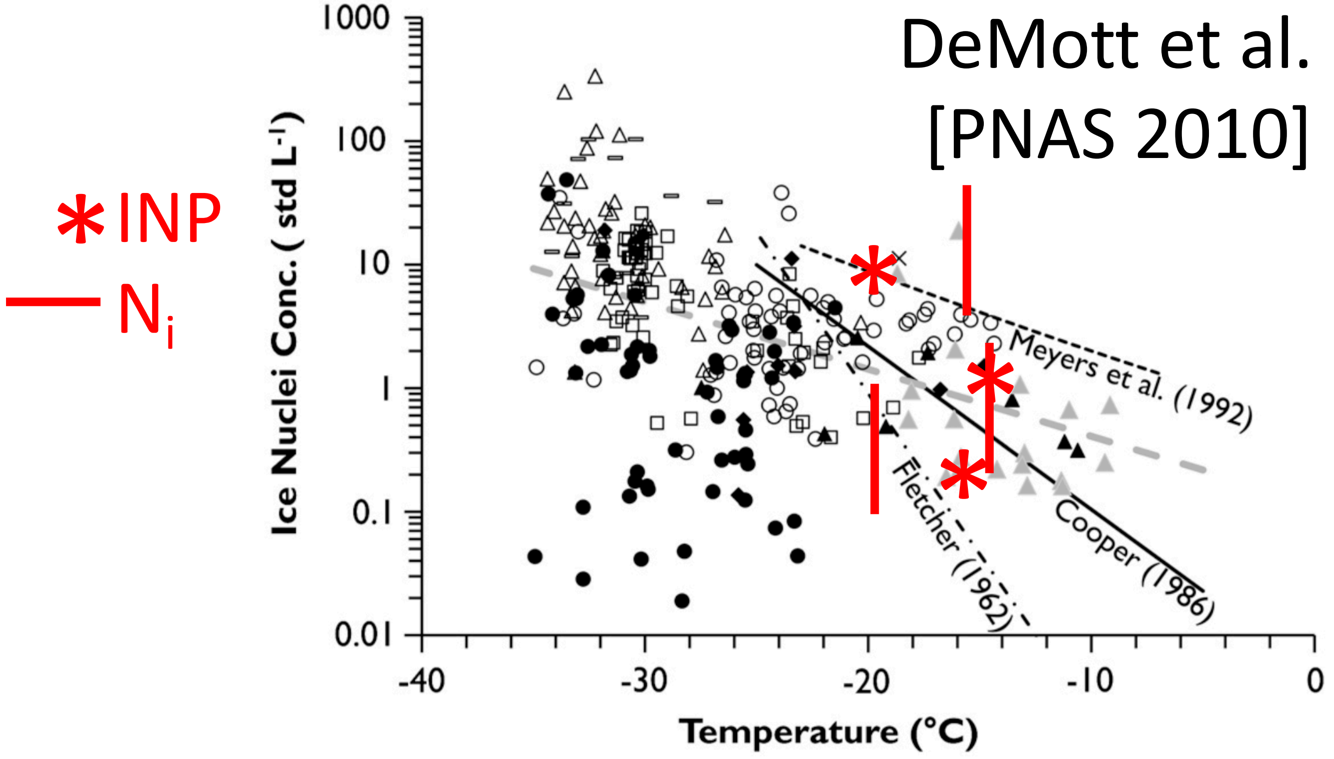
DeMott et al. [PNAS 2010]

Mechanism	T, °C	S[a]	Dependence[b]	Description[c]
			Heterogeneous Nucleation	
Contact mode	−4 to −14	–	$f_{lin}(T)$	drop + $\mathrm{IN}_{aerosol}$ → ice crystal
Condensation mode	−8 to −22	$S_w > 0$	$f_{lin}(T)$	vapor + $\mathrm{IN}_{aerosol}$ → ice crystal
Deposition mode	<−10	$S_i > 0$	$f_{exp}(S_i)$	vapor + $\mathrm{IN}_{aerosol}$ → ice crystal
Immersion mode	−10 to −24	–	$f_{lin}(T)$	drop + IN_{drop} → ice crystal
			Ice Multiplication	
Rime splintering	−3 to −8[d]	–	$f_{lin}(T)$	one ice crystal per 250 collisions
Drop shattering	<0	–	–	$D_{drop} > 50\ \mu m$, multiplication factor of two
Ice-ice collision	<0	–	–	fragment number based on momentum change

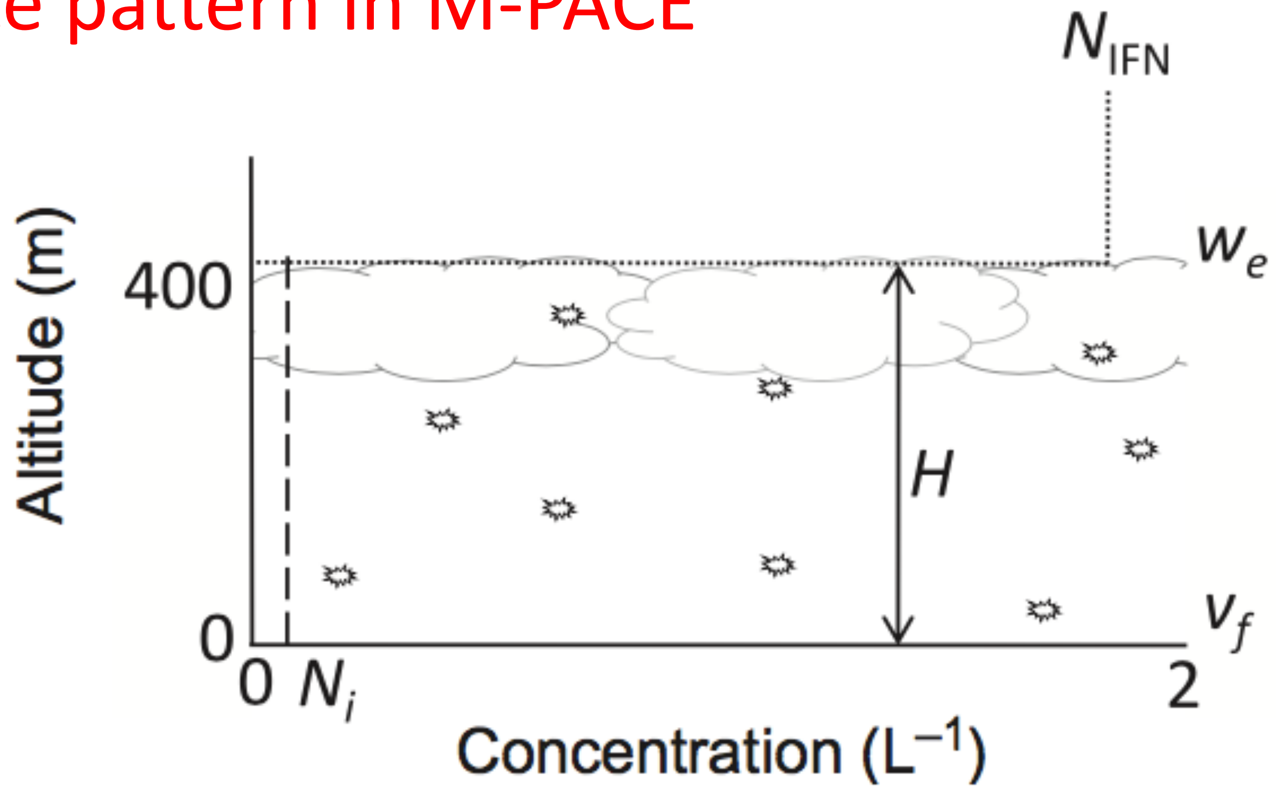
Fridlind et al. [2007, 2012]

INP consumption

- ice crystal lifetime ~ 1 h
- PBL mixing time ~ 1 h
- should expect N_i << INP
- opposite pattern in M-PACE



DeMott et al. [PNAS 2010]



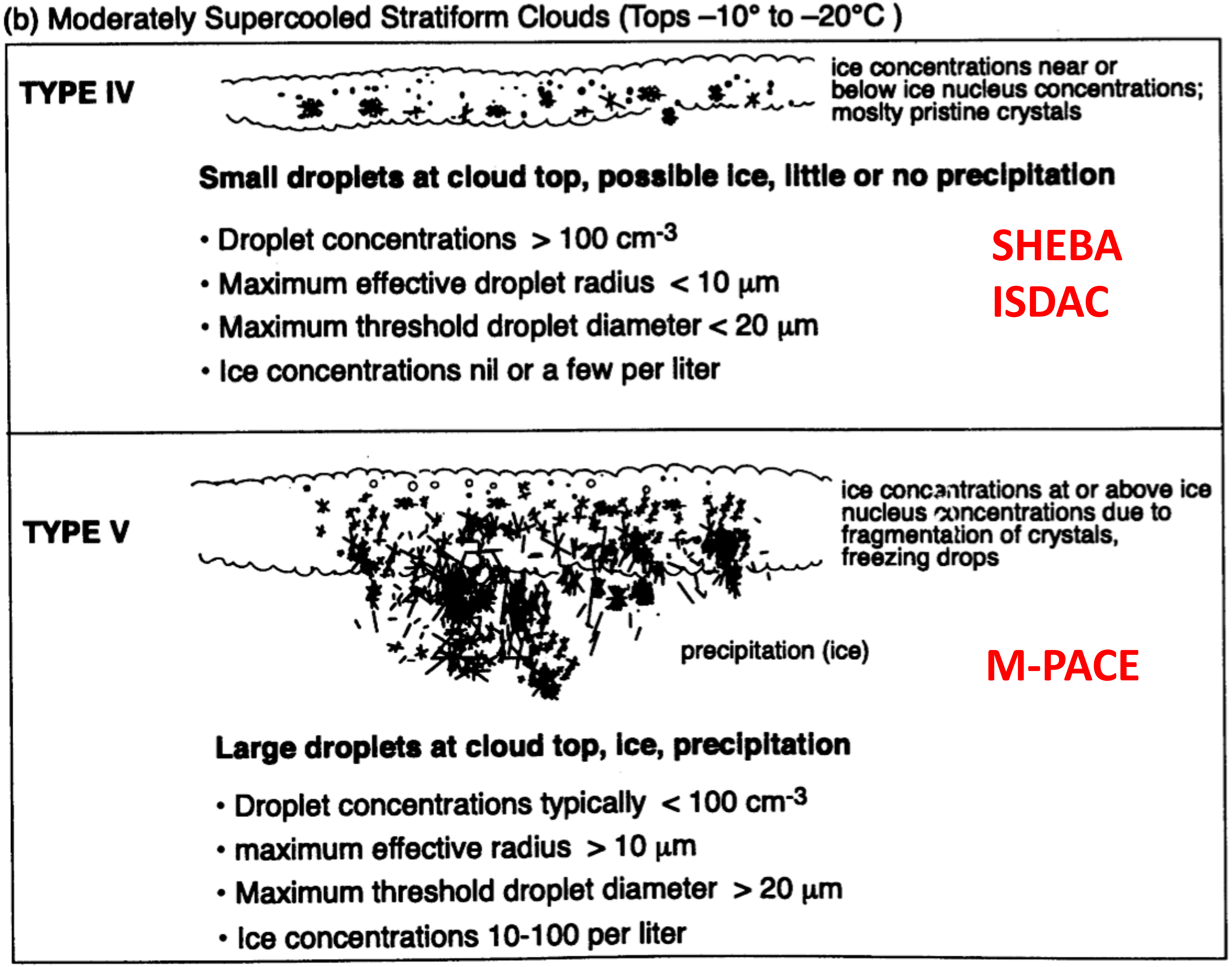
$$H\, dN_i/dt = w_e N_{IFN} - v_f N_i = 0$$

$$N_i/N_{IFN} = w_e/v_f << 1$$

Fridlind and Ackerman [2018], see also Harrington and Olsson [2001]

SHEBA

Rangno and Hobbs
[JGR 2001]



(b) Moderately Supercooled Stratiform Clouds (Tops –10° to –20°C)

TYPE IV

ice concentrations near or below ice nucleus concentrations; moslty pristine crystals

Small droplets at cloud top, possible ice, little or no precipitation

- Droplet concentrations > 100 cm^{-3}
- Maximum effective droplet radius < 10 µm
- Maximum threshold droplet diameter < 20 µm
- Ice concentrations nil or a few per liter

SHEBA
ISDAC

TYPE V

ice concentrations at or above ice nucleus concentrations due to fragmentation of crystals, freezing drops

precipitation (ice)

M-PACE

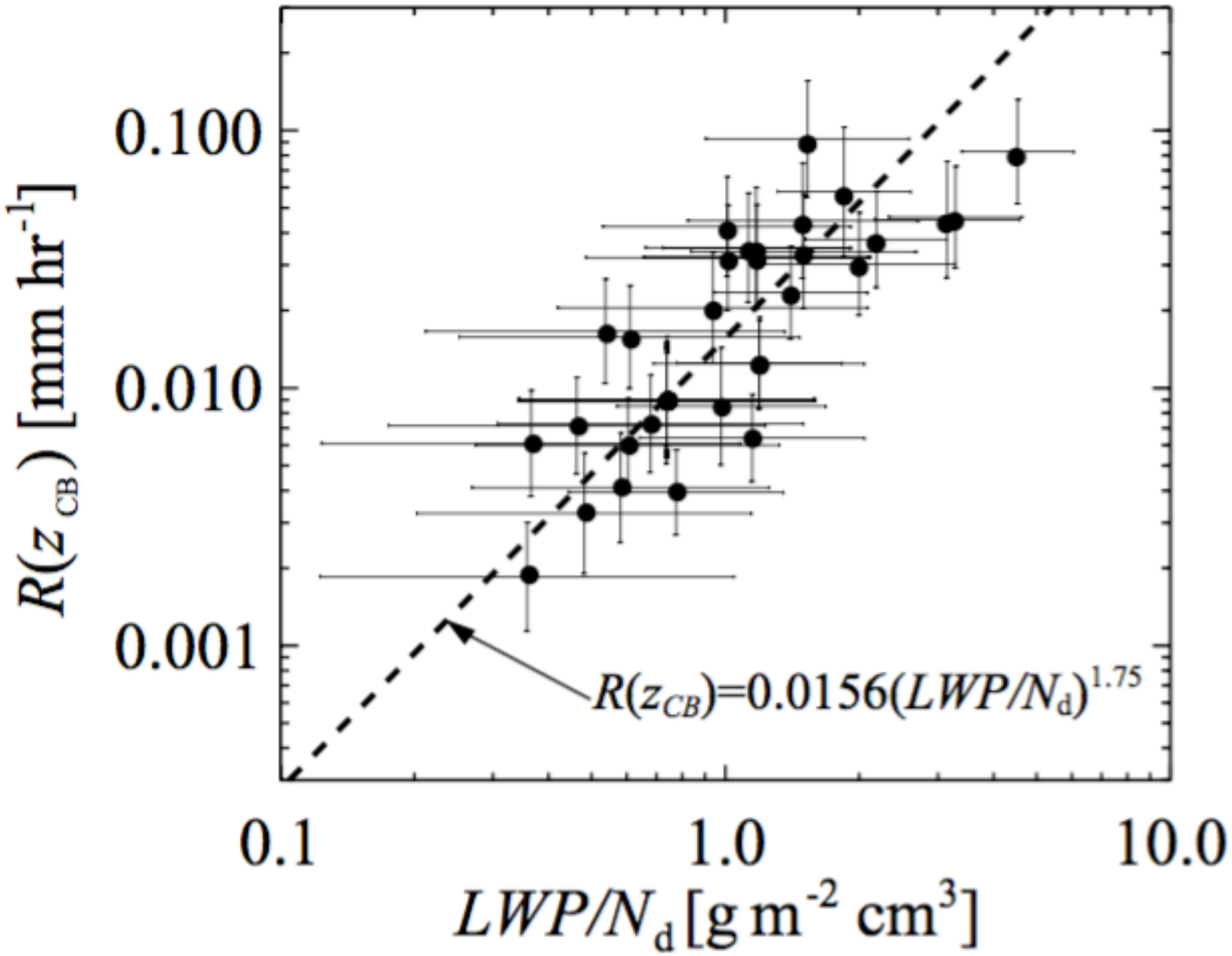
Large droplets at cloud top, ice, precipitation

- Droplet concentrations typically < 100 cm^{-3}
- maximum effective radius > 10 µm
- Maximum threshold droplet diameter > 20 µm
- Ice concentrations 10-100 per liter

Coupling of CCN and INP in drizzling clouds

- CCN → N_d
- LWP/N_d → drizzle
- $N_i \sim f(INP, 1/CCN)$
- otherwise $N_i \sim f(INP)$

Comstock et al. [2004]

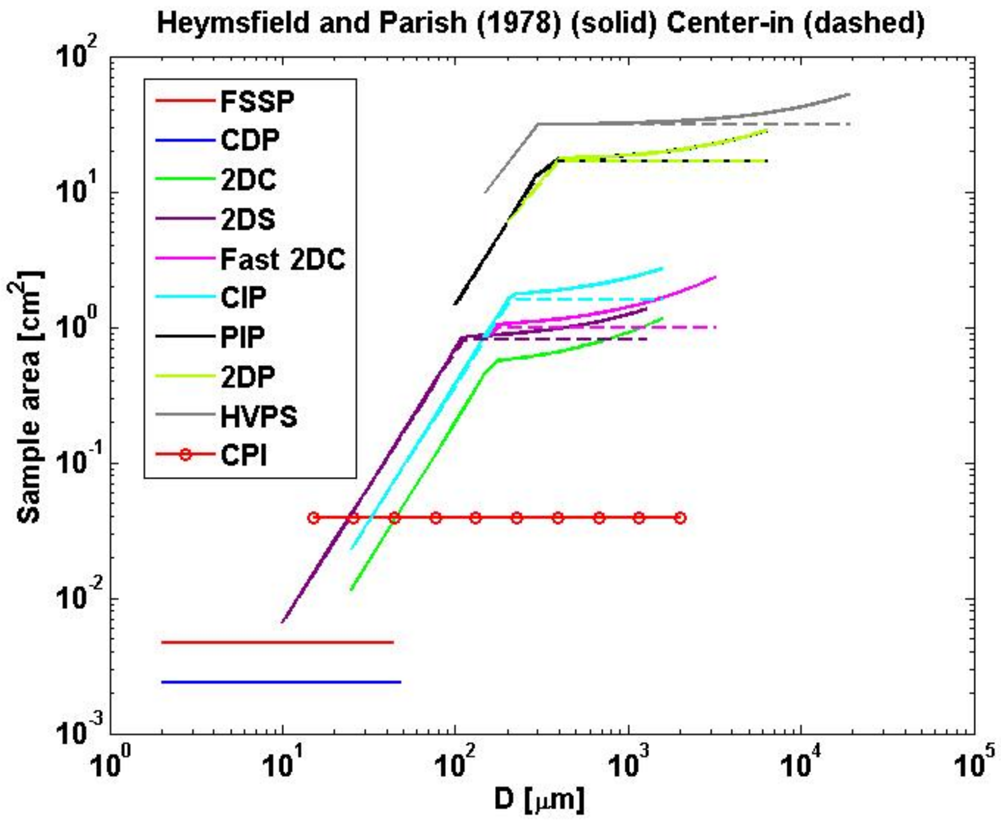


Mixed-phase stratiform clouds

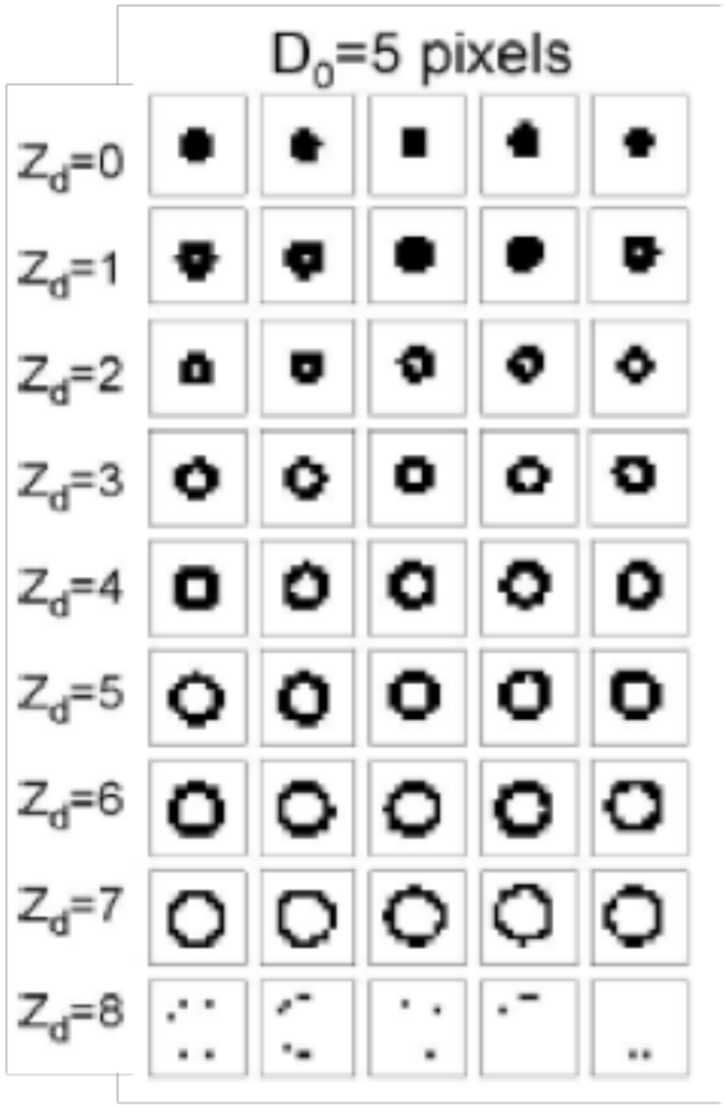
- N_i >> INP (opposite expected) when drizzling
  - outside of Hallett-Mossop temperature range
  - not explained by existing mechanisms (sufficient lab data)
- two recent papers focus generally on this knowledge gap, review potentially active mechanisms [Field et al. 2019, Korolev et al. ACP 2020]
- new observations of multiplication
  - SOCRATES
  - long-term remote-sensing [Luke et al., this mtg]

D < ~100 µm highly uncertain

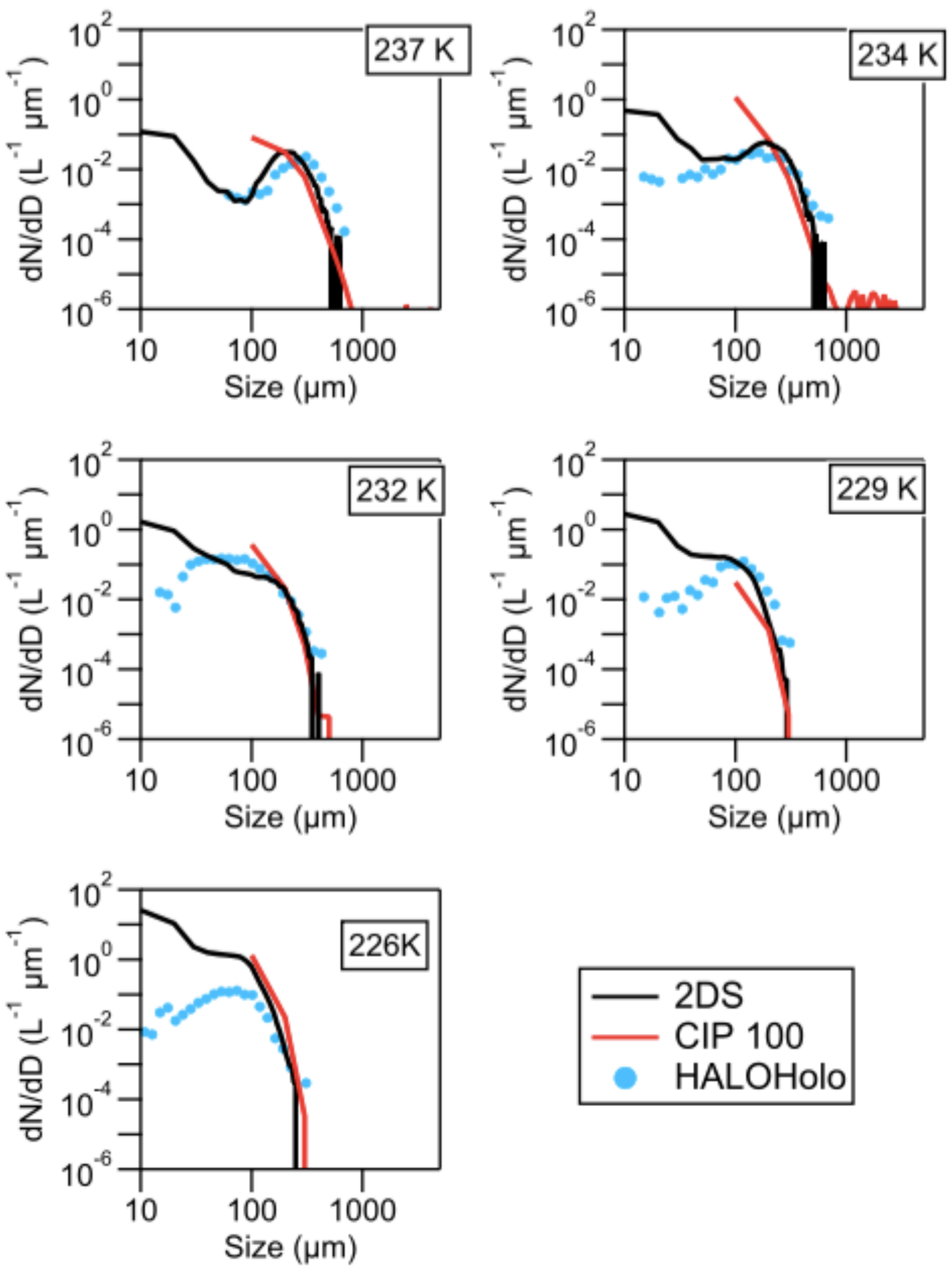
- in situ measurement uncertainties > 2X



Courtesy of Greg McFarquhar



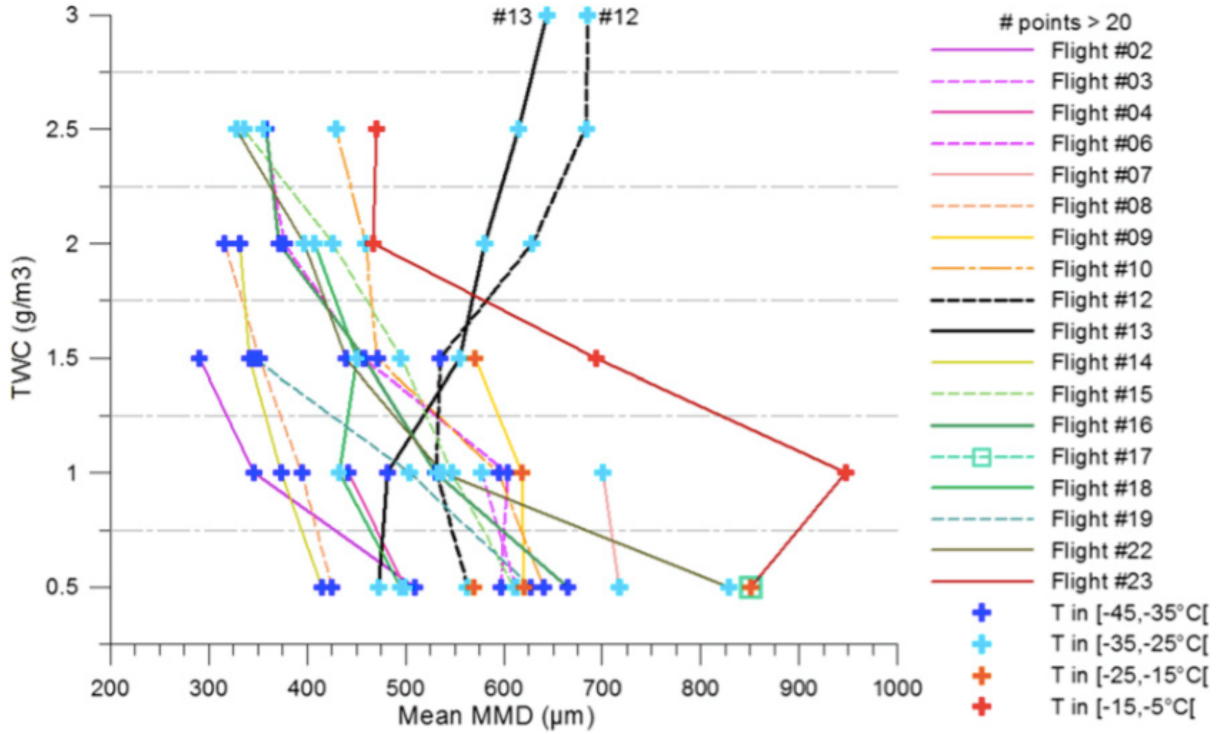
Korolev [2007]



O'Shea et al. [JGR 2016]

Tropical mesoscale convective system (MCS)

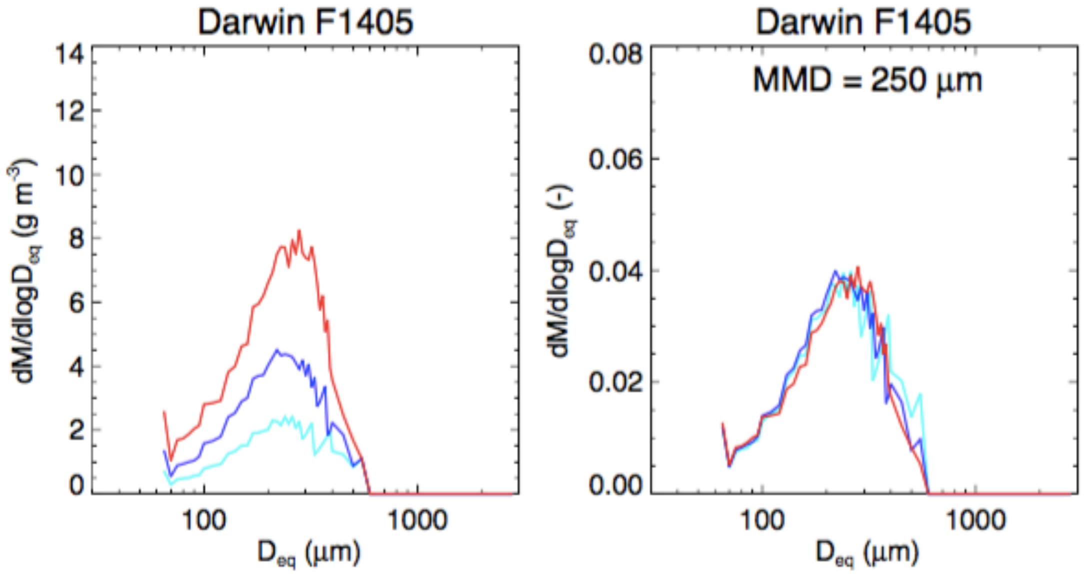
- High Altitude Ice Crystals / High Ice Water Content (HAIC/HIWC) campaign
  - – mass dominated by ≈300–600-µm ice
  - – size weakly correlated with IWC
  - – capped columns common

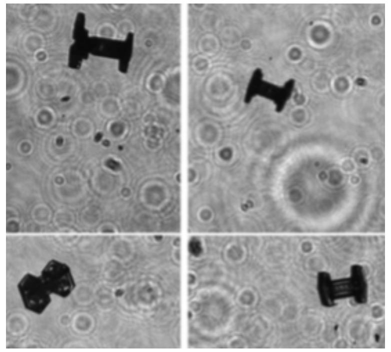


Leroy et al. [JTECH, 2017]

Fridlind et al. [ACP, 2016]
at –43°C near Cayenne (Airbus)

> 4 g/m^3
2–4 g/m^3
1-2 g/m^3

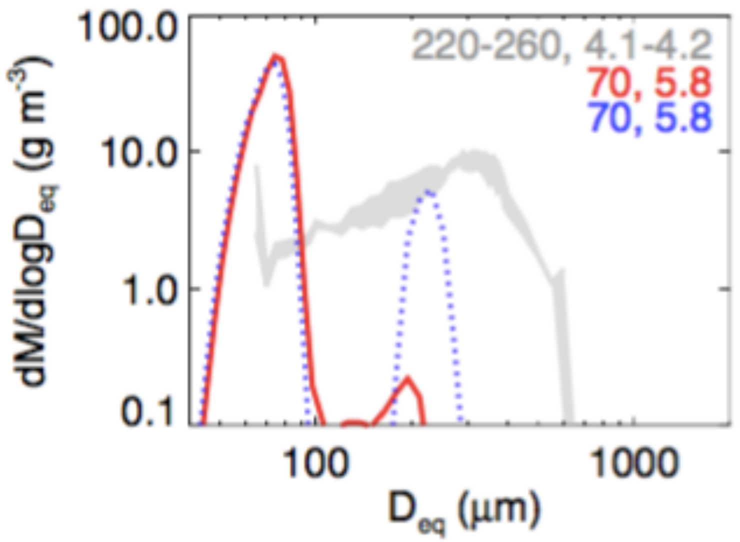




Ackerman et al.
[ACP, 2016]

Tropical deep convection (MCS conditions)

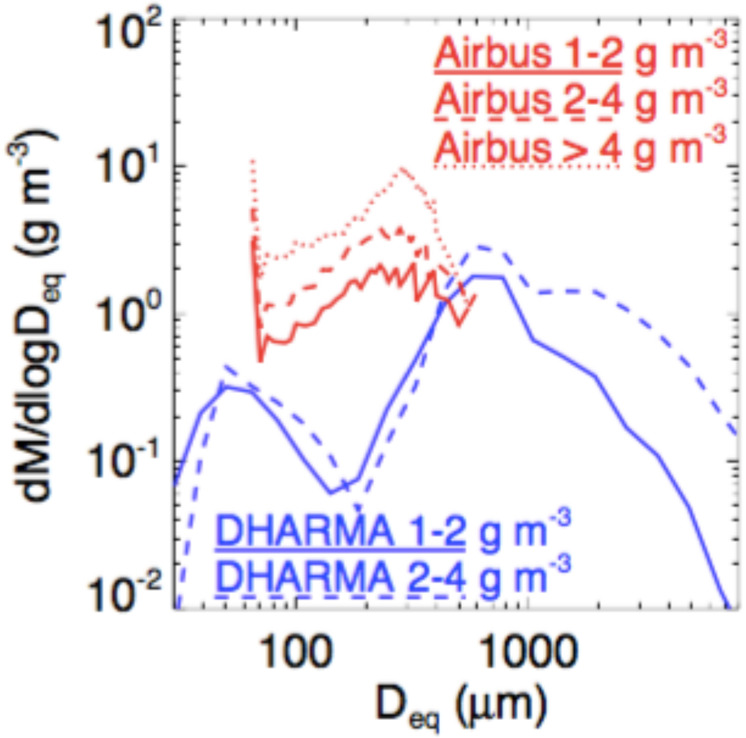
- How do you make a mass size distribution peak at $D_{eq} \approx 300\ \mu m$?
  - ≈1 cm^{-3} ice crystals warmer than –10°C [cf. Lawson et al. 2015, ICE-T]



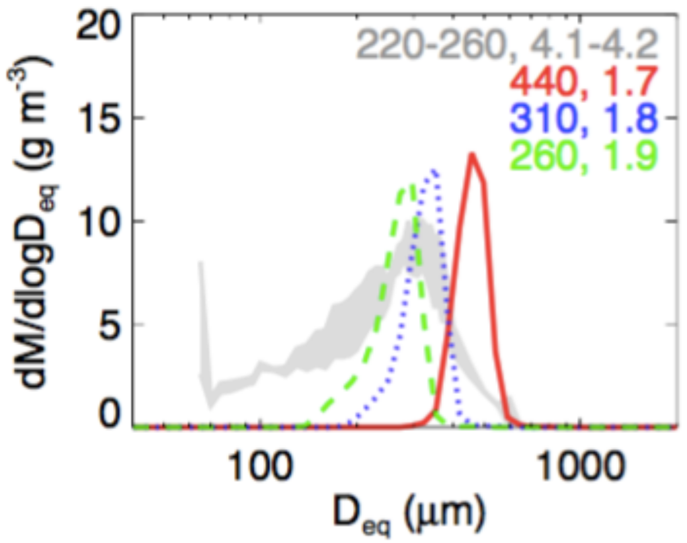
immersion INPs

"pseudo-Hallet-Mossop"

3D DHARMA simulations at –43°C



DHARMA sedimenting parcel simulations at –40°C



pseudo-Hallet-Mossop

1 cm^3

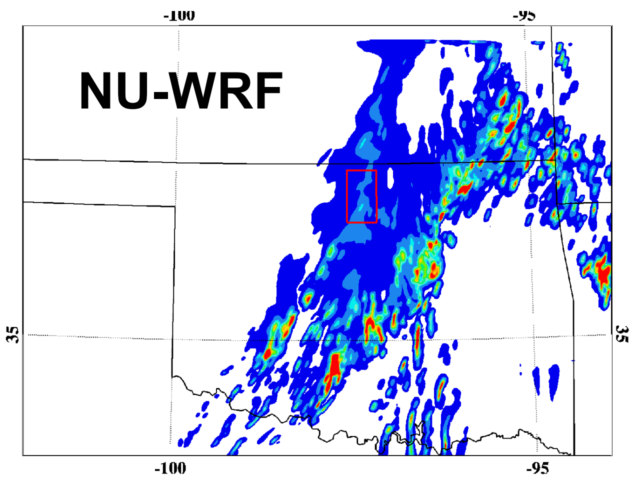
2 cm^3

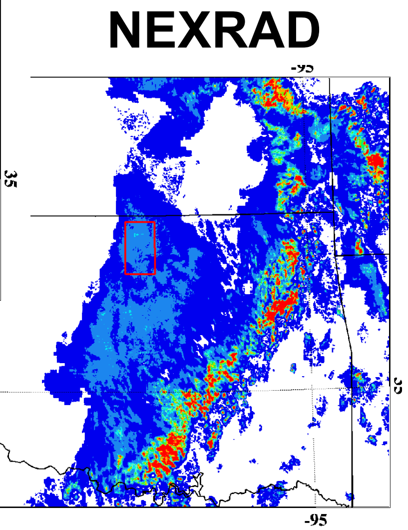
3 cm^3

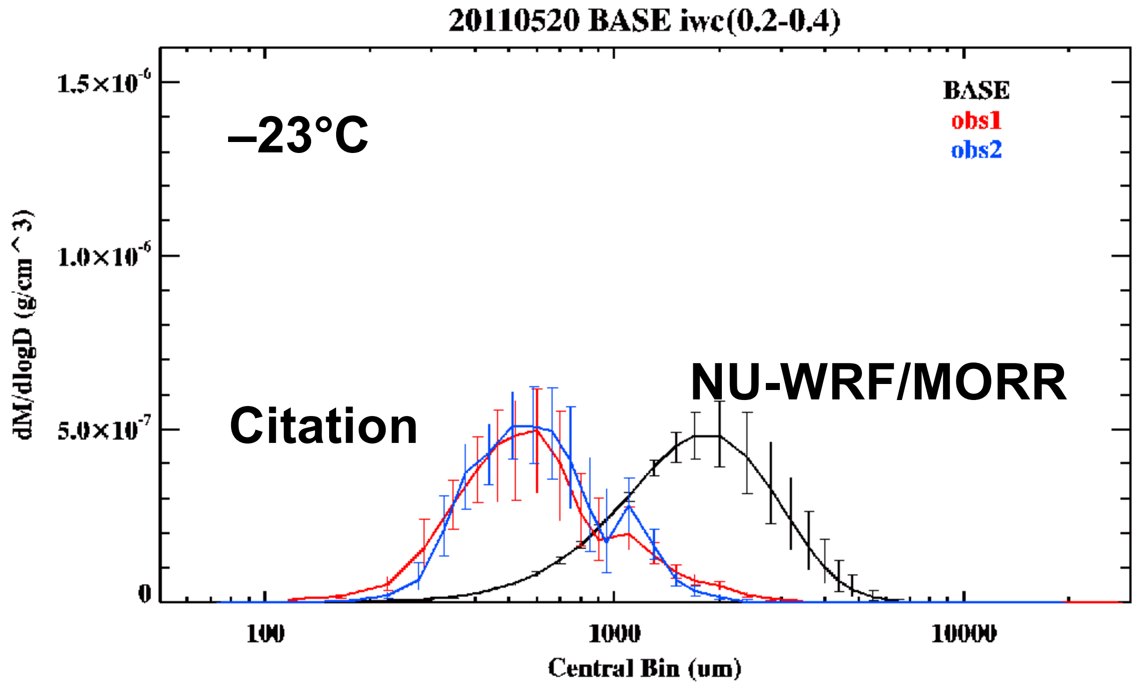
Ackerman et al. [ACP, 2016]

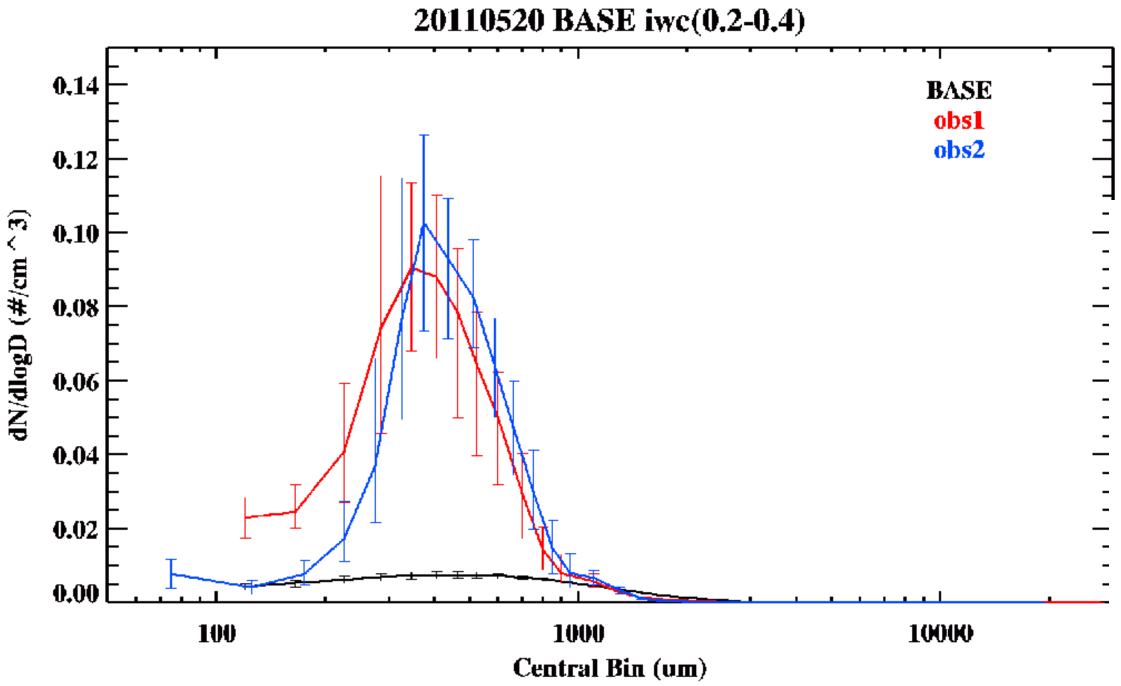
Springtime in Oklahoma during MC3E

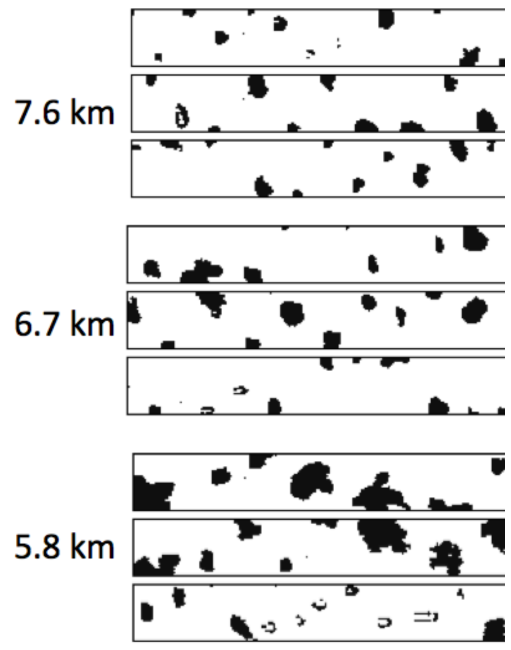
- similar conditions as HAIC/HIWC
- despite grossly differing updraft strength
- similar errors in model physics
- see also Shpund et al. [2019] ...







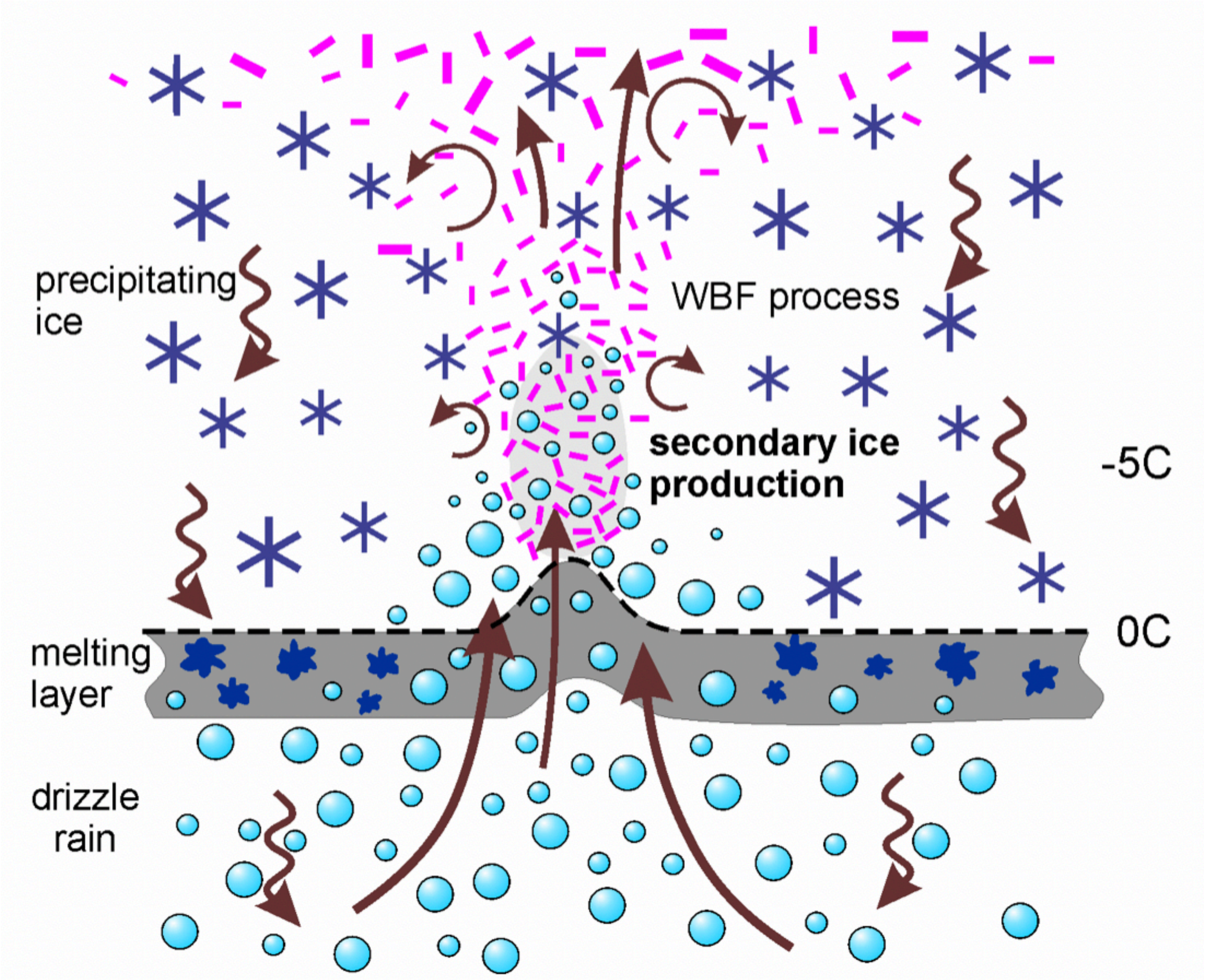


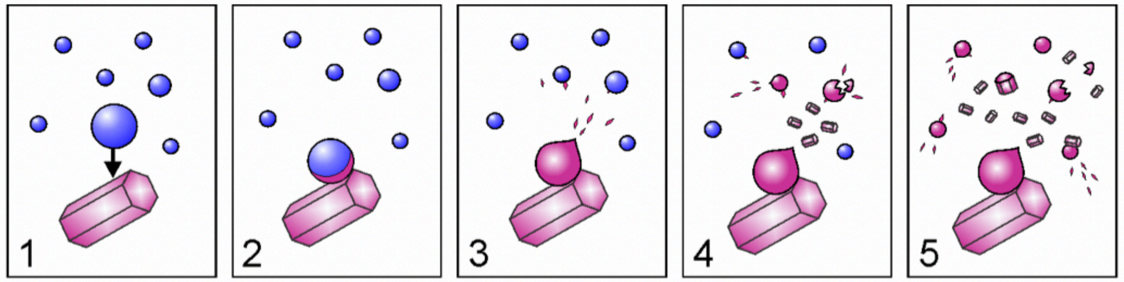


Fridlind et al. [ACP 2017]

Tropical MCS and mid-latitude frontal clouds

- Korolev et al. [ACP 2020]
  - examined flight legs at $-15 < T < 0^{\circ}$C
  - state-of-the-art instrumentation
  - pristine faceted crystals $D < 60$ μm
    - best estimate $N_i \gg$ INP
    - drops $D > 40$ μm necessary but not sufficient
    - graupel or rimed particles often missing
  - points to drop shattering [e.g., Lauber et al. 2018]
    - recirculation (CCN-decoupled)





Conclusions

- Mixed-phase stratiform clouds [Fridlind and Ackerman 2018]
  - N_i >> INP when drizzling via uncertain mechanism(s)
- Deep convection with stratiform outflow [Fridlind et al. 2017]
  - stratiform N_i apparently dominated by warm-temperature multiplication
  - homogeneous freezing may dominate elsewhere [e.g., Stith et al. 2014]
- Strategies for progress [cf. Morrison et al. JAMES, submitted]
  - more laboratory studies of ice multiplication (repeatable results)
  - improved *in situ* instrumentation, in wider use (esp. $D_i < \sim 100\ \mu m$)
  - observationally driven modeling studies with prognostic CCN and INP
  - elephants in the room → major uncertainties in simulated glaciation, lifetime, radiative effects, sensitivity to CCN and INP

Thanks for listening!

- feedback welcomed