ICE GENESIS Final Public Workshop

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Toulouse, France

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SNOW TECHNOSTREAM

Highlight outcomes & gaps: WP5

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Highlight outcomes & gaps

WP5 - Instrumentation & F/T campaign

AIH / CNRS / EPFL

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1. Recall IG snow campaign

2. Machine learning tools for additional snow retrievals

3. IWC statistics (in situ, remote sensing)

4. Individual snow particle properties (beyond integral IWC):
   - properties are size dependent
   - properties are crystal morphology dependent

5. Conclusions

AIH / CNRS / EPFL

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1. IG Snow Measurements: Motivation / Setup

Literature:

- Snowflake diameters mainly between 2 and 5 mm, ranging up to 15 mm (Pruppacher 2010)

- Snowflake density from 0.005 to 0.2 g cm^{-3}, inversely proportional to diameter, density almost four times larger for wet than for dry snowflakes.

- **Recent measurement campaigns:**
  - E.g. OLYMPEX or GCPEX: detailed µ-phys snow characterization is rare in terms of size dependent statistics of numerous microphysical & morphological snow particle properties.

1. IG Snow Measurements: Motivation / Setup

Within ICE GENESIS:

- **Proper ground and flight tests** have been conducted in snow conditions

- Overall objective has been the **most detailed characterization** of all relevant snow and precipitation particle related microphysical parameters

- Synergy with the **development of snow numerical tools** and for **comparison with artificial snow** generated in test facilities

…

1. IG Snow Measurements: Motivation / Setup

Instruments used during IG snow campaign for snow properties retrieval:

- Multi Angle Snowflake Camera MASC (ground): individual snowflake properties – shape, riming degree, liquid/wet snow

- Dual frequency radar: W & X-band profiling Doppler radar (ground)

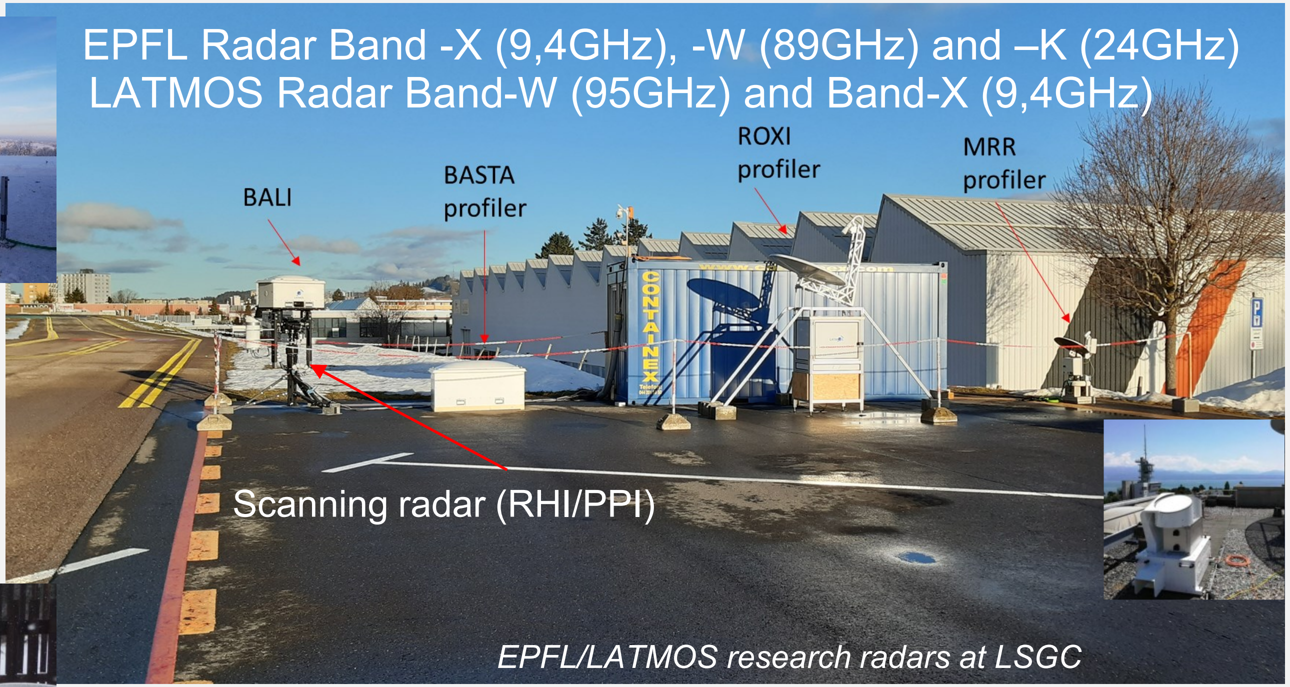
- In situ (aircraft) : CVI based measurement of TWC (IWC+LWC), CDP for estimation of LWC, 2DS & PIP imaging probes for quantitative PSDs of snow particle number, mass, density, sphericity, etc…

- W-band Doppler radar RASTA (aircraft): retrieval of TWC – Statistics in column

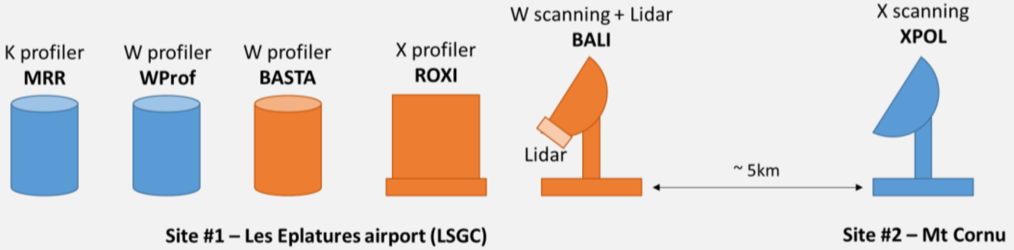
1. IG Snow Measurements: Motivation / Setup

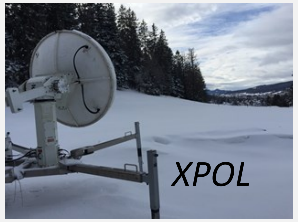
- EPFL/LATMOS **radars** and EPFL **MASC** installed at ground site (Les Eplatures / Swiss Jura)

MXpol – dual polarization RHI/PPI (Mont Cornu)



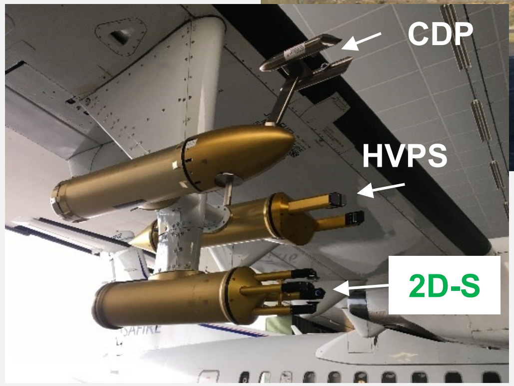
WProf





1. IG Snow Measurements: Motivation / Setup

- **ATR-42: Period:** 19-30/01/2021; **Location:** **5 flights** over Jura Swiss in **falling snow conditions; 20 F/H;**



CDP [2-50µm] and Robust (TWC)
2D-S [10-1280µm]
HVPS [150-19200µm]

CIP [25-50µm]
PIP [100-6200µm]

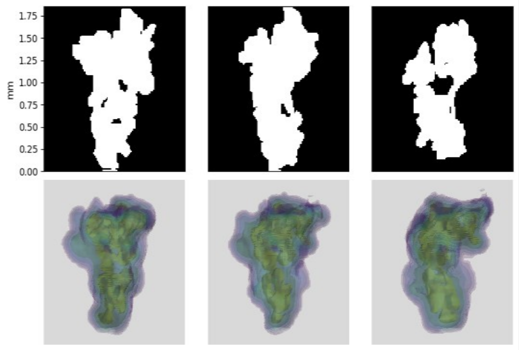
2. Machine learning tools implemented for additional snow retrievals

… Several Neural Networks implemented for snow properties' retrievals

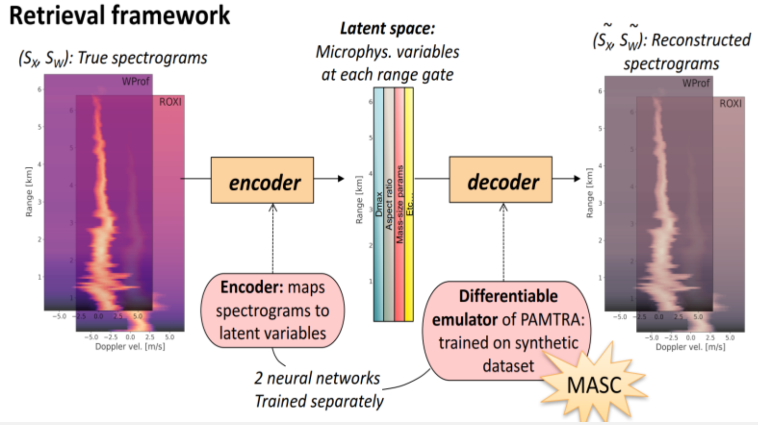
1.

GAN (Generative adversarial network) deep learning method to generate 3D structures (and descriptors) from **MASC** 2D images: ***Leinonen et al. (2021)***

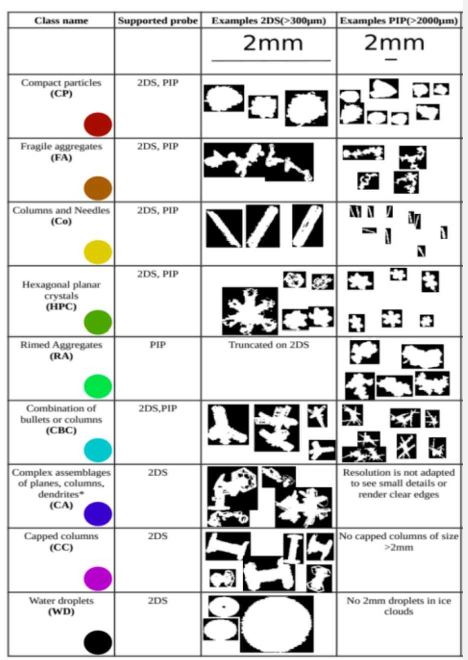
MASC projections



2. **Dual-frequency retrieval** (neural networks!) of snow properties: ***Billault-Roux et al. (2022)***
Doppler spectrogram: vertical stack of Doppler spectra, the latter is the radar reflectivity as a function of Doppler velocity



3. **CNN** (***Jaffeux 2022 AMT***) morphological retrieval (2DS & PIP OAP) and related crystal class statistics of snow descriptors.



Class name	Supported probe	Examples 2DS(>300µm)	Examples PIP(>2000µm)
		2mm	2mm
Compact particles **(CP)**	2DS, PIP		
Fragile aggregates **(FA)**	2DS, PIP		
Columns and Needles **(Co)**	2DS, PIP		
Hexagonal planar crystals **(HPC)**	2DS, PIP		
Rimed Aggregates **(RA)**	PIP	Truncated on 2DS	
Combination of bullets or columns **(CBC)**	2DS,PIP		
Complex assemblages of planes, columns, dendrites* **(CA)**	2DS		Resolution is not adapted to see small details or render clear edges
Capped columns **(CC)**	2DS		No capped columns of size >2mm
Water droplets **(WD)**	2DS		No 2mm droplets in ice clouds

2. Machine learning tools implemented for additional snow retrievals

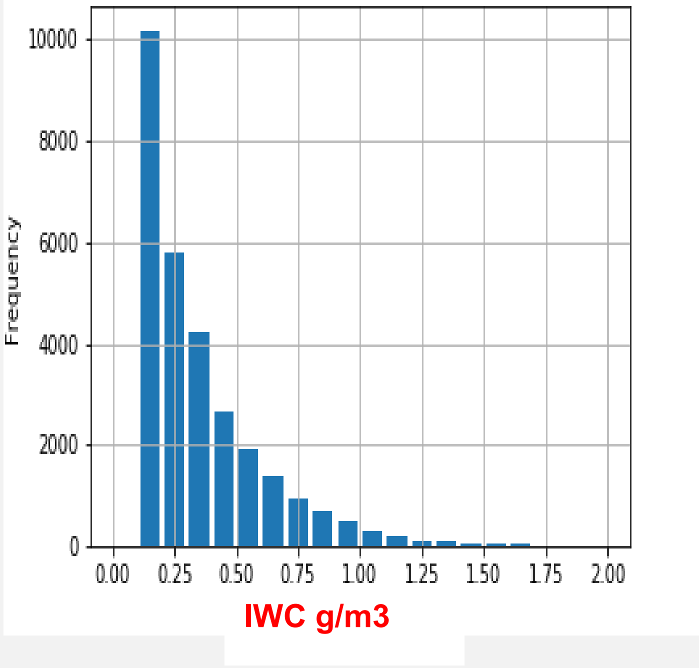
Instruments used for snow properties retrievals

- Multi Angle Snowflake Camera MASC (ground): individual snowflake properties – shape, riming degree, liquid/wet snow, **retrieval of 3D descriptors (mass, density, etc…)**
- Dual frequency radar: W & X-band profiling Doppler radar (ground):
  IWC, D_0 of exponential number PSD, m-D, aspect ratio – Statistics in column
- In situ (aircraft) : CVI based measurement of TWC (IWC+LWC), CDP for estimation of LWC, 2DS & PIP imaging probes for quantitative PSDs of snow particle number, mass, density, sphericity, etc… **even morphology dependent PSDs of those parameters!**
- W-band Doppler radar RASTA (aircraft): retrieval of TWC – Statistics in column

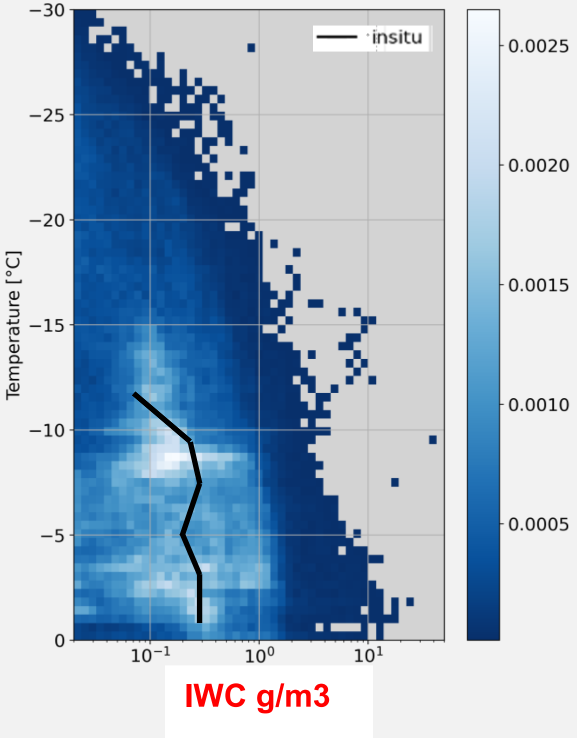
3. Snow IWC statistics (in situ, remote sensing)

- Dual frequency retrievals (W- and X-band ground radars), multi antenna cloud radar retrievals from RASTA / comparison with in situ

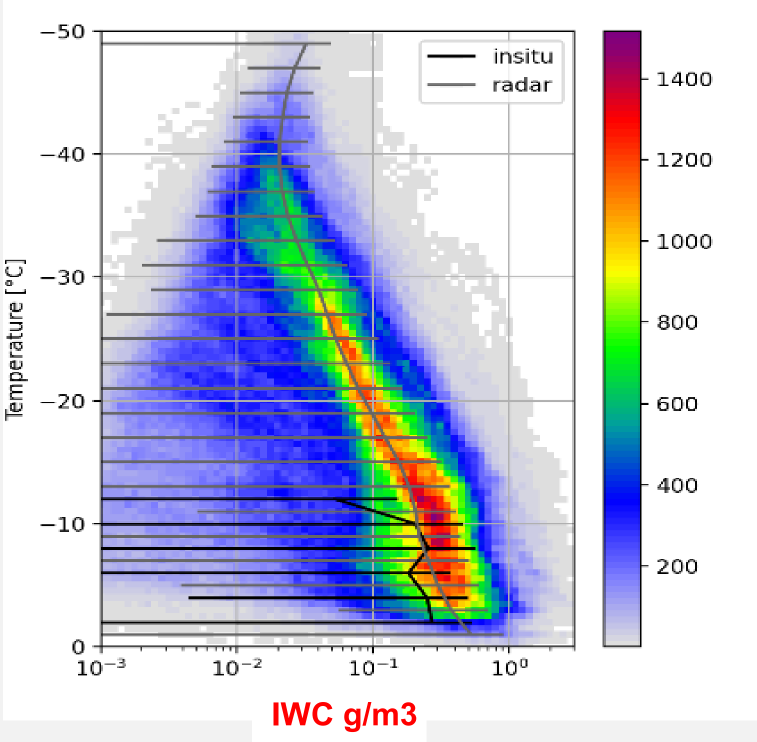
CVI bulk IWC on ATR



Dual frequency radar (X, W-band): IWC retrievals in vertical column



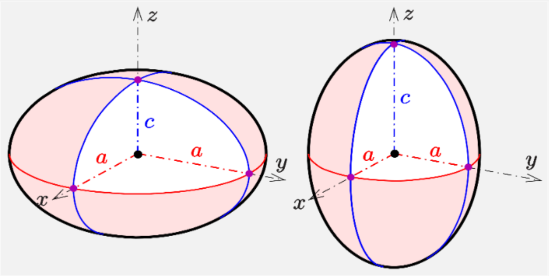
Multi-antenna W-band cloud radar Retrievals of IWC in column



4.1. spheroid approach for 2D to 3D conversion

3D descriptor retrieval from 2D images

Reference: Aguilar et al, 2022



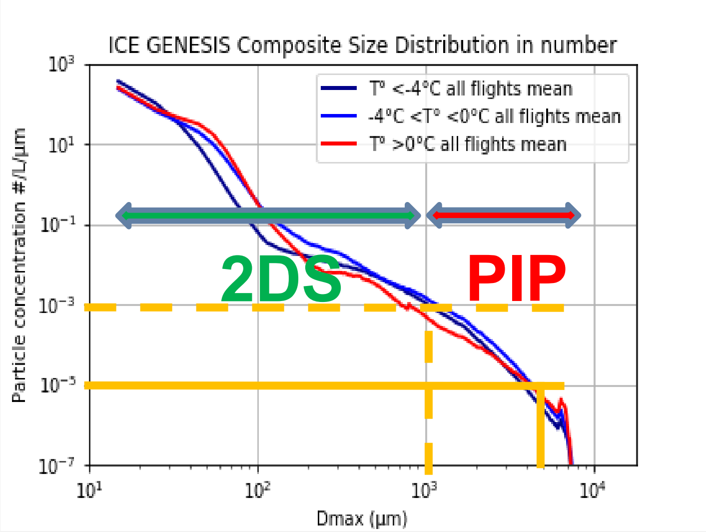
Oblate (top left) and prolate (top right) spheroids as 3D approximation for 2D crystal images.

Good match of experimental versus theoretical spheroid drag behavior documented at TUDA / AIH.

Full name	Abbreviation	Formula	Shape parameter required
Volume of ellipsoid	V_{ell}	$V_{ell} = \frac{4}{3} \cdot \pi \cdot (length/2)^2 \cdot width/2$ (oblate) $V_{ell} = \frac{4}{3} \cdot \pi \cdot (width/2)^2 \cdot length/2$ (prolate)	Length, Width
Surface of ellipsoid	S_{ell}	$S_{ell} = 2\pi {D_{\max}}^2 \cdot (1 + \frac{{D_{\max,\perp}}^2}{e \cdot {D_{\max}}^2}) \cdot$arctanh(e) with e^2=1-$(\frac{D_{max,\perp}}{D_{max}})^2$ (oblate) $S_{ell} = 2\pi {D_{\max}}^2 \cdot (1 + \frac{D_{max}}{e \cdot D_{max,\perp}}) \cdot$arcsin(e) with e^2=1-$(\frac{D_{max,\perp}}{D_{max}})^2$ (prolate)	Length, Width
Diameter of the sphere with same volume as ellipsoid	D_V	$D_V = \sqrt[3]{\frac{6V_{ell}}{\pi \cdot}}$	Length, Width
Sphericity (3D)	Φ	$\Phi = \frac{\pi \cdot {D_V}^2}{S_{ell}}$	Length, Width
Area ratio	Ar_r	$Ar_r = \frac{A_\perp}{\frac{\pi}{4} \cdot {D_{\max}}^2}$ or $Ar_r = \frac{A_\perp}{\frac{\pi}{4} \cdot {D_V}^2}$	Projected area, length, width
Orthogonal Sphericity (= inverse 2D Ar_r)	$\Phi_\perp$	$\Phi_\perp = \frac{\frac{\pi}{4} \cdot {D_V}^2}{A_\perp}$	Length, Width, Projected Area
Bulk density	ρ_p	$\rho_p = \frac{m_p}{V_{ell}}$ or $\rho_p = \frac{m_p}{V_{D_{\max}}}$	Length, Width, particle mass estimation

4.2. size dependency of 2D/3D descriptors

- Number PSD statistics (PSD: function of crystal D)



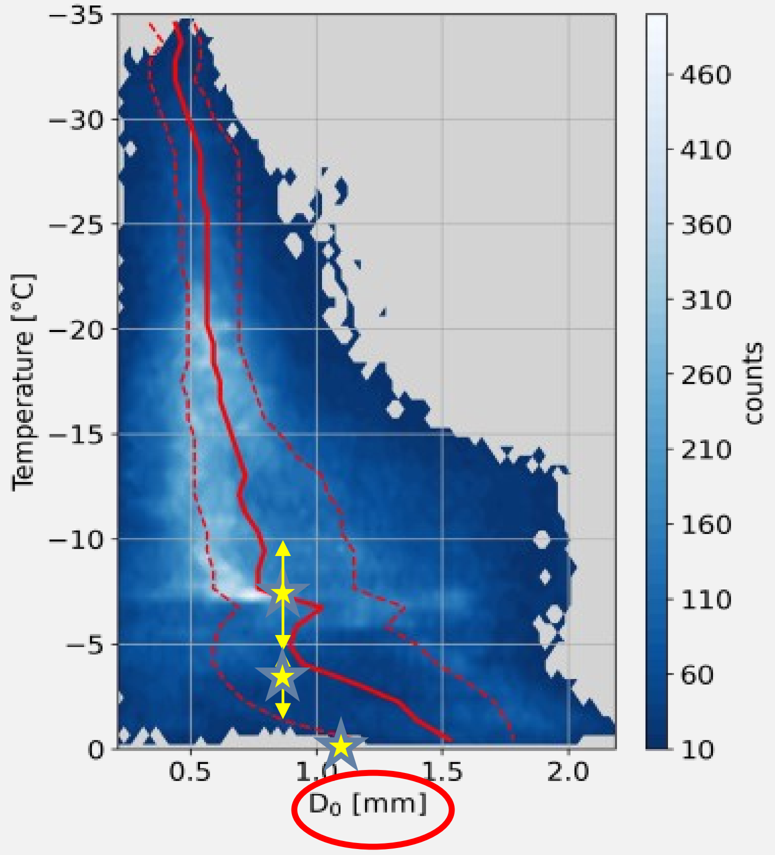
In situ 2DS + PIP imaging probes:

Composite number PSD for 3 T intervals

Exponential Fit (2-6mm):

$$N = N_o . e^{-\lambda D} = N_o . e^{-D/D_o}$$

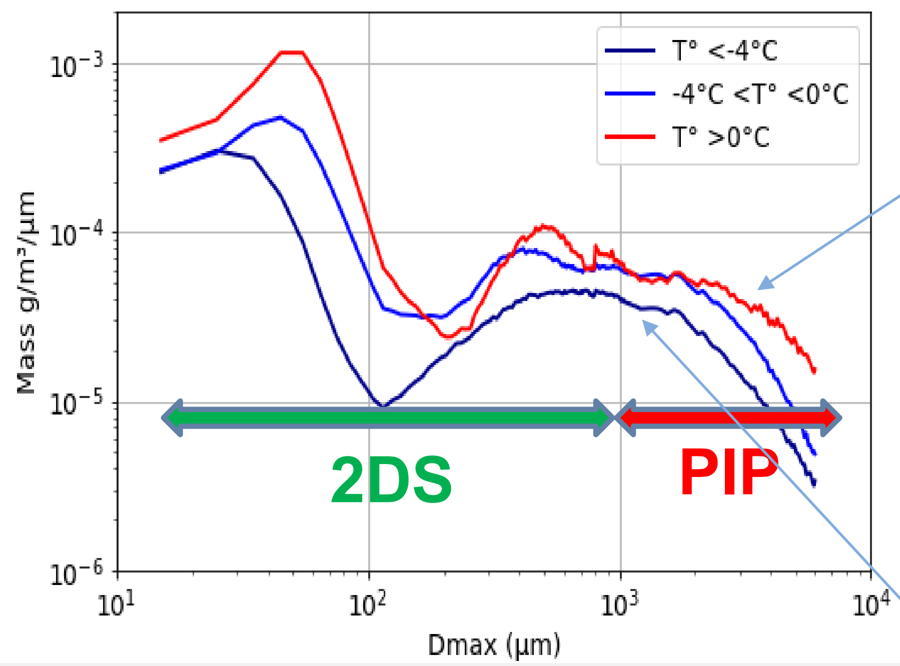
	All·data	T<-4°C	4°C<T<0°C	T>0°C
N>1200·µm·(#/m3)	460	629	615	219
λ(mm-1)	1.21	1.24	1.24	0.93
D_0·(mm)	0.83	0.81	0.81	1.07

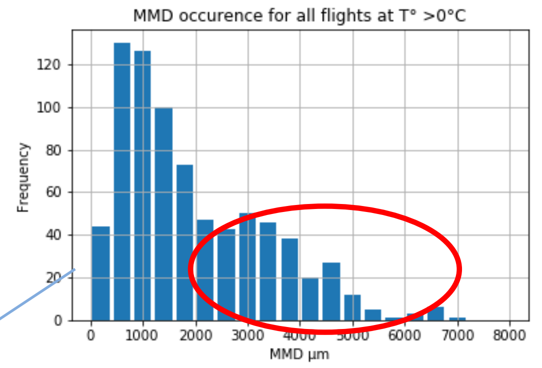


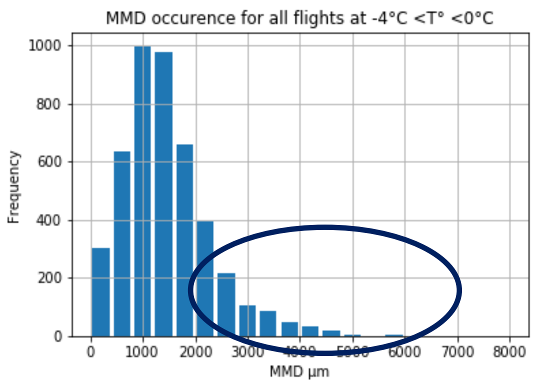
Distribution of dual frequency retrieved D_0 as a function of temperature:

4.2. size dependency of 2D/3D descriptors

- Mass PSD statistics





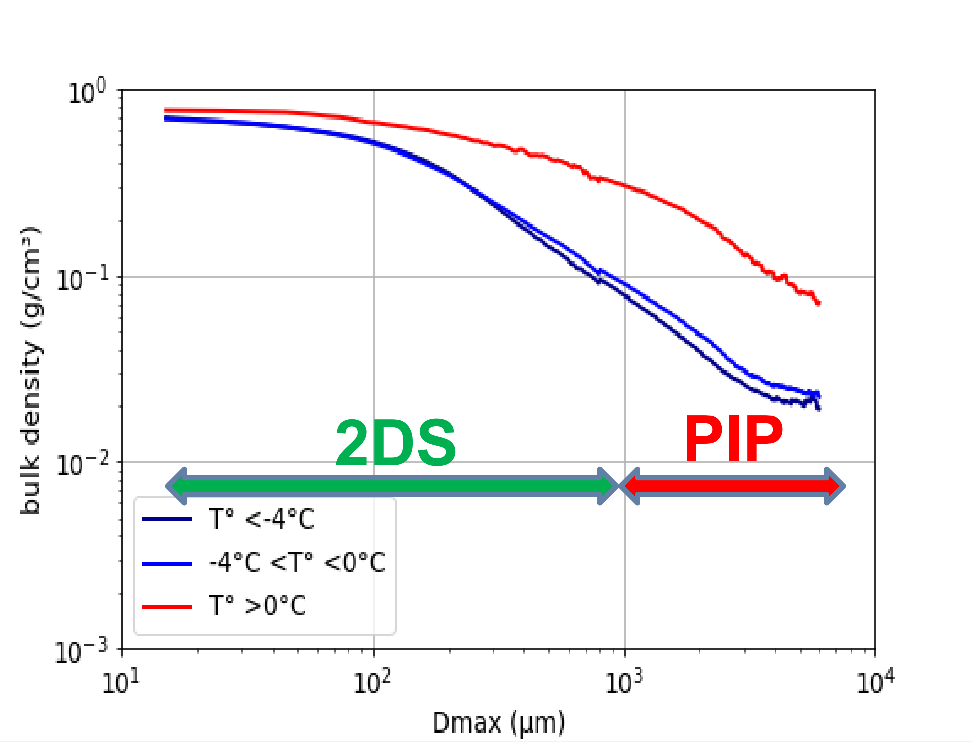


$m_p = 0.135 \cdot CSP^{\,0.793} \qquad (with\ CSP = A \cdot W \cdot \frac{2L+2W}{P})$

Baker & Lawson (2006)

4.2. size dependency of 2D/3D descriptors

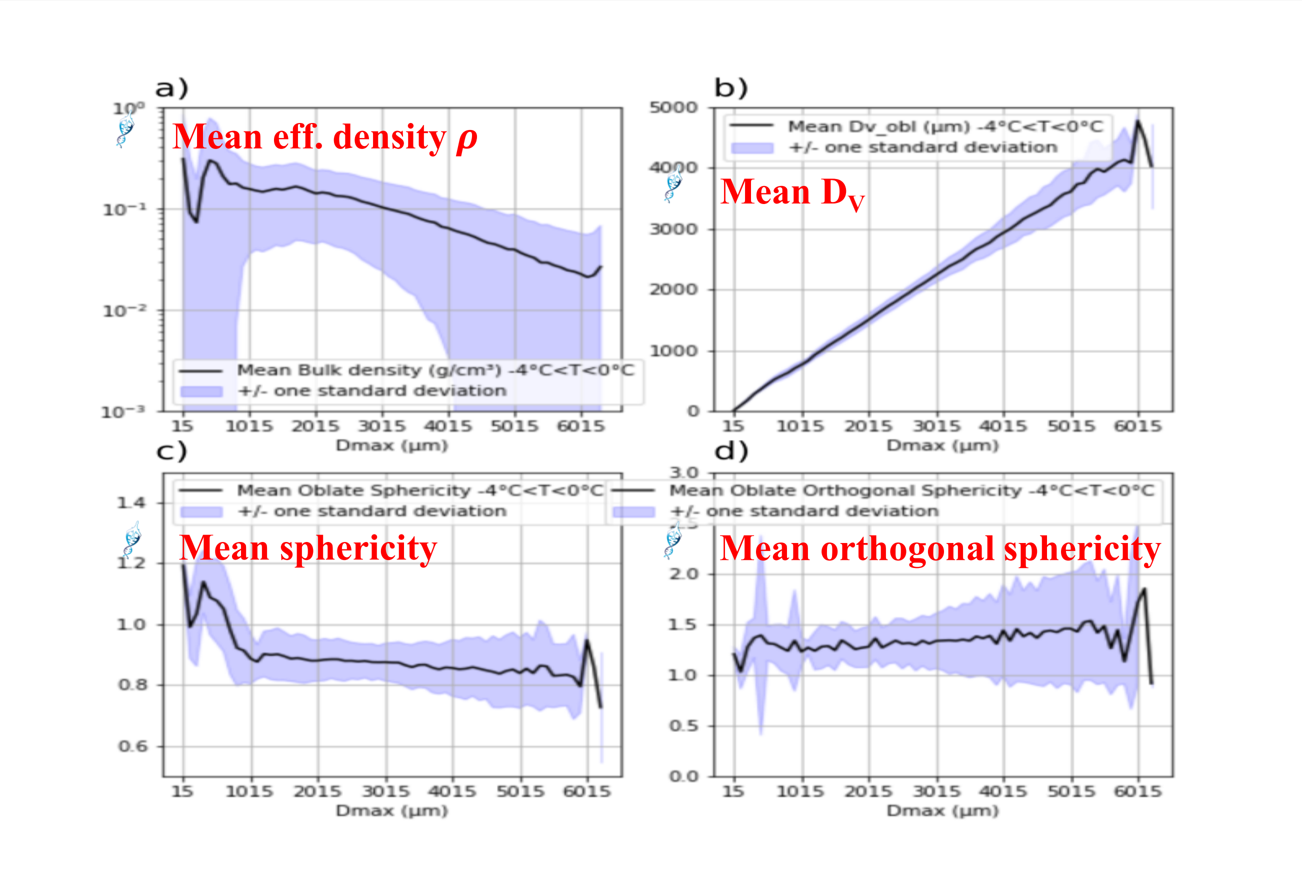
- Effective / bulk density PSD statistics



3 temperature intervals

4.2. size dependency of 2D/3D descriptors

Composite distributions (2DS &PIP)



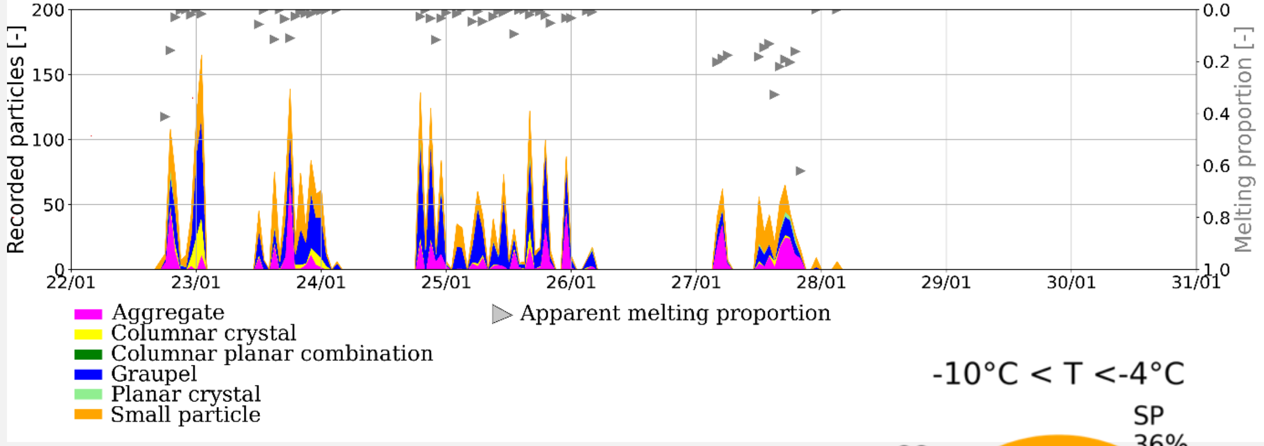
Class Number	Mass Fraction (%)	Mean D_{max} (µm)	Mean D_V (µm)	Mean Φ	Mean Φ⊥	Bulk density (g/cm³)
1	20	305	323.9	0.89	1.34	0.21
2	10	615	549.1	0.81	1.33	0.12
3	10	955	762.5	0.75	1.32	0.09
4	10	1345	1075.4	0.77	1.26	0.07
5	10	1745	1360.1	0.76	1.26	0.05
6	10	2215	1708.6	0.76	1.29	0.04
7	10	2835	2153.7	0.75	1.31	0.03
8	10	3765	2827.6	0.74	1.33	0.03
9	10	5625	4109.5	0.71	1.38	0.02

Message:

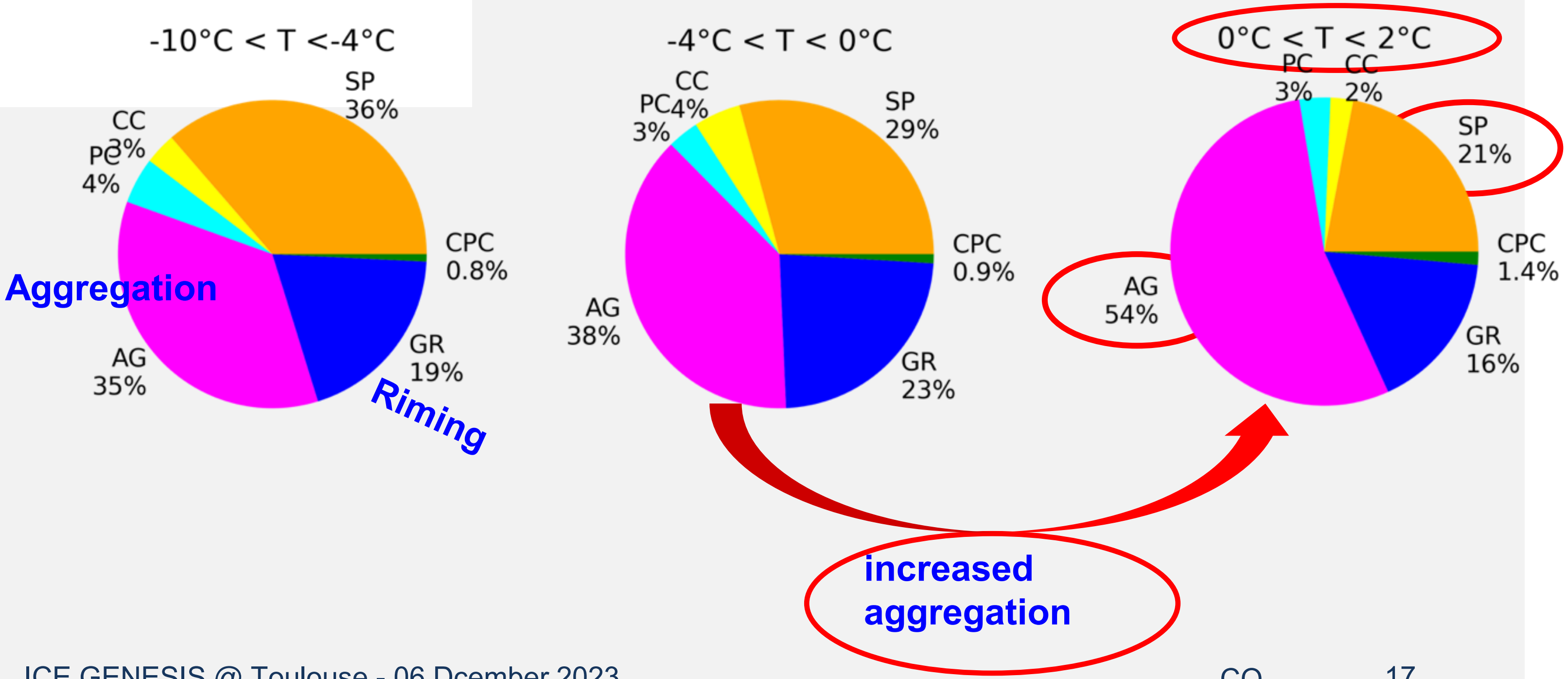
considerable spread / 1σ of 3D/2D descriptor values

4.3. size and morphology dependency of 2D/3D descriptors

Morphological Analysis : crystal shapes of MASC images



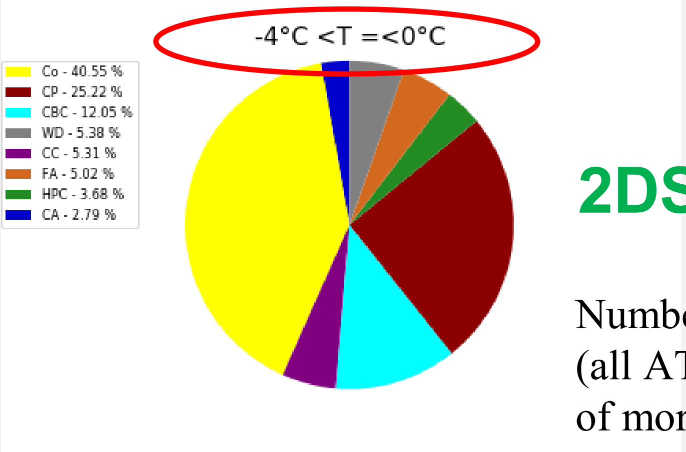
Time series of **morphological classification** and **melting proportion.** All data T< 2°C with hourly time intervals with at least 5 particles recorded.



4.3. size and morphology dependency of 2D/3D descriptors

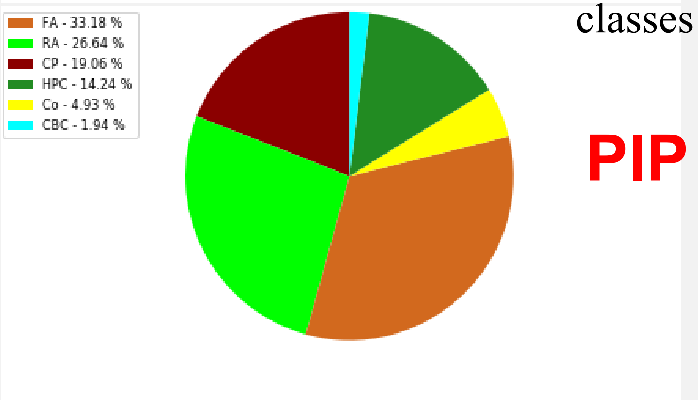
Morphological Analysis : crystal shapes

Reference: Jaffeux et al, 2022



2DS

Number fractions (all ATR-42 data) of morphological classes

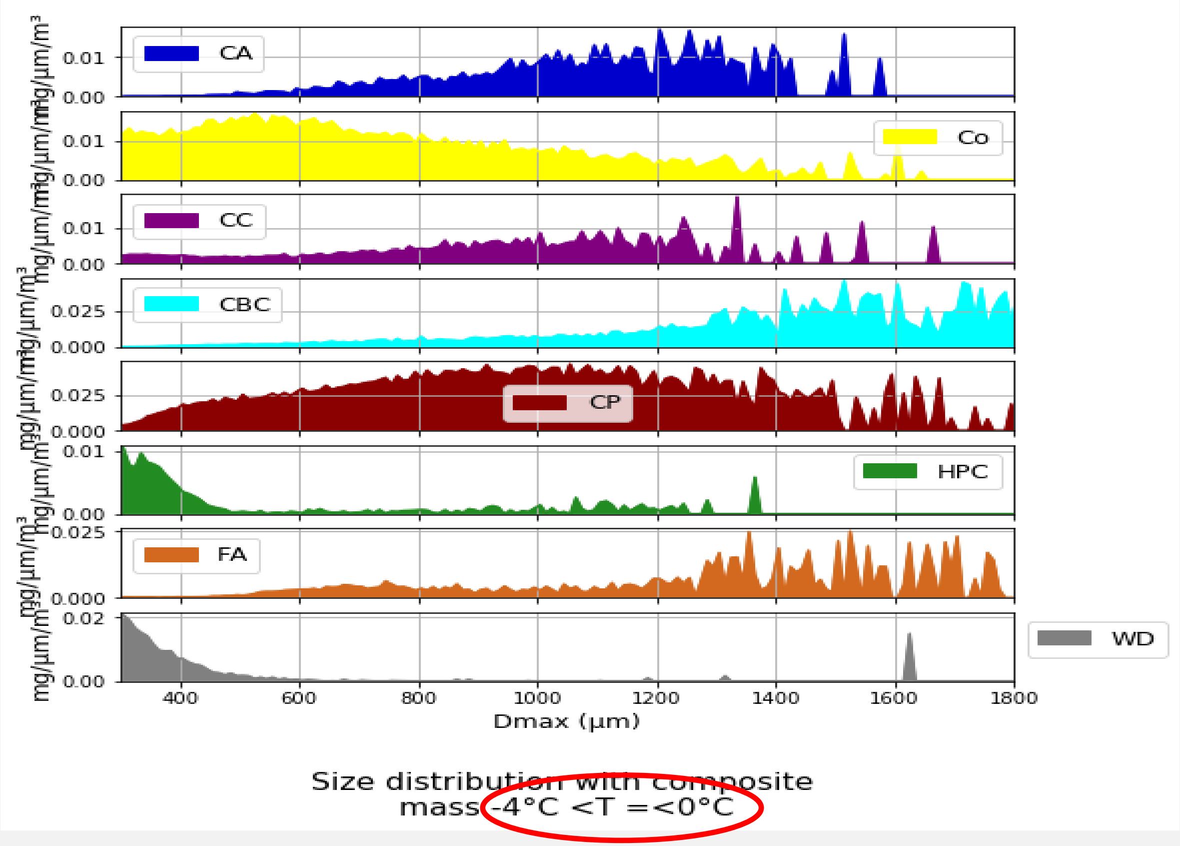


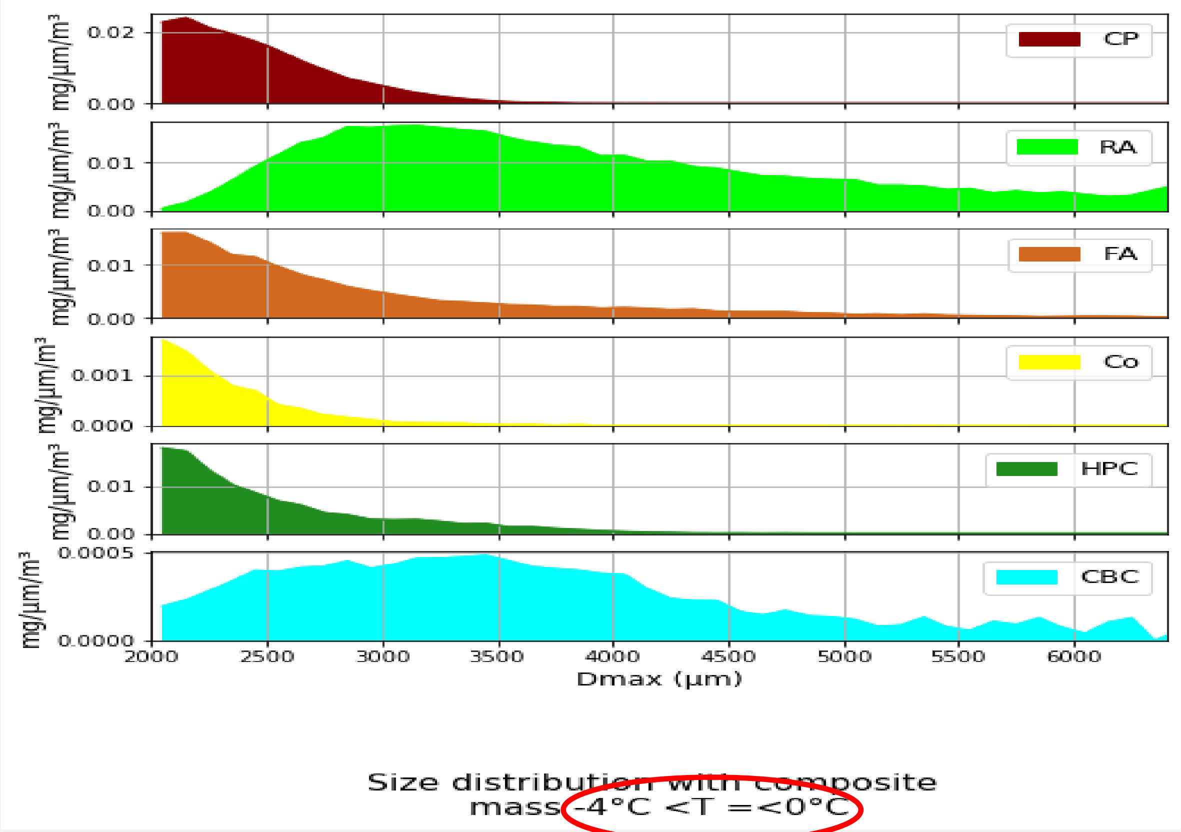
PIP

Class name	Supported probe	2DS 2mm	PIP 2mm	Description	Dominant micro-physical processes		
					Vapor diffusion	Riming	Aggregation
Compact particles **(CP)**	2DS, PIP			Heavily rimed, compact, Graupels		+	
Fragile aggregates **(FA)**	2DS, PIP			Irregular, likely aggregated, unrimed, weak bridges			+
Columns and Needles **(Co)**	2DS, PIP			Singular columns, needles or sheethes	+	−	−
Hexagonal planar crystals **(HPC)**	2DS, PIP			Singular stellar dendrites or plates	+	−	−
Rimed Aggregates **(RA)**	PIP	Truncated on 2DS		Large, likely aggregated heavily rimed		+	+
Combination of bullets or columns **(CBC)**	2DS,PIP			Bullet rosettes, aggregation or combination of bullet rosette and/or columns. Only aggregated columns and/or rosettes for the PIP	+	−	
Complex assemblages of planes, columns, dendrites* **(CA)**	2DS		Resolution is not adapted to see small details or render clear edges	Unrimed, aggregated or not, combinations of plates, columns, dendrites	+	−	
Capped columns **(CC)**	2DS		No capped columns of size >2mm		+	−	−
Water droplets **(WD)**	2DS		No 2mm droplets in ice clouds		+		+

4.3. size and morphology dependency of 2D/3D descriptors

- Mass PSD: striking differences !



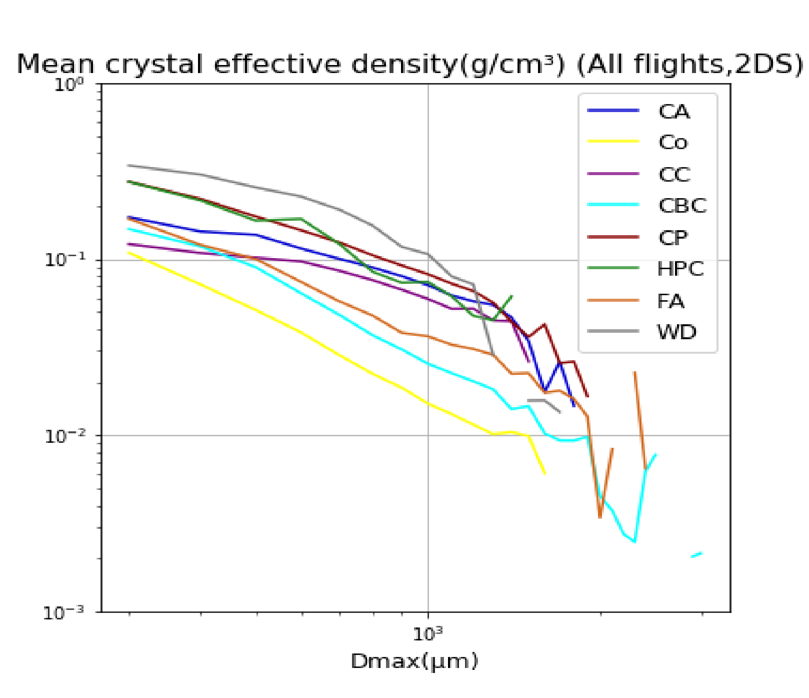


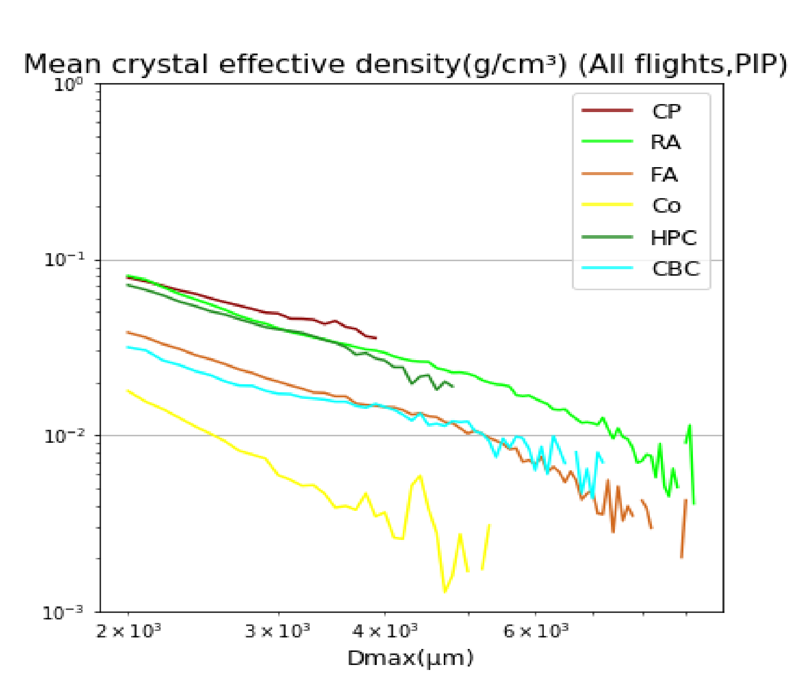
2DS

PIP

4.3. size and morphology dependency of 2D/3D descriptors

- Morphological Analysis : bulk/effective densities & parametrizations





2DS

PIP

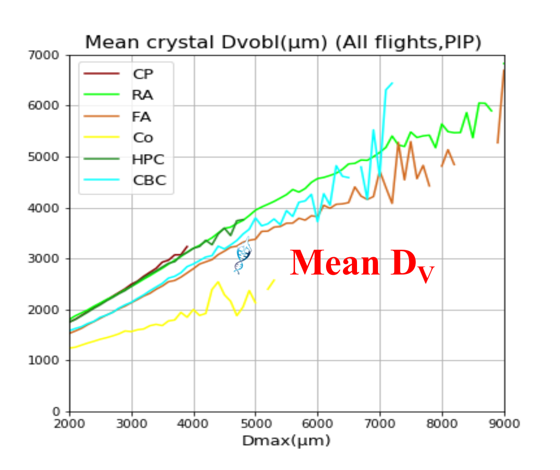
Class	α(2DS)	β(2DS)	α(PIP)	β(PIP)
CP	$2.92 \,.\, 10^{-3}$	-1.38	$1.26 \,.\, 10^{-2}$	-1.13
FA	$9.30 \,.\, 10^{-4}$	-1.55	$2.71 \,.\, 10^{-3}$	-1.73
Co	$3.27 \,.\, 10^{-4}$	-1.68	$3.52 \,.\, 10^{-4}$	-2.44
HPC	$3.25 \,.\, 10^{-3}$	-1.32	$6.01. 10^{-3}$	-1.56
RA			$6.06 \,.\, 10^{-3}$	-1.66
CBC	$3.09 \,.\, 10^{-4}$	-1.89	$3.74 \,.\, 10^{-3}$	-1.36
CA	$6.11 \,.\, 10^{-3}$	-1.02		
CC	$8.39. 10^{-3}$	-0.83		

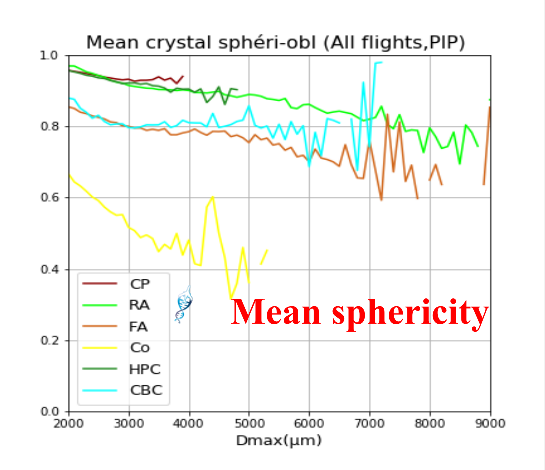
$$\rho = \alpha \,.\, D_{max}^{\beta}$$

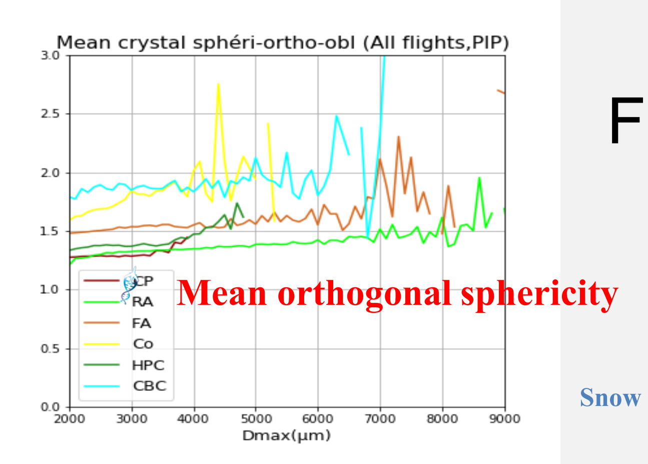
(D_{max} in cm, ρ in g/cm³)

4.3. size and morphology dependency of 2D/3D descriptors

Morphological Analysis : 3D descriptors, class variability and parametrizations







Figures for **PIP** only

Class Name	D_{max} range (µm)	D_V (µm)	Φ	$Φ^{\perp}$
2DS CA	300-1200	0.80 x D_{max} + 26	-3.00E-5 x D_{max} + 0.95	7.72E-5 x D_{max} + 1.33
2DS Co	300-1200	0.44 x D_{max} + 105	-2.89E-4 x D_{max} + 0.84	4.05E-4 x D_{max} + 1.21
2DS CC	300-1200	0.77 x D_{max} + 12	-1.48E-5 x D_{max} + 0.89	4.26E-4 x D_{max} + 1.09
2DS CBC	300-1200	0.55 x D_{max} + 113	-2.46E-4 x D_{max} + 0.97	4.67E-4 x D_{max} + 1.26
2DS CP	300-1200	0.80 x D_{max} + 36	-5.07E-5 x D_{max} + 0.98	1.88E-4 x D_{max} + 1.15
2DS HPC	300-1200	0.66 x D_{max} + 126	-1.91E-4 x D_{max} + 1.08	5.24E-4 x D_{max} + 0.95
2DS FA	2000-6400	0.59 x D_{max} + 94	-2.01E-4 x D_{max} + 0.96	2.41E-4 x D_{max} + 1.22
PIP CP	2000-6400	0.78 x D_{max} + 176	-1.26E-6 x D_{max} + 0.97	6.29E-5 x D_{max} + 1.12
PIP RA	2000-6400	0.69 x D_{max} + 409	-3.88E-5 x D_{max} + 1.04	5.12E-5 x D_{max} + 1.16
PIP FA	2000-6400	0.63 x D_{max} + 256	-3.94E-5 x D_{max} + 0.92	3.49E-5 x D_{max} + 1.42
PIP Co	2000-6400	0.34 x D_{max} + 567	-1.14E-4 x D_{max} + 0.87	1.49E-4 x D_{max} + 1.32
PIP HPC	2000-6400	0.73 x D_{max} + 273	-2.78E-5 x D_{max} + 1.01	3.77E-5 x D_{max} + 1.27
PIP CBC	2000-6400	0.66 x D_{max} + 192	-3.15E-5 x D_{max} + 0.91	3.16E-6 x D_{max} + 1.77

Snow particle Dv (top left), sphericity (top right) and orthogonal sphericity (bottom left) for the oblate spheroid approach for PIP images.

5. Conclusions

- Valuable falling snow data gathered during winter 2020/21 for ICE GENESIS

- Developped synergies of ATR-42 & ground site 'Les Eplatures' in situ & remote sensing : Machine learning to explain significant variability of size and morphology dependent 3D descriptors of snow particles = **realistic representation** of ice crystal population rather than averaged properties

- IG snow data set (winter 2020/21) as one sophisticated snow « sample » within imaginable snow situations, comparable in terms of IWC and MMD to an **existing AIH snow data set** !

- Parametrizations are available to calculate 3D descriptors as a function of size & morphology

  ⇒ Allows studying the behavior of different crystal types in ice accretion modeling