Secondary ice processes: a modulator of global mixed-phase clouds

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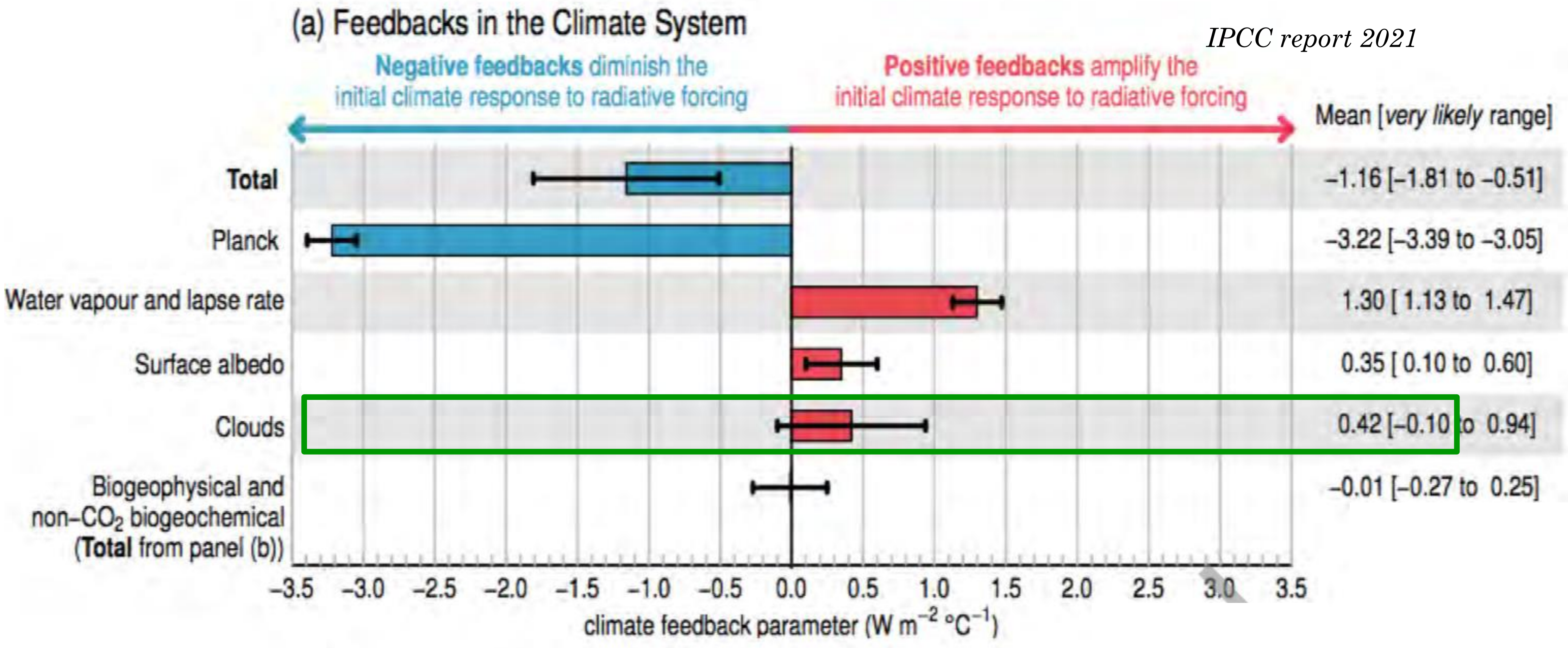
INP Colloquium Talk

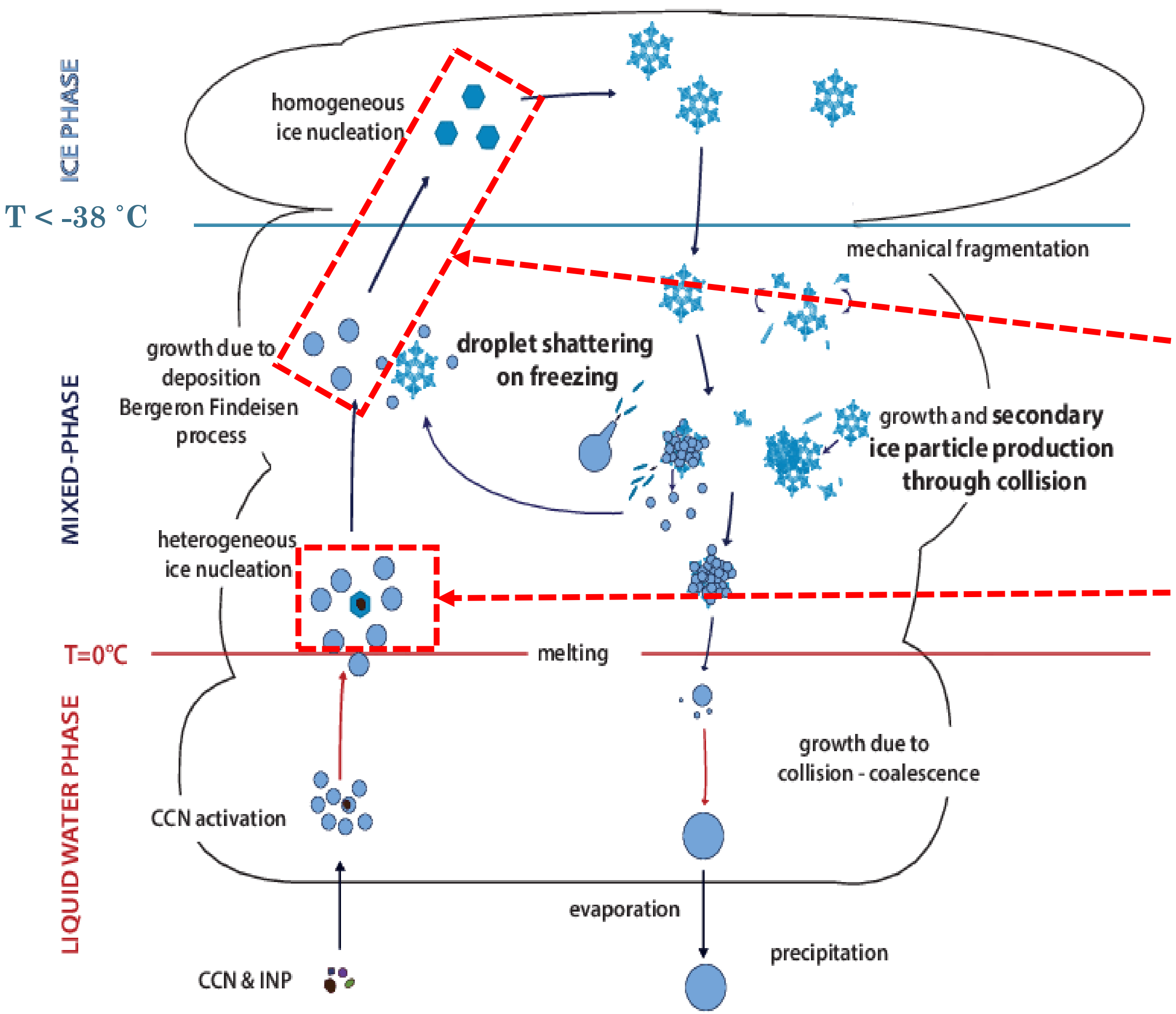
December 8, 2022

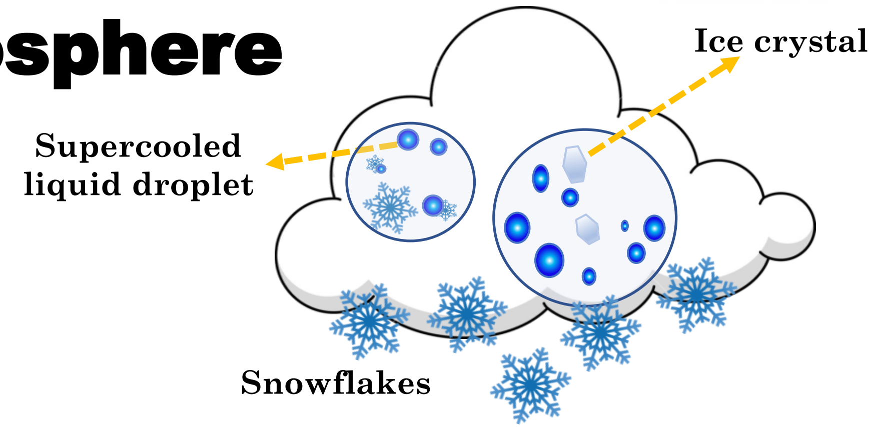
Research: *Motivation*



Clouds are the largest source of uncertainty in projections of future climate

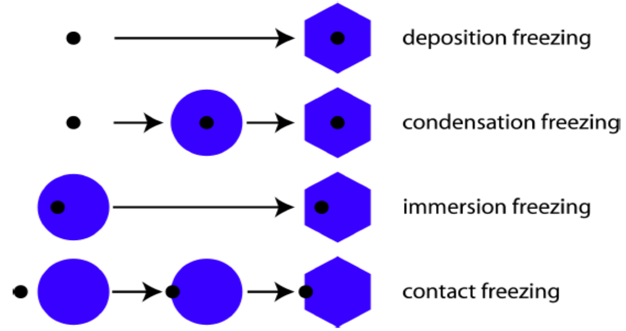
Mixed-phase clouds (MPCs) in the atmosphere



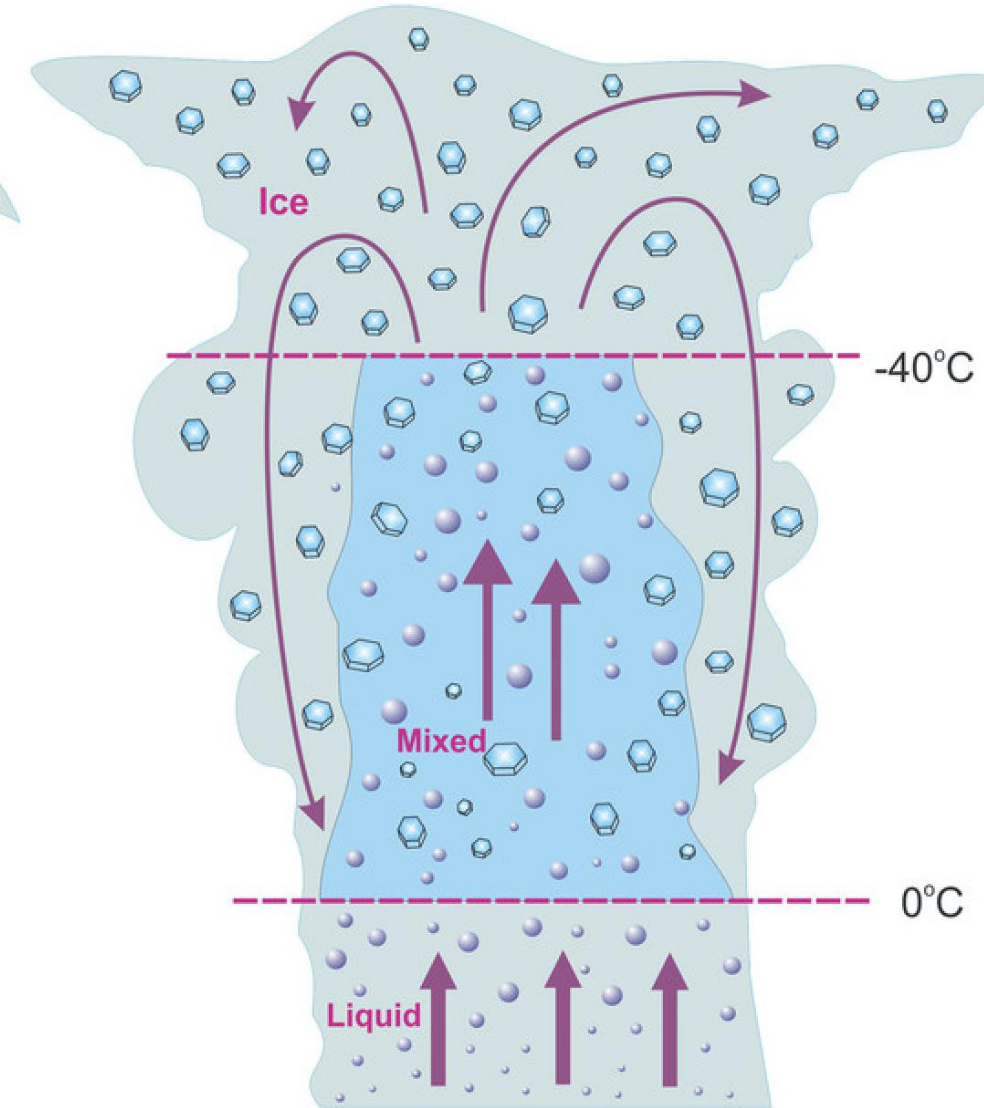


Homogeneous (& Heterogeneous) freezing:
At **T < -38 ˚C** ice nucleation occurs from the liquid phase (and also with the assistance of INPs).

Heterogeneous freezing:
Under mixed-phase conditions (**-38˚C < T< 0 ˚C**) the assistance of ice nucleating particles (INPs) is needed to initiate primary ice production



Mixed-Phase clouds control precipitation

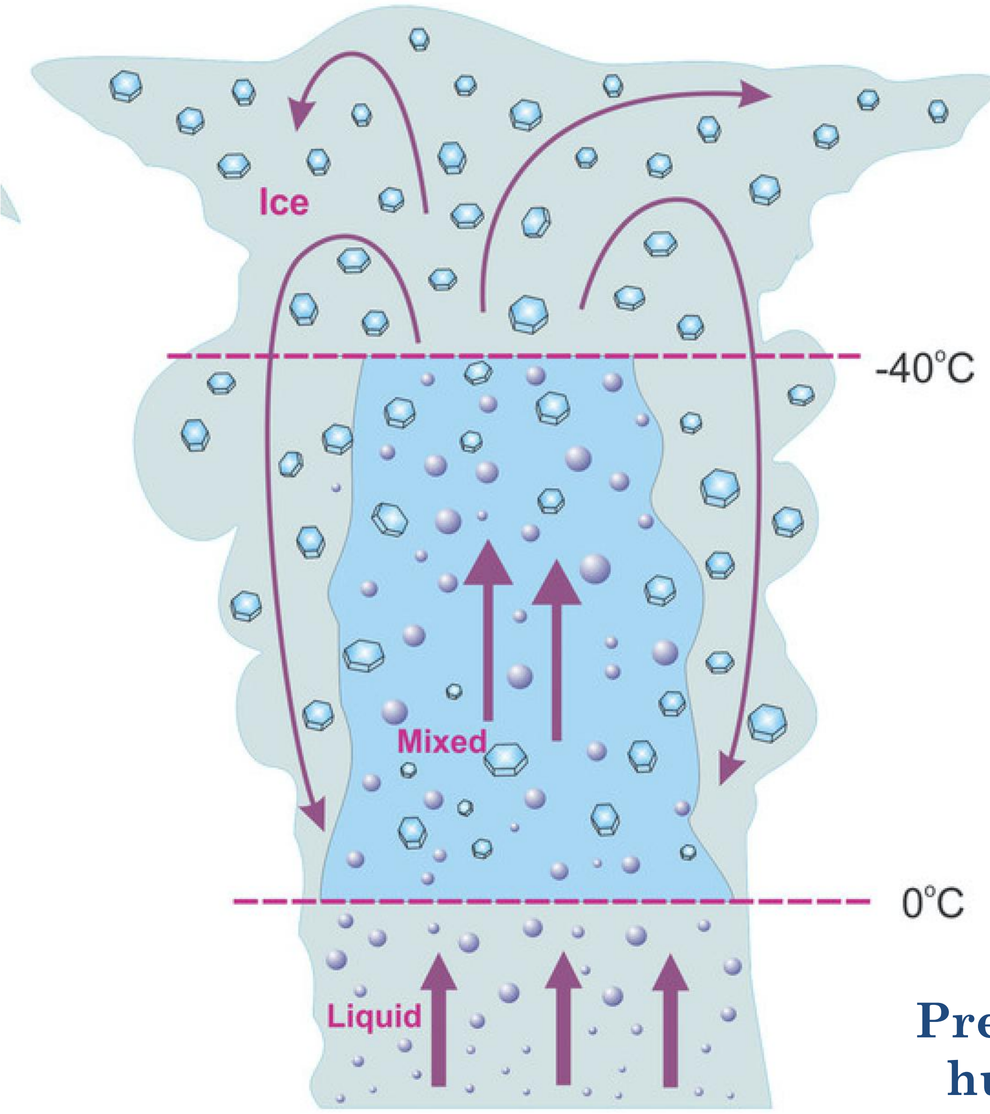


Precipitation at mid- and high-latitudes mostly generated from the mixed- and ice- cloud phase

Mulmenstadt et al . 2015

EPFL

Mixed-Phase clouds control precipitation



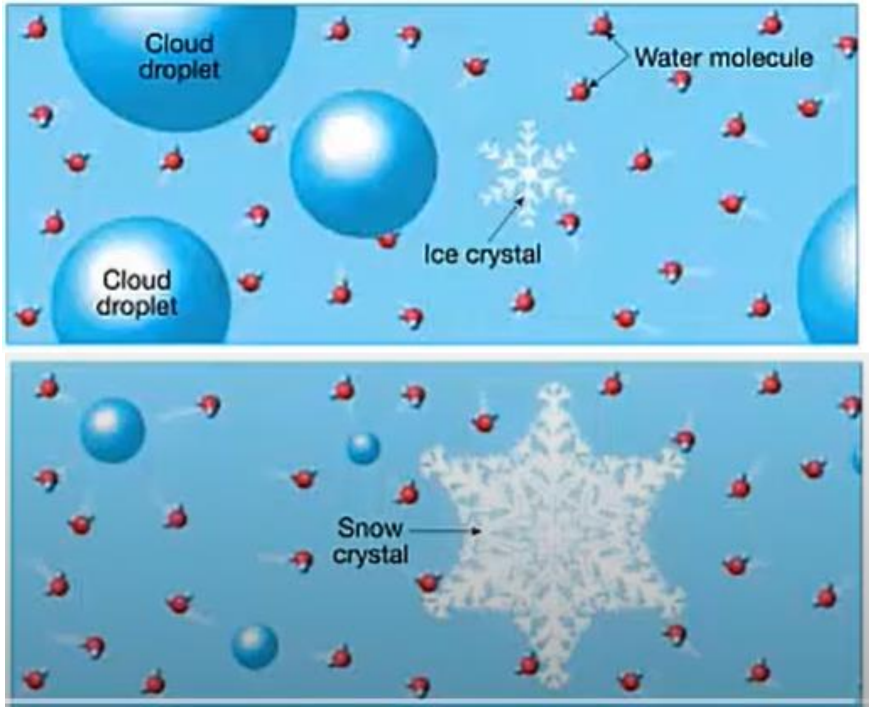
Precipitation at mid- and high-latitudes mostly generated from the mixed- and ice- cloud phase

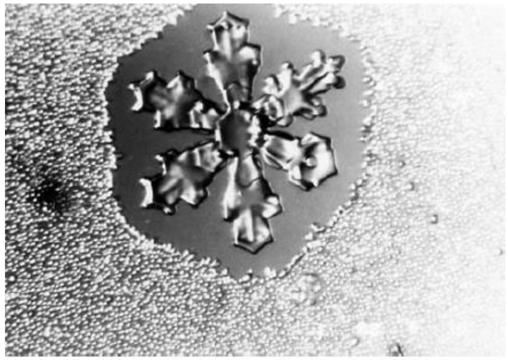
Mulmenstadt et al . 2015

Precipitation extremes have huge impacts on economy and society at large.

Challenges of representing MPCs within modeling frameworks

- ✓ Important to predict the **amount** and **distribution** of ice and liquid (liquid-ice phase partitioning) in MPCs
- ✓ Models tend to convert water to the ice phase too aggressively



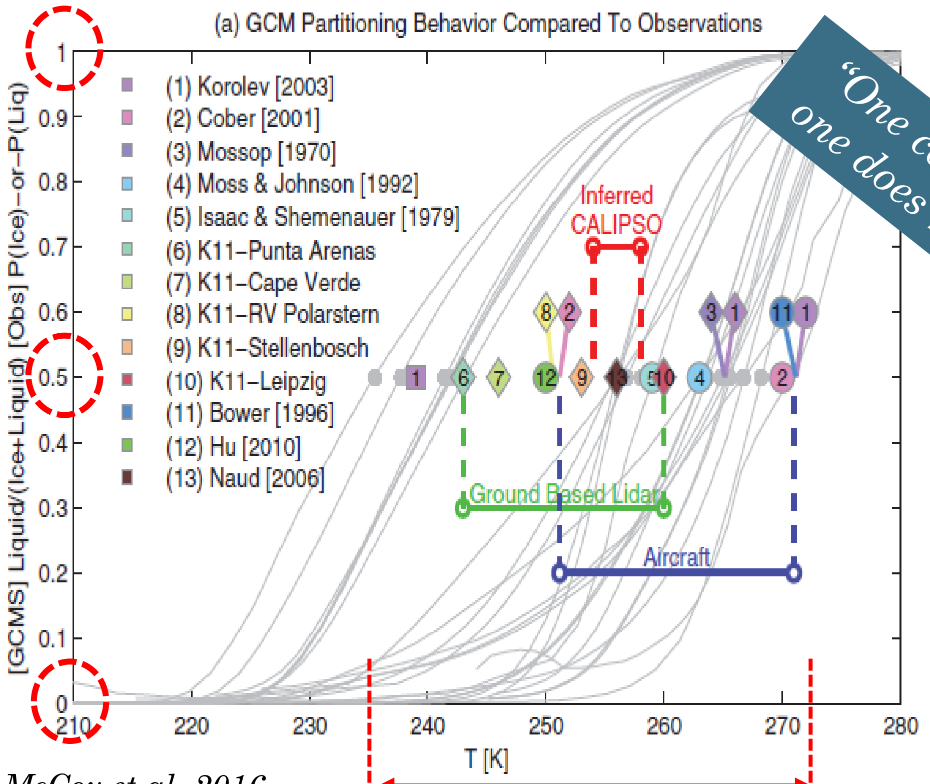


Wegener-Bergeron-Findeisen process (WBF)

Pure liquid cloud

50% liquid 50% ice

Pure ice cloud



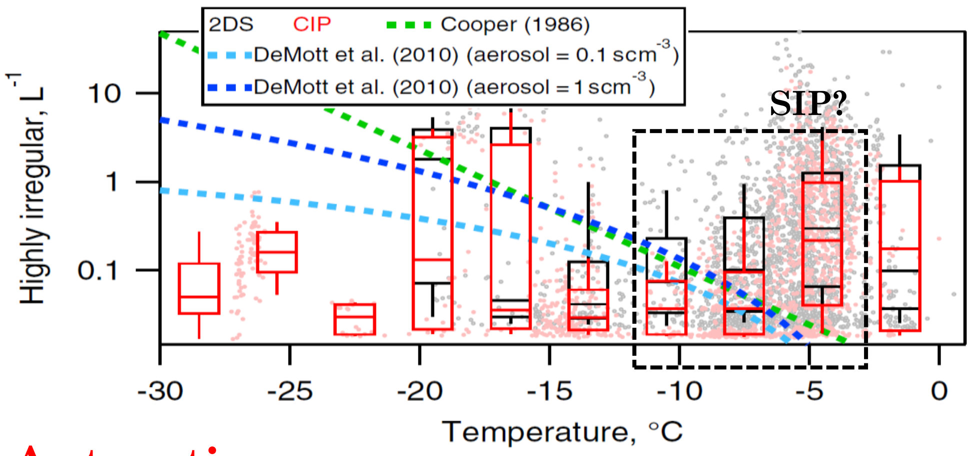
McCoy et al. 2016

mixed-phase temperature range

"One cannot model what one does not understand"

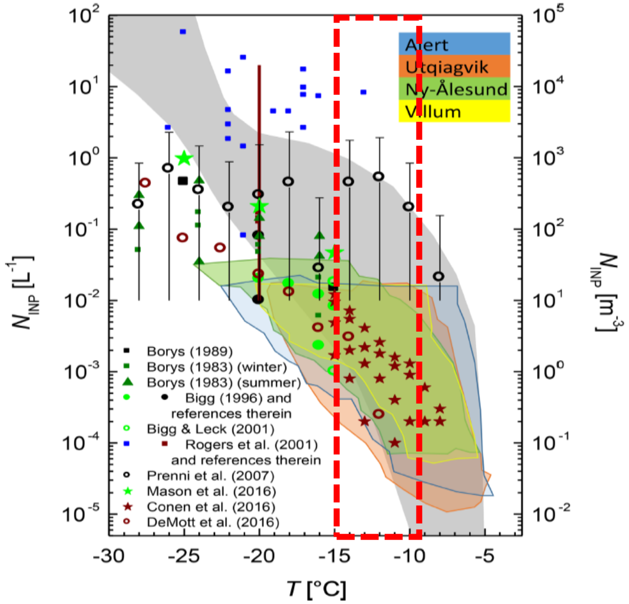
Measured Ice Crystal Number Concentrations (ICNCs) ≫ pre-cloud INPs

- ✓ Ice Nucleating Particles (INPs) are few in remote polar regions - compared to the ice crystal (ICNCs)
- ✓ Alpine (orographic) clouds have the same behavior.
- ✓ Secondary Ice Production (SIP) processes must be invoked to explain the large difference between INPs and ICNCs



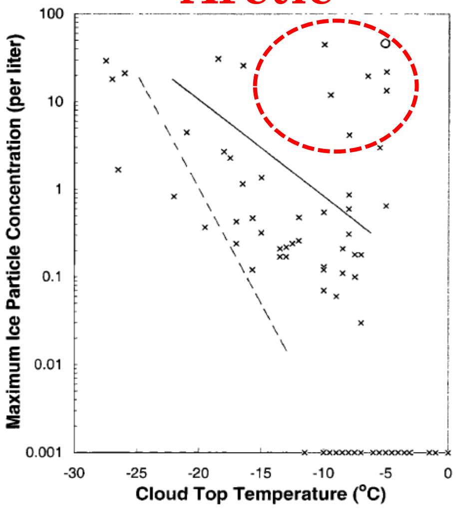
Antarctic

O'Shea et al. 2017



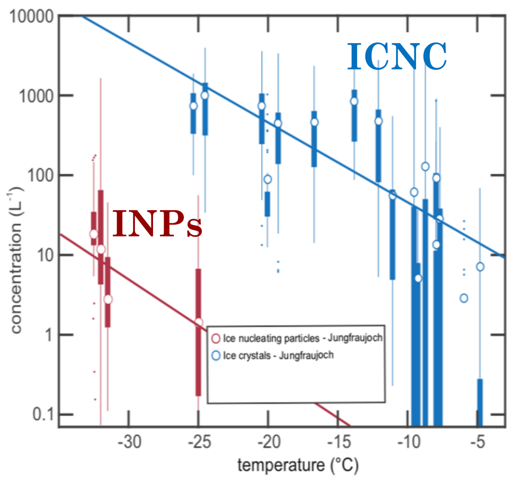
Wex et al. 2019

Arctic

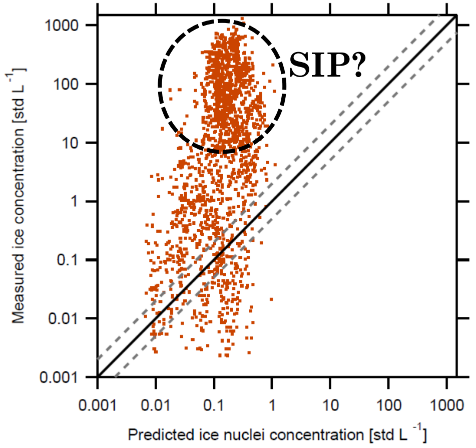


Ragno & Hobbs 2001

Alps



Beck et al. 2018

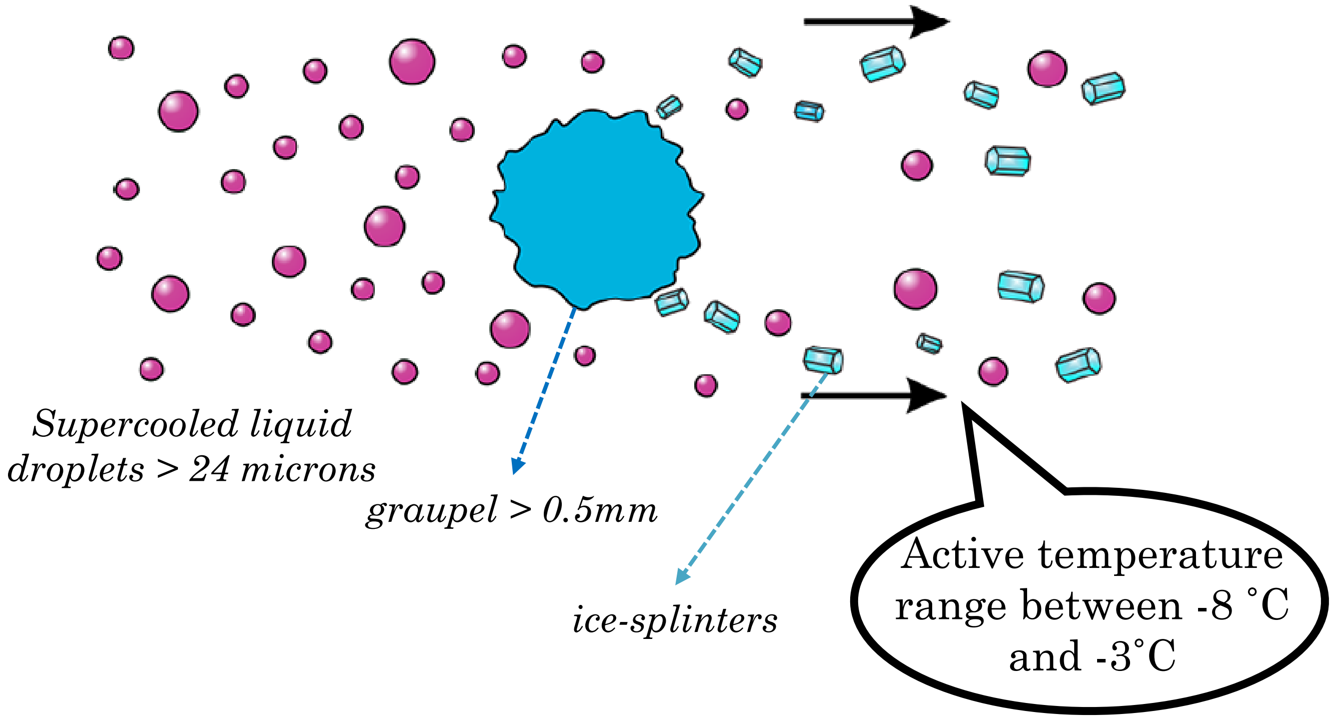


Lloyd et al. 2015

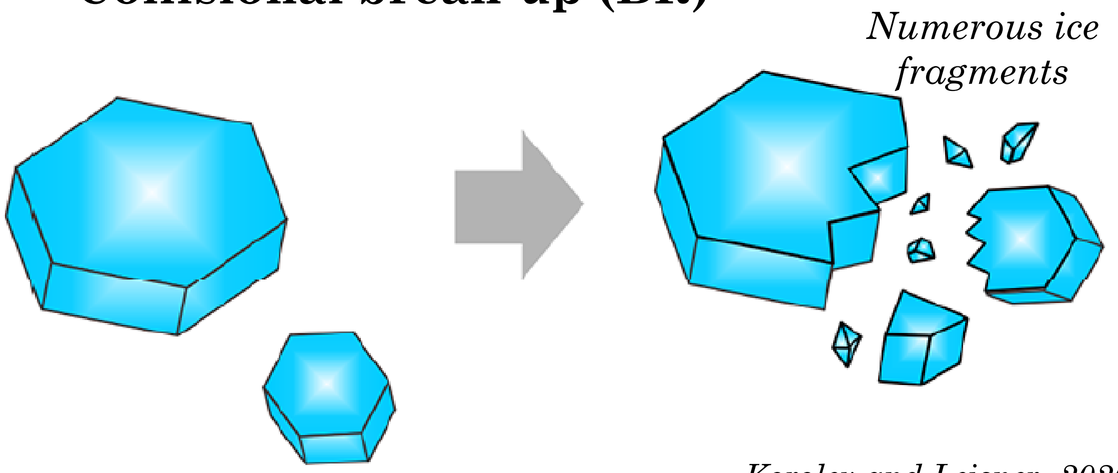
The cause of this cloud-ice paradox → Secondary Ice Production (SIP)*

* SIP = multiplication of primary ice crystals through "other processes" not involving INPs

✓ **Rime Splintering (RS) or the Hallett-Mossop process (H-M)**

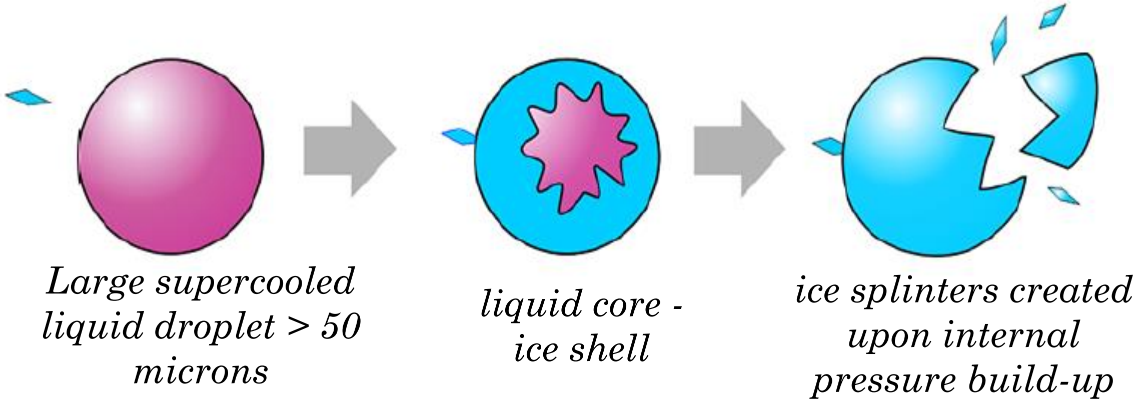


✓ **Collisional break-up (BR)**



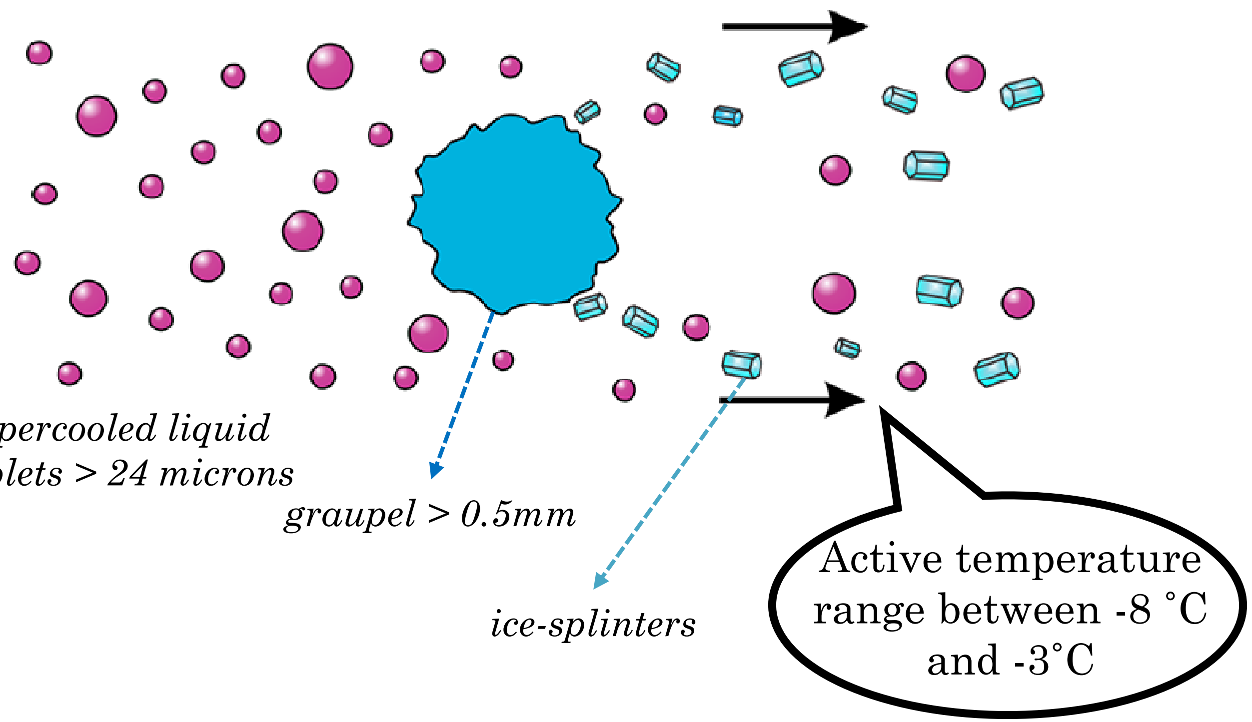
Korolev and Leisner, 2020

✓ **Droplet Shattering (DS) during freezing**



What's included mostly in models:

✓ **Rime Splintering (RS) or the Hallett-Mossop process (H-M)**



✓ **Collisional break-up (BR)**

Korolev and Leisner, 2020

✓ **Droplet Shattering (DS) during freezing**

What’s included mostly in models:

✓ Collisional break-up (BR)

✓ **Rime Splintering process (H-M)**

What happens when we begin including all these processes together?

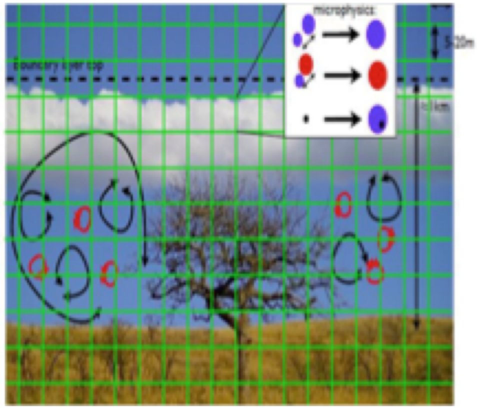
Let’s see for different cloud types and model hierarchies (LES, mesoscale, global).

luring freezing

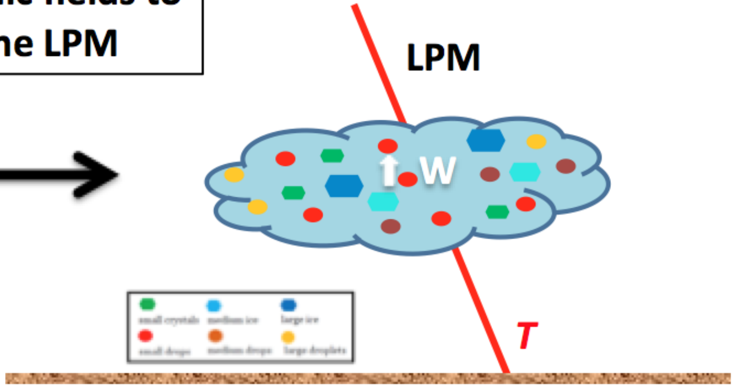
Secondary ice effects in an Arctic cloud deck MIMICA LES with a Lagrangian parcel model (LES-scale)

Aerosol-Cloud Coupling and Climate Interactions in the Arctic (ACCACIA) campaign (Svlabard 3,4,7/2013)

LES



The LES provides the thermodynamic fields to initialize the LPM

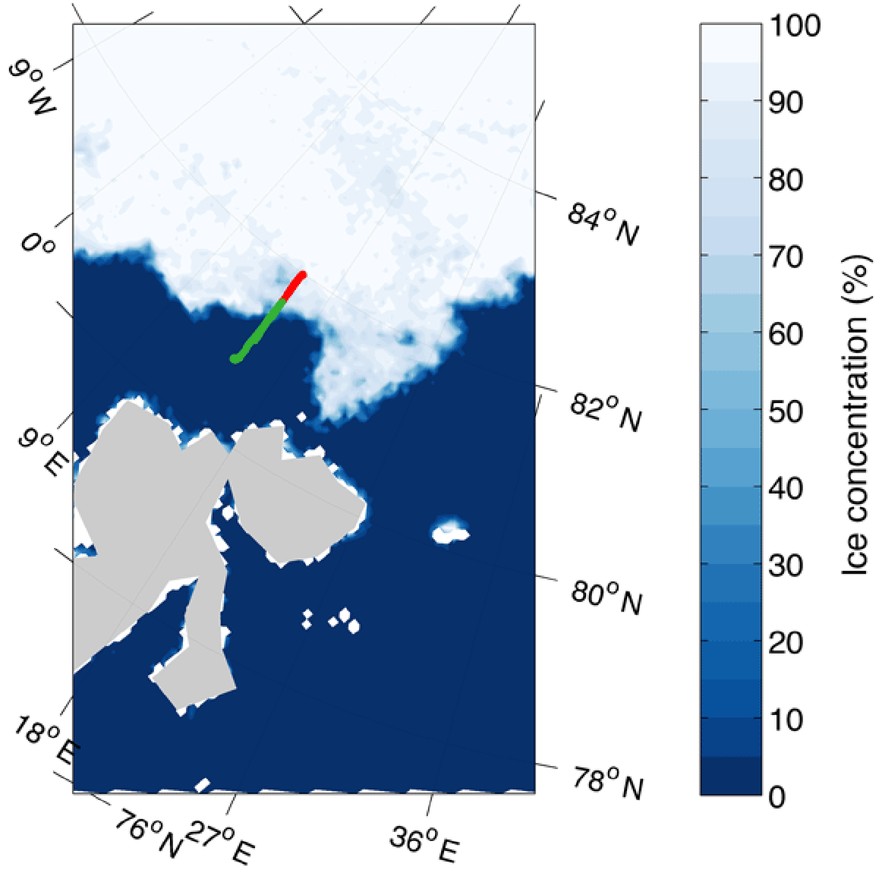


Phillips et al. (2017, 2018) parameterizations

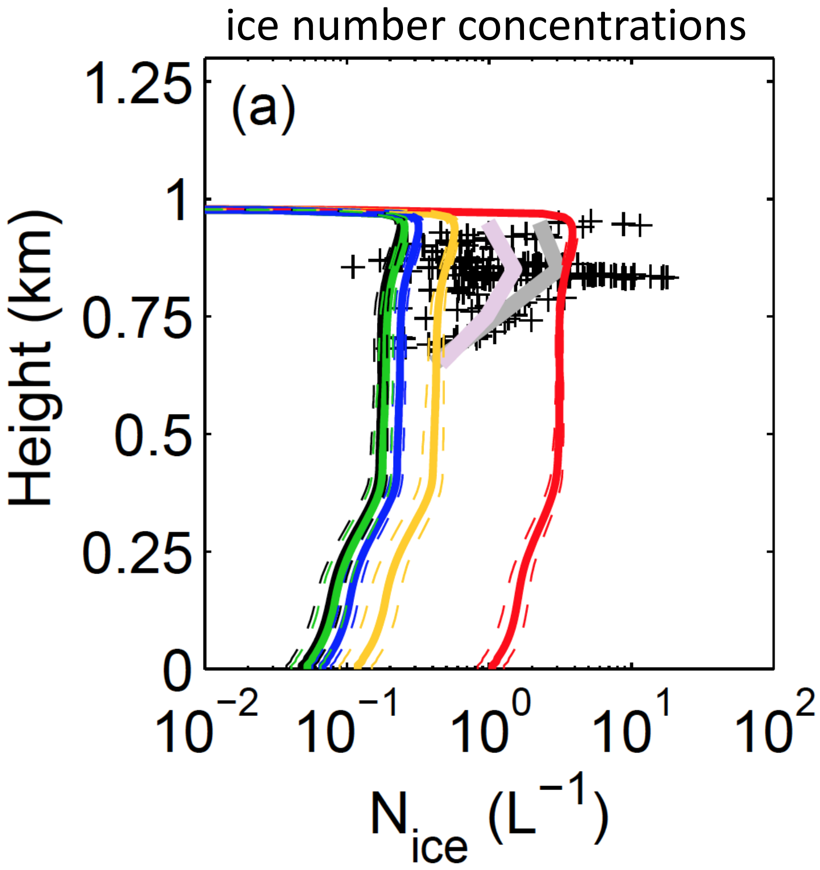
Ice enhancement due to SIP is estimated with the LPM

Ice enhancement factors are provided to the LES through Look-Up Tables as a function of cloud base temperature and updraft velocity

Sotiropoulou et al. 2020



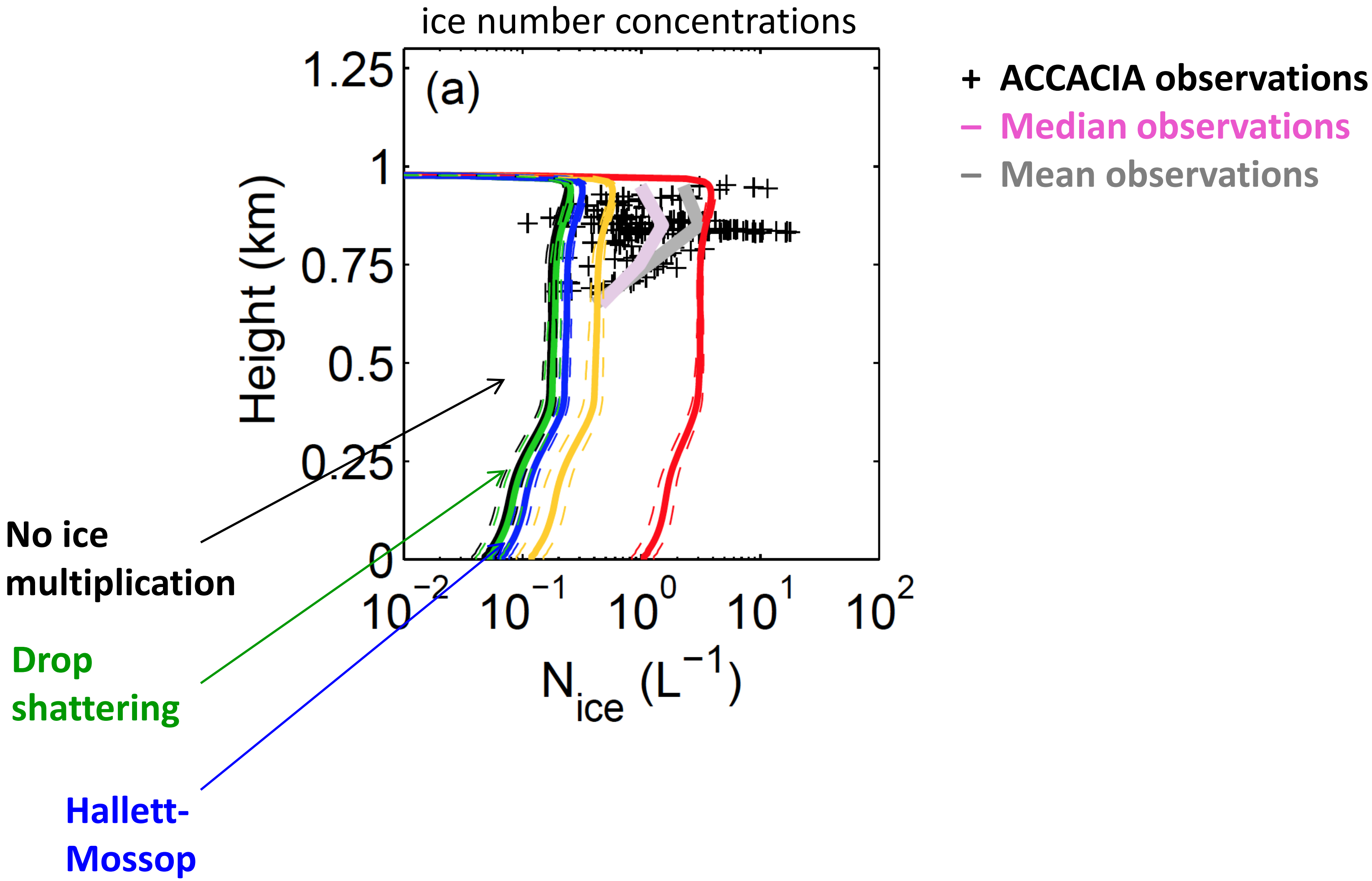
LES simulations of Arctic clouds



+ ACCACIA observations
– Median observations
– Mean observations

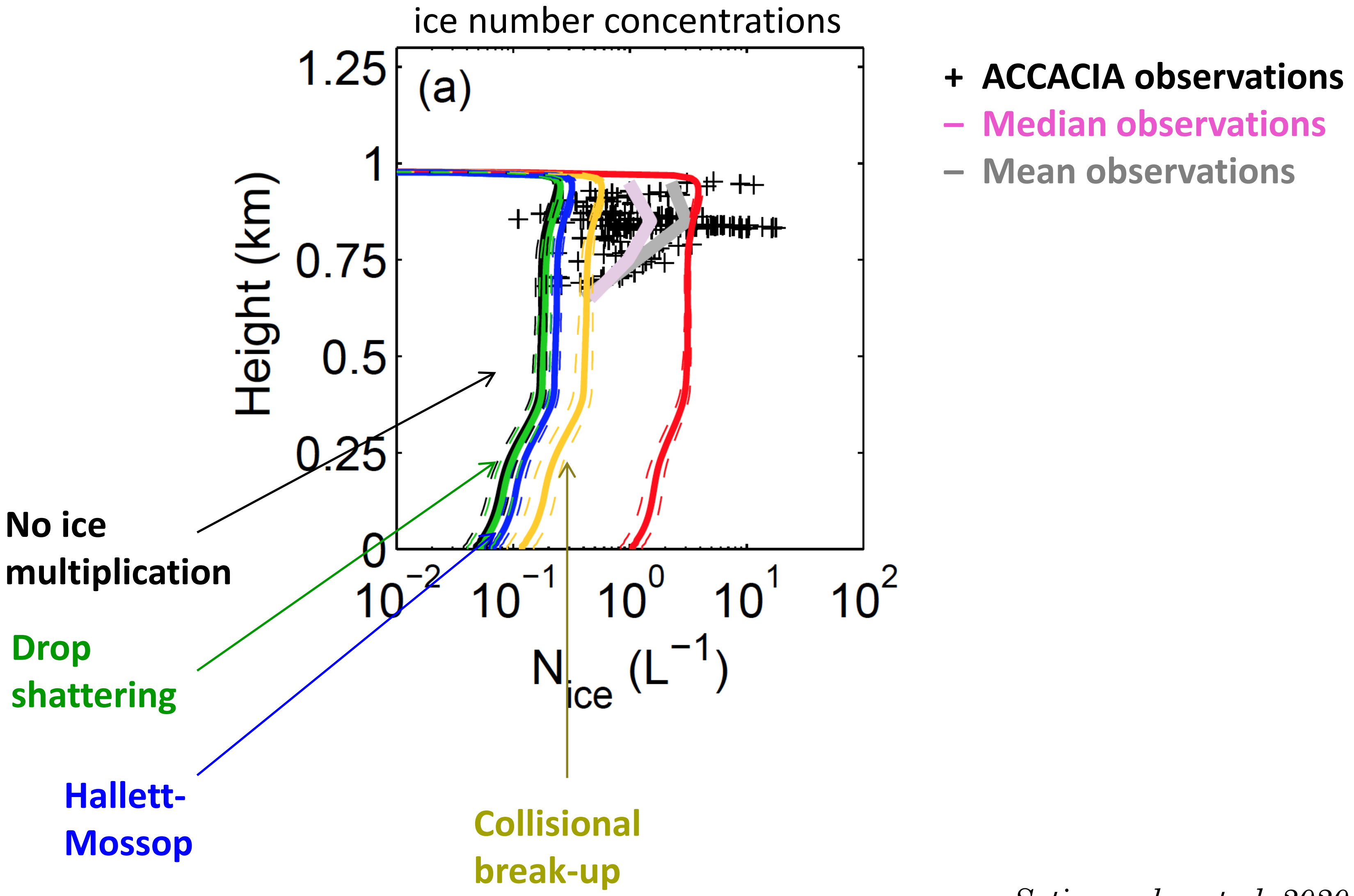
Sotiropoulou et al. 2020

LES simulations of Arctic clouds



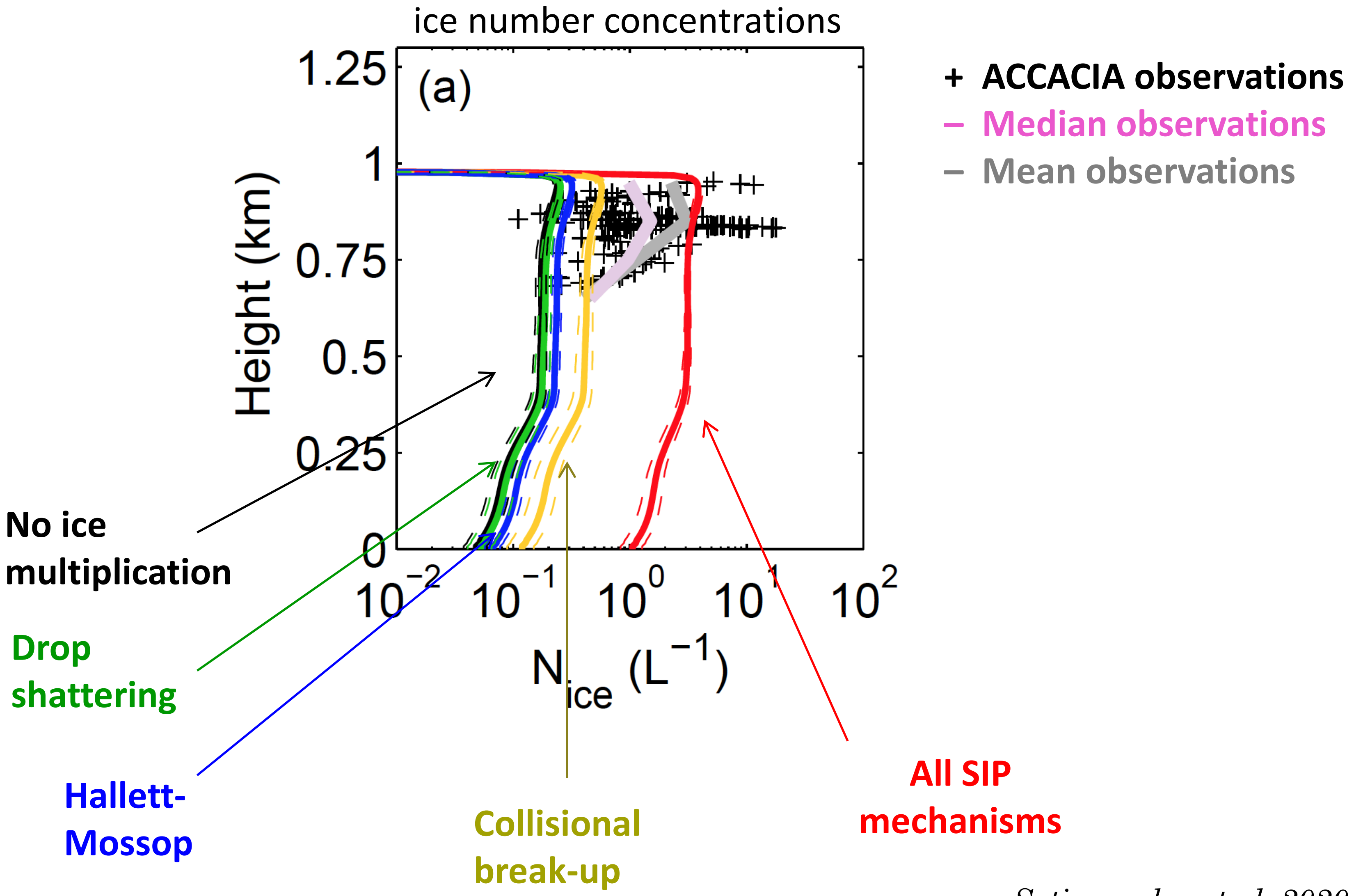
Sotiropoulou et al. 2020

LES simulations of Arctic clouds



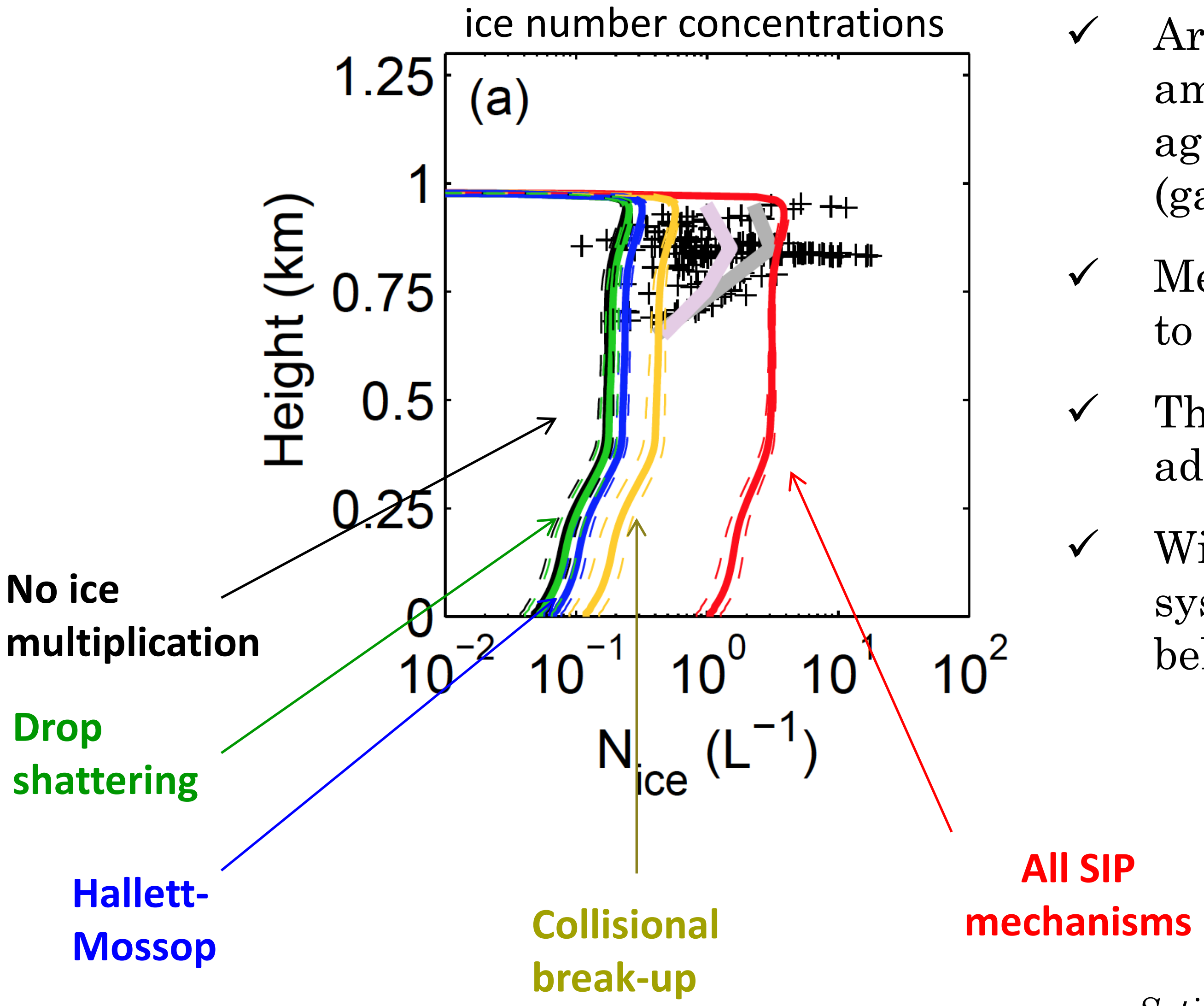
Sotiropoulou et al. 2020

LES simulations of Arctic clouds



Sotiropoulou et al. 2020

LES simulations of Arctic clouds

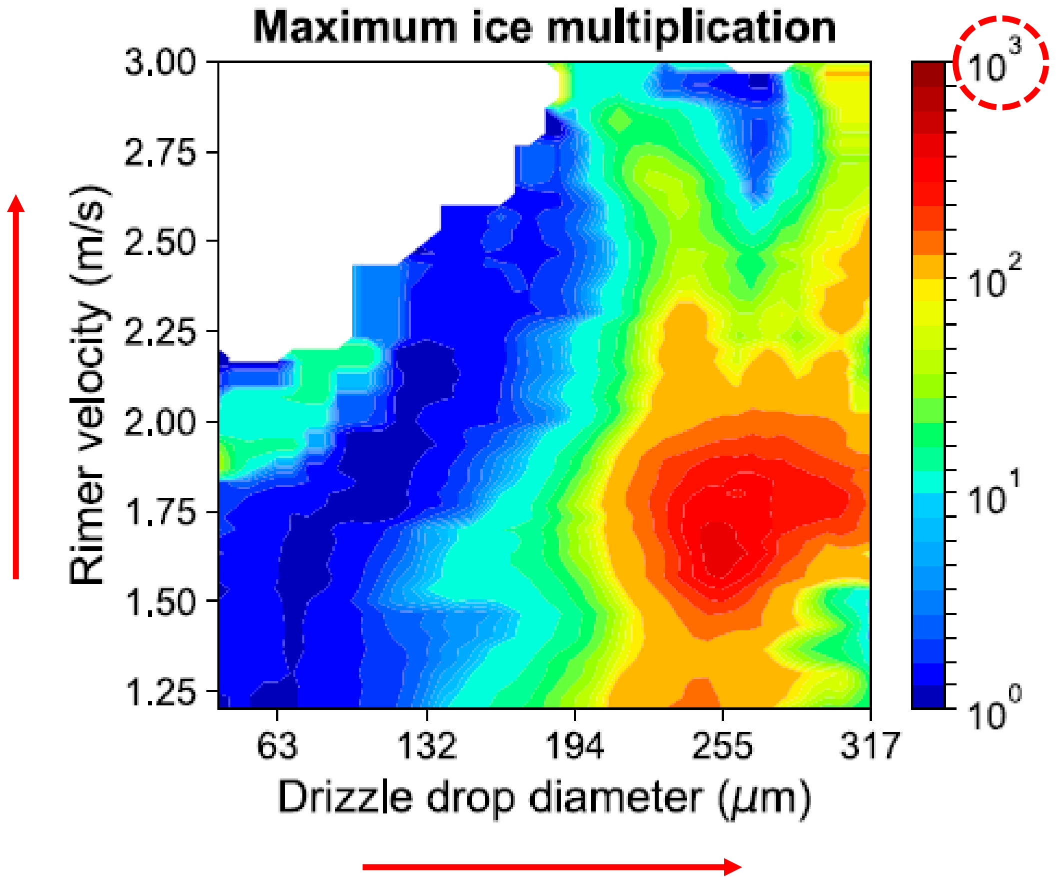


- ✓ Arctic clouds can have considerable amounts of SIP – which goes against established thought (gained from only Hallett-Mossop)
- ✓ Mechanisms can act synergistically to produce ice
- ✓ The effects are not necessarily additive.
- ✓ With many mechanisms active, the system often can exhibit buffered behavior (not shown).

Sotiropoulou et al. 2020

Droplet shattering can be important as well

- ✓ 6 years of **cloud radar** data of slightly supercooled Arctic clouds **(-10 ˚C < T < 0 ˚C)** in Utqiagvik (Barrow), Alaska (2013 – 2019)
- ✓ Relative frequency of SIP **<10%**
- ✓ Even if rare, our models don't reproduce this behavior means there is improvement needed in getting the big droplets there.

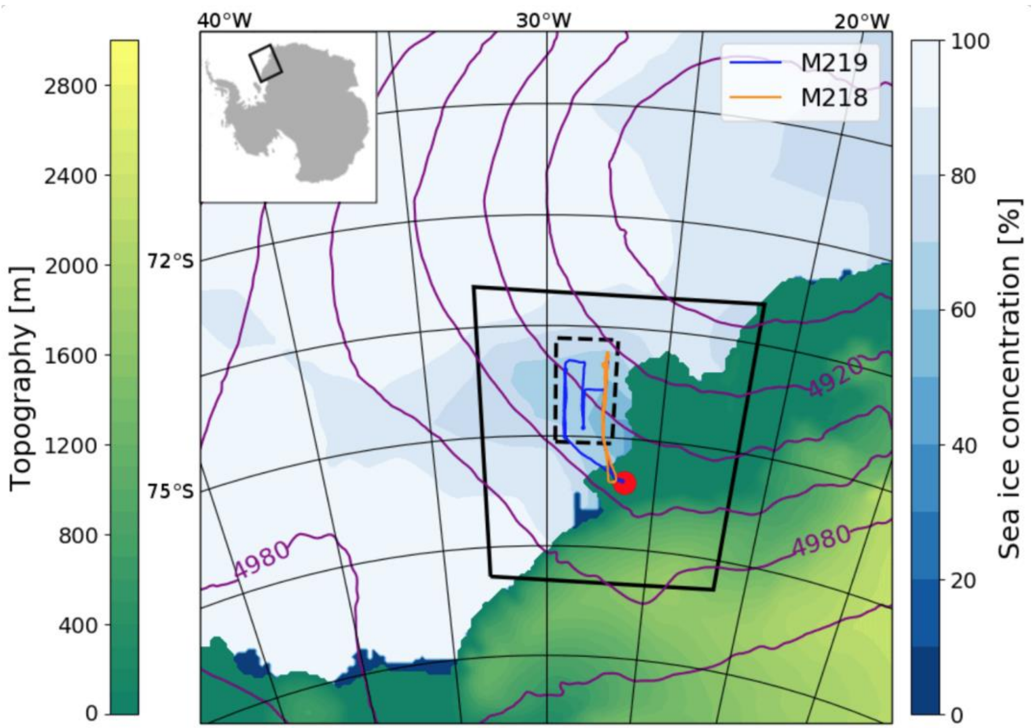


Conditions with large drizzle drops can lead to explosive SIP!

Quantification of the ice-enhancement factor (i.e., the enhancement in ice number concentration due to SIP)

Luke et al., 2021, PNAS

Secondary ice effects in Antarctic clouds
WRF (Weather Research & Forecasting model) (regional scale)



Simulations of 2 MAC (Microphysics of Antarctic clouds campaign) flights. November–December 2015 over coastal Antarctica and the Weddell Sea

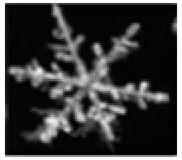
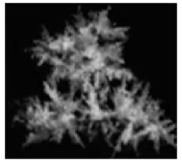
Sotiropoulou et al. 2021

WRF Implementation

Collisional Break-up

Morrison scheme: 2-moment bulk microphysics, 5 hydrometeor species:

(1) **cloud droplets** (2) **raindrops**

(3) **cloud ice**  (4) **graupel**  (5) **snow** 

Fragmentation is assumed to occur after:

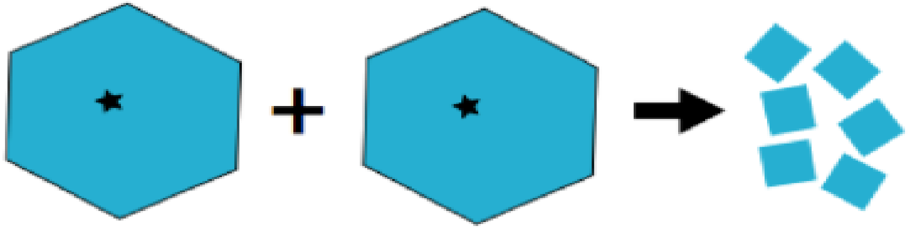
(1) cloud ice – graupel collisions → fragmentation of ice

(2) cloud ice – snow collisions → fragmentation of ice

(3) snow – graupel collisions → fragmentation of snow

(4) snow – snow collisions → fragmentation of snow

(5) graupel – graupel collisions → fragmentation of graupel



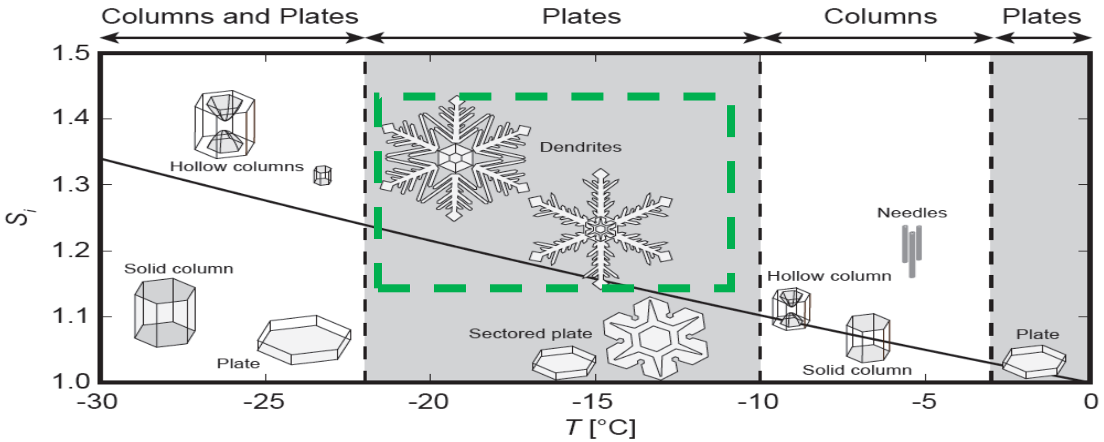
Fragments are added to **cloud ice** category

SIP implementation in WRF

Fragments per collision: parameterizations

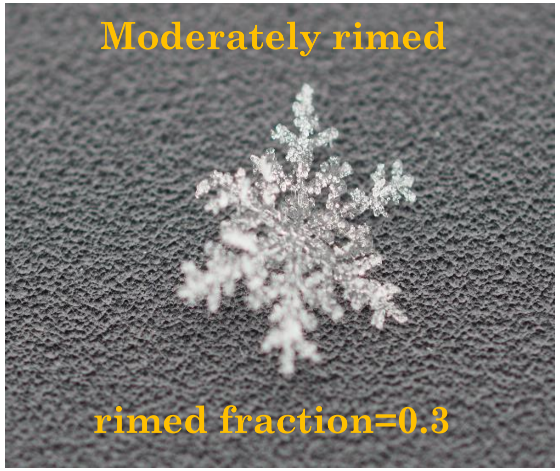
I. Following Phillips et al. (2017)

$$F_{BR} = aA\left(1 - exp\left\{-\left[\frac{C\,Ko}{aA}\right]^{\gamma}\right\}\right) \quad , \quad a = \pi \mathbf{D}^2$$



F_{BR} is a function of (i) **collisional kinetic energy**, (ii) **size**, (iii) **ice type**, (iv) **ice habit** and (v) **rimed fraction**

Parameter	Collision Type			
	Type I: Collisions of graupel (size: $5\times10^{-4} < D < 5\times10^{-3}$ m) with graupel/hail	Type I: Collisions between hail only	Types II or III: Collisions of either crystals or snow (rimed fraction: $\Psi < 0.5$; size: $5\times10^{-4} < D < 5\times10^{-3}$ m) with any ice (crystals, snow, or graupel/hail)	
			Dendrites (e.g., −12° to −17°C)	Spatial planar (e.g., −40° to −17°C, −9° to −12°C)
A (m^{-2})	$\frac{a_0}{3} + \max\left(\frac{2a_0}{3} - \frac{a_0}{9}\lvert T - T_0\rvert, 0\right)$	$\frac{a_0}{3} + \max\left(\frac{2a_0}{3} - \frac{a_0}{9}\lvert T - T_0\rvert, 0\right)$	$(1.41\times10^6)\times(1+100\Psi^2)\times\left(1+\frac{3.98\times10^{-5}}{D^{1.5}}\right)$	$1.58\times10^7\times(1+100\Psi^2)\times\left(1+\frac{1.33\times10^{-4}}{D^{1.5}}\right)$
C (J^{-1})	$(6.30\times10^6)\times\psi$	3.31×10^5	$(3.09\times10^6)\times\psi$	$(7.08\times10^6)\times\psi$
γ	0.3	0.54	$0.50 - 0.25\Psi$	$0.50 - 0.25\Psi$
a_0 (m^{-2})	$(3.78\times10^4)\times\left(1+\frac{0.0079}{D^{1.5}}\right)$	4.35×10^5	—	—
T_0 (°C)	−15	−15	—	—
$\mathcal{N}_{max}$	100	1000	100	100
ψ	3.5×10^{-3}	3.5×10^{-3}	3.5×10^{-3}	3.5×10^{-3}
ζ	0.001	10^{-6}	0.001	0.001



SIP implementation in WRF

Fragments per collision: parameterizations

II. Following Sullivan et al. (2018)

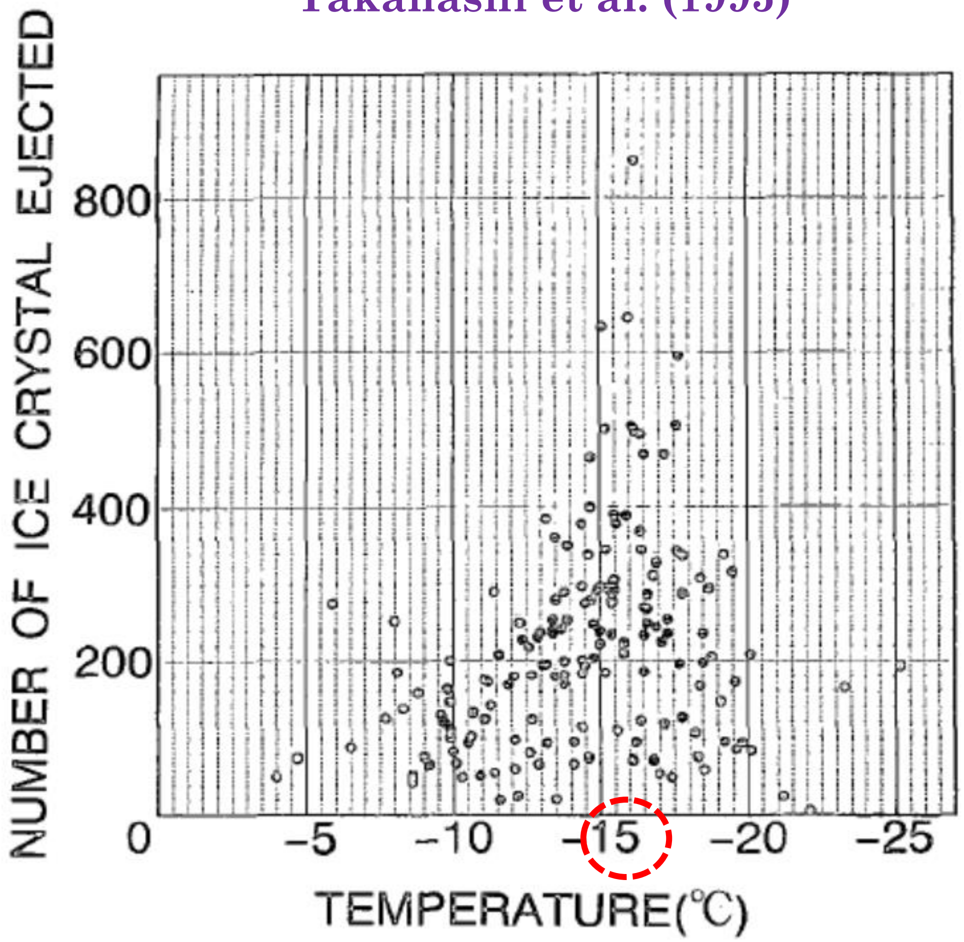
$$F_{BR} = 280(\boldsymbol{T} - 252)^{1.2} \exp\left(-\frac{(T-252)}{5}\right) \frac{\boldsymbol{D}}{D0}$$

F_{BR} is a function of (i) **temperature** and is further scaled to include the influence of (ii) **size**

Note! Takahashi et al. (1995) used 2-cm hailballs in their experiments (D0 = 0.02 m)

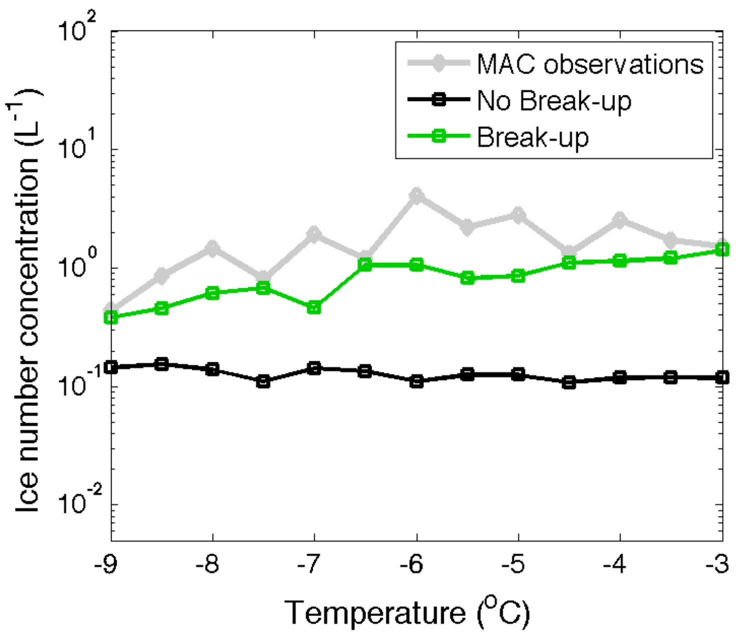
max ice splinter production rate at ∽ **-16 °C**

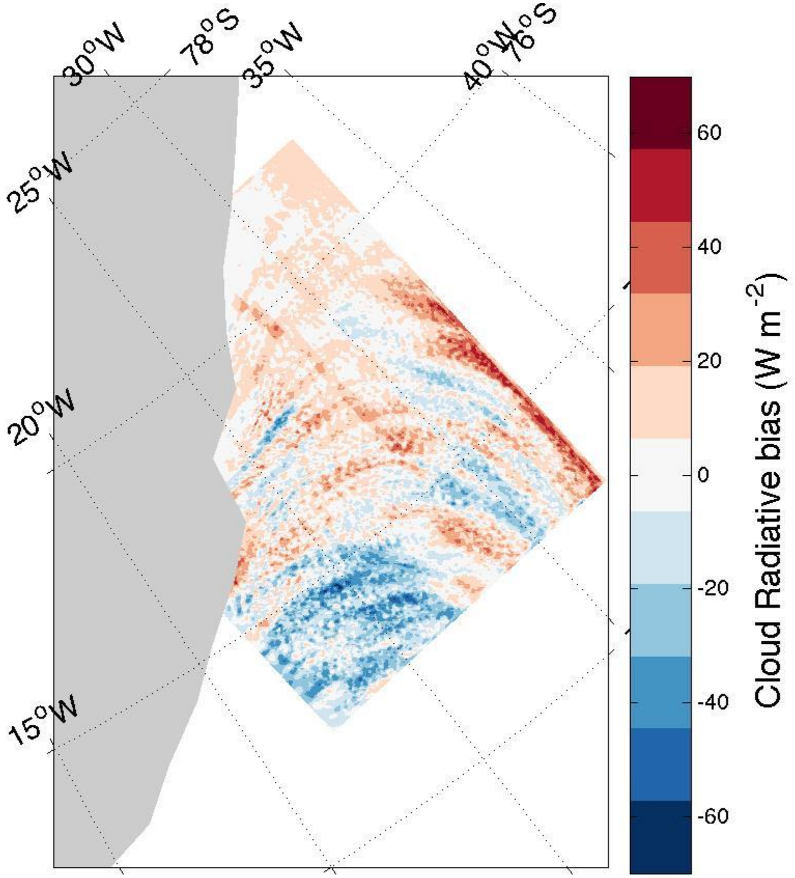
Laboratory experiment by Takahashi et al. (1995)



SIP impacts on Antarctic clouds (regional scale)

MAC (Microphysics of Antarctic clouds campaign)





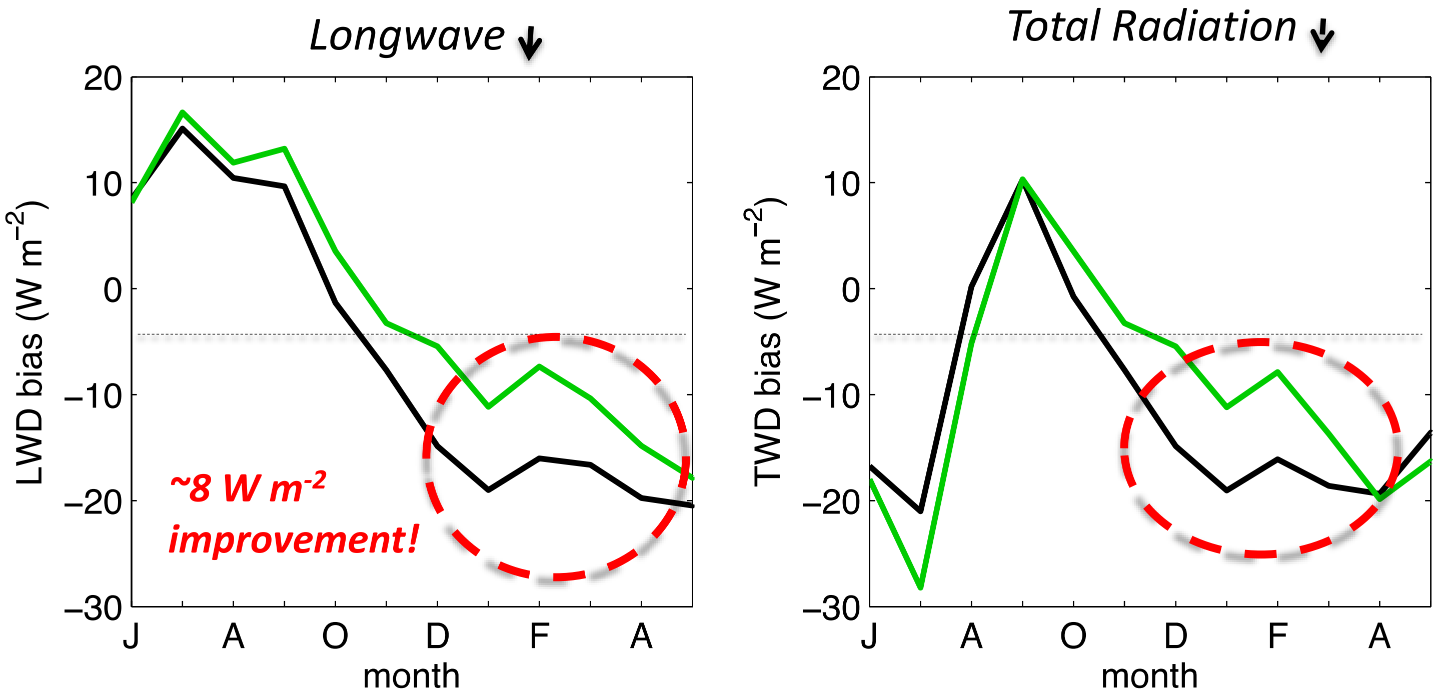
Implementation of the missing mechanism bridges the gap between observed and modeled ice number concentrations

The newly implemented process alters cloud-induced warming by up to 60 W m^{-2}

Sotiropoulou et al. 2021a

SIP effects in the NorESM2 climate model (global scale)

Radiation biases (model –EBAF satellite observations) over the Arctic region (2016-2017)



– standard* model (only 1 SIP mechanism: Hallett-Mossop)

– additional SIP mechanisms (BR, DS)

Sotiropoulou et al., J. Clim., in review

**ice aggregation adjusted for Arctic clouds following Chellini et al. (2022)*

SIP processes in orographic MPCs

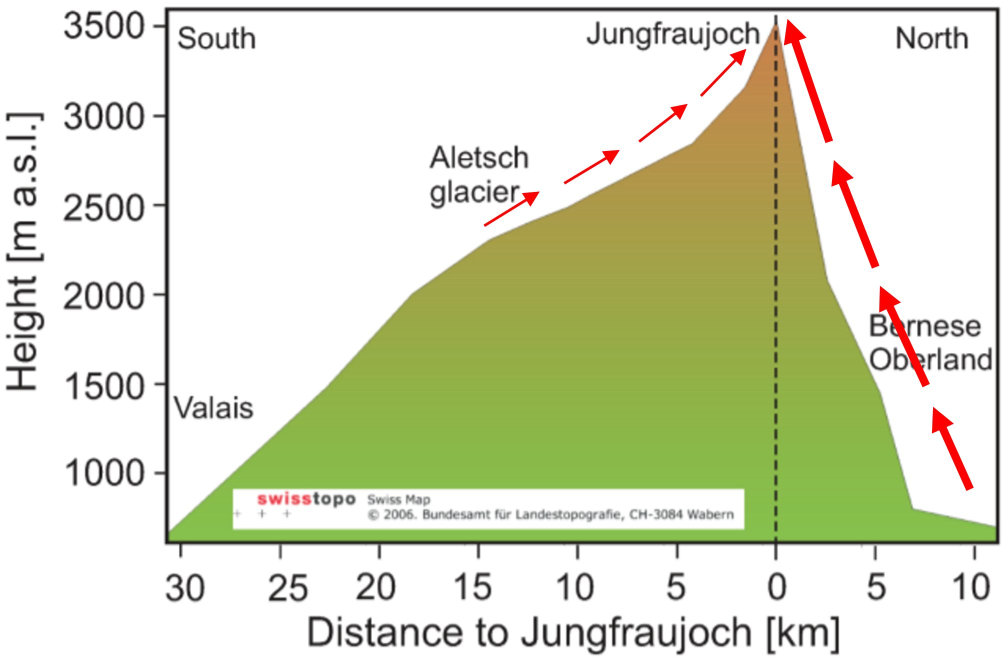
CLACE 2014 field campaign

"Cloud Aerosol Characterization Experiments" (Lloyd et al. 2015)

Lohmann et al., 2016

SE winds

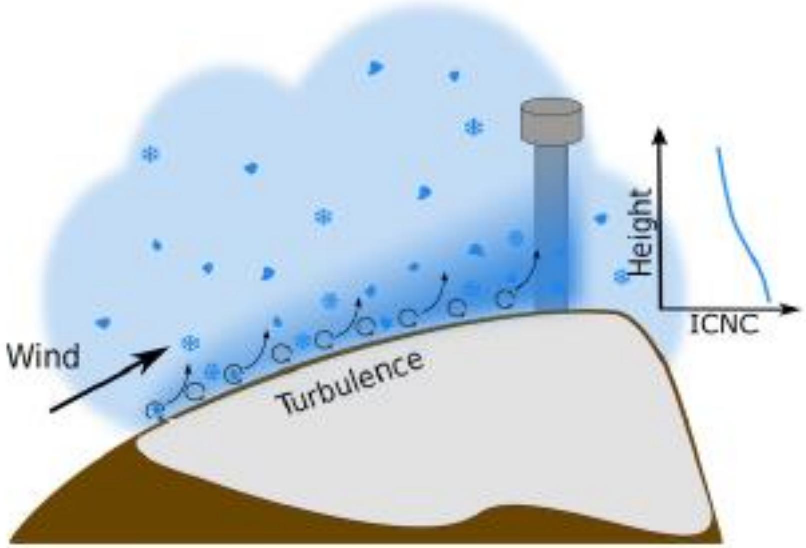
- ✓ Gentle ascent
- ✓ Weak updrafts
- ✓ Low supersaturations
- ✓ Glaciated clouds



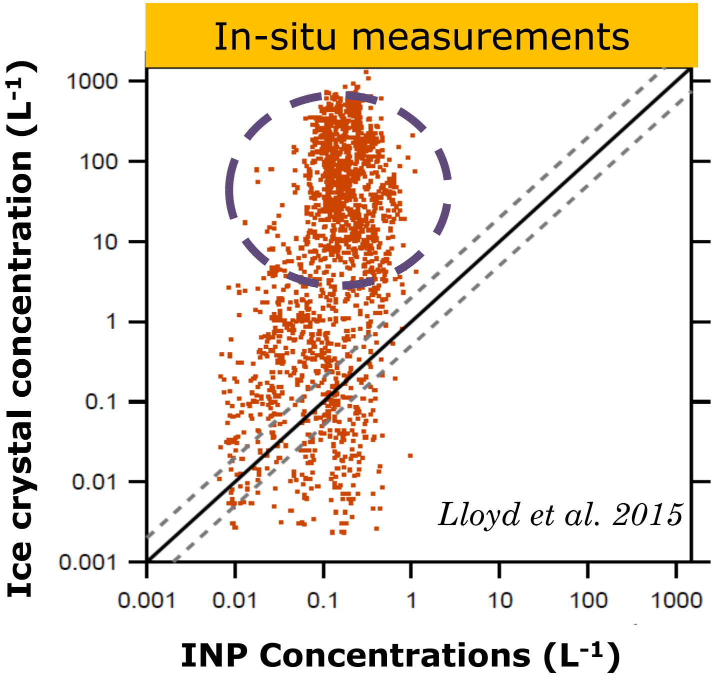
NW winds

- ✓ Very steep ascent
- ✓ Stronger updrafts
- ✓ High supersaturations
- ✓ Frequent mixed-phase conditions

SIP processes in orographic MPCs



Blowing Snow: *surface winds lift snowflakes which can provide ice crystals to the clouds above*



During the CLACE2014 campaign at Jungfraujoch (Alps), **blowing snow** was proposed to responsible for the enhanced ice number concentrations when:

- ✓ Wind speed $\gtrsim$ 5 ms^{-1}
- ✓ Ice number concentrations $\lesssim$ 100 L^{-1}

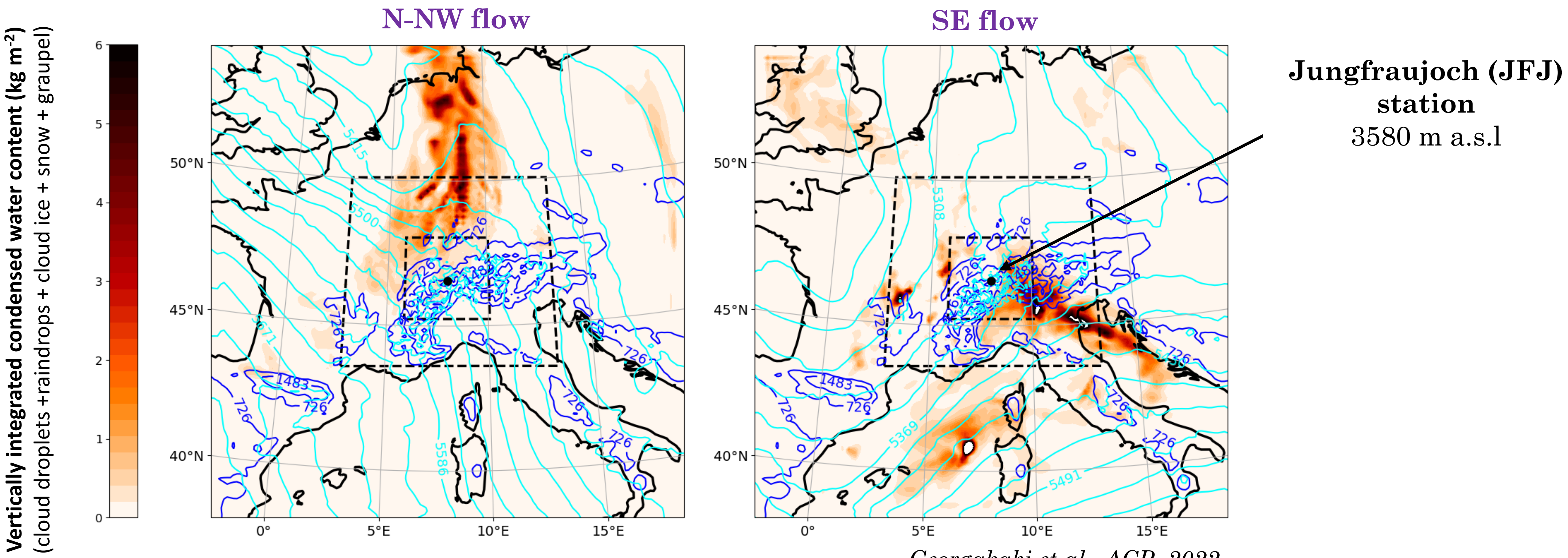
Other SIP mechanisms overlooked!!

SIP processes in orographic MPCs
Modeling with WRF

CLACE 2014 field campaign

"Cloud Aerosol Characterization Experiments" (Lloyd et al. 2015)

✓ 3 nested domains surrounding JFJ with horizontal resolution: **12km - 3km - 1 km**



Georgakaki et al., ACP, 2022

Two simulation periods in order to investigate the dynamical influence caused by the local orography:

✓ **25.01.2014 00.00 UTC – 28.01.2014 00.00 UTC** : steep ascent of the airmasses before arriving at JFJ

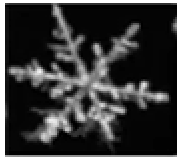
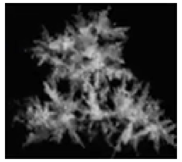
✓ **29.01.2014 00.00 UTC – 01.02.2014 00.00 UTC :** gentle ascent of the airmasses over the Aletsch Glacier

SIP implementation in WRF

Collisional Break-up

Morrison scheme: 2-moment bulk microphysics, 5 hydrometeor species:

(1) **cloud droplets** (2) **raindrops**

(3) **cloud ice**  (4) **graupel**  (5) **snow** 

Fragmentation is assumed to occur after:

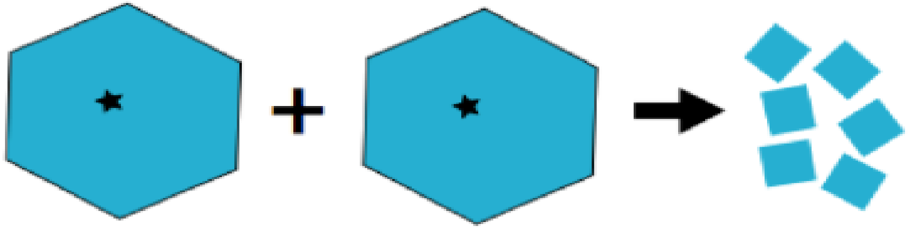
(1) cloud ice – graupel collisions → fragmentation of ice

(2) cloud ice – snow collisions → fragmentation of ice

(3) snow – graupel collisions → fragmentation of snow

(4) snow – snow collisions → fragmentation of snow

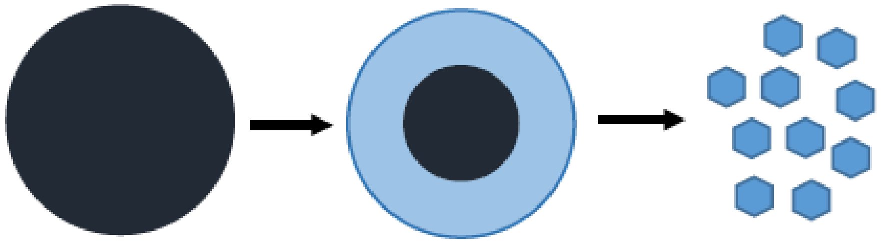
(5) graupel – graupel collisions → fragmentation of graupel



Fragments are added to **cloud ice** category

SIP implementation in WRF

Freezing and shattering droplets



Following Phillips et al. (2018)

Fragmentation of freezing raindrops is assumed to occur during:

- **MODE 1:** Collision with smaller ice-particle (cloud ice) or heterogeneous drop freezing → both **BIG** and **tiny** fragments will be emitted as a function of **temperature** and **droplet size** → tiny ejected splinters initiated as new cloud ice

$$N_{DS} = \Xi(\mathbf{D})\Omega(\mathbf{T})\left[\frac{\zeta\eta^2}{(\mathbf{T}-\mathrm{T0})^2} + \beta\mathbf{T}\right]$$

- **MODE 2:** Collision with more massive ice-particle (snow/graupel) → only tiny splinters are generated as a function of **temperature**, **droplet size** and **collisional kinetic energy**.

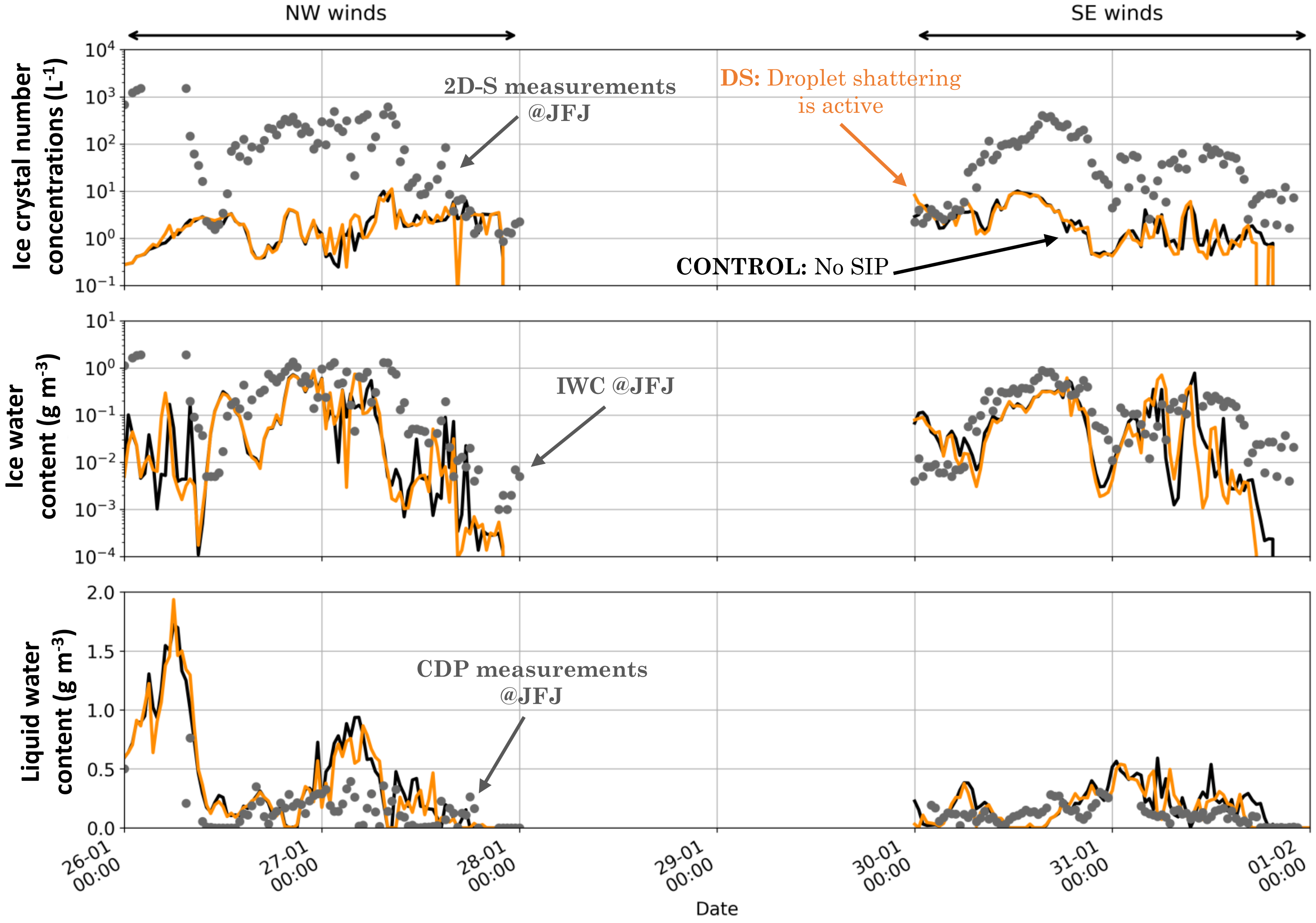
$$N_{DS} = 3\,\Phi(\mathbf{T}) \times [1 - f(\mathbf{T})] \times \max(\boldsymbol{DE} - DE_{crit}, 0)$$

Georgakaki et al., ACP, 2022

SIP processes in orographic MPCs

CLACE 2014: effect of DS mechanism alone

- ✓ CONTROL (black line) and DS (orange line) **underestimate** the ice crystal number concentrations by 2-3 orders of magnitude
- ✓ The modeled ice water content is outside the observed range
- ✓ The cloud liquid water is **overestimated**

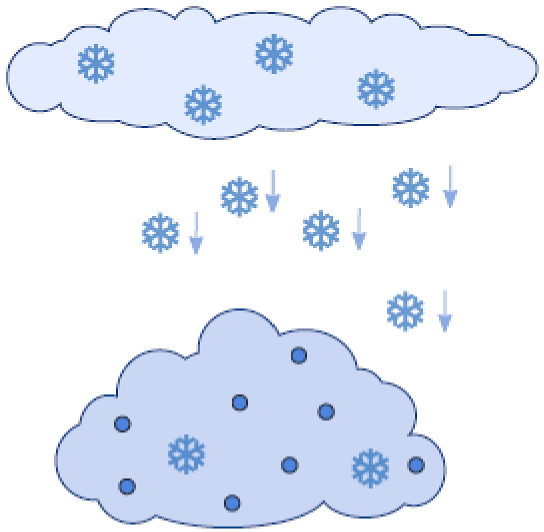


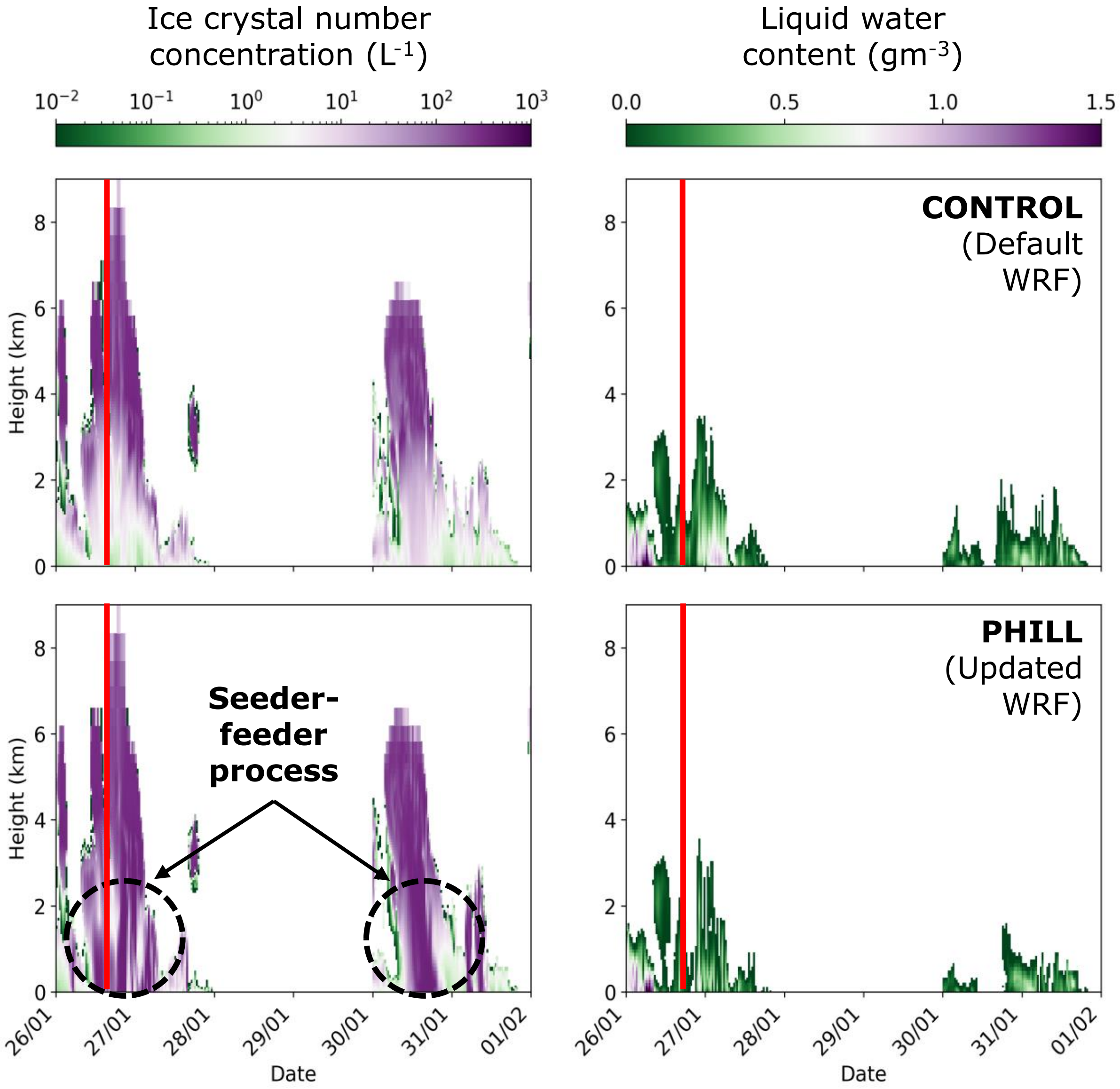
Georgakaki et al., ACP, 2022

SIP processes in orographic MPCs

CLACE 2014: effects from ice-ice collisions

External seeder-feeder process

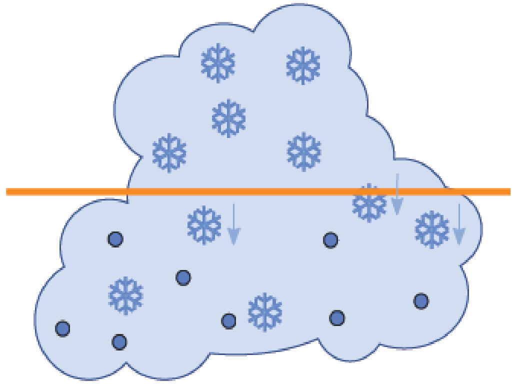




✓ **Seeding ice crystals** can enhance the **collision efficiencies** and hence SIP through BR in the lower-lying parts of the cloud

✓ Satellite observations reveal that **seeder-feeder situations** (both external and in-cloud) occur frequently over Switzerland (Proske et al., 2021)

In-cloud seeding



Proske et al. 2021

Georgakaki et al., ACP, 2022

SIP processes in orographic MPCs

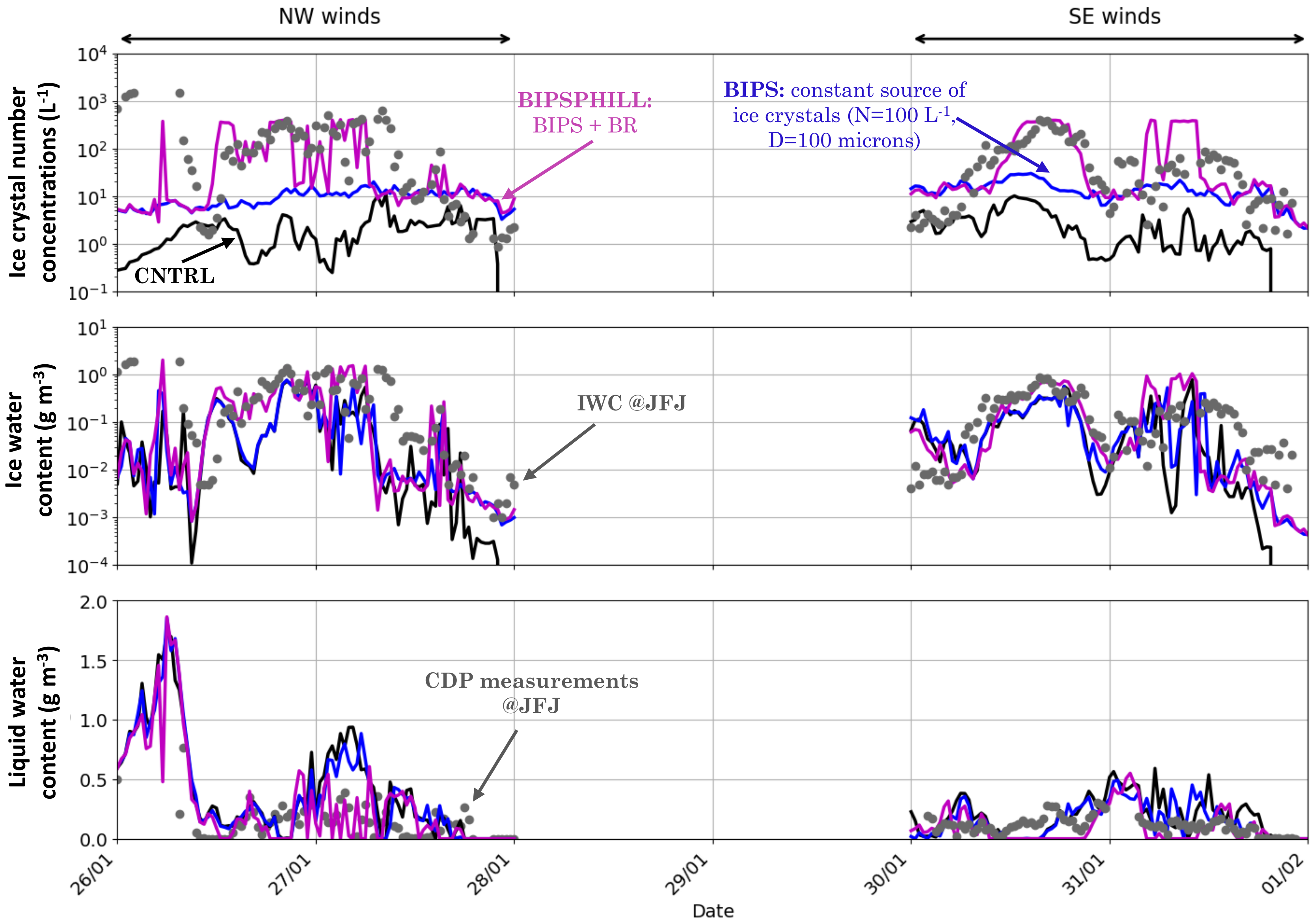
CLACE 2014: impact of "blowing snow"

Blowing snow representation:

Constant **source of ice crystals** ($100\ L^{-1}$) with sizes of 100 microns in the first cell of WRF

- ✓ Blowing snow alone (**light blue line**) cannot account for the observed ice particle concentrations, as it never predicts ICNCs ≳ 50 L^{-1}
- ✓ "Blowing snow" is important when a cloud is near the ground (i.e., ice supersaturated environment)
- ✓ The combined effect of blowing snow and collisional break-up (**magenta line**) results in best agreement with measured ICNCs

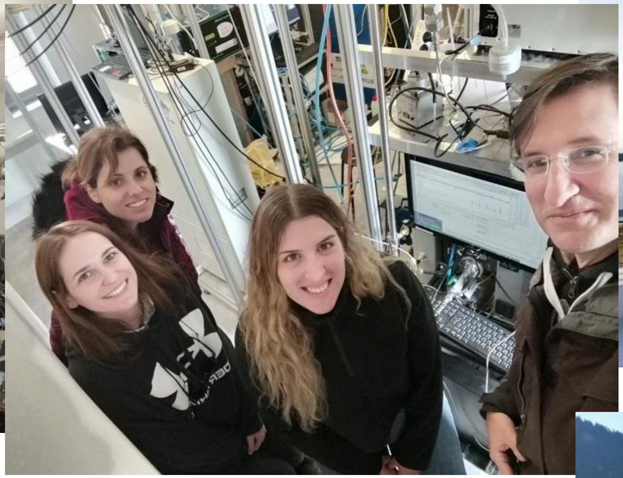
Georgakaki et al., ACP, 2022



CALISHTO campaign: https://calishto.panacea-ri.gr/

Cloud-AerosoL InteractionS in the Helmos background Troposphere (Oct.21-Feb.22)





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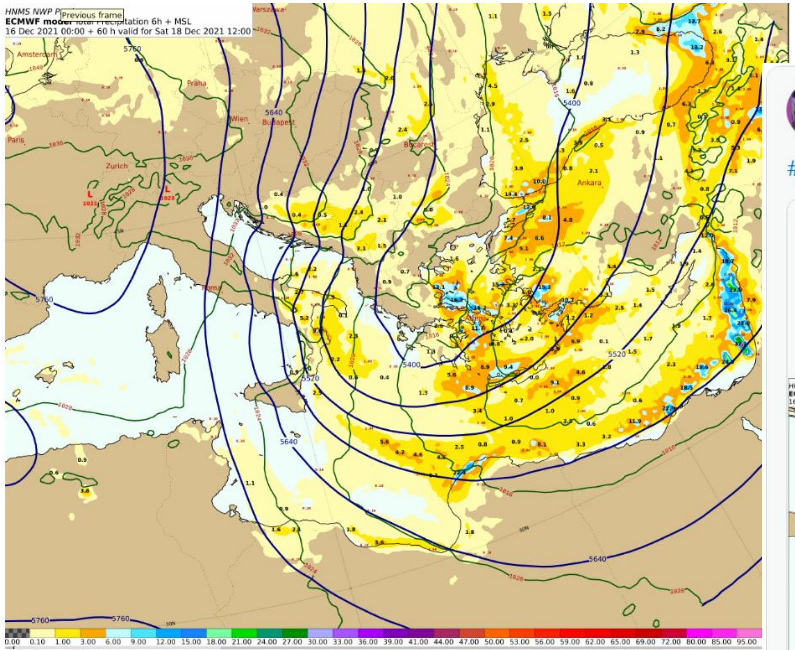
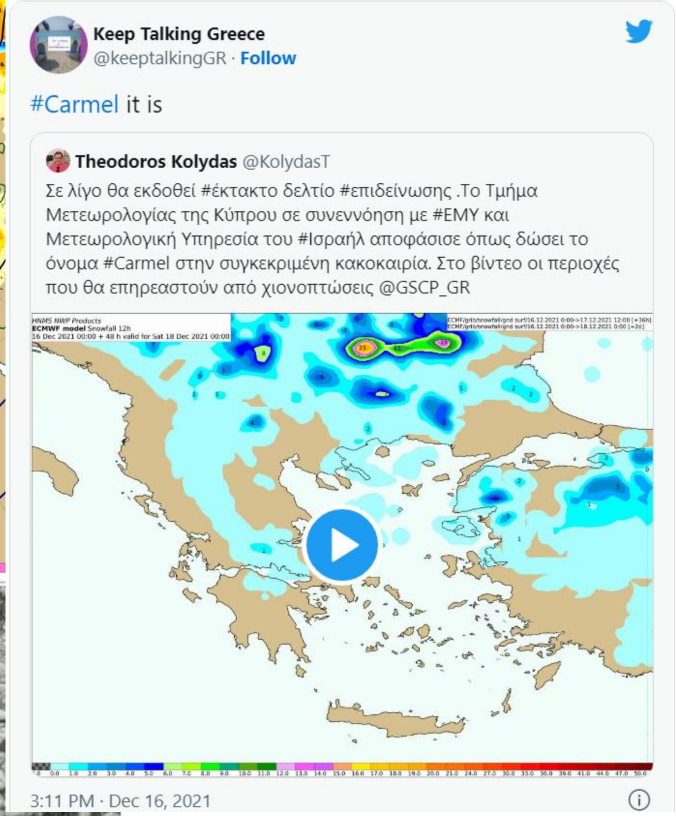
Case study: Storm Carmel visiting Greece



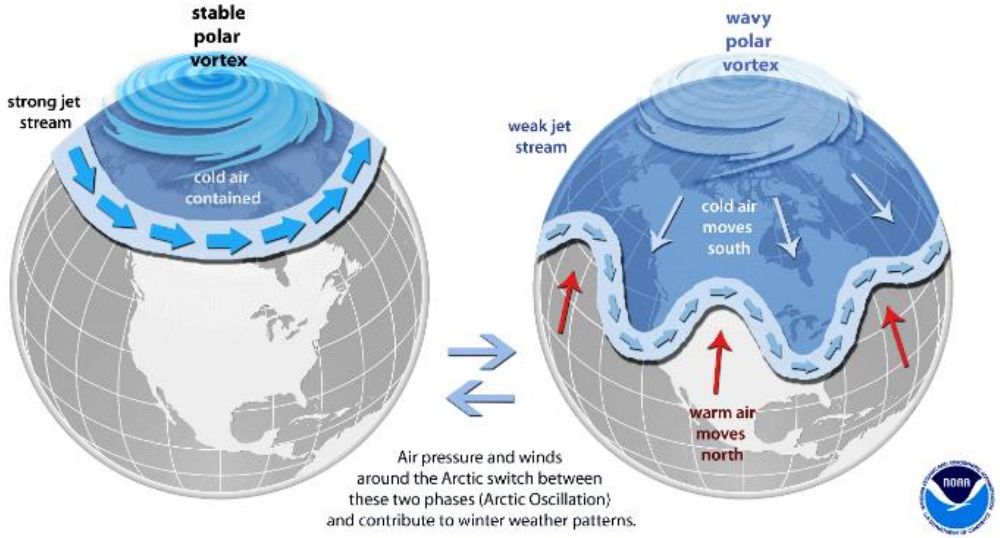


Snowfall Forecast by the National Meteorological Service (EMY)

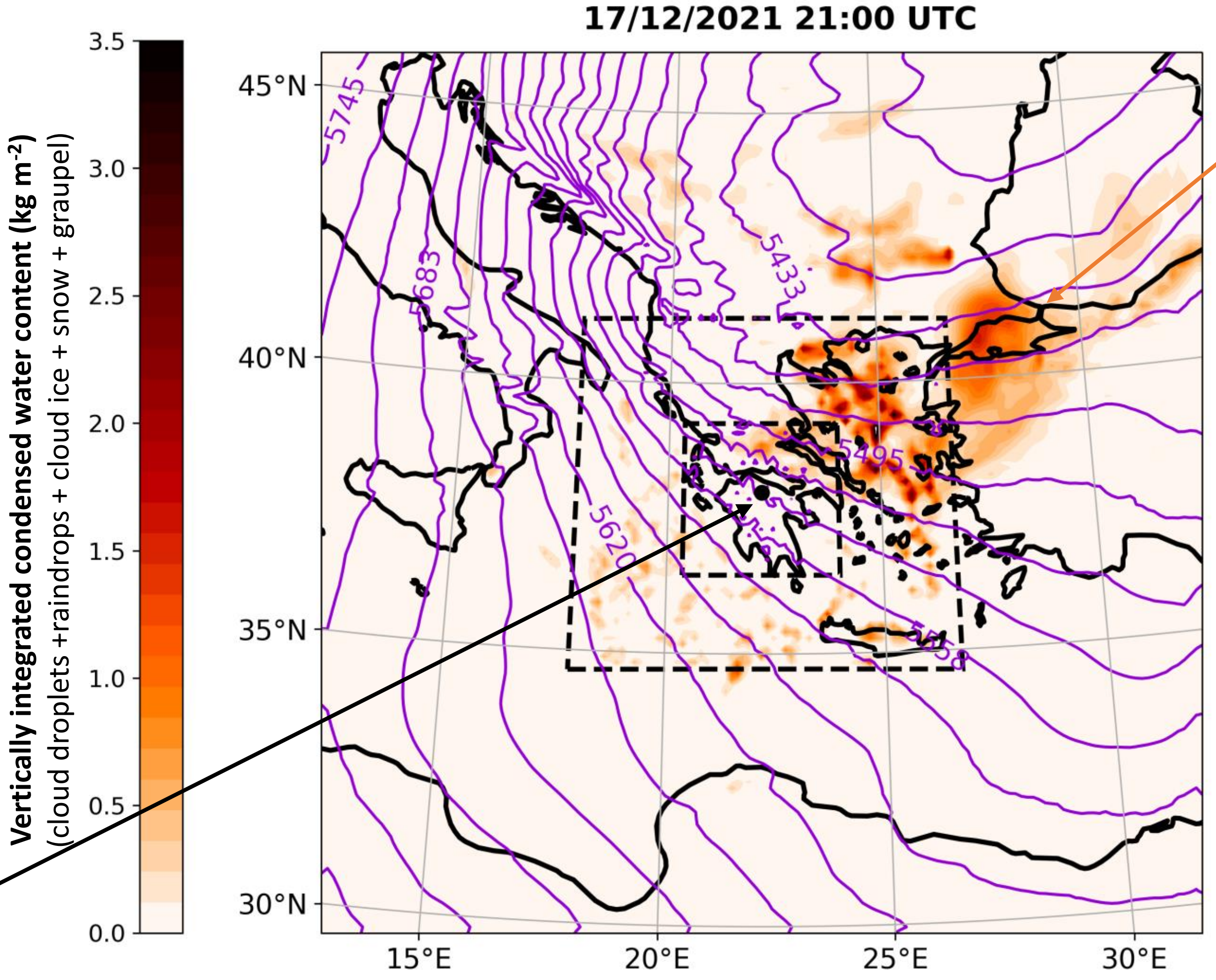
Sharp temperature drop, stormy winds and snowfall in the central and southern parts of Greece on ***December 18th***.

The "culprit" behind the storm?

...a visit from the polar vortex breaking out of the Arctic



Modeling Storm Carmel with the Weather Research and Forecasting model (WRF)

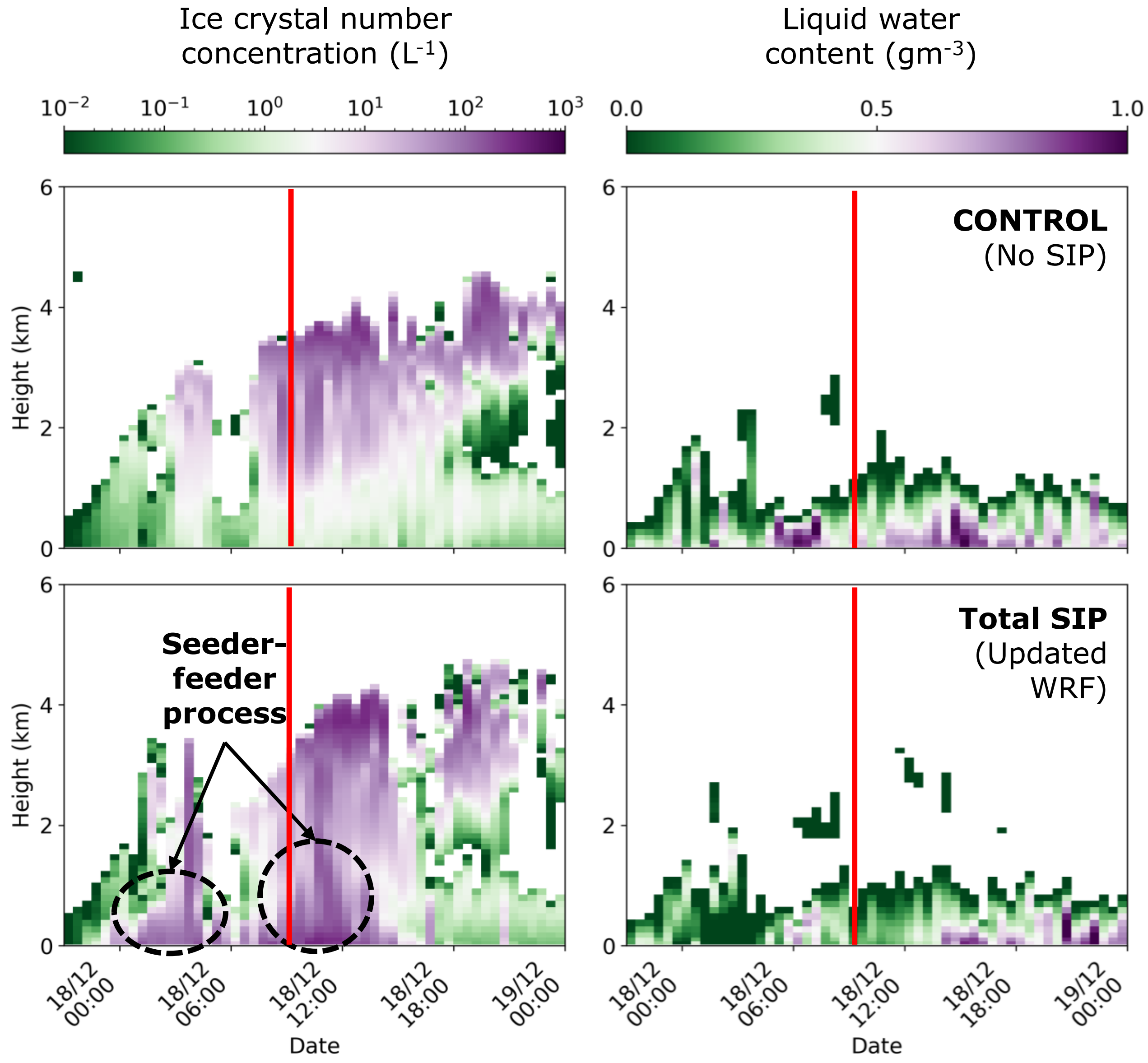


Polar airmasses arriving from the Northeast

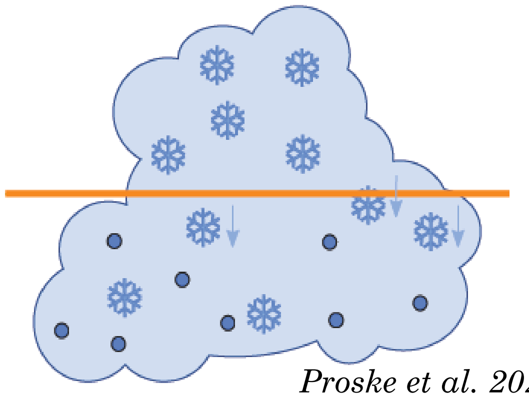
- 3 nested domains surrounding the HAC station with horizontal resolution: **12km - 3km - 1 km**
- **Simulation period**: 17.12.2021 00.00 UTC – 19.12.2021 00.00 UTC
- Spin-up time: 21 hours
- **Time-step**: 36s-9s-3s

- reference lat/lon = 37.984˚N, 22.196˚E (@HAC station)

Conditions favoring ice multiplication at Mt Helmos



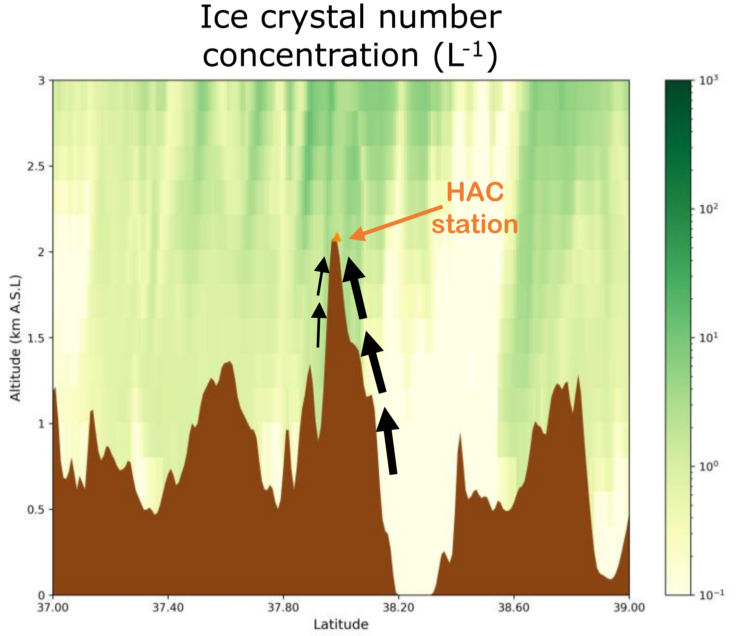
In-cloud seeding



Proske et al. 2021

1. Seeding ice crystals enhance the collision efficiencies and SIP through BR in the lower-lying parts of the cloud

2. Steep ascent of the airmasses due to **strong orographic forcing** → mixed-phase conditions maintained

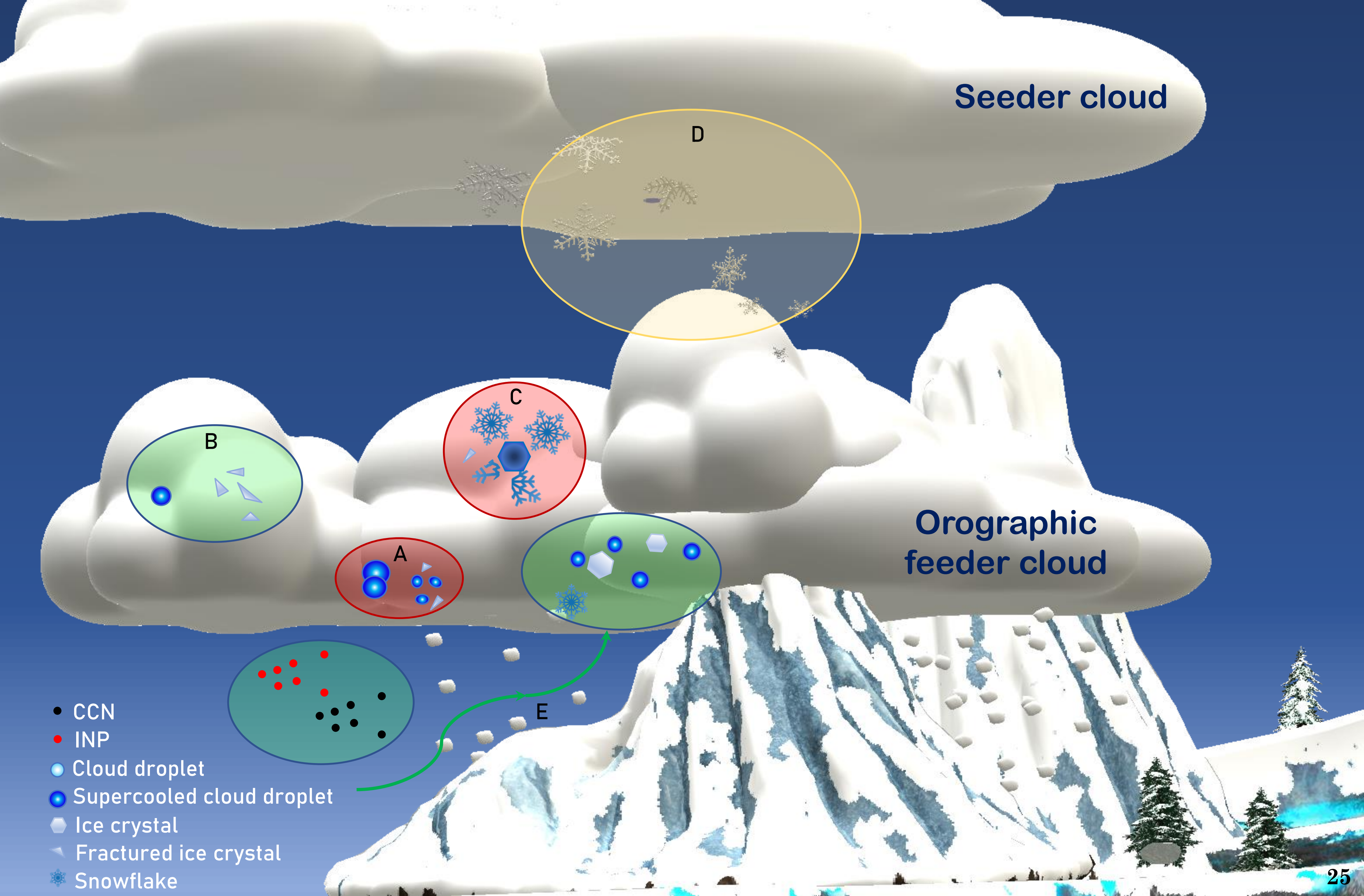


@18/12 10:30 UTC

EPFL

Wintertime orographic mixed-phase clouds

- ✓ The Hallett-Mossop process→ ineffective since T < -8 ˚C [A]
- ✓ The Droplet Shattering process→ not efficient due to a lack of big raindrops [B]
- ✓ The collisional break-up process→ elevates ICNCs up to 3 orders of magnitude but is activated in certain cases [C]
- ✓ The seeder feeder effect → frequent over Switzerland → enhanced collision efficiency in the low-level feeder clouds → further promotes cloud glaciation [D]
- ✓ Blowing snow → significant contribution when cloud is near the ground → further facilitates SIP through BR [E]



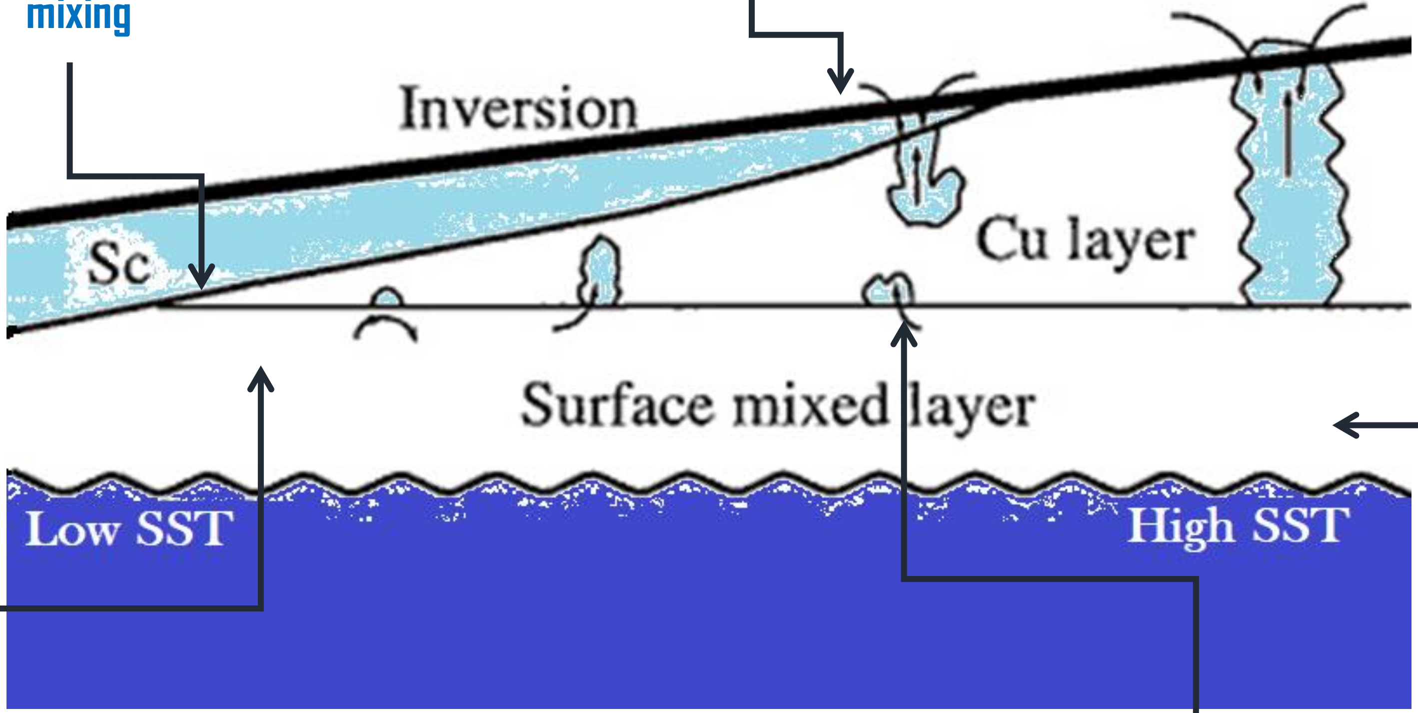
SIP effects on Stratocumulus- to-Cumulus Transition (Cold air outbreaks)

Growing cumuli produce more precipitation.
Drying downdrafts help drain the Sc layer

Increased surface fluxes lead to increased in-cloud mixing

Stratiform Cloud

Stratocumulus-to-cumulus Transition



Stratocu-cumulus transition completed

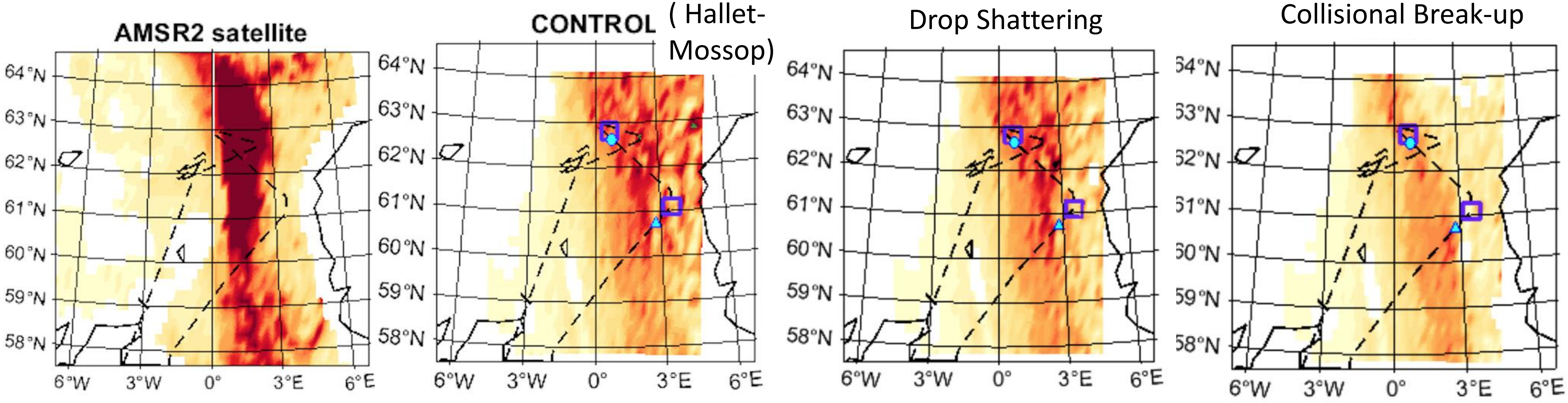
Decoupling due to boundary-layer deepening & evaporation of precipitation

Cumulus clouds grow while the decoupled stratocumulus layer dissipates

Wyant et al. 1997

SIP effects on Stratocumulus- to-Cumulus Transition (Cold air outbreaks)

Simulations of a CAO event (with WRF) observed north of UK (Nov.2013)

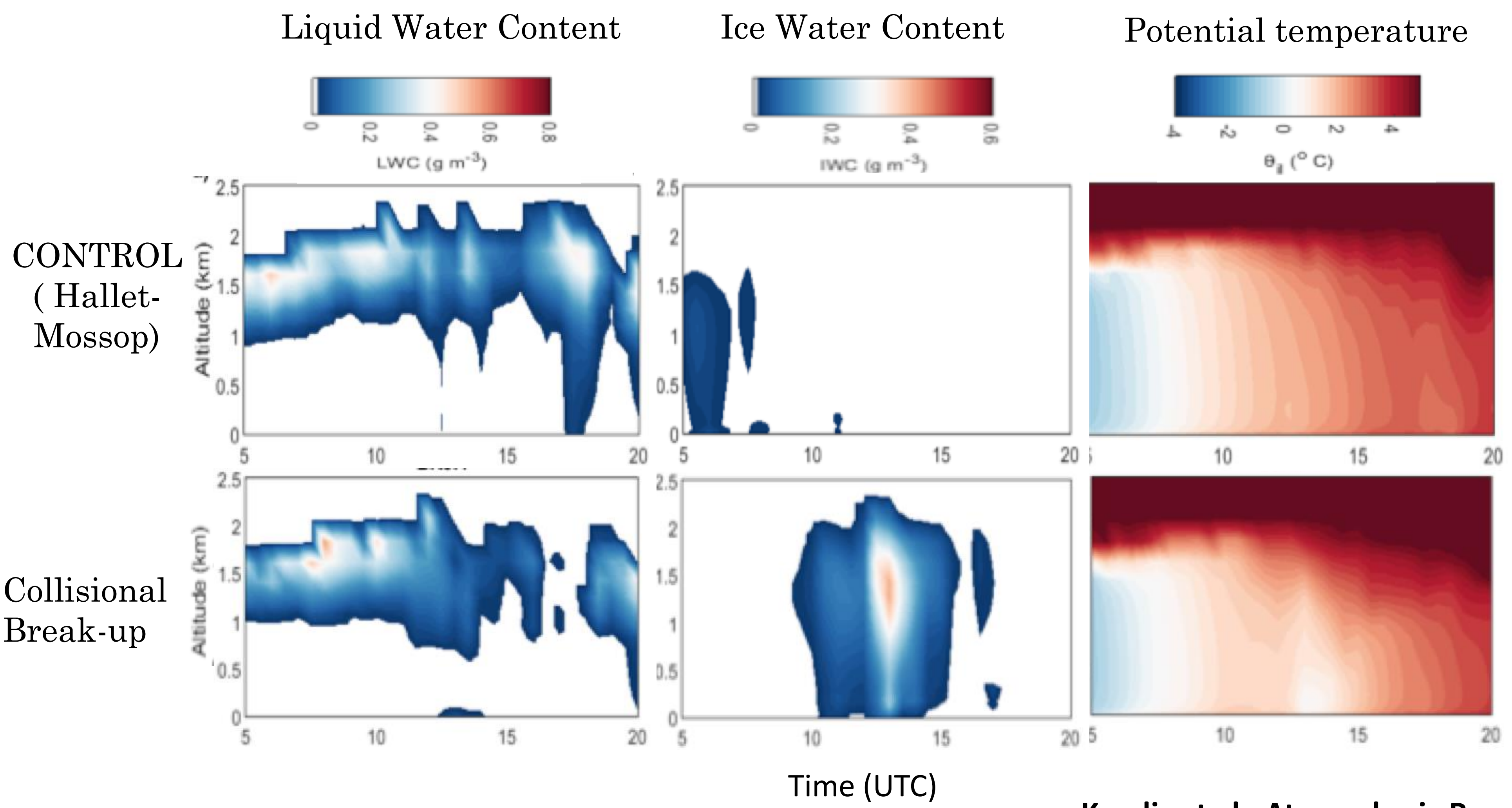


Liquid Water Path

Karalis et al., Atmospheric Research (2022)

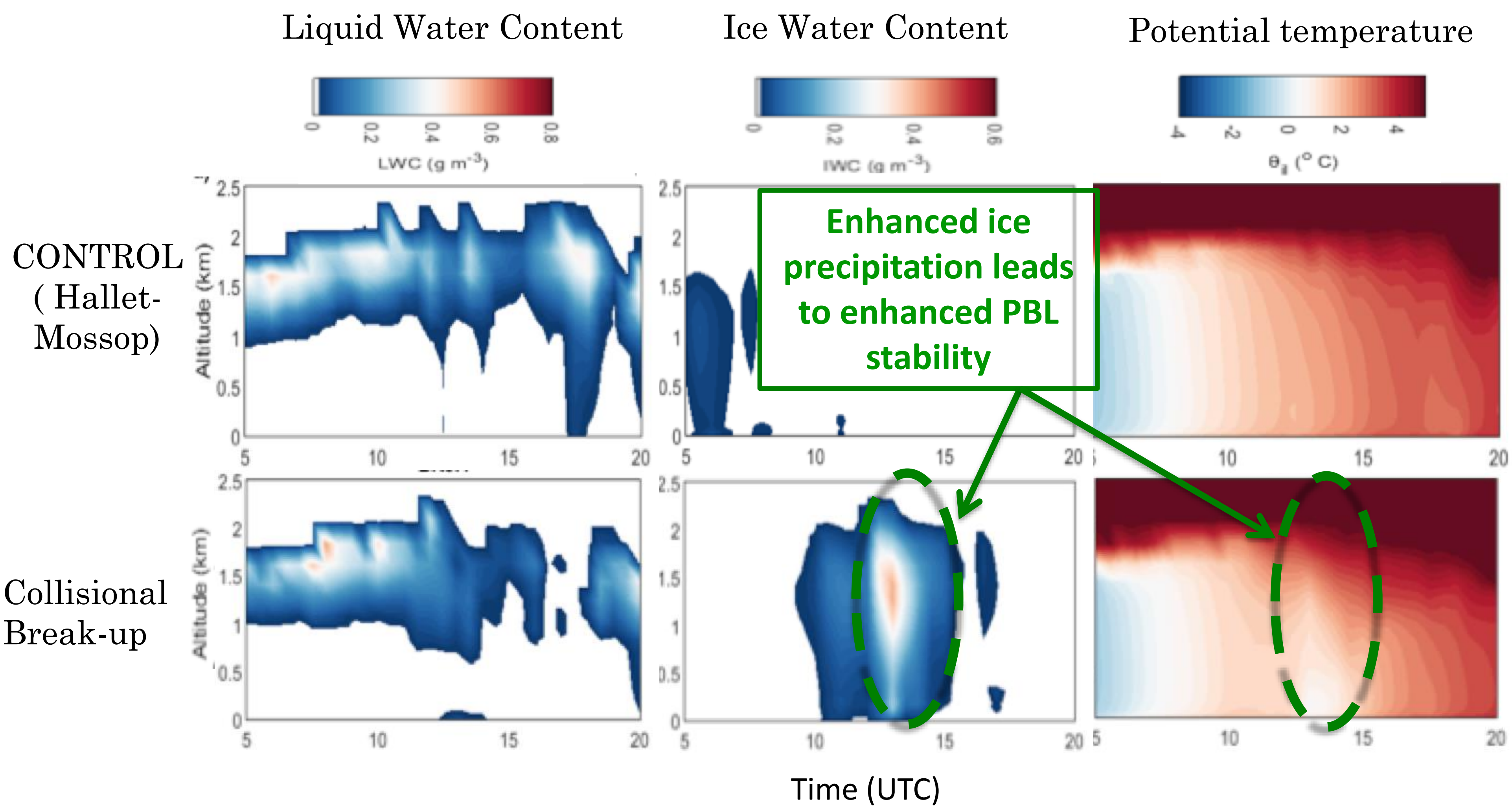
- ✓ Standard WRF (CONTROL) cannot reproduce the Stratocumulus-to-Cumulus transition correctly
- ✓ Increasing ice production through drop-shattering & especially collisional break-up improves the transition

SIP effects on Stratocumulus- to-Cumulus Transition (Cold air outbreaks)



Karalis et al., Atmospheric Research (2022)

SIP effects on Stratocumulus- to-Cumulus Transition (Cold air outbreaks)



Karalis et al., Atmospheric Research (2022)

SIP effects on Stratocumulus- to-Cumulus Transition (Cold air outbreaks)

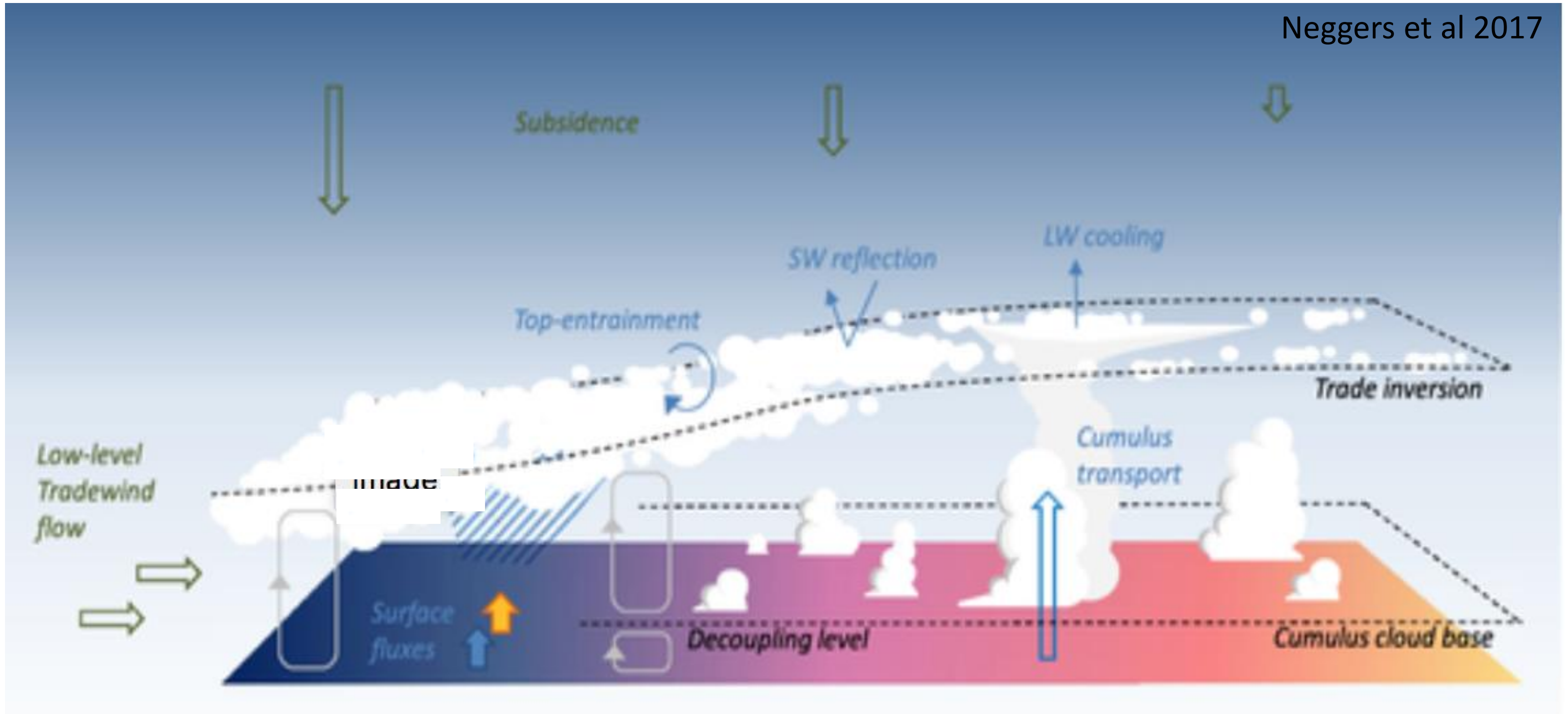
Activation of the missing SIP mechanisms *(collisional break-up mostly)*

↓

Enhanced precipitation

↓

Enhanced boundary-layer decoupling



Karalis et al., Atmospheric Research (2022)

↓

Accelerated onset of the stratocumulus-to-cumulus transition

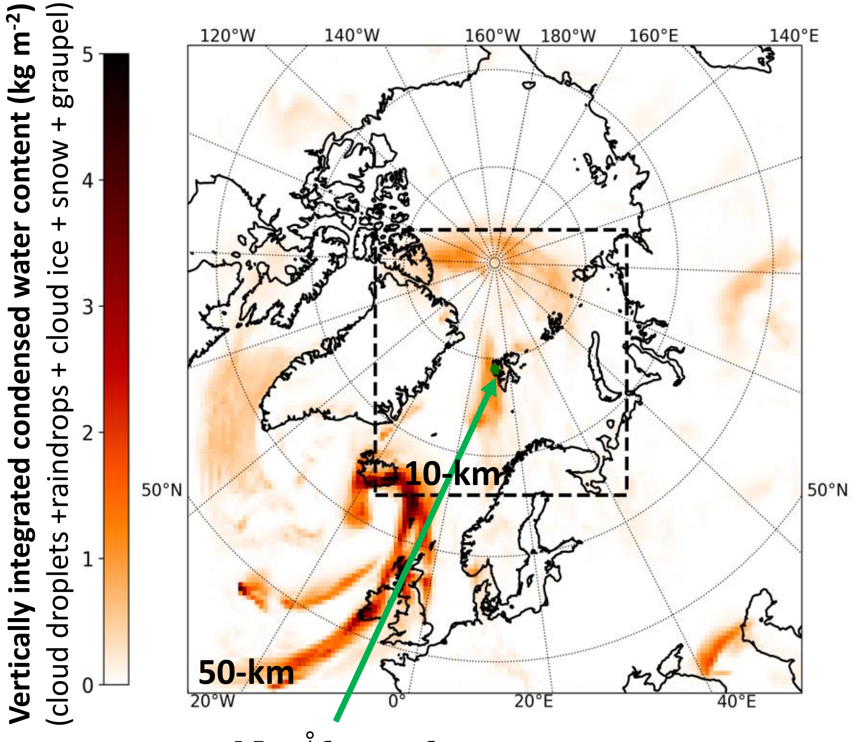
Our approach to parameterize SIP in polar stratiform clouds

Total ice crystal number = **Primary ice** × **Ice Enhancement Factor (IEF)**

Primary ice production (PIP) described in all kind of models

Parameterized expression developed in this study

Perform "regional climate" simulations with the WRF model



Ny-Ålesund research station

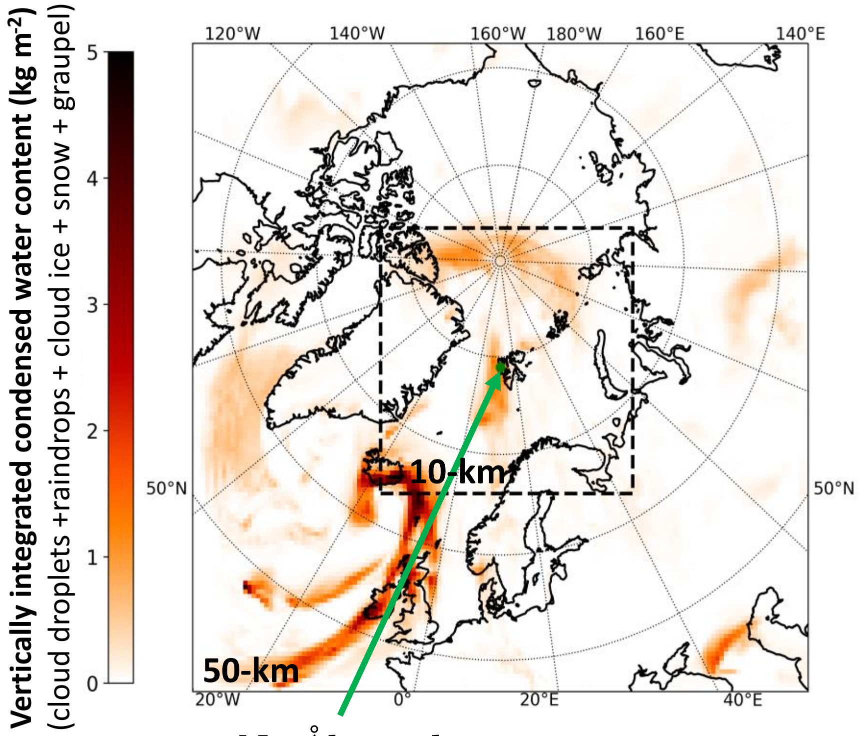
Georgakaki et al., in preparation

- ✓ Focus on **Arctic mixed-phase clouds**
- ✓ 2-year simulation period: 2016-2017, Ny-Ålesund
- ✓ Ice processes in the updated version of WRF:
  - **i. Primary ice production** → Homogeneous freezing; Heterogeneous freezing
  - **ii.Secondary ice production** → Hallett-Mossop; Collisional break-up; Droplet shattering

Our approach to parameterize SIP in polar stratiform clouds

Total ice crystal number = **Primary ice** × **Ice Enhancement Factor (IEF)**

Perform "regional climate" simulations with the WRF model



Ny-Ålesund research station

Georgakaki et al., in preparation

- ✓ Outputs extracted from the 10 km-resolution (nest)
- ✓ IEF encompasses the effect of all 3 important SIP processes:

$$\boldsymbol{IEF = IEF_{BR} + IEF_{DS} + IEF_{HM}}$$

$$IEF_i = 1 + \frac{SIP_i\ rate}{PIP\ rate}$$

Developing SIP parameterization: Random Forest (RaFSIP) regressor

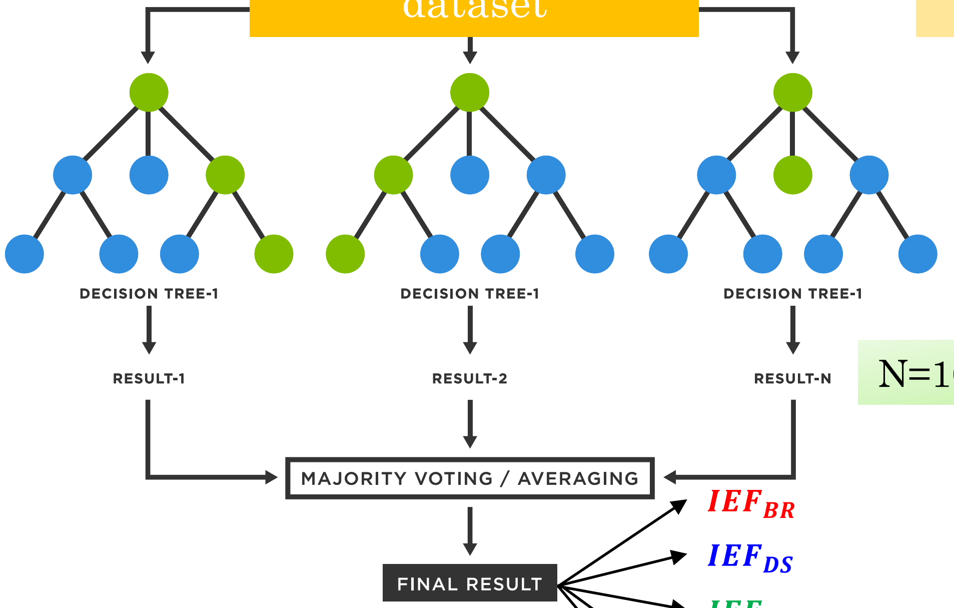
Inputs/ Features
- Ice water content
- Liquid water content
- Temperature
- Relative humidity w.r.t ice (RHI)
- Cloud droplet riming
- Raindrop riming
- Raindrop mass mixing ratio

Developed using the RandomForestRegressor class from the **scikit-learn** package

WRF 2-year high-resolution outputs

90% → Training/validation dataset

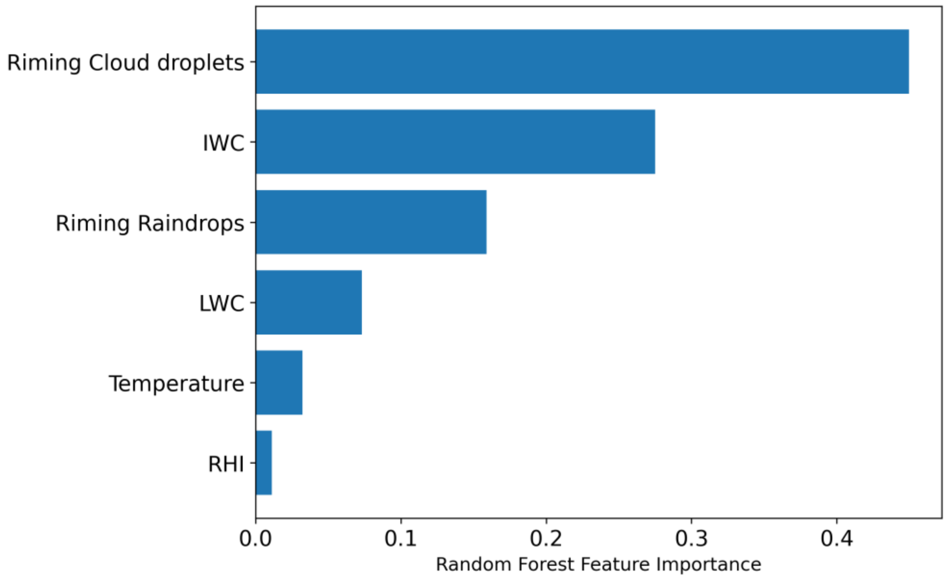
10% → Testing dataset



Each tree is trained on a random subset of the original dataset → **prevents overfitting**

N=10 decision trees

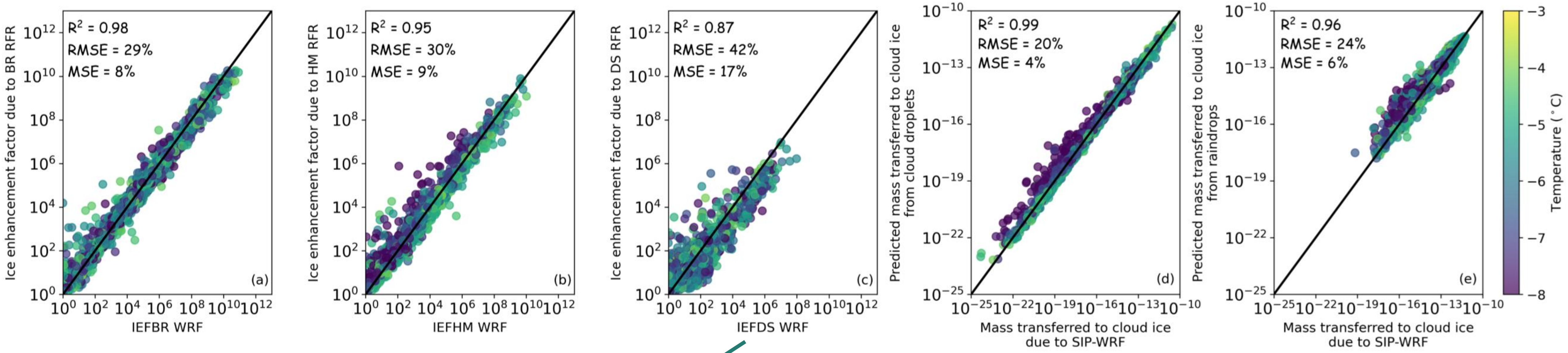
- IEF_{BR}
- IEF_{DS}
- IEF_{HM}
- Mass transferred from cloud droplets to cloud ice
- Mass transferred from raindrops to cloud ice



Georgakaki et al., in preparation

Offline performance of the RaFSIP algorithms

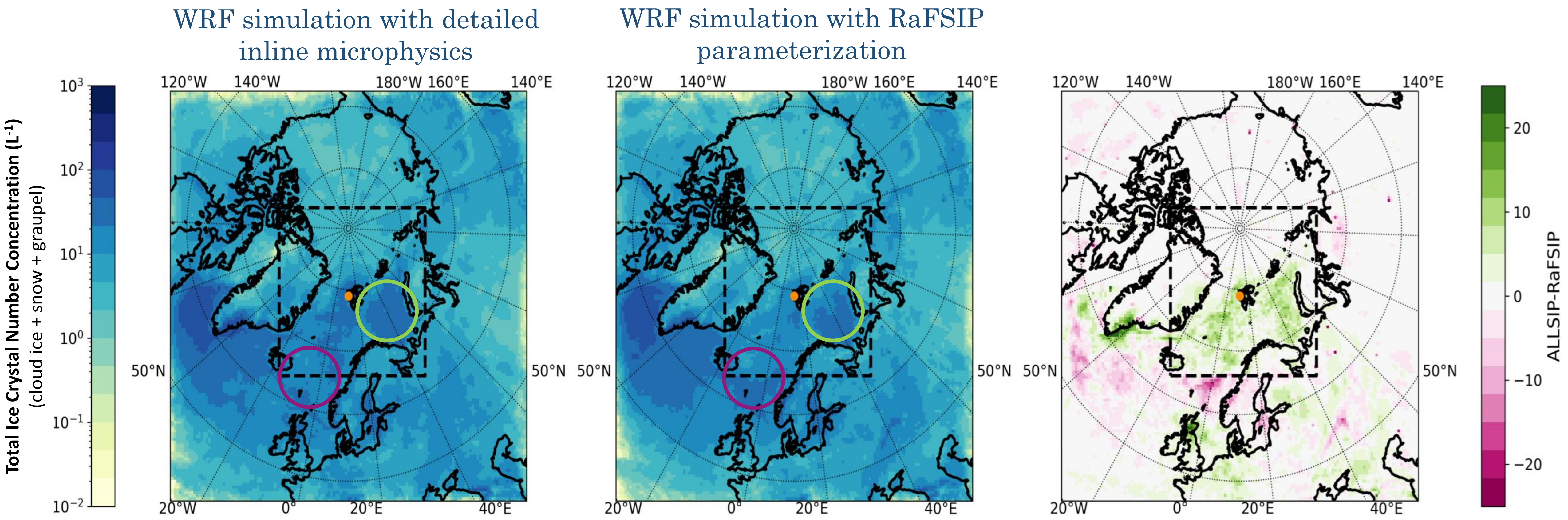
Conditions		RaFSIP model	RaFSIP predictions				
Temperature	Rain mass mixing ratio		IEFBR	IEFHM	IEFDS		
-8≤T<-3°C	>0	forestALL	✔	✔	✔	✔	✔



Less constrained IEF due to DS probably because of less training examples compared with the other SIP processes

Georgakaki et al., in preparation

Online performance of the new RaFSIP parameterization

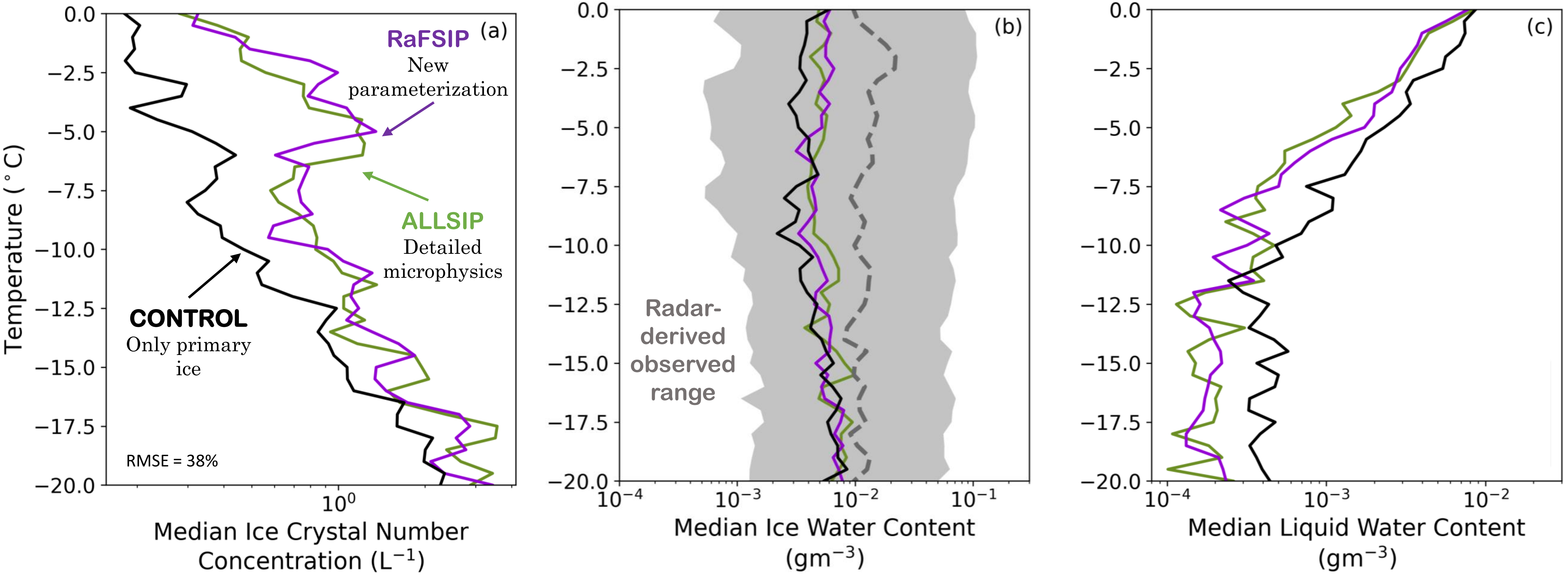


* Averaged concentrations within the PBL

- ✓ Good performance over the continental regions
- ✓ Certain regions where the new RaFSIP leads to **overestimations**/**underestimations** mainly over sea-ice → the RaFSIP is trained over continental grid points

Georgakaki et al., in preparation

Focusing on the Ny-Ålesund model grid point



- ✓ A factor of up to **~5** increase in the ice crystal concentrations
- ✓ Not significant change in IWC due to a shift towards smaller ice particles
- ✓ Slight ↓ in LWC through the ice growth properties (WBF + riming) of the small secondary ice particles

Georgakaki et al., in preparation

Ongoing and Future Work:

FORCeS Ice Experiment (FOR-ICE)

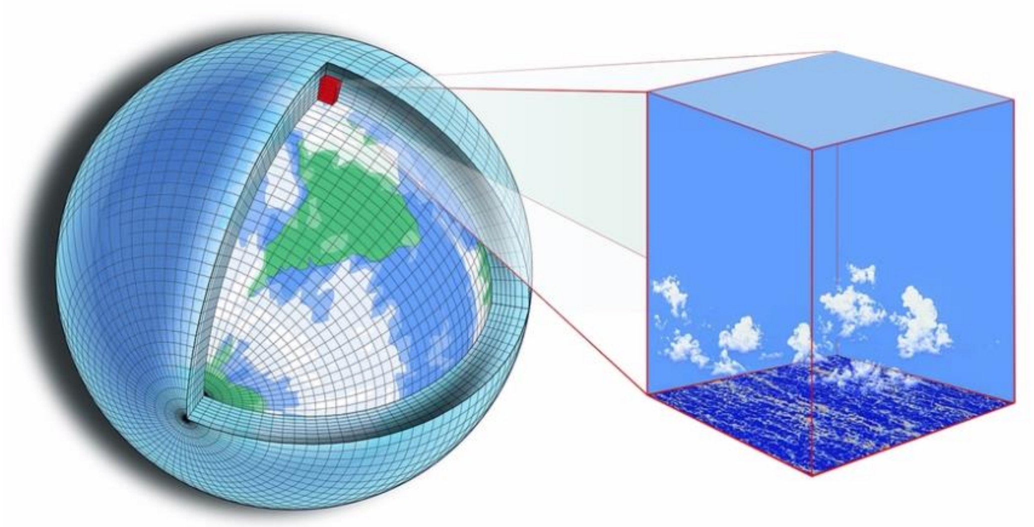
Climate model intercomparison project (NorESM2, ICON-HAM, EC-Earth) to quantify the sensitivity to:

- ✓ Ice Nucleation
- ✓ Secondary ice production
- ✓ Sedimentation
- ✓ Wegener-Bergeron-Findeisen process
- ✓ Large-scale, convective & turbulent ice transport

FORCeS

European Research Council

Established by the European Commission



Take home messages about the importance of SIP

- Primary Ice Production is critical to “get right”, no matter what.

- Secondary Ice Production can have larger influence on ice formation than primary ice at T < -15°C. *It seems to be acting everywhere we looked at.*

- In Polar and Orographic environments, “seeder-feeder” configurations can lead to considerable secondary ice production. *Completely new view…*

- Enhanced precipitation rates associated with secondary ice can affect the development of larger-scale cloud systems, such as Statocu-to-Cu transitions during cold air outbreaks.

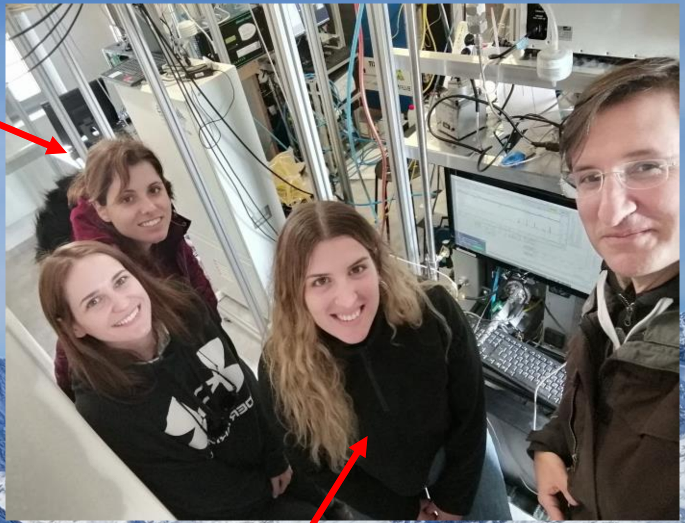
- Secondary ice processes are highly uncertain, but can affect most types of MPC with important implications for radiation, precip and glaciation fraction.

EPFL

Stockholm University

FORTH C·STACC Center for the Study of Air Quality & Climate Change

Dr. Georgia Sotiropoulou



Paraskevi Georgakaki

THANK YOU!

erc European Research Council Established by the European Commission

Marie Skłodowska-Curie Actions

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