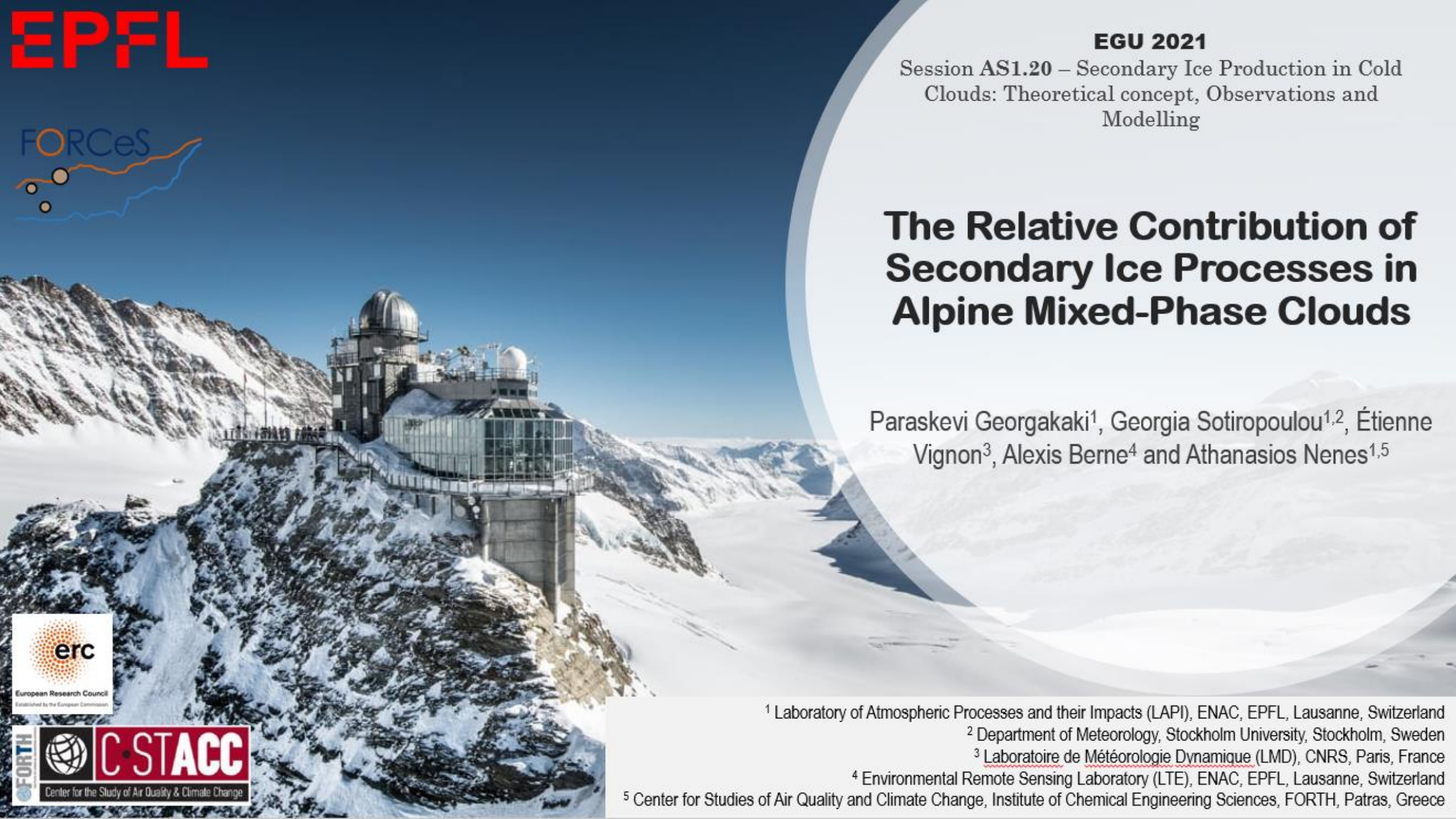

EGU 2021

Session AS1.20 – Secondary Ice Production in Cold Clouds: Theoretical concept, Observations and Modelling

The Relative Contribution of Secondary Ice Processes in Alpine Mixed-Phase Clouds

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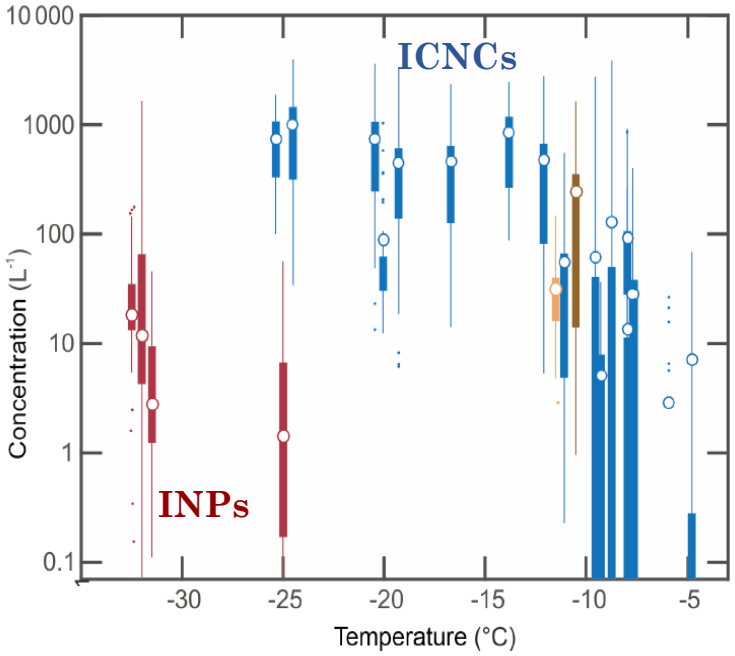
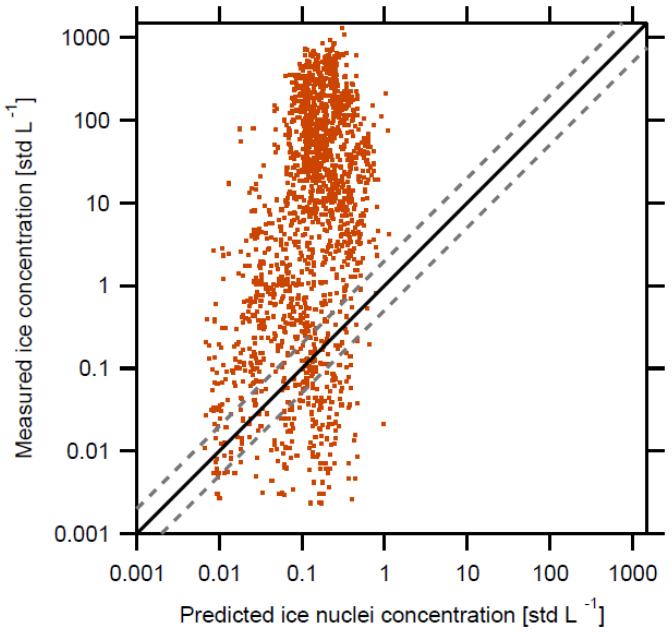
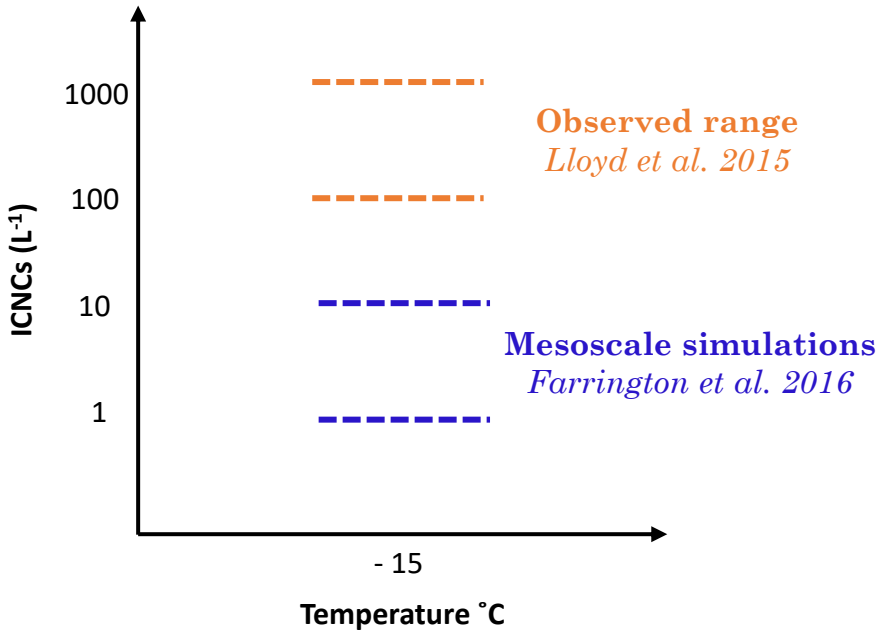
The source of ice crystals observed at mountain-top stations remains an enigma

Beck et al. 2018



Lloyd et al. 2015

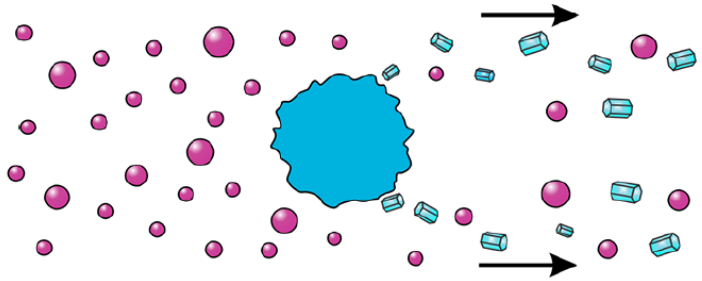




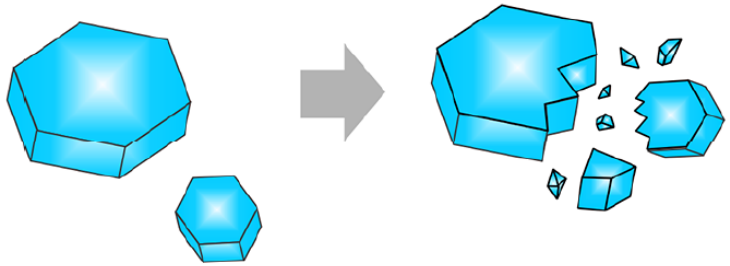
- ✓ In-situ observations of orographic mixed-phase clouds (MPCs) report that Ice Crystal Number Concentrations (ICNCs) are **much higher** than the primary Ice Nucleating Particles (INPs)
- ✓ Simulations of Alpine clouds **underestimate** the amount of ice compared with observations

Could Secondary Ice Production (SIP) account for the enhanced ice crystal concentrations observed in the Alpine MPCs?

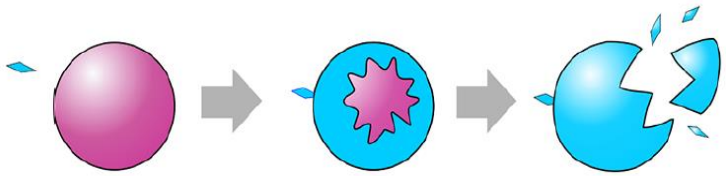
Rime Splintering (RS) or the Hallett-Mossop process (H-M)



Collisional break-up (BR)



Droplet Shattering (DS) during freezing



Korolev and Leisner, 2020

- ✓ The H-M process is the **only SIP mechanism** extensively implemented in most weather prediction and climate models
- ✓ **Surface-based process**, such as blowing snow and airborne hoar frost, are frequent invoked to explain the discrepancy between ICNCs and INPs
- ✓ SIP through BR or DS are **overlooked**

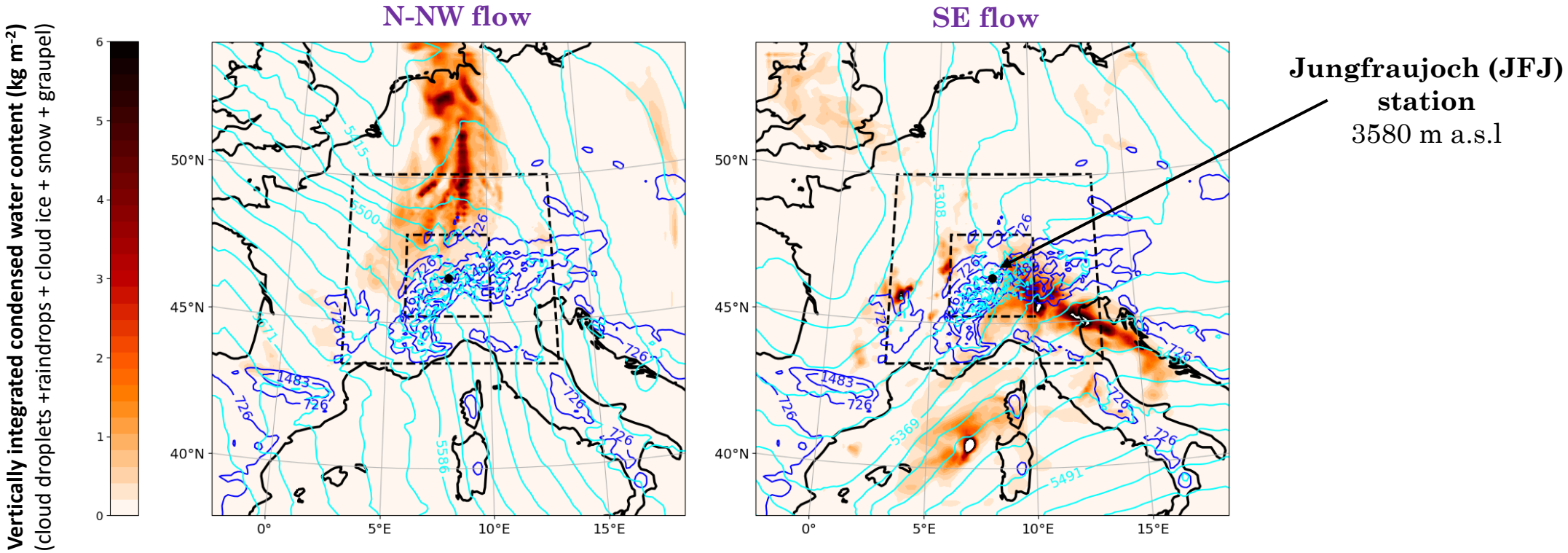
Does considering additional SIP processes bridge the gap between observed and modeled ICNCs?

Modeling SIP processes in orographic MPCs with the Weather Research and Forecasting model (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**

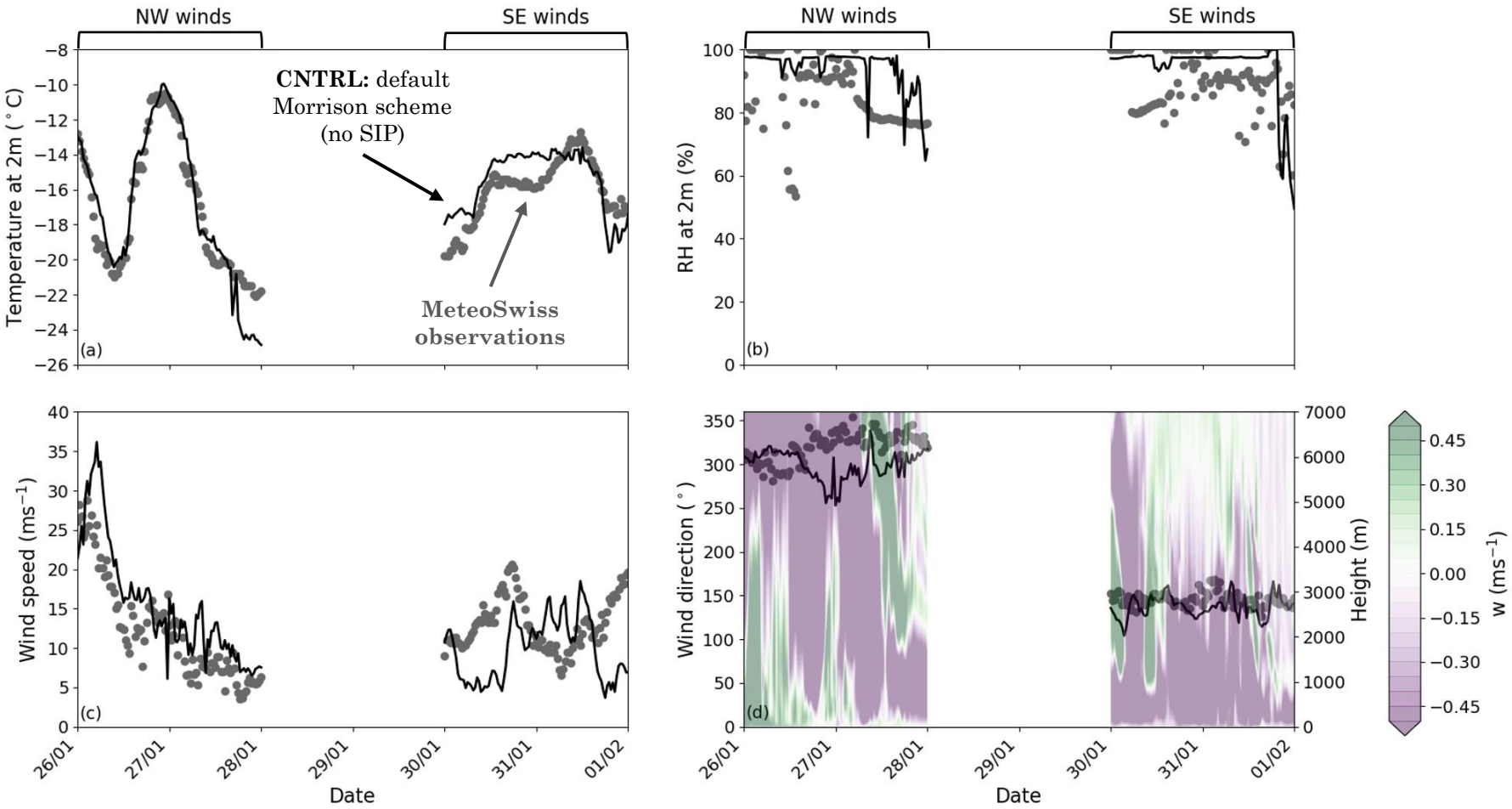


Two simulation periods in order to investigate the dynamical influence caused by the local orography:

✓ **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

Modeling SIP processes in orographic MPCs with WRF: Model validation (default version of WRF)

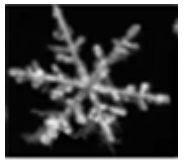
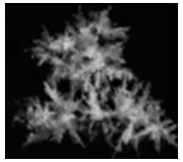


- ✓ The **H-M process** (the only SIP mechanism included in the default version of WRF) is **ruled out** as the simulated **temperatures < -8 °C**
- ✓ **Stronger updrafts** during **NW winds** → higher supersaturations favoring the persistence of mixed-phase conditions (Lohmann et al., 2016)
- ✓ **Weaker updrafts** during **SE winds** → more glaciated clouds

Implementation of Collisional Break-up in Morrison microphysics scheme (described in Sotiropoulou et al., 2021)

Morrison: 2-moment bulk microphysics scheme that accounts for 5 hydrometeor species:

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

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

Fragmentation is assumed to occur after:

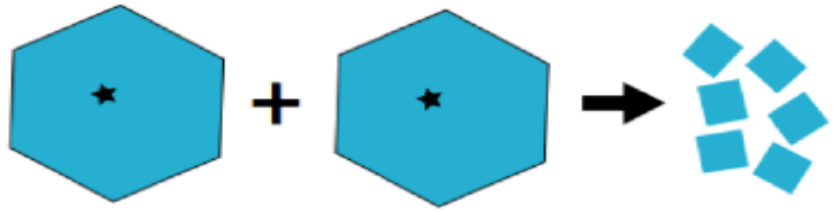
(1) cloud ice – graupel collisions → fragmentation of ice

(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

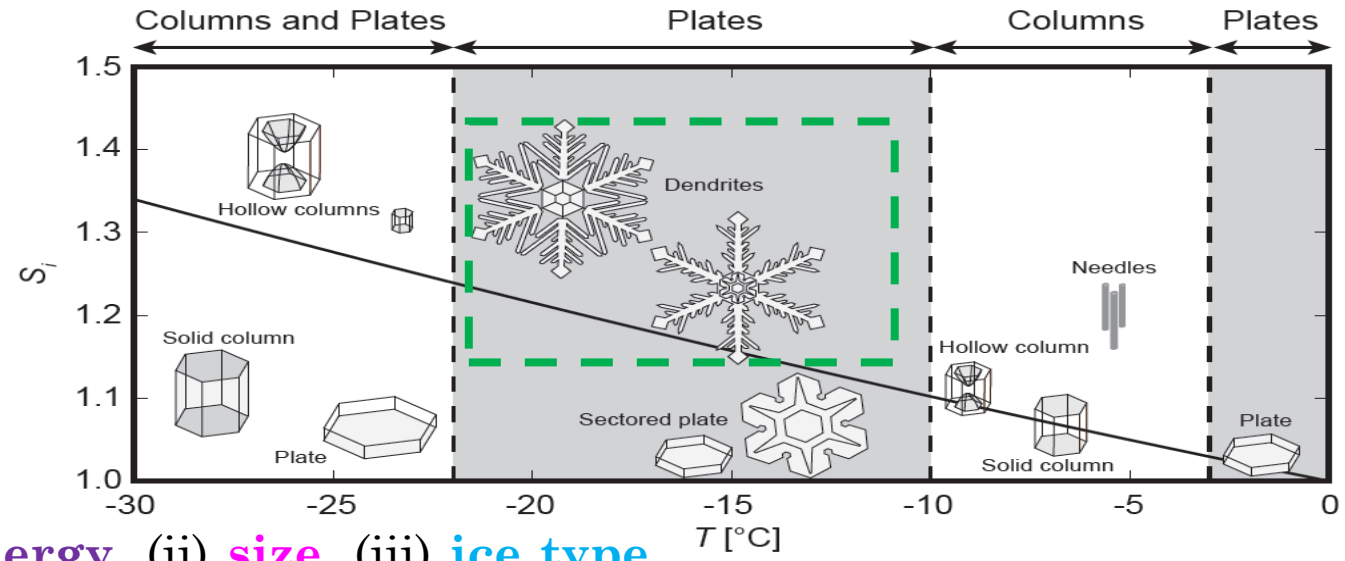


Fragments are added to **cloud ice** category

Two approaches to parameterize the number of fragments generated per collision

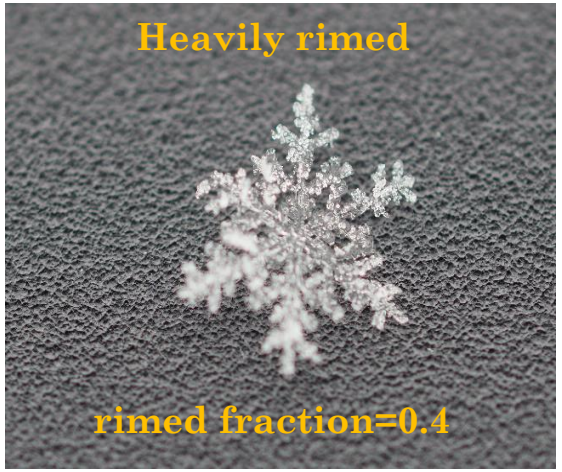
I. Following Phillips et al. (2017)

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



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

	Collision Type			
			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)	
Parameter	Type I: Collisions of graupel (size: $5\times10^{-4} < D < 5\times10^{-3}$ m) with graupel/hail	Type I: Collisions between hail only	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



Two approaches to parameterize the number of fragments generated per collision

II. Following Sullivan et al. (2018)

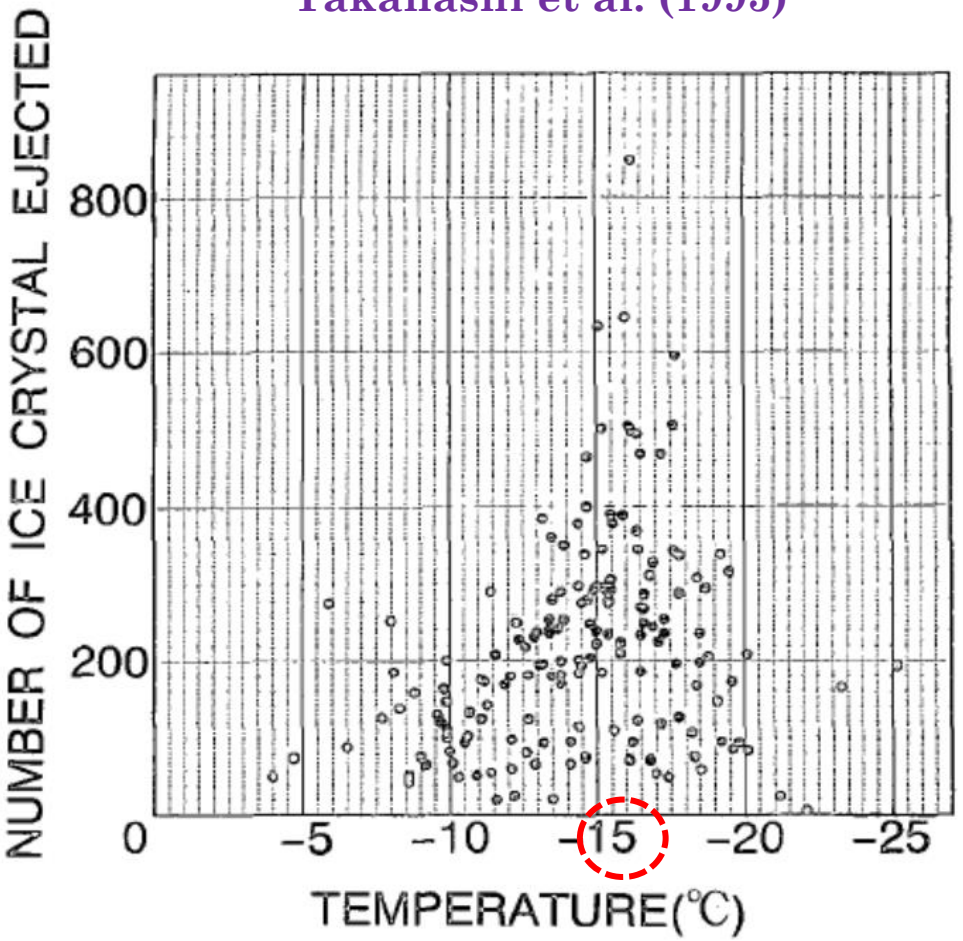
$$F_{BR} = 280(T - 252)^{1.2} \exp\left(-\frac{(T-252)}{5}\right) \frac{D}{D0}$$

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

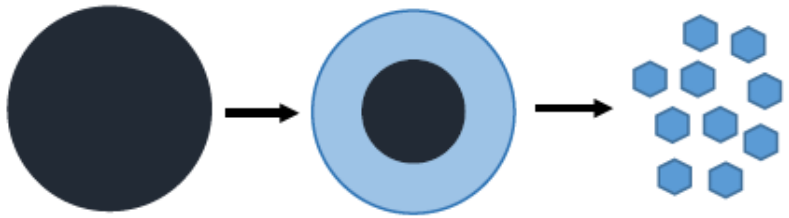
Note! Takahashi et al. (1995) used 2-cm hailballs in their experiments (D0 = 0.02 m)

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

Laboratory experiment by Takahashi et al. (1995)



Parameterizing the number of fragments per frozen raindrop in Morrison microphysics scheme



Following Phillips et al. (2018)

Fragmentation of freezing raindrops is assumed to occur during:

- **MODE 1:** Collision with smaller ice-particle (cloud ice) or INPs (immersion 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

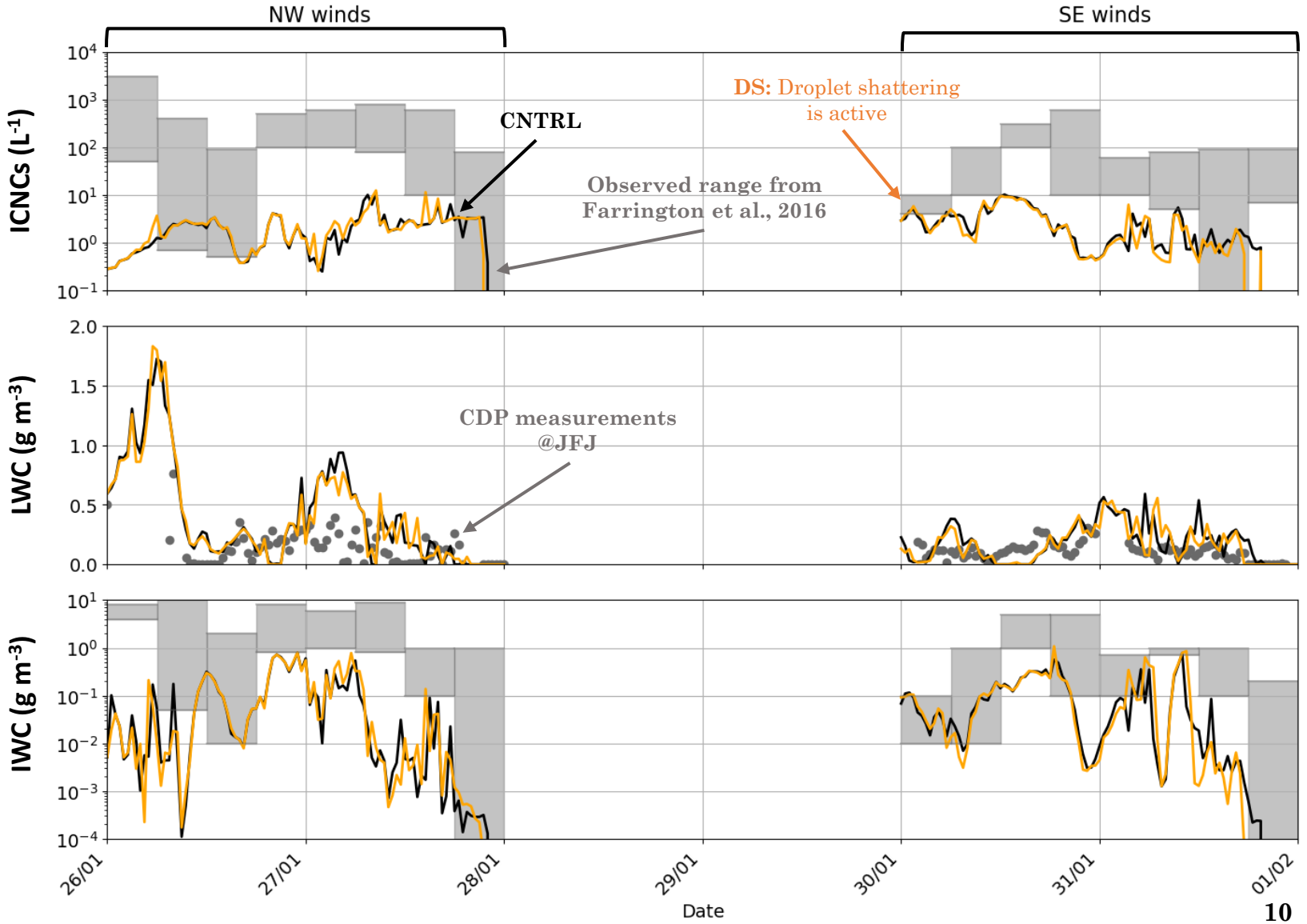
$$N_{DS} = \Xi(\mathrm{D})\Omega(\mathrm{T})\left[\frac{\zeta\eta^2}{(\mathrm{T}-\mathrm{T0})^2}+\beta\mathrm{T}\right]$$

- **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**.

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

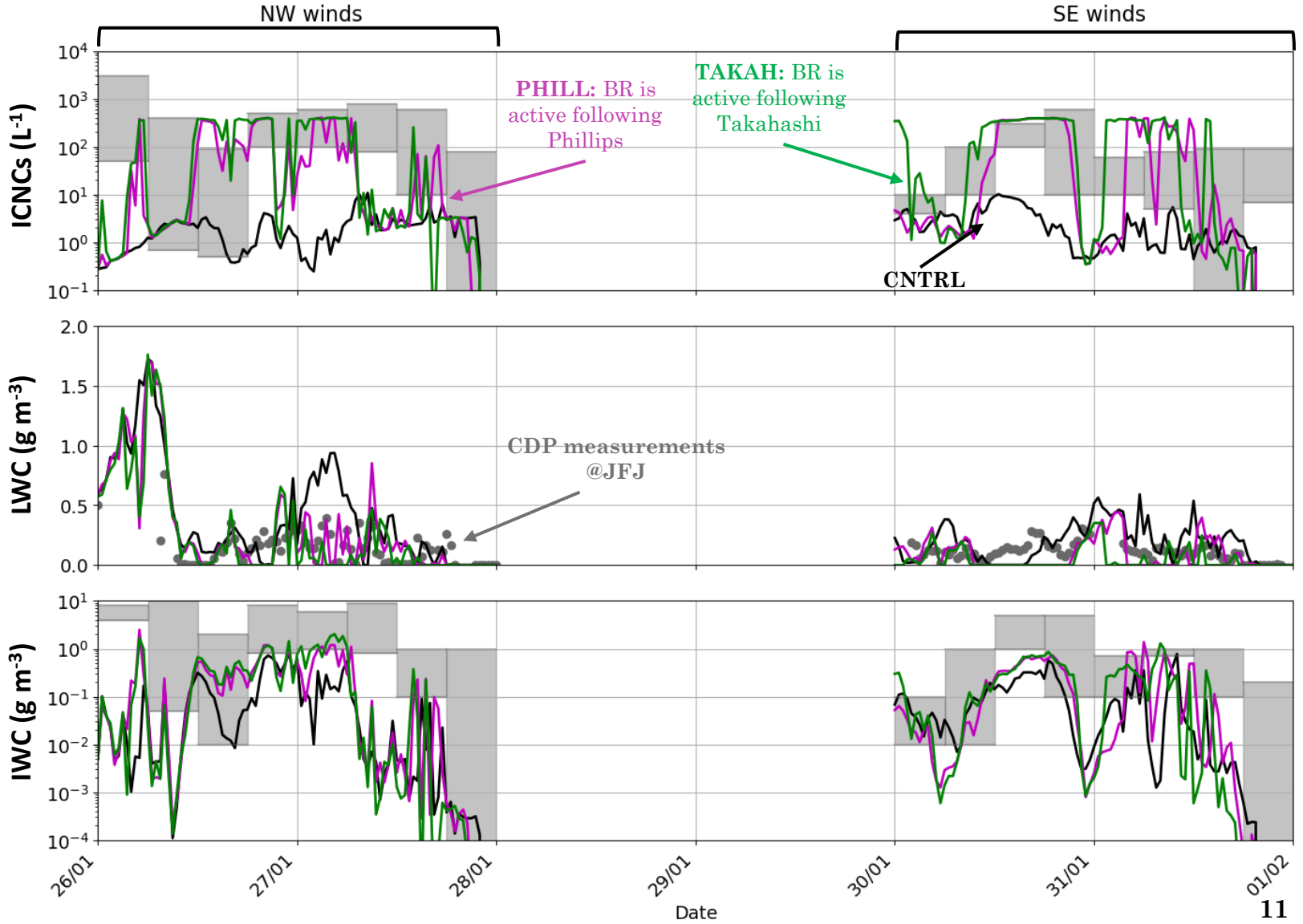
Modeling CLACE 2014 case-study with the updated microphysics scheme: testing the efficiency of the DS mechanism

- ✓ CNTRL (black line) and DS (orange line) **underestimate** ICNCs by 2-3 orders of magnitude and **overestimate** the cloud liquid water (LWC)
- ✓ DS remains **ineffective** even during the more convective period (i.e., NW winds) due to the absence of sufficiently large raindrops



Modeling CLACE 2014 case-study with the updated microphysics scheme: testing the efficiency of the BR mechanism

- ✓ TAKAH (green line) slightly overestimates ICNCs compared with PHILL (magenta line), especially when the simulated temperatures fall below ∽-16 ˚C
- ✓ Both PHILL and TAKAH produce up to 3 orders of magnitude elevated ICNCs compared with CNTRL
- ✓ Better agreement with the LWC measurements
- ✓ Cloud ice water content (IWC) is occasionally improved, but generally remains underestimated

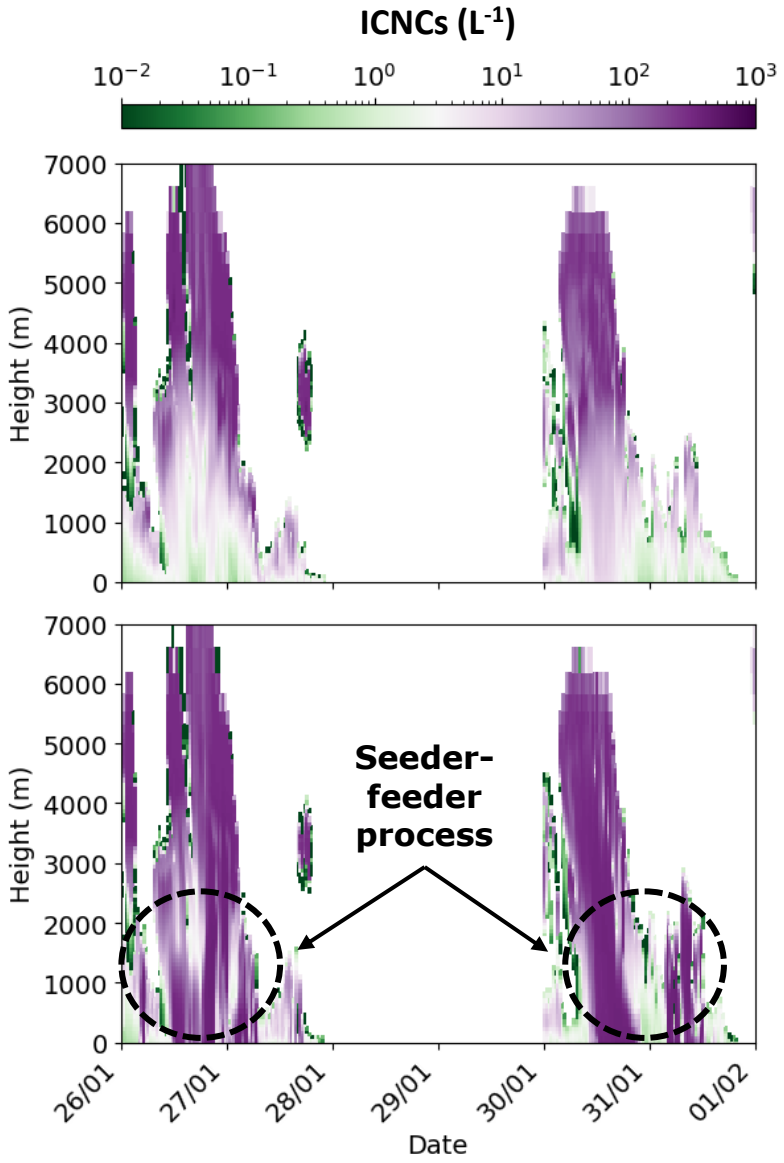


Conditions favoring ice multiplication through BR in the Alps

External seeder-feeder process



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

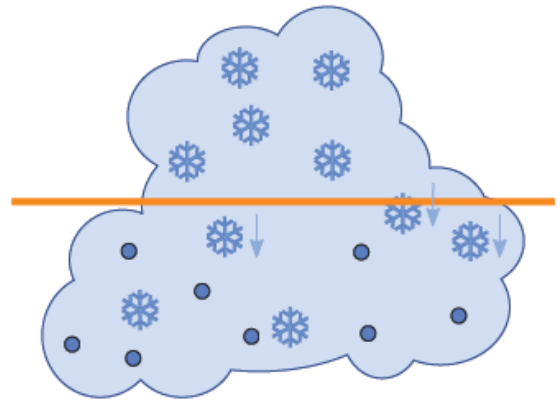


CNTRL (Default WRF)

PHILL (Updated WRF)

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

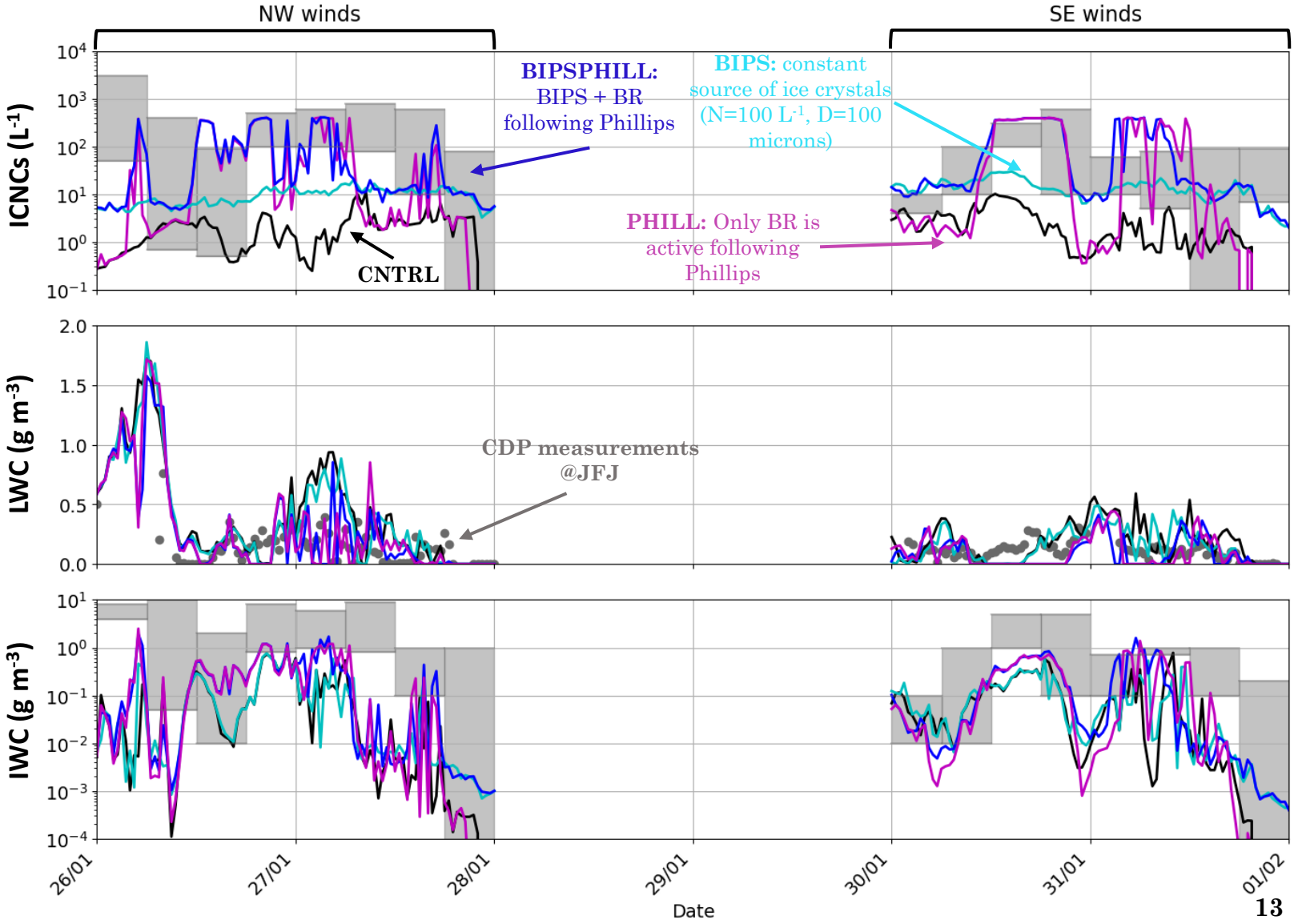
In-cloud seeding



Proske et al. 2021

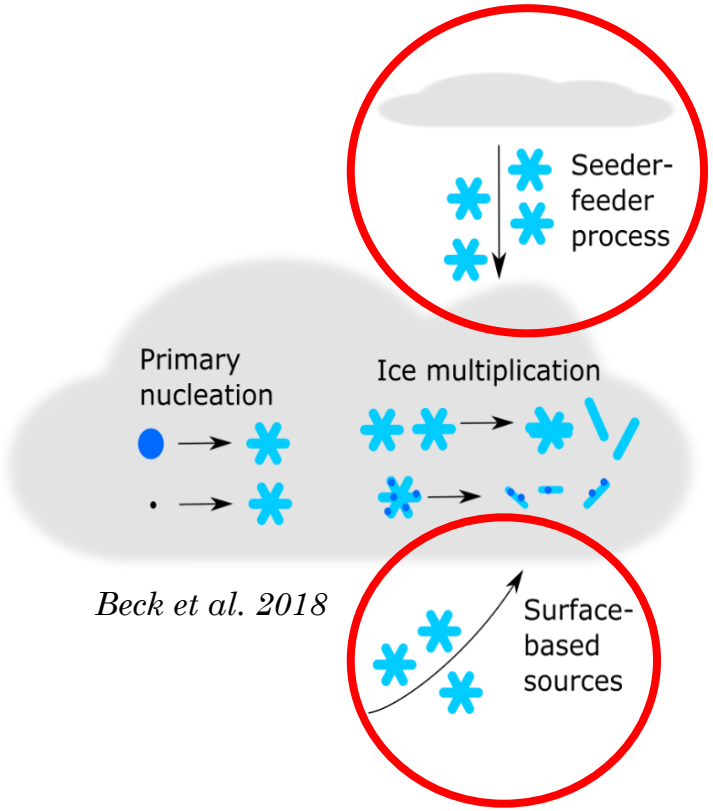
Modeling CLACE 2014 case-study with the updated microphysics scheme: testing the impact of "blowing snow"

- ✓ Our results show that blowing snow alone (cyan line) cannot account for the observed ICNCs, as it never predicts ICNCs $\gtrsim 50$ L^{-1}
- ✓ The effect of "blowing snow" is important when a cloud is near the ground (i.e., ice supersaturated environment)
- ✓ The combined effect of blowing snow and BR (blue line) results in best agreement with measured ICNCs



Conclusions

The sensitivities that include a representation of the BR mechanism are found to elevate the modeled ICNCs up to ∽ 500 L^{-1} reaching the observed levels



Beck et al. 2018

The initiation of the BR mechanism is associated with the occurrence of seeder-feeder situations

The DS process cannot account for the enhanced ICNCs due to a lack of big raindrops (> 50 μm)

Outside the H-M temperature range, considering both secondary ice and an "external" seeding mechanism – primarily falling ice from above and to a lesser degree blowing ice from the surface, is essential to predict the correct ice-liquid phase partitioning in the orographic MPCs



Thank you for your interest!

If you have any questions about our work, please contact us via **chat** or **e-mail**:

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https://www.epfl.ch/labs/lapi/

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