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**Evaluation of the AROME model's ability to represent ice
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1 **Evaluation of the AROME model’s ability to**
2 **represent ice crystal icing using in situ observations**
3 **from the HAIC 2015 field campaign**

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Abstract:

Since pilots generally avoid intense convective areas, Ice Crystals Icing (ICI) is an aeronautical weather incident that mainly occur in the anvil of tropical deep convective clouds. Samples of favorable conditions for the occurrence of ICI and data from the High Altitude Ice Crystals (HAIC) 2015 field campaign in French Guiana are investigated and compared to simulations of the French operational mesoscale forecast system AROME. To this end, a contextualization of convective systems into convective, stratiform and cirriform regions is employed for both observations and AROME. General features of the microphysics of deep tropical convective systems are identified. The concentration number of crystals larger than $125\mu\text{m}$ and total water content (TWC) are strongly correlated at each temperature level and both decrease the further they are from convective cores. AROME is able to reproduce the general behavior of the observed microphysics, especially TWC, but seems unable to simulate extreme ICI events. Reasons are sought in the assumptions performed in the microphysical scheme ICE3 and guidelines are proposed to enhance its skills in the context of ICI. In particular, the representation of the snow particle size distribution is adjusted across observations using a generalized gamma shape. This shape is found to outperform the usual Marshall-Palmer and gamma shapes. Additionally, a temperature and snow content dependency of generalized gamma parameters has been found. These changes are found to significantly improve the snow concentration diagnostic of ICE3 and these modifications open room for improvements in the ICE3 scheme.

1 **1) Introduction**

2 As early as 1963, Simpson (1963) reported icing on aircraft at temperatures as low as -
3 60°C. This was attributed to the presence of supercooled liquid water in the highest levels
4 of the convective updrafts. Such a hypothesis was refuted by Schaefer (1962), who
5 claimed that supercooled cloud droplets cannot be found at temperatures lower than -
6 40°C. Further studies (e.g. Heymsfield & Miloshevich, 1993; DeMott & Rogers, 1990)
7 found no supercooled cloud droplets either at temperatures colder than -38°C.

8 Later, during the '90s, multiple flight incidents due to the accretion of ice on the engines
9 or on the aircraft instruments occurred at relatively high altitudes in low air temperatures
10 (between -27°C and -33°C) and mainly while aircraft were cruising in regions of the
11 convective system considered as safe (Lawson et al. 1998). The presence of supercooled
12 cloud droplets was not expected at such altitudes (Bernstein et al., 2009). Inquiries based
13 on pilots' reports helped to comprehend the cloud microphysical characteristics and the
14 environmental weather conditions of these events (Mason et al., 2006; Grzych & Mason,
15 2010; Mason & Grzych, 2011; Bravin & Strapp 2019). They concluded that high ice
16 water contents (IWC) of relatively small ice particles in high concentrations are
17 responsible for these incidents. Such ice particles, when hitting the aircraft engines or its
18 instrumentation, can melt due to the heat released by friction or by the engines, and
19 freeze afterwards, leading to ice accretion through time (Mason et al. 2006). This kind of
20 icing event is referred to as ice crystals icing (ICI). During an ICI event, pilots encounter
21 low to moderate turbulence with neither supercooled liquid water nor graupel, but high

1 and sustained IWC, in spite of no warning signal on the onboard radar. It was specifically
2 highlighted in these studies that ICI seems to be more frequent in the anvil of oceanic
3 tropical mesoscale convective systems (MCS) (Houze, 2018) in their mature to
4 dissipating stage (Houze, 1982).

5 To avoid severe weather, including convective towers, aircraft are equipped with an
6 onboard X-band (~ 10 GHz) radar. Green echos ($Z < 30$ dBZ) are recognized as safe.
7 Orange or red echos ($Z > 30$ dBZ) are considered as hazardous and correspond to clouds
8 containing high quantities of liquid water or large rimed particles including graupel and
9 hail. Proctor et al. (2017) showed that, even in cases of high IWC, the reflectivity,
10 without rimed particles, remains below 30 dBZ. As a consequence, while onboard radar
11 enables the avoidance of high IWC found in MCS convective regions (due to its
12 sensitivity to large rimed particles) allowing pilots to deroute, it is unable to detect the
13 presence of the high IWC near these cores, which could lead to ICI.

14 Houze et al. (1980) separate MCS into three distinct dynamical regions referenced as the
15 convective, stratiform (precipitating anvil) and cirriform (nonprecipitating anvil) regions.
16 Each region is associated with different microphysics (Barnes & Houze, 2014) which is
17 worth documenting, especially in the context of ICI.

18 The sharp ascending region of MCSs is known as the convective region. As a result of
19 the condensation in the ascending air, cloud droplets and ice crystals form. Interactions
20 between hydrometeors result in the formation of snow, graupel or hail (Heymsfield,
21 1978). Heavy precipitation is usually found within or near convective cores (Zipser,

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1977). When reaching a negative buoyancy barrier (which can be the tropopause), hydrometeors are transported horizontally forming the anvil cloud. Covering broad areas with sustained rain underneath (Steiner et al. 1995; Houze 1997), the precipitating anvil is known as the stratiform region. Here, vertical motions persist as moderate mesoscale ascents in the ice phase region of the cloud and mesoscale descents in the liquid phase of the cloud (Zipser 1977; Gamache & Houze, 1982) are respectively attributed to latent heating and evaporation cooling (Cifelli & Rutledge 1998; Brown, 1979). This circulation favors the formation and the sedimentation of aggregates and large ice particles can be found at the base of ice stratiform clouds, while smaller crystals are generally found aloft (Barnes & Houze, 2014). ICI is generally encountered within the uppermost region of these anvils. Further away from the convective region, the nonprecipitating anvil is called the cirriform region. This thinner region of the MCS is composed of ice crystals and small aggregates (Protat et al. 2011). It is maintained aloft by a radiative instability leading to weak but large extended ascents. (Gasparini et al. 2019; Wall et al. 2020). Within these clouds, ice crystals formed in situ by heterogeneous nucleation such as bullet rosettes can be found (Lawson et al. 2010; Protat et al. 2011).

Although the large-scale organization of MCSs is well understood, detecting, forecasting and understanding the processes leading to ICI conditions, remains a challenge. As a consequence, the High Altitude Ice Crystals (HAIC) European project together with the US High Ice Water Content project (HIWC) was conducted and resulted in three airborne field campaigns (Darwin in 2014, French Guiana in 2015 and La Reunion/Darwin in 2016) coordinated with advances in satellite-based detection (DeLaat et al. 2017; Yost et

1 al. 2018; Haggerty et al. 2019) of ICI being developed, as well as a now-casting product
2 based on ground based radar, geostationary satellites, and numerical weather prediction
3 (NWP) (Haggerty et al., 2020).

4 During these campaigns, it has been found that secondary ice production (Korolev et al.
5 2020), and deposition (Leroy et al. 2017) favor the formation of a mode of a few
6 hundreds of micrometers in the particle size distribution (PSD), responsible for the high
7 ice water content.

8 Numerical studies were also conducted: Ackerman et al. (2015), by performing
9 sensitivity tests using a bin microphysical model not only pointed out the role of several
10 microphysical processes such as secondary ice production and deposition, but also
11 highlighted environmental conditions such as the updraft strength and the number of
12 cloud condensation nuclei (CCN). Cloud resolving simulations were also part of HAIC
13 and HIWC: Huang et al. (2020) or Franklin et al. (2016) using several microphysical
14 schemes (including two moment schemes and evolutions of their microphysical schemes)
15 conclude the need to better handle cloud water and graupel to successfully simulate X-
16 band reflectivities. Turbulence was also singled out as an important process which may
17 play a key role in the simulation of vertical velocities and the modification of cloud
18 microphysical composition and processes. Proctor et al. (2017) using large eddy
19 simulations were successful in simulating broad areas of high IWC with low X-band
20 reflectivities in spite of a simple single moment bulk microphysical scheme.

21 Following on from these previous studies, the present paper aims to identify the

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1 microphysical characteristics favorable to ICI in MCSs and to assess the ICI prediction
2 skills of the French operational mesoscale model AROME (Application of Research to
3 Operations at Mesoscales). In order to do this, MCSs sampled during the HAIC 2015
4 field campaign and the corresponding simulated MCS in AROME are analyzed
5 separately in convective, stratiform and cirriform regions.

6 Section 2 describes the model and provides an overview of the data used in the present
7 study. The comparison method based on the identification of the different dynamical
8 regions of MCSs for both in situ data (using independent microwave and infrared satellite
9 images) and the AROME NWP model is presented in section 3. The in situ data is then
10 analyzed in light of this dynamical context in section 4 and compared in section 5 to
11 AROME outputs. In section 6 investigations of the observed PSD are carried out to
12 propose improvements for AROME.

13 **2) Data**

14 **2.1) In situ observations of the 2015 HAIC field campaign**

15 This study makes use of data collected during the second HAIC field campaign which
16 took place in May 2015 in French Guiana by the Falcon-20 operated by the French
17 scientific national research center (CNRS - *Centre National de la Recherche Scientifique*:
18 *National centre of scientific research*) SAFIRE (*Service des Avions Français*
19 *Instrumentés pour la Recherche en Environnement*, the French facility for airborne

1 *research*).

2 This aircraft performed 17 flights (including one test flight), which lasted for
3 approximately 3 hours. For safety reasons, flights were scheduled during day-light time.

4 The month of May corresponds to the second maximum of the rainy season over French
5 Guiana after a more commonly drier spell in March. At this time of year, the inter-
6 tropical convergence zone moves northward from the amazonian forest bringing warm
7 and moist air favorable to deep convection (Boyé et al. 1979). The Falcon-20 favored the
8 sampling of mature to decaying oceanic MCS cloud anvils where total water content
9 (TWC) is higher than 0.1 g/m^3 at usual commercial flight levels corresponding to the
10 temperature levels: -10°C , -30°C and -45°C . More precisely, these three levels were
11 sampled in the range -8°C to -15°C ; -22°C to -34°C and -37°C to -45°C respectively.

12 Intense convective towers associated with lightning, high turbulence and X band on-
13 board radar reflectivities higher than 30 dBz were avoided as much as possible (Strapp et
14 al. 2016; Coutris 2019).

15 Among others, the Falcon-20 was equipped with advanced instruments enabling a fine
16 sampling of the cloud microphysics:

17 - The RASTA (RAdar SysTem Airborne) (Protat et al. 2009, Delanoë et al. 2007)
18 95GHz Doppler radar.

19 - A cloud droplet spectrometer probe (CDP-2) (Lance et al. 2010) measuring the PSD
20 concentration of liquid particles and very small ice particles in the range of $2\text{-}50 \text{ }\mu\text{m}$.

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1 Supercooled liquid water was rarely sampled especially at -30°C and -45°C levels
2 (Schwarzenboeck et al. 2018), consistent with Stith et al. (2004), and pilots' reports.
3 CDP-2 ice particle measurements can be very noisy in the case of high concentration and
4 are therefore hard to deal with statistically so are not used in this study.

5 - The Iso-Kinetic Probe (IKP-2) sampling the cloud TWC at the flight level every second
6 with a confidence level above 0.1 g/m^3 . It was specifically designed to sample high TWC
7 at high speed. It can measure up to at least 10 g/m^3 at a 200m/s air speed with a 20%
8 accuracy as an objective (Davison et al. 2008). Uncertainties of this instrument are fully
9 reviewed in Davison et al. (2016).

10 - The 2D Stereo probe (2DS) (Lawson et al. 2006) and Precipitation Imaging Probe (PIP)
11 (Field et al. 2006) are crystal imagers. 2DS samples crystals range from 10 to $1280\mu\text{m}$
12 and PIP from 100 to $6400\mu\text{m}$. Their combination allows the derivation of a PSD between
13 10 and $12850\mu\text{m}$ every 5 seconds with a resolution of $10\mu\text{m}$ and a total propagated
14 uncertainty ranging from 10 to 100% (Baumgardner et al. 2017). The 2DS is employed
15 between $10\mu\text{m}$ to $800\mu\text{m}$ while the PIP is employed between $1200\mu\text{m}$ to $12850\mu\text{m}$.
16 Between 800 and $1200\mu\text{m}$ a linear interpolation between the two measured spectra is
17 made for self consistency (Leroy et al. 2016). Particles larger than $6400\mu\text{m}$ may be
18 partly sampled by the PIP and the size correction of Korolev & Sussman (2000) enables
19 the extension of the PSD up to $12850\mu\text{m}$. Although anti-shattering tips were developed
20 on probes (Korolev et al., 2013) and data post-processing was improved to detect
21 shattering (Field et al. 2006; Korolev & Field 2015), the small crystal concentrations

1 have to be carefully considered as shattering of ice crystals on the probe may artificially
2 increase the concentration in the smallest bins.

3 Many diameter definitions may be considered in order to represent the size of three
4 dimensional particles sampled by two dimensional images. Wu and McFarquhar (2016)
5 showed that different definitions can lead to errors of up to a factor of 6 in the
6 concentration estimates for crystals larger than $2000\mu\text{m}$ or smaller than $200\mu\text{m}$. In this
7 study, D_{max} , defined as the maximum possible diameter passing through the barycentre of
8 the two dimension crystal picture (see Figure 1 of Leroy et al. (2016)) is chosen. The
9 AROME model uses Locatelli & Hobbs (1974) relationships using D_{max} . Hence,
10 choosing D_{max} will facilitate the comparison between HAIC observations and AROME.

11 Because of shattering, ice crystals smaller than $125\mu\text{m}$ are excluded and the total
12 concentration number (N) is defined by integrating the PSD from $125\mu\text{m}$ to $12850\mu\text{m}$.
13 Note that crystals smaller than $125\mu\text{m}$ do not account for much of the TWC. In our data
14 set, the mass of crystals below this threshold generally represents less than 3% of the
15 TWC. Setting this lower integration boundary to $125\mu\text{m}$ also separates the two modes
16 commonly observed in ice PSDs (Ackerman 2015; Leroy et al. 2017; Fontaine et al.
17 2020; Field & Heymsfield 2003; Wu & McFarquhar 2016 among others).

18 Using IKP-2 and a 3D ice particle model, a mass-diameter relationship has been derived
19 from each observed PSD by adjusting a power law (Equation 1) (Leroy et al. 2016;
20 Fontaine et al. 2014):

1 $m(D) = a^* D^{b^*}$ (1)

2 Hence, a pair of parameters (a^* , b^*) representative of the best mass-diameter
3 relationships are available for each observed PSD.

4 As a result, the mass size distribution (MSD) can be computed for each PSD $n(D)$:

5 $MSD(D) = n(D)m(D)$ (2)

6 This mass distribution is commonly characterized using the median mass diameter
7 (MMD) which is the median diameter of the ice mass distribution, and here computed as
8 in Mitchell (1991).

9 **2.2) The French operational mesoscale model AROME**

10 AROME simulations are performed starting from 00UTC in the domain of Figure 1
11 between May 09, 2015 and May 29, 2015 corresponding to the first and last days of
12 operation of the Falcon-20 during the HAIC field campaign of 2015. The AROME model
13 (Seity et al., 2011; Brousseau et al. 2016) is a non-hydrostatic limited area model used by
14 the French operational meteorological service for up to 48-h forecasts. It shares its
15 package of physical parameterizations with the Mesoscale Non-Hydrostatic (Meso-NH)
16 French research model (Lac et al., 2018), and its dynamical core with Aladin-NH
17 (Bubnová et al. 1995). AROME functions not only in France and continental Europe in
18 its operations but also overseas (Faure et al., 2020). As a result, a specific AROME

1 domain of approximately 1200 km length and 900 km width is implemented in French
2 Guiana (Figure 1). The model is run with its operational setups: 60 seconds time step and
3 a 2.5km horizontal resolution. The vertical dimension extends from ~5m up to ~34 km
4 using 90 vertical levels, most of them located near the surface meaning a vertical
5 resolution decrease overhead from 10m near the surface to 100m at the top of the mixing
6 layer and roughly 400m at 10km high.

7 Because of a grid change, before the AROME model was operational over Guyana, the
8 initial and forcing conditions usually provided by the European Centre for Medium-
9 Range Weather Forecasts Integrated Forecasting System (ECMWF-IFS) have been
10 replaced by the ones provided by ARPEGE (Action de Recherche Petite Echelle Grande
11 Echelle, Courtier et al., 1991), the French operational global forecast system. This
12 alteration should not impact the results presented here.

13 The incremental analysis update algorithm from Bloom et al. (1996) is used to reduce
14 model spin-up. An initial AROME run beginning 6 hours before the 00UTC network is
15 used to initialize water related variables at the 00UTC network. Nevertheless, spin-up can
16 still influence the results of cloud microphysics for the very first hours of forecast. As a
17 result, the first three hours of simulations are not considered.

18 AROME implements fine descriptions of atmospheric and surface physics. It uses a
19 convection-permitting 2.5 km grid spacing and shallow convection is parameterized
20 following Pergaud et al. (2009). A radiation scheme based on Mlawer et al. (1997),
21 Fouquart and Bonnel (1980) and Morcrette (1991) is used to describe atmospheric

1 radiative transfer. The atmospheric turbulence is described by a one dimension scheme,
2 so without any horizontal mixing, based on a prognostic equation of Turbulent Kinetic
3 Energy (Cuxart et al., 2000). The simulation domain (Figure 1) includes a large fraction
4 of oceanic surface (~70%). The state of the ocean surface largely influences not only
5 cloud organization and the convection life cycle of low clouds (Chung et al., 2012; Klein
6 & Hartmann, 1993), but also that of deep convective clouds (Costa et al., 2001). The
7 coupling with oceanic surface is performed by a 1D column model (CMO, Lebeaupin,
8 2007) initialized by the MERCATOR PSY4 ocean model at a resolution of 1/12 of a
9 degree (Lellouche et al., 2018). Interactions between continental surfaces and atmosphere
10 are described by the surface scheme SURface Externalisée (SURFEX, Masson et al.,
11 2013).

12 The operational model AROME implements the ICE3 single moment bulk microphysical
13 scheme (Pinty and Jabouille, 1998). In addition to the water vapor, three ice species
14 (pristine ice, snow and graupel) and two liquid water species (cloud droplets and rain
15 drops) are used in order to represent the cloud microphysics. For each hydrometeor type
16 the only prognostic variable is the mass mixing ratio. The ICE3 has been further
17 improved by Riette (2020) with a reduction to the time-step dependency. The warm phase
18 is described by the Kessler (1969) scheme. Each hydrometeor is described using two
19 power-laws taken from Locatelli & Hobbs (1974) and Heymsfield (1972) for ice
20 hydrometeors. The mass-diameter and terminal fall velocity – diameter relationships are
21 expressed as power laws (see Equation 1) using for each ice species a and c as prefactors
22 and b and d as exponents. The respective values are given in Table I.

1 A generalized gamma distribution is used to represent the PSD of each hydrometeor:

$$2 \quad n(D) = N_t \cdot \frac{\alpha}{\Gamma(\nu)} \lambda^{\alpha\nu} D^{\alpha\nu-1} \exp(-(\lambda D)^\alpha) \quad (3)$$

3 Here, N_t is the total number concentration of the described species and α , ν are called
 4 shape parameters (see Table I) for the different ice species. When $\alpha=1$ only two free
 5 parameters remain and the PSD is named gamma in the following. If in addition ν is set
 6 to 1 the PSD is named Marshall-Palmer (MP) (Marshall & Palmer, 1948).

7 The λ parameter is physically linked to the proportion of small versus large
 8 hydrometeors: the higher the λ , the higher proportion of small hydrometeors (this feature
 9 of λ can be deduced from Equation 11). Cloud liquid water PSD is set differently based
 10 on the surface type (oceanic or continental) underneath the cloud in order to indirectly
 11 take into account the population of cloud condensation nuclei (Albrecht, 1989; Hudson &
 12 Yum, 2001).

13 For a given hydrometeor type, the total number concentration N_t (m^{-3}) is linked to the
 14 mass content r (kg/m^3) through Equation 4:

$$15 \quad N_t = \frac{r\lambda^b}{aG(\alpha, \nu, b)} \quad (4)$$

16 with:

$$G(\alpha, \nu, b) = \frac{\Gamma(\nu + \frac{b}{\alpha})}{\Gamma(\nu)} \quad (5)$$

17 As ICE3 is a single moment scheme a closure assumption on N_t or on λ is needed to
 18 completely describe the PSD. Using a MP law, Passarelli (1978) proposed to link N to λ

1 through a power law for snow, graupel and rain such as:

2
$$N_t = C \lambda^x \tag{6}$$

3 Different values of C and x can be found in the literature for snow and graupel. Caniaux
4 (1993) tested multiple values of C and x. Among them, the values given in Table I are
5 used in the operational version of AROME.

6 Using Equation 6 in Equation 4:

7
$$\lambda = \left(\frac{aCG(\alpha, \nu, b)}{r} \right)^{\frac{1}{b-\alpha}} \tag{7}$$

8 Then, for precipitating ice species, the whole PSD can be deduced from the only
9 prognostic variable r.

10 Cloud droplet concentration is a function of land surface and takes the constant value of
11 3×10^8 and $1 \times 10^8 \text{ m}^{-3}$ over land and sea areas, respectively. For pristine ice, the
12 computation of N_t is based on the supersaturation over ice (Meyers et al. 1992). The auto-
13 conversion of pristine ice to snow is allowed when it reaches a mass content threshold
14 dependent on the air temperature (Ryan, 2000; Chaboureaud and Pinty, 2006).

15 TWC (g/m^3) in AROME is defined as the sum of each condensed species mass content
16 per volume unit.

17 **3) Contextualization and comparison method**

1 Comparing in situ data to numerical simulations is tricky, especially in the case of deep
2 convection. A point to point comparison cannot be performed as location errors are
3 frequent in numerical simulations and because punctual observations have to be averaged
4 to a comparable spatial and temporal model grid point scale. To overcome this issue, the
5 three different dynamical regions of MCS, as described in the introduction are identified
6 for both the in situ observations and AROME outputs. The different microphysical
7 parameters of both observations and model outputs can then be compared individually in
8 each region.

9 **3.1) Observations**

10 Spaceborne observations are well suited for identifying the various MCS regions since
11 they offer a 2D mapping of convective systems and are independent of the in situ
12 observations. Hence this method can also be used without the presence of airborne
13 observations. The French Guiana region was in 2015 continuously sampled by the
14 geostationary satellite GOES13 and regularly by the microwave radiometers of the
15 Global Precipitation Measurement (GPM) constellation.

16 The GPM constellation includes nine microwave radiometers implementing a channel
17 close to 90 GHz where Polarization-Corrected Temperature (PCT) (Spencer et al. 1989)
18 can be computed. In 2015, the average revisit time was around 1.5 hours on French
19 Guiana and the resolution of radiometers is approximately 4.4×7.3 km (Hou et al. 2014).

20 PCTs at 90GHz are commonly used to identify the cloud convective and stratiform areas

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1 within tropical deep convection. The 90 GHz channel is sensitive to the hydrometeor
2 scattering which is expected to be more important in the convective regions because of
3 strong updrafts forming diffusive ice such as graupel. Less diffusive ice, such as snow, is
4 expected to be found in the stratiform regions. Following Mohr and Zipser (1996), 250K
5 and 225K thresholds are used to identify the stratiform and convective areas of the MCS
6 (Figure 2a). The 90Ghz PCT can be linked to surface precipitation rates (Adler et al.,
7 1990; Spencer et al, 1989). with the 250K and 225K levels corresponding to precipitation
8 rates higher than 3mm/h and 12mm/h, respectively (Mohr and Zipser, 1996).

9 Infrared brightness temperatures from GOES13 are used to delimit the cirriform envelope
10 of the MCS. As in previous studies (Roca et al. 2017; Duvel 1989; Bouniol et al. 2016)
11 the 235K threshold is used in the present study. These data are available every 30 minutes
12 at a 4km horizontal resolution.

13 The combination of PCT and infrared images reasonably defines the system dynamics in
14 two dimensions as viewed from space (Figure 2 (b)).

15 Among the 16 flights performed during the HAIC 2015 campaign, 8 flights have
16 simultaneous data acquisition by at least one satellite of the GPM constellation. For the 8
17 others, when possible, extrapolations were made thanks to PCT acquired just before or
18 after the flight time. Unfortunately some images were missing during the field campaign,
19 especially for flights of May 21, 2015 and May 25, 2015 which were excluded due to the
20 lack of both PCT and infrared images.

1 Good consistency between the RASTA vertical velocity and reflectivity measurements
2 with the corresponding identified region of MCSs was observed, confirming the
3 suitability of the satellite separation method (see supplement S1 and S3).

4 Aircraft data were sorted based on the sampled MCS region and split into 120 second
5 segments. All the ascents and descents of the Falcon-20 were excluded in order to keep a
6 homogeneous temperature sampling. In the following, a segment is defined as a small
7 flight leg performed at a given altitude in a given region of the MCS (convective,
8 stratiform or cirriform). To enable an inter-comparison of these segments, a constant
9 segment length of 120 seconds is set. A sensitivity test (not shown) for this threshold has
10 been conducted by setting the segment length to 60 and 30 seconds without a change in
11 the results. In the case of ICI conditions, this period can be considered as sufficient for
12 ice accretion on the aircraft's engine.

13 Figure 2 shows an illustration of this contextualization process. The Falcon-20 was flying
14 in a deep coastal MCS at an altitude where air temperature was close to -30°C . Thanks to
15 the PCT (Figure 2a) the convective and stratiform regions of the MCS are identified
16 (dash-dotted and dashed contours). GOES-13 infrared images are used to identify the
17 cirriform cloud edges with the 235K threshold (solid contour in Figure 2b). The Falcon-
18 20 sampled the cirriform, stratiform and convective regions (before 0955 UTC, from
19 0955 UTC to 1000 UTC and from 1000 UTC to 1007 UTC respectively). A complete
20 summary of the data set after the segmentation process is given in Table II. In general the
21 sampled MCSs are oceanic and 82% of segments are found in anvil clouds.

1 **3.2) AROME**

2 The same kind of contextualization can in theory be applied from the radiative transfer
3 for television and the infrared observation satellite operational vertical sounder (RTTOV)
4 radiative transfer model (Saunders et al., 2018) and used on AROME’s outputs, enabling
5 the simulation of spaceborne sensors. RTTOV implements additional microphysical
6 assumptions that may not be completely in agreement with the ICE3 assumptions
7 however and differ among the infrared and microwave domains. Since the purpose of the
8 present study is an in depth analysis of in situ data and the evaluation of AROME,
9 avoiding additional assumptions on the microphysics is preferable. The simulated PCTs
10 (see supplement S2) are found to be consistent however with the identification method
11 using model variables (see further below), the choice has rather been to keep criteria
12 closer to AROME physics in order to identify convective, stratiform and cirriform
13 regions within the model simulations. The cirriform MCS envelope is defined by an ice
14 water path (IWP) larger than 0.5kg/m². This criterion is used as a necessary condition for
15 a column to belong to a MCS and ensures a sufficient glaciated development of the cloud
16 excluding cumulus clouds. Several thresholds were tested from 0,01kg/m² to 3kg/m². A
17 too-low IWP criterion implies the detection of thin cirrus whereas a too-high threshold
18 may be too restrictive.

19 Many different methods have been proposed in order to identify MCS convective and
20 stratiform regions, most of them based on precipitation rates, vertical velocities and liquid
21 water content or IWC. Lang et al. (2003) performed a comparison of these different

1 methods. The variability of the criteria and thresholds is large, but the main features of
2 the convective and stratiform regions are shared. In our study, in addition to an IWP
3 criterion and following Xu (1995) and Lang et al. (2003), a column is considered as
4 convective if the maximum vertical velocity is larger than 2.5m/s or if surface
5 precipitation rain rate is larger than 15 mm/h. The vertical velocity threshold allows the
6 identification of the strong ascents in the convective towers. Stratiform regions are
7 identified as non convective columns and with a surface rain rate larger than 1mm/h.
8 Note that the chosen rain rate thresholds are close to those expected under the stratiform
9 and convective classification by PCT (cf. Section 3.1).

10 Figure 3 shows the convective system shown in Figure 2 simulated by AROME and
11 observed after the identification of the various MCS regions. In spite of the fact that
12 AROME simulates a smaller system, located further inland, the applied criteria show that
13 the model is able to simulate organized convection. One of the major interests of this
14 technique is to compare the different MCS regions by overcoming the error in the
15 simulated location of MCSs as observed in Figure 3. As a result, a statistical comparison
16 between in situ data and AROME simulations is made possible in a given dynamical
17 environment and temperature range.

18 **4) Microphysical parameters of observed clouds.**

19 In this section, observations of the 2015 HAIC field campaign are analyzed in light of the
20 contextualization detailed in section 3. In the context of ICI, particular attention is paid to

the behavior of TWC, N and their relationships. The sampled ice crystals are also studied through the analysis of their mass-diameter relationship and MMD.

4.1) TWC

TWC is a key parameter to examine since it is at the source of an ICI flight incident. TWC has to be high up along a long enough path for substantial ice accretion on aircraft engines or instruments to occur. Moreover, it is directly related to AROME ICE3 prognostic variables.

$$Spread = \log_{10}(percentile_{90}(TWC)) - \log_{10}(percentile_{10}(TWC))$$

Each 120 seconds segment is characterized by two parameters: the median TWC and the spread of TWC within the segment. This spread is computed from percentile 10 and 90 as:

This measure enables the removal of extreme and unusual values within the segment and the characterization of the spread of TWC which spans over several orders of magnitude. High median TWC with low spread segments could be favorable to hazardous ICI. The highest values of TWC are found in the convective regions (Figure 4a) for temperatures as low as -30°C, with relatively low spread. Such conditions may be attributed to convective updrafts where water vapor condenses. At the -45°C level, spread increases and TWC decreases, although high values can occasionally be encountered. This could be attributed to the weaker updrafts unable to sustain large crystals at this level or to the detrainment and entrainment processes (Kain & Fritsch 1990).

In other regions of the system (Figure 4b and c), the same temperature dependency of

1 TWC exists: higher TWC can generally be found at the lowest levels of the cloud in
2 agreement with Heymsfield et al. (2017) for tropical clouds. They argue that tropical
3 stratiform clouds are mainly composed of small ice crystals maximizing the deposition
4 process because of their low fall speed velocities in a moist environment. The measures
5 of TWC of Heymsfield et al. (2017) are much lower however than those found in the
6 HAIC stratiform clouds and may rather correspond to the values in cirriform regions.

7 High TWC in the stratiform regions may be due to both detrainment of high TWC from
8 the convective region and the mesoscale ascents, generally more vigorous at the lower
9 levels (Gamache & Houze, 1985), enabling the maintenance of the falling crystals and
10 the accumulation of ice.

11 TWC tends to decrease the further it is away from convection: cirriform regions (Figure
12 4c) have lower TWC than stratiform regions (Figure 4b) which have lower TWC than
13 convective regions (Figure 4a). Such a decrease in TWC was already pointed out by
14 Lawson et al. (1998) and Protat et al. (2016). One may also argue that the ice content
15 source through deposition process or heterogeneous nucleation in the stratiform and
16 cirriform regions is less efficient than the loss by sedimentation or sublimation. In the
17 meantime, spread within segments increases as the distance from convective core
18 increases.

19 In stratiform regions, the spread is slightly higher at the -30°C level, though it shows a
20 larger variability in comparison with the convective regions. In the cirriform regions,
21 spread is higher at -10°C because cirriform clouds are generally hardly maintained at

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1 these lower altitudes but rather maintained aloft thanks to ascents produced by radiative
2 effects (Gasparini et al. 2019, Wall et al. 2020).

3 Interesting extreme segments with high median TWC and low spread are found inside the
4 stratiform clouds and more rarely in cirriform clouds. Most of these segments are found
5 at the -10°C level, but some of them can be found at the -30°C or the -45°C level. These
6 segments with high TWC and low spread aloft may be particularly favorable to ICI. In
7 stratiform regions, sustained TWC of about 2.5 g/m³ and 1 g/m³ with low spread were
8 sampled at the -30°C and -45°C levels, respectively. These particular segments were
9 individually examined, and correspond to a relative diversity of situations in terms of
10 MCS life cycles or land/sea environments.

11 **4.2) Concentration number**

12 The same analysis as for TWC is applied to concentration number (N) and is shown in
13 Figure 4. The highest concentrations are found in MCS convective regions (Figure 4d)
14 due to the formation of new ice hydrometeors in convective updrafts. These crystals may
15 be formed by heterogeneous nucleation (Hoose and Möhler, 2012). The strong dynamic
16 and numerous hydrometeor interactions inside convective regions can however also
17 induce other processes of ice formation such as the glaciation of supercooled liquid water
18 (Stith et al. 2004), and the formation of secondary ice (Korolev et al., 2020).

19 As for TWC, and as observed by Lawson et al. (2019) in mid-latitude continental anvils,
20 N tends to decrease when moving away from convection. Gamache (1990) suggested that

1 the majority of ice hydrometeors are brought from convective updrafts and are diluted in
2 a larger volume due to transportation, leading to a concentration decrease.

3 Aggregation and deposition processes make the larger crystal concentration increase at
4 the expense of the smaller one, and sedimentation brings them to lower levels. In
5 addition, aggregation becomes more efficient as temperature increases (Kajikawa &
6 Heymsfield, 1989), resulting in an enhancement of this concentration sink.

7 As for TWC, high N with low spread can be found especially at -30°C and -45°C in the
8 cirriform and in the stratiform regions (Figure 4e and f). As a result, sustained median N
9 higher than 10^5 m^{-3} are occasionally found. These segments are the same identified with
10 high TWC and are hence of a particular interest in the context of ICI.

11 **4.3) Link between TWC and Concentration**

12 To study the relationship between TWC and N, in the context of ICI, only stratiform and
13 cirriform regions are considered. As a result of aggregation and sedimentation in these
14 regions, a majority of aggregates are expected to be found at the -10°C and -30°C levels
15 (Barnes & Houze 2014; Lawson et al. 2010).

16 A strong relationship exists between these two parameters as shown in Figure 5 where
17 each dot corresponds to the median value of N and TWC in each segment. Linear
18 regression on a logarithmic scale between these two variables at each temperature level
19 results in high correlation ($r=0.82$ at -10°C , $r=0.94$ at -30°C and $r=0.95$ at -45°C). Such a
20 correlation level has already been observed in Mediterranean convective systems

(Taufour et al., 2018). The lower correlation at the -10°C level is explained by a steeper increase of N for higher TWC compared to lower ones. The TWC/ N scatter plot is also organized according to the temperature. Deposition and aggregation processes could explain such a tendency.

The relationship between N and r for snow proposed by Caniaux (1993) (Equation 4 and 6) and implemented in ICE3 is shown by the black line in Figure 5. The behavior of this relationship is in opposition with the observations.

Houze et al. (1979) and Heymsfield (2003) proposed an exponential temperature dependency parameterization of λ assuming a Marshall-Palmer shape for the PSD (see section 6.4). Although Heymsfield (2003) proposed generally higher values for λ than Houze et al. (1979) the behavior of these two parameterizations is similar. Assuming the temperature dependent parameterization of λ from Houze et al. (1979) and using Equation 4, N and TWC are linked with a relatively good agreement in the observations. This parameterization overestimates (resp. underestimates) concentration at the -30°C and -45°C (resp. -10°C) levels but reproduces well the increase in N with TWC.

4.4) Mass-diameter relationship coefficients (a, b)

As detailed in section 2.1, a pair of (a^* , b^*) values of mass-size relationships (Equation 1) are available for each PSD. The median of each parameter in each segment is computed and shown in Figures 6a and b. These parameters give integrated information about the crystal density and are strongly linked.

1 Mass size parameters depend on altitude, and both a^* and b^* have the same behavior and
2 decrease as temperature decreases (Schmitt and Heymsfield, 2010). The comparison
3 between obtained values in stratiform regions and the literature suggests that anvils are
4 mainly composed of aggregates (Locatelli & Hobbs, 1974; Cox, 1988; Lawson et al.,
5 2010; Heymsfield et al., 2002). Convective regions have slightly higher mass size
6 parameters at the -10°C and -45°C levels than cirriform and stratiform regions. It may be
7 the result of a higher proportion of rimed ice or graupel for the -10°C level and of more
8 pristine ice, or of different crystal shapes for the -45°C level. Overall however, as with
9 stratiform and cirriform regions, aggregates seem the most represented hydrometeors in
10 convective regions. The flight sampling strategy used during the HAIC field campaign
11 where graupel was avoided as much as possible could be a possible reason for this
12 behavior.

13 4.5) MMD

14 As found by Leroy et al. (2017), the MMD increases with temperature (Figure 6c) and
15 therefore smaller crystals account for a greater part of total mass at higher altitudes. This
16 phenomenon can be explained by sedimentation and the gradual growth of crystals by
17 aggregation and deposition and a more efficient aggregation for higher temperatures
18 (Kajikawa & Heymsfield, 1989).

19 At the -10°C level, convective regions have slightly lower MMDs compared to stratiform
20 regions, which may be due to the formation of new small ice hydrometeors consistent
21 with the higher concentrations found in section 4.2. On the contrary, stratiform ice

1 crystals at lower levels are not formed in situ but mostly result from lifted and detrained
2 particles of the convective regions which then sediment, aggregate and are subject to
3 deposition. At the -30°C level, MMDs are generally similar between the convective,
4 stratiform and cirriform regions which could be the result of detrainment. In contrast, at -
5 45°C , as ascent strength decreases from the convective to the stratiform and cirriform
6 regions, the largest hydrometeors cannot be maintained aloft, and MMD decreases.

7 **5) Evaluation of AROME-ICE3 with respect to observations**

8 For this evaluation, all outputs from AROME are considered on the same days as HAIC
9 2015 flight days. For each flight, convective cells that are both similar and geographically
10 close to the one sampled by the aircraft, are identified and manually tracked.
11 Characteristics of each sub-region of the MCS are compared to the in situ data by using
12 the contextualization method described in section 3. For both TWC and concentration
13 additional temperature levels are added to identify possible biases in the simulated cloud
14 vertical extent. Little supercooled cloud water was found in the simulated systems by
15 AROME at temperatures colder than -10°C . Graupel contents represent about 30% of the
16 mean TWC in the stratiform region at -10°C , but only 15% and 10% at -30°C and -45°C
17 respectively (mean vertical microphysical profiles is shown in supplement S4).

18 Microphysical properties in the model are strongly controlled by the dynamical and
19 thermodynamical environment. The AROME simulation is initialized and forced at the
20 boundaries by the ARPEGE which has a full assimilating system based on Veersé and

Thépaut (1998). A relatively good description of the large scale environment can be assumed. Evaluating in depth the cloud dynamics and thermodynamic is a hard task since few data are available. Nevertheless, an acceptable consistency was found between the mean, percentiles 90 and 95 of the simulated vertical velocities of the convective region and those sampled by RASTA (see supplement S3). Temperature profiles sampled by Falcon-20 were also found to be consistent with AROME (see supplement S3).

5.1) TWC

TWC is a key parameter in ICE3 as the mass mixing ratio of each species are the only prognostic variables. Similarly to Figure 4, Figure 7 is built from AROME outputs, in which each point represents the median and the spread of a given microphysical parameter for the MCS sub-regions at the selected times. For comparison, observed median and extreme values are superimposed.

AROME is able to reproduce the main observed behavior of TWC, in particular an increase in TWC with the temperature, and a decrease when moving away from convective regions. Median values of TWC are of the same order of magnitude as the observed ones, though slightly too low, especially aloft. The spread in AROME is higher than observed. The fact that the whole sub-region is taken into account in AROME and not only a smaller part as for the observed segments explains this higher spread.

AROME does not simulate high enough TWC in altitude in convective towers, especially near -30°C . As the cirriform clouds are rather found at cold temperatures (cf.

1 Introduction), TWC decreases and spread increases for temperatures higher than -10°C .

2 The variability is too high compared to the observations and cases of high TWC aloft are
3 very rare, especially in the stratiform and cirriform regions. The highest values are lower
4 than the observed ones, especially in the stratiform regions. As a result, ICE3 does not
5 seem able to produce satisfying ICI conditions in the stratiform and cirriform regions.

6 **5.2) Concentration**

7 In ICE3, concentration is entirely diagnostic (see section 2.2) and is hereafter derived
8 from the sum of all ice PSD and as in observations over diameters larger than $125\mu\text{m}$.

9 The order of magnitude of simulated concentration (Figure 7d, e and f) is generally
10 underestimated by more than a factor of 10 and the tendencies of concentration with
11 temperature and MCS sub-region are in opposition with those observed (Figure 4d, e and
12 f): the concentration slightly increases while moving away from convection. The
13 dispersion is generally very low. These differences are the result of the parameterization
14 of snow concentration (Equation 6, Figure 5).

15 **5.3) Mass diameter parameters (a, b)**

16 Even if the separation of the different ice hydrometeor types in a given observed ice PSD
17 is possible (Protat et al. 2011), such estimations are not available in our observational
18 dataset. For the sake of comparison, similar estimation of (a^*, b^*) as the ones of Leroy et

al (2017) (see Section 2.1) are performed with AROME outputs. The complete ice PSD is reconstructed by adding up the PSD for each ICE3 ice species computed from Equation 3.

A linear regression between $\log\left(\frac{MSD(D)}{n(D)}\right)$ and $\log(D)$ is then applied. Using Equations 1 and 2, the intercept and the slope of this regression correspond respectively to a model estimate of $\log(a^*)$ and b^* .

AROME's (a^* , b^*) parameters are in relatively good agreement with the ones observed (Figure 6) which are computed from the observations (Section 2.1). Convective regions show slightly higher values, which could correspond to a higher proportion of graupel particles. The avoidance of graupel in the flight plan of the HAIC field campaign could also be partly responsible of this bias however (see Section 2.1).

5.4) MMD

MMD is also computed from the AROME PSD including all ice species. In ICE3, MMDs are too large by about one order of magnitude (Figure 6c) and thus simulated PSDs are formed from crystals which are too large. Such behavior could be expected as snow concentrations (section 4.3) and λ (section 6.4) are too low in the case of high snow content. Changing the shape of the PSD may also impact the MMD estimates and this room for improvement is explored in section 6. Nevertheless, AROME manages to reproduce the variations of the MMD with temperature.

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1 **6) Description of PSD in the stratiform and cirriform regions**

2 TWC and N are not the only moments used in a bulk microphysical schemes such as
3 ICE3, but several moments of the PSD are involved in the different microphysical
4 processes. For instance the first moment is used in the deposition mass flux. Hence, the
5 calculation of microphysical processes is dependent on the chosen PSD shape.

6 As detailed in section 2.2, the ICE3 scheme implements a generalized gamma with fixed
7 ($\alpha=1$, $\nu=1$) parameters leading to a MP law to describe the snow PSD. This choice is
8 questionable. Indeed, Houze et al. (1979) reported that deviations of the PSD from the
9 MP shape are very common. A mode of between diameters of 200 μm and 500 μm is
10 common in the observed anvil PSD (Ackerman 2015; Leroy et al. 2017; Fontaine et al.
11 2020; Field & Heymsfield 2003; Wu & McFarquhar 2016 among others). This section
12 aims at assessing a more suitable law for representing PSD within the stratiform and
13 cirriform clouds of MCS, keeping in mind that the ICE3 implements a generalized
14 gamma law. Therefore additional variability in the PSD shape (and improvement of the
15 microphysical process representation) may be sought either in fixing α and ν to a
16 different value or even by varying them with thermodynamical situation.

17 **6.1) On the choice of generalized gamma and moments to fit PSD**

18 Gamma laws were already used to improve the representation of the ice PSD in anvil
19 clouds for NWP (Thompson et al. 2008). The use of a generalized gamma law is rather
20 rare in the literature and gamma or MP laws are generally found more convenient

(Milbrandt & Yau, 2005; Ziegler, 1985). Field et al. (2005) tried to fit observed PSD with a generalized gamma law and found that this shape was not able to fully catch both the mode for crystals of a few hundreds of μm and the exponential tail as predicted by Westbrook et al. (2004). Still, in the present study generalized gamma shape has been used to fit PSD to stay within the frame of ICE3. In our simulations, the higher fraction of the IWC in the anvil is due to snow (see S4 in the supplement). We therefore mainly seek to improve the description of the snow distribution, here considered as a crystal size larger than $125\mu\text{m}$.

Former studies used different moments to fit PSDs. Field et al. (2005) and Elsaesser et al. (2017) used pairs among moments 2, 3 and 4, and Heymsfield (2002) used moments 1, 2 and 6. As several moments are used in ICE3 parameterizations, it is necessary to determine the pairs (or higher order combination) that are the most representative of the whole PSD. Using the methods describe in Appendix A1 and assuming $\alpha=v=1$, three different moment combinations are tested to retrieve λ parameter and compared in Figure 8. As described in section 2.2 this parameter is physically linked to the proportion of small versus large hydrometeors. λ obtained from a linear regression assuming a MP shape for crystals larger than $125\mu\text{m}$ is taken as a reference. Using moments 3 and 4 leads to results very close to this reference with a correlation coefficient of $r=0.97$. A clear difference appears when λ is estimated from moments 1 and 2, even if correlation remains as high as $r = 0.81$. This difference can be explained by the fact that this λ better fits the smaller crystals parts of the PSD. The four moments method (from 1 to 4) detailed in Appendix A1 is found to be a good compromise for λ to fit the whole

1 distribution. In this case $r=0.94$. The four moments method is used hereafter as it equally
2 weighs large and small crystals of each PSD.

3 **6.2) Finding the best compromise for PSD shape parameters**

4 This section aims at finding the best PSD shape parameters for snow. To do so, a measure
5 named “gap” representing the distance between the computed and observed moments is
6 defined (Appendix A.2). The (α, ν) pair corresponding to the minimum of this “gap”
7 enables the most accurate moment computation. The studied sample is restricted to PSDs
8 where TWC exceeds 0.1 g/m^3 in the stratiform regions and in the cirriform regions where
9 the air temperature is also above -30°C . These regions are mostly composed of snow.

10 Figure 9a displays the ratio (in percentage) of the gap relatively to its absolute minimum
11 in the α, ν space. As a result the closer to 100% this ratio is, the closer this gap value is to
12 the absolute gap minimum. The lower values of the gap are aligned along a straight line
13 which links α to ν . As a consequence, multiple values of α and ν minimize Equation 16.
14 Among them, $\alpha = 0.21 \nu = 43.7$ corresponds to the absolute minimum.

15 The specific cases of a MP ($\alpha = \nu = 1$) and a gamma law ($\nu = 1.3$) are generally
16 acceptable. The benefit of the “best” generalized gamma shape is illustrated in Figure 9b
17 where the mean observed PSD is fitted with the different retrieved shapes. The MP is
18 unable to reproduce the mode for crystals of a few hundred μm . The gamma law is close
19 to the MP but represents this mode. The generalized gamma law compromise is more
20 realistic with a more pronounced mode, a steeper decrease for small crystals (which are

not considered as snow particles here) and a curving for crystals larger than a few hundreds of μm leading to a higher and more realistic proportion of large crystals.

6.3) Temperature dependency of PSD shape

Further investigations may further reduce this distance between observed and theoretical PSD, especially for the case of high TWC, by studying dependency to physical parameters (as proposed by Elsaesser et al. 2017).

The process used in section 6.2 is repeated separately on the three different temperature levels. The region of minimum gap evolves, leading to different relationships between α and ν for the different temperature levels (Figure 10). The MP still gives reasonable agreement at the -10°C temperature level (Figure 10a). However aloft, at the -30°C or -45°C level the MP is not satisfactory enough to be considered as a good shape compromise (Figure 10b and c). A temperature-dependent parameterization of the snow PSD shape is thus worth considering. Table III gives the retrieved values of the best (α, ν) at each temperature level. To ease the analysis dependency with temperature, ν values with constant α (1, 0.5 and 0.25) are included in this Table.

The dependency of α and ν with TWC has also been investigated, but no clear dependency has been found (not shown).

6.4) Analysis of λ for snow

The dependency of λ with TWC in the observations is studied in this section. The λ

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1 values are recovered with our moment method (A.1) assuming the best shape found in
2 section 6.2.

3 Linking λ to N using Equation 6 (Caniaux, 1993) induces a link between λ and TWC
4 (Equation 7). Figure 11 shows λ as a function of TWC values and no such link can be
5 directly observed. Specifically, high values of λ for high TWC are possible, while not
6 allowed by the parameterization of Caniaux (1993).

7 λ can be linked to temperature (Houze et al., 1979, Heymsfield, 2003) and seems more
8 adapted to our sample. A temperature dependent parameterization of λ has already been
9 used in a NWP system (Thompson et al. 2008). As a result, λ increases as temperature
10 decreases (Figure 11). Such a dependency can be explained by aggregation (which is in
11 addition supposed to be more efficient as the temperature increases (Kajikawa &
12 Heymsfield, 1989), deposition and the quicker sedimentation of larger crystals. Setting
13 such a temperature dependency allows the satisfactory diagnosis of concentration using
14 Equation 4 (Figure 5).

15 Nevertheless, these parameterizations cannot reproduce all the λ variability as the
16 dispersion around the diagnostic value remains high (Figure 11). Heymsfield (2003) and
17 Field and Heymsfield (2003) argued that this temperature dependency is blurred by the
18 cloud top height. Indeed, larger cloud depths provide more time for sedimentation and
19 aggregation. This could possibly result in different parameterizations depending on the
20 cloud location. Tropical clouds are generally warmer in the troposphere for a given height
21 than mid-latitude or polar clouds. This could partly explain the major differences between

our observation made in the tropics and the one of Houze et al. (1979) made in mid-latitude (Figure 11).

For a given temperature level, especially at the -10°C level, a weak dependence on FWC can be observed in Figure 11. For TWC between 0.1g/m^3 and 1g/m^3 λ decreases slightly as the TWC increases. Indeed, a higher TWC results in a higher concentration (Figure 5), which should lead to more collisions between crystals and to more aggregation. However for TWC higher than $\sim 1\text{g/m}^3$ scatter plots tend to bend towards a higher λ and thus the proportion of smaller crystals is higher. This is particularly interesting in the context of ICI conditions. These hydrometeors could result from the detrainment of a high concentration of crystals formed in the convective updrafts. As λ is linked to N by Equation 4, this bending for high TWC could be linked to the similar one seen in Figure 5 especially at the -10°C level. Third order polynomial regressions using the method of least squares are performed between λ and TWC for each temperature level (Equation 9) and highlight this dependency.

(9)

Hence a new formulation of λ based on the temperature level and the TWC may be proposed.

7) Conclusion and outlook

This study aimed at analyzing the microphysical characteristics of favorable conditions of ICI and the behavior of the operational mesoscale model AROME for their simulation.

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1 The contextualization method used in this study for both observations and model outputs
2 has enabled an in-depth analysis of the in situ observations of the HAIC 2015 field
3 campaign and the assessment of AROME using the ICE3 microphysical scheme. With
4 this comparison method, general microphysical behaviors of tropical MCSs have been
5 identified.

6 Firstly, getting closer to convective towers, TWC and N increase. These two parameters
7 are strongly linked at each temperature level, and N increases when TWC increases.

8 Multiple microphysical parameters were found to depend on temperature. When the
9 temperature decreases, the TWC, general mass-diameter parameters (a^* , b^*) and MMD
10 decrease, while λ increases. Particular flight segments potentially favorable to the
11 occurrence of ICI events with high and sustained TWC (and N) were identified in the
12 stratiform and cirriform regions.

13 Some of the microphysical characteristics simulated in AROME are in agreement with
14 our observations. Indeed, AROME is able to reproduce a decrease of general mass-
15 diameter parameters (a^* , b^*), MMD and TWC when the temperature decreases or the
16 TWC decrease as they get further away from convective regions.

17 The snow concentration diagnostic derived from the hypothesis of Caniaux (1993) has
18 been proven to be unsatisfactory as forcing an erroneous anti-correlation between TWC
19 and N. It leads to the underestimation of N by a factor 10 and to excessively large
20 MMDs. As a result, AROME is not able to simulate the sustained high TWC conditions
21 at high altitudes, expected in the case of ICI, as crystals which are too big may sediment

1 too quickly.

2 The microphysical evaluation of ICE3 carried out in this paper highlights biases and
3 proposes some modifications of the scheme that could help the operational model
4 AROME to better forecast ICI conditions.

5 Assuming a generalized gamma law, the PSD of the stratiform and of the middle to lower
6 region of cirriform clouds has been investigated. We proved that the MP law is an
7 acceptable approximation at the -10°C temperature level but it can be supplanted by the
8 widely used gamma law (Elsaesser et al 2017; Field et al. 2005; Heymsfield 2003)
9 especially at higher altitude. An even better description of higher and lower moments is
10 possible using a generalized gamma law. A new parameterization of λ , taking into
11 account its dependence on temperature (and eventually by adding a weak TWC
12 dependency) as proposed in section 6.4 could be implemented in bulk microphysical
13 schemes (Thompson et al. 2008). Better describing the snow distribution in
14 microphysical schemes could strongly aid a better representation of concentration and of
15 some processes such as snow sedimentation, aggregation or deposition of vapor on snow
16 for example. The use of a generalized gamma law may enable to compute more
17 accurately some microphysical processes where calibration factors are involved. A
18 positive impact on microphysical schemes with more than one moment is likely.

19 To implement in microphysical schemes the temperature dependencies found for λ , α and
20 v , relationships found in this article have to be extrapolated to other temperatures with
21 caution and the use of additional datasets may be required (Houze et al. 1979;

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1 Heymsfield et al. 2003). Using a process-based determination of λ (Mitchell (1988,
2 1991)) could be even more realistic and is not temperature dependent.

3 Using the proposed parameterization elsewhere other than in French Guiana seems
4 possible and may improve the realism of AROME for other types of weather such as
5 mid-latitude fronts or heavy precipitating Mediterranean events (Taufour et al. 2018) but
6 may vary in function of the location. In addition to the reasons evoked in section 6.4, the
7 variability of CCN and ice freezing nuclei number and types may affect the microphysics
8 of cloud, the PSD of ice and thus N , λ , α and v .

9 An enhanced description of pristine ice may also improve the realism of ICI conditions in
10 AROME. As summarized in section 2.2, the pristine ice diagnostic is deduced from
11 Meyers et al. (1992) using supersaturation over ice. This latter is kept artificially low
12 however because it is reduced by an adjustment to the saturation, and hence pristine ice
13 concentration is kept unrealistically low.

14 The 2-moment microphysical scheme LIMA (Liquid Ice Multiple Aerosols, Vié et al.
15 2016), which is under evaluation in AROME and currently used for research purposes
16 (Taufour et al., 2018, Ducongé et al., 2020) may improve the representation of pristine
17 ice. In particular, it implements a prognostic concentration for pristine ice and cloud
18 water particles, has a prognostic representation of aerosols and their interactions with
19 clouds, and allows supersaturation over ice to develop freely. This should enhance the
20 description of cloud water and its depletion, the description of ice and of the deposition
21 process. Secondary ice production processes (Korolev et al. 2020) can then be taken into

1 account and may help to correct some possible biases of single moment schemes. LIMA
2 enables the use of a second moment for snow, and its potential benefit over our proposed
3 parameterization may be worth documenting.

4 In a following paper, sensitivity to the derived parameterizations will be explored to
5 enhance the forecast of ICI conditions with AROME.

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6 *Appendix*

7 *Generalized gamma law fits method using distribution moments*

8 In bulk microphysical schemes only moments of the distribution computed through
9 Equation 11 are used as prognostic variables and feed the various parameterizations.
10 Doing so enables considerable reductions in the calculation costs (Tripoli et al., 1988).
11 Using several moments of the observed PSD, the objective of this section is to propose a
12 methodology to fit the observed PSD with a generalized gamma distribution.

13 **A.1) Determination of λ**

14 $n \in \mathbb{R}$
The n^{th} moment of any distribution $n(D)$ is defined as:

15
$$M(n) = \int_0^{+\infty} n(D) D^n dD \quad (9)$$

16 The generalized gamma distribution is defined using a triplet of parameters (α, v, λ) , any

moment of the PSD is then linked to this triplet through:

$$M(n) = \frac{G(\alpha, \nu, b)}{\lambda^n} \quad (10)$$

G defined in Equation 5.

By using Equation 11 twice for two different moments n and m , λ can be derived:

$$\lambda = \left(\frac{M(n)}{M(m)} \cdot \frac{\Gamma\left(\nu + \frac{m}{\alpha}\right)}{\Gamma\left(\nu + \frac{n}{\alpha}\right)} \right)^{\frac{1}{m-n}} \quad (11)$$

Different moments can be chosen for estimating λ . To put weight on more moments,

Equation 11 can be used for two pairs of moments, e.g. $(n, m) = (1, 2)$ and $(n, m) = (3, 4)$.

In order for the weights to be equally distributed on a broad range of crystal diameters:

$$\lambda(\alpha, \nu) =$$

Note that moments 5 and 6 were not used as many PSDs were too noisy for the largest crystals. We call this method the “four moments method”.

A.2) Determination of the best (α, ν) pairs by fitting observed PSD

The moment of the observed PSD, $I_{P,observed}(n)$, numerically integrated. For each PSD p , the corresponding λ is computed using the four moments method (see A.1) and assuming

different values of α and ν . The theoretical moments of the PSD P ($M_p^{theoric}(\alpha, \nu)$) using Equation 10. The theoretical concentration, 0th moment, is computed using Equation 4 in which r is taken from the IKP-2. The values of the mass diameter parameters (a , b) are set constant to the ones used in AROME for snow (cf. Table I).

The difference between the observed and the theoretical n^{th} moment normalized by its concentration N for each PSD p is computed as:

$$\Delta_p(\alpha, \nu, n) = \left(\frac{M_p^{observed}(n)}{N_p^{observed}} - \frac{M_p^{theoric}(\alpha, \nu, n)}{N_p^{theoric}(\alpha, \nu, n)} \right) \quad \mathbf{P}$$

This process is repeated for moments from 1 to 4, for the K PSDs of the ensemble of PSD (see section 6.2 for definition) and for values of α and ν ranging (logarithmically) from 0.1 to 3 and 0.1 to 75 over 50 values.

Because the order of magnitude of each moment is different and depends on the values of α and ν , the same weight is given to each moment by normalizing :

$$\Delta_p^{norm}(\alpha, \nu, n) = \frac{\Delta_p(\alpha, \nu, n)}{\sigma(n)} - \mu(n)$$

Where $\mu(n)$ and $\sigma(n)$ are the mean and the standard deviation of Δ_p across the number of PSD (K) belonging to α, ν , times the 50 times 50 values of tested α and ν values.

The (α, ν) pairs which minimize:

$$Gap(\alpha, \nu) = \sum_{n=1}^4 \left(\frac{1}{K} \sum_{p \in \mathbf{P}} \Delta_p^{norm}(\alpha, \nu, n) \right) \quad (15)$$

are considered as the best fit.

Supporting information

A supplement related to this article is available. It is composed of four sections S1 to S4 with a total of eleven additional figures.

S.1 Qualitative evaluation of the consistency of the convective, stratiform, cirriform

PCT/IR classification used in the observations using RASTA reflectivity measurements

S.2 Qualitative evaluation of the consistency of the convective, stratiform, cirriform

classifications between model and observations

S.3 Evaluation of the simulated thermodynamical and dynamical environment using

ancillary HAIC data

S.4 Contribution of each cloud species mass content to TWC

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Tables:

	Graupel	Pristine ice (plates)	Snow	Rain	Liquid cloud water
a	19,6	0,82	0,02	524	524
b	2.8	2.5	1.9	3	3
c	124	800	5.1	842	3.2x10 ⁷
d	0.66	1	0.27	0.8	2
<i>α</i>	1	3	1	1	3 (ocean)

					1 (continent)
v	1	3	1	1	1 (ocean) 3 (continent)
C	1E5	X	5	8E6	X
x	-0.5	X	1	-1	X

Table I – Coefficient values (S.I. unit), describing the ICE-3 ice species

	Convective	Stratiform	Cirriform
Number of segments	103	241	226

Table II – Distribution of observations regarding the MCS sub-regions.

	(α; v)	v for $\alpha=1$	v for $\alpha=0,5$	v for $\alpha=0,25$
All PSDs	(0.214; 43.7)	1.3	7.54	38.2
-10°C	(0.163; 75)	1.14	7.54	33.3
-30°C	(0.25; 38.2)	1.49	9.88	38.2

-45°C	(0.247; 43.7)	1.95	11.3	50
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Table III – Best (α , v) pairs for all PSDs and at -10°C , -30°C and -45°C temperatures.
In the last three rows, setting α constant, the best corresponding v values are given for
each ensemble.

Figures:

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2 *FIGURE 1 – AROME domain over French Guiana. The color scale shows the orography.*

3 *The dotted lines correspond to country borders.*

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FIGURE 2 – MCS sampled on May 29, 2015 around 1000 UTC by the Falcon-20 flying at an elevation where air temperature is around -30°C . The colored line shows the TWC measured by IKP2 along the flight path. The MCS is observed in the (a) microwave by SSMIS at 0940UTC and (b) in the infrared by GOES-13 (b). Identified MCS regions are shown using black lines (see text for definitions).

FIGURE 3 – Identification of convective/stratiform/cirriform regions of the MCS

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*sampled on May 29, 2015 at 1000UTC (a) in AROME and (b) classified using
spaceborne observations.*

*FIGURE 4 – Spread of TWC (a, b and c) and N (d, e and f) as a function of median
values within each segment (dots) for the different MCS regions: (a, d) convective (b, e)
stratiform and (c, f) cirriform. Colors show the segment temperature. Triangles represent
the median of all segments for a given temperature level. Maximum median TWC and N
for each temperature level are highlighted by a vertical bar of the corresponding color.*

FIGURE 5 – Median N as a function of median TWC (dots) for each stratiform and cirriform segment and temperature level are shown in colors. Colored lines show the diagnostic concentration of Houze et al. (1979) in warm colors and as deduced from Caniaux (1993) in black.

1 *FIGURE 6 – Box-plots of mass diameter coefficients (a^* , b^*) and MMD as a function of*
2 *the dynamical environment partitioned by temperature. Hatched box-plots represent*
3 *observed values, while filled box-plots are for AROME outputs.*

FIGURE 7 – As in Figure 4 but for AROME. Stars represent the simulated medians for a given temperature level. Median (colored triangles) and maximum median (dotted line) are the observed values from Figure 4.

FIGURE 8 – Scatter plot of λ retrieved assuming different moment combinations as a function of λ deduced from linear regressions assuming a MP distribution. Solid lines correspond to the linear regression performed for each moment combinations.

FIGURE 9 – (a) Ratio of the gap minimum over the gap value for a given α and ν (in per cent, color-scale) . Red crosses, pentagons and stars indicate the location of the Marshall-Palmer ($\alpha=\nu=1$), the best gamma fit ($\alpha=1$) and the best generalized gamma fit, respectively. These shapes (respectively black, yellow and red lines) are used to fit the mean PSD (purple line) in (b).

FIGURE 10 – As in Figure 9a, but for three of the temperature levels (-10°C (a), -30°C (b) and -45°C (c))

FIGURE 11 – λ as a function of TWC and temperature (colors) Houze et al. (1979) diagnostic is indicated by dashed lines for the three different temperature levels and the Caniaux (1993) diagnostic by the dashed -dotted line. Polynomial fits are represented by filled lines.

AROME domain over French Guiana. The color scale shows the orography. The dotted lines correspond to country borders.

1058x705mm (72 x 72 DPI)

MCS sampled on May 29, 2015 around 1000 UTC by the Falcon-20 flying at an elevation where air temperature is around -30°C. The colored line shows the TWC measured by IKP2 along the flight path. The MCS is observed in the (a) microwave by SSMIS at 0940UTC and (b) in the infrared by GOES-13 (b). Identified MCS regions are shown using black lines (see text for definitions).

254x127mm (800 x 800 DPI)

Identification of convective/stratiform/cirriform regions of the MCS sampled on May 29, 2015 at 1000UTC
(a) in AROME and (b) classified using spaceborne observations.

1726x763mm (72 x 72 DPI)

Spread of TWC (a, b and c) and N (d, e and f) as a function of median values within each segment (dots) for the different MCS regions: (a, d) convective (b, e) stratiform and (c, f) cirriform. Colors show the segment temperature. Triangles represent the median of all segments for a given temperature level. Maximum median TWC and N for each temperature level are highlighted by a vertical bar of the corresponding color.

Median N as a function of median TWC (dots) for each stratiform and cirriform segment and temperature level are shown in colors. Colored lines show the diagnostic concentration of Houze et al. (1979) in warm colors and as deduced from Caniaux (1993) in black.

As in Figure 4 but for AROME. Stars represent the simulated medians for a given temperature level. Median (colored triangles) and maximum median (dotted line) are the observed values from Figure 4.

1917x1089mm (72 x 72 DPI)

Scatter plot of λ retrieved assuming different moment combinations as a function of λ deduced from linear regressions assuming a MP distribution. Solid lines correspond to the linear regression performed for each moment combinations.

114x114mm (300 x 300 DPI)

(a) Ratio of the gap minimum over the gap value for a given α and ν (in per cent, color-scale). Red crosses, pentagons and stars indicate the location of the Marshall-Palmer ($\alpha=\nu=1$), the best gamma fit ($\alpha=1$) and the best generalized gamma fit, respectively. These shapes (respectively black, yellow and red lines) are used to fit the mean PSD (purple line) in (b).

411x537mm (72 x 72 DPI)

As in Figure 9a, but for three of the temperature levels (-10°C (a), -30°C (b) and -45°C (c))

379x102mm (400 x 400 DPI)

λ as a function of TWC and temperature (colors) Houze et al. (1979) diagnostic is indicated by dashed lines for the three different temperature levels and the Caniaux (1993) diagnostic by the dashed -dotted line. Polynomial fits are represented by filled lines.

127x76mm (400 x 400 DPI)

	Graupel	Pristine ice (plates)	Snow	Rain	Liquid cloud water
a	19,6	0,82	0,02	524	524
b	2.8	2.5	1.9	3	3
c	124	800	5.1	842	3.2x10 ⁷
d	0.66	1	0.27	0.8	2
α	1	3	1	1	3 (ocean) 1 (continent)
v	1	3	1	1	1 (ocean) 3 (continent)
C	1E5	X	5	8E6	X
x	-0.5	X	1	-1	X

Table I – Coefficient values (S.I. unit), describing the ICE-3 ice species

	Convective	Stratiform	Cirriiform
Number of segments	103	241	226

Table II – Distribution of observations regarding the MCS sub-regions.

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	$(\alpha; \nu)$	ν for $\alpha=1$	ν for $\alpha=0,5$	ν for $\alpha=0,25$
All PSDs	(0.214; 43.7)	1.3	7.54	38.2
-10°C	(0.163; 75)	1.14	7.54	33.3
-30°C	(0.25; 38.2)	1.49	9.88	38.2
-45°C	(0.247; 43.7)	1.95	11.3	50

Table III – Best (α, ν) pairs for all PSDs and at -10°C , -30°C and -45°C temperatures. In the last three rows, setting α constant, the best corresponding ν values are given for each ensemble.

Dynamic-wise evaluation of the microphysics of the
AROME model in the context of ice crystal icing using in-
situ data of the HAIC 2015 field campaign

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In some deep tropical convective clouds, Ice Crystal Icing is an unavoidable threat for aeronautics. The possibility to forecast such event with the french meso-scale model AROME is investigated in this article thanks to the HAIC 2015 field campaign and a contextualization of the deep convective clouds into convective, stratiform and cirriform parts. Guidelines including modifications on the snow particle size distribution and snow concentration diagnostic are given to improve the skills of microphysical schemes.