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# ***Spaceborne remote sensing and airborne in situ observations of Arctic mixed-phase clouds.***

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## **Abstract**

Our predictive capability of Arctic climate change is severely hampered by a lack of understanding about key processes, notably related to mixed-phase clouds (MPC). These cloud related processes are suspected to play a major role in the Arctic energy budget due to their persistence and peculiar microphysical properties. This chapter focuses on the characterization of MPC properties in the Arctic region from in situ and satellite observations. The frequency of occurrence of MPC over the Arctic region is determined from the CALIPSO and CloudSat satellite active remote sensing observations. Results highlight that the spatial, vertical and seasonal variability of MPC can be in part linked to the influence of the North Atlantic Ocean and the melting of sea ice.

The microphysical and optical properties of the ice crystals and liquid droplets within MPC and the associated formation and growth processes responsible of the cloud life cycle are evaluated based on in situ airborne observations. Finally, the coupling of in situ MPC airborne measurements with the satellite active remote sensing is presented through a validation study to evaluate remote sensing retrieval algorithms and products such as the cloud detection or cloud phase.

**Keywords:** Arctic mixed-phase clouds, ice and liquid microphysical properties, in situ measurements, satellite remote sensing observations

## **1. Introduction**

The Arctic is a sentinel for global climate change as it is warming at more than twice the global mean rate showing acute visible signs such as the fast retreat of the sea-ice (Deser and Teng, 2008; IPCC, 2013; Serreze et al., 2007; Stroeve et al., 2007). This region also experiences a significant increase of the aerosol loading as a receptor for pollution transported from distant source regions at mid-latitudes (Law et al., 2014; Stohl, 2006) combined with an enhancement of local emission sources. The dramatic changes observed in the Arctic climate also have strong consequences on the global climate. However, the observed rate of climate change in the Arctic is not accurately reproduced in climate models (Eckhardt et al., 2013). The predictive capability of Arctic climate change is severely hampered by a lack of understanding about key processes influencing the atmosphere-ice-terrestrial-ocean system and feedbacks. Within this system, cloud related processes play a crucial role in Arctic climate system and its evolution, impacting and determining the local radiation budget (Curry, 1995; Curry et al., 1996; Kay et al., 2012; Kay and Gettelman, 2009; Morrison et al., 2012). Clouds interact with shortwave and longwave radiations, cooling or warming the surface and the atmosphere depending on their macrophysical, microphysical and optical properties. The low sun elevation in summer and the lack of solar radiation during the winter polar night are responsible for the predominant longwave radiative effect in the Arctic (Lubin and Vogelmann, 2006), tending to a regional net warming effect (Solomon et al., 2007; Stephens, 2005). However, major uncertainties surround our knowledge of the complex and numerous interactions and feedbacks between the physical processes involved in the cloud life cycle (Liu et al., 2012). This complexity reflects in the large discrepancies of the cloud related processes representation in models at all scales. In the last IPCC report Boucher et al. (2013) showed that, in particular, ice cloud microphysics must be significantly improved in order to reduce the low confidence attributed to model estimates of aerosol-cloud feedbacks. For instance our knowledge of the local and large scale processes responsible for the persistence of Arctic Mixed-Phase Clouds is still very basic.

Mixed-phase clouds (MPC) are characterized by a microphysically unstable mixture of liquid droplets and ice crystals. However, observations show that these clouds are ubiquitous in the Arctic and persist for several days

under a variety of meteorological conditions (Mioche et al., 2015; Morrison et al., 2012; Shupe et al., 2011; Shupe and Intrieri, 2004). They occur as single or multiple stratiform layers of supercooled droplets near the cloud top from which ice crystals form and precipitate (Gayet et al., 2009; McFarquhar et al., 2007). The strong impact of MPC on the energy budget stems from their persistence and microphysical properties. The longevity of MPC results from interactions between fast local dynamical, radiative, surface and microphysical processes and larger scale meteorological or environmental conditions that greatly complicate their understanding and modelling. In particular, the ice microphysical processes which impact the cloud top radiative cooling trigger the turbulence responsible for the maintenance of MPC. Aerosol-cloud interaction processes also play a key role as atmospheric aerosols can influence the persistence of MPC by changing their microphysical properties. In MPC, ice crystals formation is expected to be initiated by the presence of the liquid phase through different heterogeneous nucleation mechanisms depending on the temperature, supersaturation and aerosol properties. The balance between Cloud Condensation Nuclei (CCN) and Ice Nuclei (IN) concentration is critical as it directly impacts the ice production. On one hand, modelling studies have shown that even a slight increase of IN concentration can lead to a rapid conversion of MPC to pure ice cloud (Harrington et al., 1999; Jiang et al., 2000; Morrison et al., 2011; Pinto, 1998; Prenni et al., 2007). Under weak updraft velocities or high IN concentration, ice crystals can grow rapidly by vapour deposition at the expense of liquid by the Wegener-Bergeron-Findeisen process if the liquid saturation is not reached (Ervens et al., 2011). On the other hand, the IN depletion through sedimentation of ice forming particles limits the continuous ice production and further maintenance of the MPC system (Westbrook and Illingworth, 2013). Moreover the number and the shape of ice crystals influence their growth and sedimentation contributing to the prevention of cloud glaciation (Ervens et al., 2011).

(Tan et al., 2016) showed that as ice forms, the liquid water is depleted restricting further ice formation through competition of water vapour and moderating the loss of supercooled water, thus forming a self-regulating process. This ice-liquid phase partitioning is also governed by the feedbacks between dynamical and microphysical processes (Avramov et al., 2011) as turbulent mixing favours the entrainment of IN particles into the cloud driven mixed layer. However, (Fridlind et al., 2012) showed that this process alone does not lead to ice concentrations in accordance with observations. Indeed, despite substantial progress most models requires an unrealistic concentration of IN to maintain ice formation (Savre and Ekman, 2015) or fail to reproduce the physical processes involved in the life cycle of MPC. The formation of ice crystals in the upper part of the cloud is a prerequisite to maintain the mixed phase conditions. Large-eddy simulations coupled with heterogeneous ice nucleation parameterizations showed that the persistence of ice production is determined by the competition between radiative cooling, cloud top entrainment and nucleation scavenging of the IN (Savre and Ekman, 2015). They emphasized that the accurate representation of processes involved in MPC requires modelling the time-evolving ability of the IN population to form ice crystals. Solomon et al. (2015) suggested that the recycling of IN particles through subcloud sublimation could maintain the ice production, slow the rate of ice loss from the mixed layer and regulate the liquid production.

Although these case studies provide a framework to understand the mechanisms responsible for the persistence of MPC, measurements at different scales are still needed to characterize the microphysical properties and the phase partitioning within such clouds. Crucial properties such as cloud top liquid water profile, the vertical particle size and shape distribution of ice crystals have to be accurately assessed as they influence the local radiative and microphysical processes maintaining the phase partitioning in the MPC. Airborne campaigns can contribute to a process-level understanding of the mechanisms involved in the MPC life cycle even though large uncertainties in the counting and sizing of ice particles still exist.

However, remote sensing observations from space or ground based stations are also needed to generate statistical datasets and allow reliable studies of MPC properties variability at a regional scale (Dong et al., 2010; Kay and Gettelman, 2009; Y. Liu et al., 2012; Shupe et al., 2011). These types of measurements coupled with a more integrated strategy may increase our level of understanding on the relationships between large scale arctic environmental properties and mixed-phase cloud characteristics (Morrison et al., 2012).

This chapter is a modest contribution to the field of microphysical properties and processes occurring within arctic mixed-phase clouds. We will start with a summary of the main results of a regional study of the cloud phase partitioning and distribution undertaken with the CALISPO/CloudSat satellite remote sensing observations (section 2). Then, a quick review of the major projects devoted to the study of Arctic MPC from in situ aircraft observations is made in section 3. Section 4 will consist in the presentation of the main findings obtained from aircraft measurements concerning the microphysical and optical properties of Arctic MPC.

Finally, section 5 will be more specially focused on an example of possible synergies between in situ airborne measurements and satellite observations to evaluate MPC retrieval products.

## 2. Observations at regional scale from satellite

Space-borne, ground based and airborne Radar-Lidar observations, when analysed at regional and global scales, offer new perspectives to better understand the cloud life cycle (formation, maintenance, dissipation) and the variability of dominant processes over different climatic regions. The recent development of ground based stations (such as Barrow (71° N), Eureka (80° N), Summit (72° N) or Ny-Ålesund (78° N)), well equipped for cloud observations plays a key role for the characterization of the cloud phase and cloud microphysical variability at a regional scale (Chernokulsky and Mokhov, 2012; Dong et al., 2010; Kay and Gettelman, 2009; Y. Liu et al., 2012; Shupe et al., 2011). However, the ground based instrumental payload may differ significantly from one site to another. Climatologies based on specific instruments can be biased by the sensitivity of the instruments and their capability to operate in extreme conditions. For instance, it is quite difficult to compare results derived from a lidar system with the ones obtained from a cloud radar as they are sensitive to different types of hydrometeors.

Since 2006, new observations of cloud properties from space are possible with active instruments like the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) lidar at 532 and 1064 nm onboard CALIPSO and the 95 GHz cloud profiling radar (CPR) on CloudSat satellites (Winker et al., 2003; Stephens et al., 2002) as part of the A-Train constellation. These Radar-Lidar observations constitute an unprecedented dataset documenting the cloud vertical structure with a high spatial resolution at a global scale. Compared to ground based observations, they present the great advantage to involve a uniform measurement technique with a very large coverage.

Before the emergence of these satellites, polar cloud climatologies from space were performed based on passive sensors, mainly:

- the Operational Vertical Sounder-Polar Pathfinder (TIROS N TOVS-Path P, Schweiger et al. (1999))
- the International Satellite Cloud Climatology Project (ISCCP, Rossow and Schiffer (1999))
- the Advanced Very High Resolution Radiometer-Polar Pathfinder (AVHRR, Wang and Key (2005))
- the Moderate Resolution Imaging Spectroradiometer (MODIS, Ackerman et al. (1998))

These instruments provided observations at regional scale in the Arctic allowing the first climatologies of Arctic clouds (Schweiger and Key, 1992). However it is now well known that these measurement techniques suffer from large shortcomings which limit the accuracy of the retrieval of cloud properties (cloud fraction, top and base altitudes...), especially in the Polar regions. Passive remote sensing technique is based on the spectral signature difference between clouds and the surface in visible, near-IR and longwave IR bands to detect clouds. The special conditions encountered in the Arctic significantly hamper the cloud detection. In particular, the lack of sunlight in winter makes useless the visible channels during this period of the year. The weak contrast between the clouds and the underlying ice-covered surfaces can also significantly impact the cloud detection close to the surface.

Therefore space-borne passive remote sensing measurements may lead to large uncertainties in Arctic cloud climatologies (Frey et al., 2008; Lubin and Morrow, 1998). For instance, it has been shown that the cloud amount retrieved from these observations is generally 5-35% less than the one derived from ground based observations, with some regional differences up to 45% (Schweiger and Key, 1992). Chan and Comiso (2013) showed that AVHRR detects only 44% of clouds measured by CALIOP. They also showed that MODIS underestimates by 13 to 30 % the cloud amount, depending on the season, surface type, day/night conditions or cloud altitude and thickness, although it has more channels available than AVHRR (36 and 5 respectively).

Active remote sensing observations may in part overcome the shortcomings associated to passive measurements and improve the cloud detection since they are less impacted by the lack of sunlight or the ice-covered surfaces. Based on these measurements, studies on the total cloud fraction over the Arctic region has been recently performed (Chan and Comiso, 2013; Chernokulsky and Mokhov, 2012; Y. Liu et al., 2012; Zyguntowska et al., 2012). These studies showed that cloud cover lies between 73 % and 86 % in average over the whole Arctic region but present a clear spatial and vertical variability and noticeable differences according to the seasons and the surface type. The maximum cloud cover is observed in autumn (86 %), and the minimum in winter (73%), while spring and summer exhibit intermediate values (76-79 %). The frequency

of occurrence of clouds is higher over the open sea (around 80 %) than over ice-covered surfaces (around 74 %). The seasonality is more pronounced on the Arctic Pacific side than over the Atlantic side (Barents and Greenland Seas). The large and almost constant cloud cover (85%) observed all year long on the Atlantic side has been associated to the frequent synoptic activities and high atmospheric humidity and temperature over open water (Serreze and Barry, 2005). The minimum cloud fraction observed during winter, especially in the Pacific side and in the Central Arctic Ocean, has been linked to the lack of moisture and the strong high pressure systems at this season.

Arctic clouds present also a strong vertical variability as they are mainly distributed below an altitude of 2 km and between 7 and 9 km. The low level cloud seasonality is associated with low level moisture advection, radiative cooling and boundary layer turbulence (Curry and Herman 1995), whereas the almost constant mid-level cloud fraction through the year is linked to the large-scale transport of moisture.

These works focused on the total cloud fraction and studies addressing the variability of the mixed-phase clouds at the Arctic regional scale are scarce. They mostly concerned local remote sensing measurements from ground based stations (Eureka, Barrow, Summit, Ny-Alesund among others) or from icebreaker ships drifting with the ice pack (SHEBA and ASCOS experiments). These measurements remain local in space and will not be described in the present chapter since the focus is made on satellite observations and in situ airborne measurements only.

The mixed-phase clouds variability at the Arctic regional scale has been particularly investigated by Mioche et al. (2015) from CALIPSO and CloudSat observations between 2007 and 2010 using the DARDAR retrieval algorithm. The DARDAR algorithm (Ceccaldi et al., 2013; Delanoë and Hogan, 2010) retrieves the atmospheric properties, in particular the scene classification (cloud, aerosol, clear sky...) and the thermodynamical phase from CALIOP lidar and CloudSat CPR measurements. The great advantage of DARDAR algorithm is that lidar and radar observations are merged on a same resolution grid (1.7 horizontal and 60 m vertical), which allows the retrieval of ice, liquid and mixed phase cloud type as the radar is more sensitive to ice crystals and thick clouds and lidar to liquid droplets and thin ice clouds.

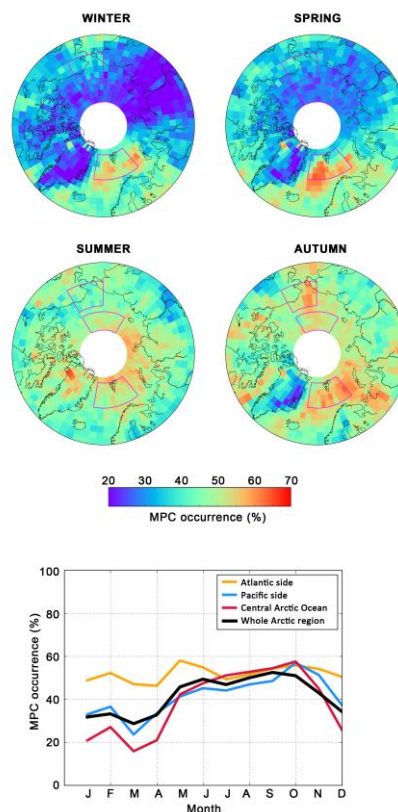


Figure 1: a) Stereographic projections of the seasonal occurrence of MPC (referring to clouds). Occurrences are computed taking into account the 500 to 12 000m altitude range; b) Monthly total MPC occurrence over the whole Arctic region

**(black), the Atlantic side (blue), the Pacific side (orange) and the Central Arctic Ocean (red), as determined in Mioche et al. (2015). The location of the 3 regions are indicated by the purple boxes in the stereographic projections.**

This study shows that MPC prevail in the Arctic all year long, as previously observed from local ground based stations (Curry et al., 1996; Intrieri et al., 2002). MPC represent between 35 % (in winter) and 65 % (in autumn and spring) of the clouds in average over the whole Arctic region. MPC are mainly located at low altitudes. Below 3km, their occurrence range lies between 70 to 90 %, especially in winter, spring and autumn. During summer, the MPC are more frequent in mid-level altitudes (3-6km). Single layer MPCs represent between 55 and 70% of the MPC amount and exhibit similar spatial, seasonal and vertical variability properties. MPCs are statistically more frequent above open sea than over land or sea ice surfaces.

Local differences are pointed out when comparing MPC properties over the entire Arctic region with other areas such as the Svalbard region or the Western Arctic as shown in Figure 1. On the Atlantic side (around Svalbard archipelago, Greenland and Barents Seas), MPC occurrence is almost constant through the year (around 55% in average). On the Pacific side (Northern Alaska, Beaufort and Chukchi Seas) or in the Central Arctic Ocean, MPC occurrence exhibits a clear variability, with the largest occurrences during autumn, and the minimum during winter.

These local differences in MPC seasonality can be partially attributed to the transport of moist air and warm water from the North Atlantic Ocean through the Arctic Ocean along the year, associated with a temperature range favourable to mixed-phase conditions. The North Atlantic Ocean supplies more moisture to the Svalbard region than the rest of the Arctic (Serreze and Barry, 2005), making easier the vertical transfer of humidity. This amplifies the cloud formation since the supply of humidity is favourable for the initiation of liquid droplets. During the melting seasons (late spring to autumn), the fraction of open seas increases and more warm water can be transported through the Arctic region, resulting in warm and moist air advection in the western Arctic. Therefore, the cloud formation and initiation of liquid phase may be amplified in such region, leading to the increase of MPC occurrence observed during this period on the Arctic Pacific side. The variability of sea ice concentration, temperature and humidity has been analysed to strengthen this assumption and a link with the MPC and cloud variability has been established. The results highlighted a strong negative correlation between sea ice concentration and MPC occurrence (see Figure 10 from Mioche et al. (2015)), confirming the previous findings that MPC and clouds prevail over open seas than iced surfaces, and the role of the melting of sea ice in the MPC seasonality. In addition, stable atmospheric conditions encountered during winter and transitions seasons in Arctic (Orbaek et al., 1999), as well as strong temperature and humidity inversions at cloud top (Nygård et al., 2014) contribute to limit the vertical extension of Arctic clouds and MPCs and thus maintain them at low altitudes levels.

On the contrary during summer, the air temperature increases and atmospheric conditions are less stable than during the rest of the year, allowing a larger vertical extension of MPC.

Obviously, MPC variability and life cycle are also dependent of numerous other regional or local scale processes. The study of the role of aerosol particles acting as cloud condensation nuclei (CCN) or ice nuclei (IN), their concentrations and composition and the contributions of local sources versus long-range aerosol transport in the Arctic is necessary to investigate the cloud-aerosol interactions in the Arctic and improve the cloud representation in models.

This cloud phase distribution analysis at regional scale can also be used to assess how local airborne experiments are representative of the variety of clouds encountered in the Arctic.

Additionally, active remote sensing measurements have inherent and well-known shortcomings near the ground level which may impact the determination of cloud and MPC amount. It is mainly the lidar laser beam attenuation by liquid layers for CALIOP observations and the contamination by radar ground echoes for CloudSat observations. Comparisons with ground-based observations (Blanchard et al., 2014; Mioche et al., 2015) estimated that the uncertainties in the cloud and MPC occurrence from the DARDAR product below 2 km of altitude can reach 20 % between 500m and 2 km, and 25 % below 500 m.

This strengthens the fact that an analysis of in situ and ground based observations of the cloud properties at low altitude is still necessary to characterize the MPC phase distribution. For instance, microphysical and optical in situ measurements from airborne campaigns provide a more accurate description of MPC at small scale. Therefore, even though these measurements are localized in time and space, they can contribute to improve our understanding of the microphysical processes involved in MPCs.

### 3. Airborne experiments in the Arctic region

Before the 90's, airborne experiments in the Arctic region remained sparse due to the limited access to the region. The earliest in situ airborne measurements of cloud microphysical properties in the Arctic concern only liquid water clouds during summer (Curry, 1986; Dergach et al., 1960; Koptev and Voskresenskii, 1962; Tsay and Jayaweera, 1984). The first measurements of the ice phase in MPC (Curry et al., 1990; Jayaweera and Ohtake, 1973; Witte, 1968 among others) showed that ice occur for a wide range of temperatures, from -8°C to -20°C. These studies are described in the review paper of Curry et al., (1996). However, regarding the large uncertainties and shortcomings associated with the measurement techniques, accurate quantitative estimates of ice crystal properties such as size, number and shape was not possible at that time.

The significant climate sensitivity of the Arctic coupled with the large impact of cloud on the surface energy budget lead the scientific community to draw a special attention to arctic cloud observations. In the last 20 years, substantial progress has been made in in situ measurement techniques, in particular to characterize the ice phase with promising aircraft experiments in the Arctic. Several international major projects emerged, and still continue to be planned today. These main projects are summarized in the Table 1. Since 1994, 14 major airborne campaigns were carried out, equally shared between two main locations: 7 of them took place in the Arctic Pacific side (also called Western Arctic), around regions of Northern Alaska and Beaufort Sea, and 7 in the North Atlantic side, around the Svalbard archipelago and the Greenland and Barents Seas. Obviously, these locations are strongly constrained by the infrastructure facilities needed to perform airborne campaigns (mainly Barrow, Fairbanks or Inuvik for the Western Arctic and Longyearbyen or Kiruna on the Atlantic side). Most of the campaigns took place in Spring, and few of them in Summer and Autumn.

Year	Period		Experiment	Location	Reference
1994	September-October	BASE	Beaufort and Arctic Storms Experiment	Beaufort Sea	Curry et al. (1997)
1998	April-July	FIRE-ACE	First International Satellite Cloud Climatology Project (ISCCP) Regional Experiment: Arctic Clouds Experiment	Beaufort Sea, Northern Alaska	Curry et al. (2000)
2004	September-October	M-PACE	Mixed-Phase Arctic Cloud Experiment	Northern Alaska	Verlinde et al. (2007)
2004	May-June	ASTAR	Arctic Study of Tropospheric cloud, Aerosol and Radiation	Greenland/Barents Seas and Svalbard	Jourdan et al. (2010)
2007	April	ASTAR	Arctic Study of Tropospheric cloud, Aerosol and Radiation	Greenland/Barents Seas and Svalbard	(J.-F. Gayet et al., 2009)
2008	March-April	POLARCAT	Polar Study using Aircraft, Remote Sensing Surface Measurements and Models of Climate, Chemistry, Aerosols and Transport	Greenland/Barents Seas and Svalbard	Delanoë et al. (2013)
2008	August	AMISA	Arctic Mechanisms for the Interaction of the Surface and Atmosphere	Arctic ocean, north of Svalbard	Persson (2010)
2008	April	ISDAC	Indirect and Semi-Direct Aerosol Campaign	Beaufort Sea, Northern Alaska	McFarquhar et al. (2011)
2008	April	ARCPAC	Aerosol, Radiation and Cloud Processes affecting the Arctic Climate	Northern Alaska	Lance et al. (2011)
2010	May	SORPIC	Solar Radiation and Phase Discrimination of Arctic Clouds experiment	Greenland/Barents Seas and Svalbard	Bierwirth et al. (2013)
2012	May	VERDI	Study on the Vertical Distribution of Ice in Arctic clouds	Beaufort Sea	Klingebiel et al. (2014)
2013	March-April-July	ACCACIA	Aerosol-Cloud Coupling And Climate Interactions in the Arctic	Greenland Sea	Lloyd et al. (2015)
2014	May	RACEPAC	Radiation-Aerosol-Cloud Experiment in the Arctic Circle	Beaufort Sea	
2017	June	ACLOUD	Arctic Cloud Observations Using airborne measurements in polar Day conditions	Arctic Ocean, north of Svalbard	

**Table 1: Main field experiments involving airborne in situ measurements of Arctic mixed-phase clouds.**

During all these campaigns, a wide variety of aircraft and in situ instrumentation were used. Cloud properties were assessed based on different measurement techniques (light scattering spectrometers, hot-wire probes, imaging probes...see Baumgardner et al. (2012) for details about in situ instrumentation). Most of the time, the flight patterns consisted in ascents and descents sequences above, into and below MPC, or horizontal flight legs at different altitude levels. Accordingly, the horizontal and vertical variability of relevant cloud properties (liquid droplet and ice crystal number and size, ice and liquid water contents, ice crystal morphology, asymmetry parameter, optical depth) was investigated to better understand the microphysical processes (formation, growth and dissipation) of ice crystals and supercooled liquid droplets at small scale.

## 4. In situ characterization of MPC properties.

This section summarizes the main findings related to the characterization of MPC properties inferred from the airborne campaigns listed in table 1. In particular, section 4.1 focuses on the discrimination of the thermodynamical phase, the interaction between the liquid and ice phases, the quantitative assessment of liquid droplets and ice crystal properties (N, size, water content, shape...) as well as the main microphysical processes involved in the formation and growth of cloud particles. Then section 4.2 describes a case study on the link between optical and microphysical properties of MPC.

One can note that the previous studies dedicated to the assessment of the microphysical properties of Arctic clouds based on *in situ* measurements (Avramov et al., 2011; Gayet et al., 2009; Rangno and Hobbs, 2001; Verlinde et al., 2007 among others) focused mainly on case studies. A few studies aimed to merge several *in situ* datasets to provide a statistical analysis and representative description of mixed-phase cloud properties (McFarquhar et al., 2007; Mioche et al., 2017).

### 4.1. Main properties from previous experiments

Arctic mixed-phase clouds occur as single or multiple stratiform layers of supercooled droplets near the cloud top from which ice crystals form and precipitate and can persist for several days. This peculiar structure has been widely observed in the airborne experiments listed in table 1. The ice and liquid properties have been characterized from the *in situ* measurements performed during these campaigns. However, the formation, evolution and persistence of these MPC result from numerous and complex interactions between aerosols, liquid droplets and ice crystals at both local and large scales. We propose here a summary of the main mechanisms which have been highlighted from *in situ* airborne observations carried out on the Arctic Atlantic or Pacific side.

The formation of a MPC is initiated by the nucleation of supercooled water droplets at the cloud base from aerosol particles (droplet concentration is correlated with aerosol number below the cloud). Then, due to adiabatic cooling, they grow during their ascent to the cloud top, leading to LWC values increasing with altitude. At cloud top of low-level MPC (down to  $-30\text{ }^{\circ}\text{C}$ ), typical LWC values are around  $0.2\text{ g}\cdot\text{m}^{-3}$ . Droplets are generally small (around  $20\text{ }\mu\text{m}$ ), but they can reach larger sizes of several hundreds of  $\mu\text{m}$  (drizzle) by collision-coalescence processes. An example of the vertical profiles of liquid phase properties derived from the statistical analysis of 4 airborne campaigns by Mioche et al. (2017) is displayed on Figure 2a-d. At cloud top, the temperature inversion and the associated entrainment of dry air lead to the evaporation of a fraction of liquid droplets, capping the vertical extension of MPC. Humidity inversion may also occur at cloud top (Nygård et al., 2014), supplying moisture to the cloud top by entrainment. This may prevent the evaporation of liquid droplets, counteract the effect of mixing of dry air due to temperature inversion and contribute to the persistence of the MPC. Moreover, some studies have shown that supercooled droplets could exhibit a bimodal size distribution at cloud top. This feature may be caused by the entrainment and activation/condensation of new aerosol particles by the dry air layer above the cloud top (Lawson et al., 2001), or by the evaporation of the larger droplets due to turbulent entrainment of clear-air-eddies (Klingebiel et al., 2014).

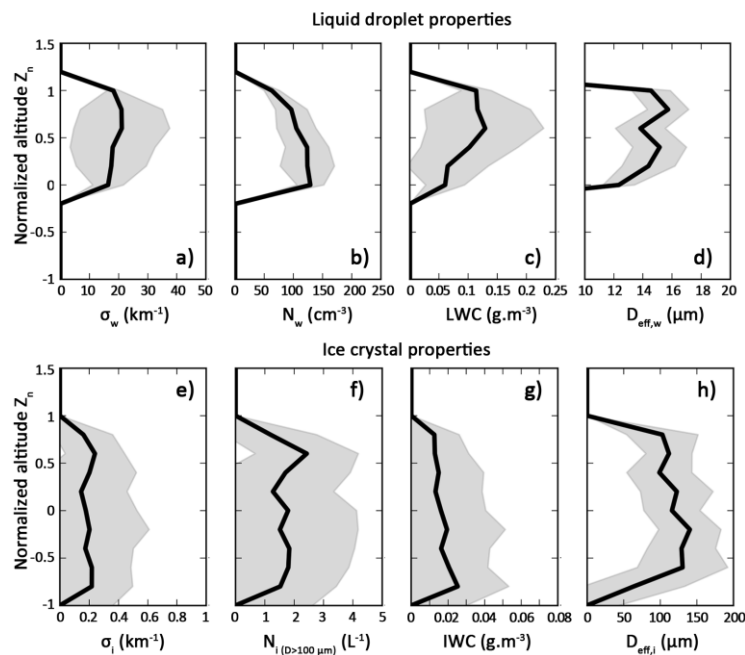
Understanding and characterizing processes responsible for the formation and growth of ice crystals from *in situ* measurements is more challenging, especially in the presence of liquid droplets. For example, the small ice particle detection (and thus the study of ice formation) is challenging, due to the shortcomings linked to shattering effect or minimum size detection thresholds. The presence of liquid water in the same sample volume also contributes to an increase of the uncertainties associated to the ice properties measurements (bulk measurements, discrimination of small spherical ice crystals from liquid droplets for example for imaging probes, ice crystal response for optical probes). Moreover, ice phase initiation depends on the IN concentration which is very small compared to the CCN concentration: CCN concentration in the atmosphere ranges from 10 to  $1000\text{ cm}^{-3}$  whereas IN concentration is  $10^5$  to  $10^6$  times smaller. Thus it is still very difficult to accurately measure the IN number in natural conditions, especially in the Arctic where the background aerosol concentration is lower than at lower latitudes. However, the numerous improvements made since the first airborne observations regarding the assessment of the ice phase properties allowed the observation and understanding of some of the main formation and evolution processes occurring in MPC.



Since the temperature range where MPC occur ( $-40\text{ °C} < T < 0\text{ °C}$ ) is too warm for homogenous ice nucleation, the initiation of the ice phase is made through heterogeneous nucleation processes (deposition, immersion freezing, condensation freezing and contact freezing) induced by the presence of aerosol particles acting as IN particles. Ice crystals can grow through several mechanisms. Riming due to the collection of droplets by ice crystals is one of the main ice growth mechanisms, leading to complex-shapes and heavy particles which fall and precipitate. Rimed particles are observed everywhere in and below the cloud. Water vapour condensation is the second main mechanism responsible of the growth of ice crystals. If supersaturation with respect to ice is reached, the excess water vapour condensate upon ice particle, leading to regular shape such as plates, stellars, or columns. If the humidity is saturated both with respect to liquid and ice, droplets and ice crystals can grow simultaneously. But conditions of supersaturation with respect to ice associated to subsaturation with respect to liquid water are most often encountered in MPC. Therefore, under these conditions, the Wegener-Bergeron-Findeisen (WBF) process occurs: liquid droplets evaporate and the subsequent water vapour condensates over ice crystals. Through this mechanism, ice crystals grow to the expense of liquid droplets, leading to the depletion of the liquid phase, and a potential rapid glaciation of the cloud. So other processes are needed to maintain the liquid phase and the cloud layer and to explain the large persistence observed. For example, the strong radiative cooling induced by the supercooled water may help to maintain the liquid phase. It leads to a decrease of the stability and produces turbulent updrafts that favours the condensational growth of droplets.

The role of dynamics and the updrafts and downdrafts play a crucial role by transporting the ice particles at all levels into the cloud. It ensures aggregation of ice particles leading to irregular shapes.

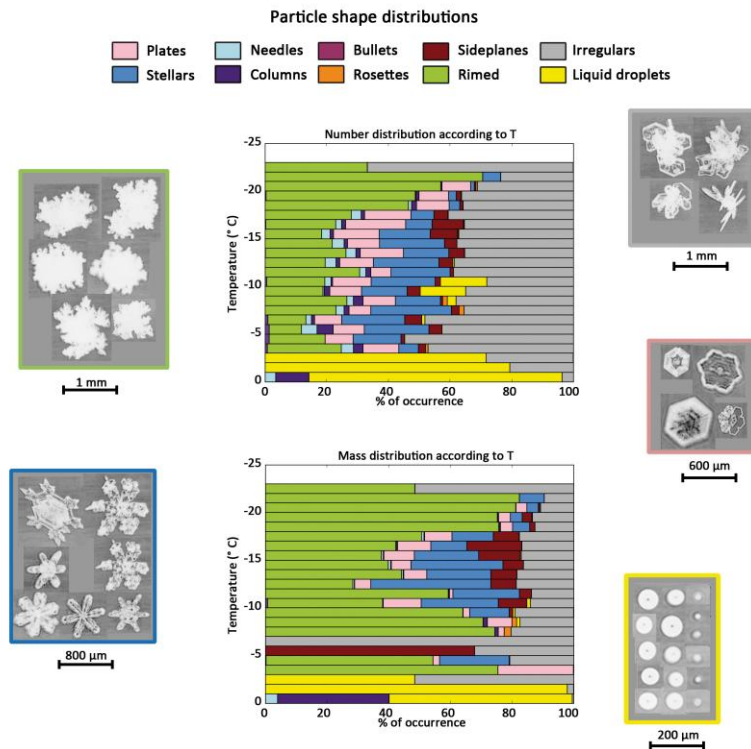
These growth mechanisms occur everywhere in and below the cloud. Consequently, the size and concentration of ice crystals and IWC do not exhibit a large vertical variability, as shown on Figure 2e-h from the Mioche et al. (2017) statistical study.



**Figure 2: Vertical profiles (expressed in normalized altitude) of liquid and ice phases from 4 airborne campaigns located in the Svalbard region (ASTAR 2004 and 2007, POLARCAT 2008 and SORPIC 2010, from Mioche et al. (2017)). Liquid droplets properties are retrieved from FSSP measurements (3-45  $\mu\text{m}$  size range): a) extinction coefficient, b) droplet concentration, c) LWC, d) droplet effective diameter, and ice crystal properties are determined from CPI measurements (15  $\mu\text{m}$  - 2.3 mm size range): e) extinction coefficient, f) ice crystal concentration, g) IWC, h) ice crystal effective diameter. The black lines are the average over all the campaigns, and the grey shaded area represent the standard deviations.**

Figure 3 shows an example of the distribution of ice crystal shapes within MPC (Mioche et al., 2017). CPI measurements from 4 airborne campaigns around the Svalbard region (ASTAR 2004, ASTAR 2007, POLARCAT 2008 and SORPIC 2010, corresponding to a total of 18 flights) have been merged to study the distribution of

particle shapes within Arctic MPC. High resolution images of ice particles (2.3  $\mu\text{m}$  pixel size) give an insight of the main microphysical growth processes occurring in MPC. For example, regular shapes such as plates and dendrites are well detected and confirm the condensational growth processes (including the WBF mechanism). Also, the large occurrence of rimed and irregular particles indicate very efficient riming process and the role of the dynamics respectively. From these results, it is thus clear that the assumption of spherical ice instead of non-spherical habits is unrealistic, may lead to an underestimation of ice growth and should not be used in modelling.



**Figure 3: Particle shape distribution (from CPI measurements and for particles larger than 100  $\mu\text{m}$ ) in MPC as a function of temperature (Mioche et al., 2017). Distributions are displayed according to particle number (upper panel) and mass (bottom panel). Some images recorded by the CPI instrument are displayed.**

Under specific mixed-phase conditions ( $T > -8$  °C, large droplets), ice crystals could also be produced by secondary production mechanisms caused by splintering of ice crystal during riming or shattering of isolated drops during freezing. Fragmentation of delicate ice crystals by collisions may also produce high ice concentration of small particles. Several studies (Bierwirth et al., 2013; Gayet et al., 2009; Lawson et al., 2001; Lloyd et al., 2015; Rangno and Hobbs, 2001) reported these secondary ice production mechanisms. They observed a high number of small ice particles ( $N_{\text{ice}} > 10 \text{ L}^{-1}$  according to Rangno and Hobbs (2001), or  $N_{\text{ice}} > 50 \text{ L}^{-1}$  according to Gayet et al. (2009)) which cannot be explained by the measured IN concentration or the one expected by Meyers et al. (1992) parameterization. Ice and liquid phase occur in pockets throughout the MPC. This distribution is linked to MPC aging since more patches are observed when the ice crystals have just blown up, according to Rangno and Hobbs (2001). These studies highlighted that the unexpected high concentration of small ice crystals depends on the largest cloud droplets formed into the cloud for “warm” MPC ( $T > -8$ °C), leading to large IWC and precipitating ice. On the contrary, in case of numerous small droplets, the concentration of precipitating ice particles is reduced.

All these findings show that the ice formation and growth processes and the subsequent cloud precipitation efficiency are closely linked to the liquid phase properties. Thus, the aerosol concentration which drives the liquid phase properties also impacts significantly and indirectly the MPC properties and the ice phase through its role on the liquid phase. Indeed, changes in CCN concentration influence the supercooled liquid droplets

number and size, and thus the ice phase properties. Several works compared polluted and clean situations (Jackson et al., 2012; Lance et al., 2011) and showed that an increase of aerosol loading (from mid-latitude long-range transport) increases the droplet concentration and reduce the ice crystal formation and growth efficiency. Hence, the number of dense and precipitating rimed crystals is reduced, and thus the cloud precipitation efficiency too. Finally, the reduced precipitation may help to the maintenance of the liquid phase and the MPC longevity since droplets are not consumed by ice crystals. On the other hand, when ice precipitate, it is removed from the cloud. So, the depletion of liquid droplets due to ice growth by riming or WBF is reduced, leading to the maintenance of the liquid phase. Indeed, one of the particularities of Arctic MPC compared to the clouds at lower latitudes is that the liquid water fraction (LWF) increases with altitude. Examples are showed in the Mioche et al., (2017) and McFarquhar et al. (2007) works. These results highlight that new LWF parameterizations are needed for Arctic single layer MPC as previous parameterizations established for MPC at different locations might not necessarily be representative in the Arctic.

Finally, in situ airborne cloud measurements performed in the Arctic from more than 20 years constitute a great step forward in the understanding of the small scale processes involved in the life cycle of MPC. The formation, growth and longevity of MPC depends on numerous interactions between aerosols, ice microphysics and liquid phase, controlling the liquid to ice conversion and precipitation rates. Obviously, these interactions and the associated feedbacks remain complex and observations, coupled with modelling is still needed to a better assessment of MPC life time processes and feedbacks.

In the following section, focus is made on the coupling of microphysical and optical properties from in situ measurements.

## **4.2. Case study and cloud-radiation interaction**

Previous studies have shown that the presence of ice crystals in MPC are expected to probably enhance their warming effect (Ehrlich et al., 2009; Wendisch et al., 2013). The solar albedo effect can be significantly reduced for increasing ice water fraction in MPC. Therefore, coupling microphysical to optical properties is an important step to assess the radiative properties of such clouds.

Ice crystals in mixed-phase Arctic clouds are characterized by a wide variety of shape and size. The shape is determined by the growth process which is related primarily to supersaturation and temperature regimes. Supersaturation is influenced by vertical velocity and dominates the internal structure and the degree of skeletal development (Keller and Hallett, 1982). Retrieval of cloud parameters from remote sensing requires in particular a precise knowledge of ice particle habits. However, most ice crystals in arctic clouds have non ideal shapes (irregulars) due to altering processes (alternating growth and sublimation), aggregation and coagulation (Korolev et al., 1999). This wide variety of nonspherical shapes introduces significant challenges for computing reliable optical properties. The surface texture (the degree of surface roughness) is another important morphological parameter that can substantially modulate the single scattering properties of ice crystals (Yang et al., 2008). For instance, experimental laboratory studies performed by Ulanowski et al. (2006) and Schnaiter et al. (2016) implied that ice crystals with rough surfaces could reflect almost twice as much incident solar radiation back to space than their smooth counterparts. The effective size of cloud particles is also an important parameter to assess as the size is a quantity playing a crucial role on the light scattering properties. Therefore, one of the main difficulties in predicting the radiative properties of arctic clouds is to couple the microphysical properties (mainly in the shape of a particle size distribution and liquid/ice partitioning) with a geometric model of the various ice crystal shapes such that its optical/radiative properties can be consistently assessed. Previous case studies have demonstrated the potential of the synergy between a cloud particle imager and a cloud nephelometer to link the microphysical and shape properties of arctic cloud particles to their single scattering characteristics (Gayet et al., 2009; Jourdan et al., 2010; Lampert et al., 2009). These observations of arctic MPC properties have revealed that the ice crystal shapes and liquid water fractions were connected to specific optical properties. Parameterizations of the cloud optical properties based on the synergetic use of statistical analysis of in situ measurements and light scattering modelling can be developed. The goal is to establish equivalent microphysical models, based on a limited set of free parameters (roughness, mixtures of idealized particle habits and aspect ratio). These models are expected to reproduce the main optical features of cloud layers characterized by different liquid water fractions and ice crystal habits.

Figure 4 represents an example of this strategy implemented during the ASTAR campaign. A principal component analysis (PCA) methodology is applied to the Polar Nephelometer scattering phase function measurements. This analysis enables us to identify and extract specific cloud layers sharing similar optical properties. The optical patterns revealed by the PCA are related to specific microphysical properties (shape, PSD, IWC/LWC) measured by the microphysical probes. The behaviours of the average phase functions are consistent with the particle habit classification derived from the CPI measurements. Then an iterative inversion method (Jourdan et al., 2003; Oshchepkov et al., 2000) using light scattering modelling of irregular ice crystals (Yang and Liou, 1996) can be applied to the average phase function to retrieve equivalent microphysical models. The results show that the use of idealized geometric shape models representing ensembles of rough ice crystals combined with a population of water droplets is suitable to describe the scattering properties of arctic MPC. The optical properties of cloud layers dominated by the liquid water phase ( $g > 0.83$ ) can be modelled by a mixture of water droplets (> 90 %) and small droxtal shaped crystals. The optical properties of cloud layers where the ice phase prevails ( $g < 0.80$ ) can be represented by a combination of water droplets (15 % - 35 %) and rough plates or columns with a varying aspect ratio (65 % - 85 %).

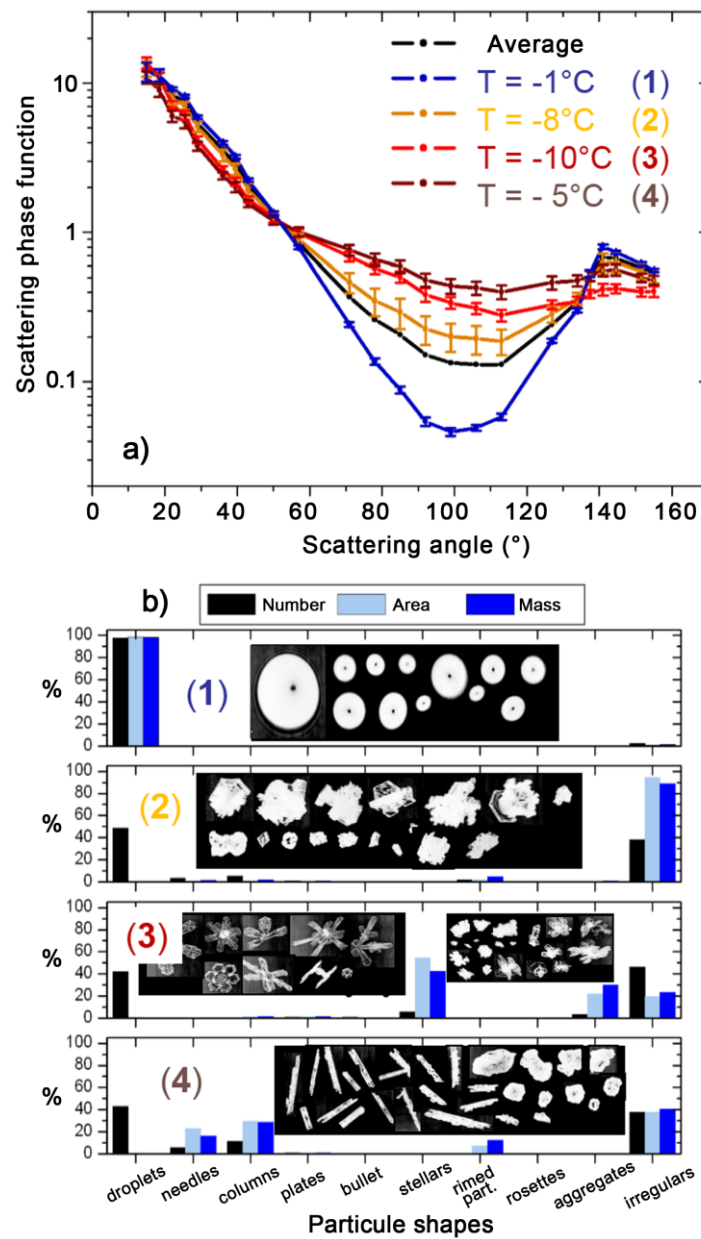


Figure 4: Scattering phase function from Polar Nephelometer measurements as a function of particle shape classification (in number, area and mass) from CPI measurements.

However, the microphysical and morphological properties derived from the CPI measurements are limited to particles with maximum dimension larger than 25-50  $\mu\text{m}$ . Jourdan et al. (2010) showed, using light scattering modelling, that the optical contribution of small particles with sizes lower than 50  $\mu\text{m}$  (droplets and ice crystals) was significant, always exceeding 50% of the total scattering signal. Thus, the influence of small ice crystals on the optical properties needs to be more accurately quantified using in situ measurements. The combination of state of the art instruments deployed during the RACEPAC or ACLOUD campaign should lead to a better estimate of the optical contribution of small particles as well as the impact of ice crystal habit on the scattering properties. This methodology applied to larger datasets should enable us to study more accurately the influence of small ice crystals, ice particle habits, and liquid-ice partitioning on the optical properties of MPC.

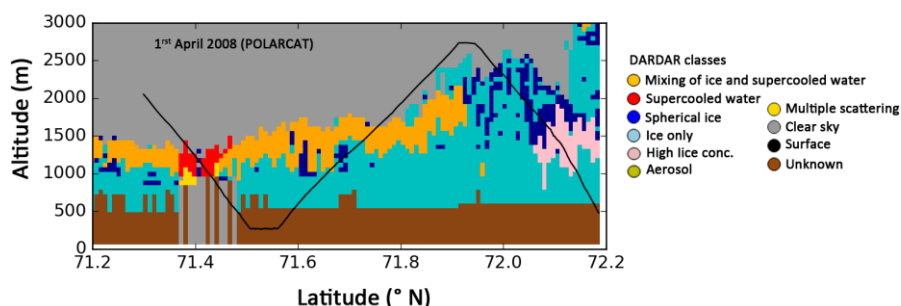
## 5. Satellite remote sensing evaluation

As shown in section 2, MPC can be observed on almost all the Arctic region using satellite measurements. However, these measurements are indirect and are based on retrieval algorithms involving hypothesis which need to be validated (Cesana et al., 2016; Mioche et al., 2010). They also provide cloud properties typically averaged over one kilometre, which may be insufficient to study cloud processes at a microphysical scale. Cesana et al. (2016) showed for example that cloud detection and phase retrieval product from CALIOP lidar measurements depend strongly on factors such as horizontal and vertical data averaging. Additionally, they suffer of inherent shortcomings at low altitude levels (Blanchard et al., 2014; Liu et al., 2017; Marchand et al., 2008). Moreover, the definition of the cloud thermodynamic phase strongly depends on the measurement technique and the observation scale.

In situ and ground based remote sensing measurements may complement the satellite observations and partially overcome their limitations by providing a detailed characterization of cloud microphysical properties at low levels. In addition, in situ observations are based on direct measurement techniques and can provide data at a higher spatial resolution (generally < 100 m). In that sense, they can be used to assess the satellite remote sensing retrieval products, such as cloud detection and thermodynamical phase by providing accurate profiles of cloud properties at the very low altitude levels.

Thus, it appears relevant to investigate the horizontal and vertical distribution of ice crystals and liquid water droplets as well as the scale dependent liquid-ice partitioning for different observational techniques.

This section illustrates the potential of co-located in situ measurements to conduct satellite remote sensing validation exercises. The retrieval algorithm evaluated in the following is the DARDAR algorithm described in Ceccaldi et al. (2013) and Delanoë and Hogan (2008 and 2010). DARDAR algorithm merges CloudSat and CALIPSO observations on a same resolution grid (1.7 horizontal and 60 m vertical) and uses the combination of lidar and radar measurements to detect clouds and retrieve their phase and properties. Four flights sampling MPC during the ASTAR 2007 and POLARCAT 2008 experiments were successfully collocated with the A-Train track. The DARDAR algorithm was operated (from CALIPSO/CloudSat satellite data) for the cloud/no cloud detection and the retrieval of the MPC thermodynamical phase. Figure 5 illustrates the vertical profile of DARDAR cloud phase product with the cloud type classification for one of the four situations. The flight track is superimposed in black line.



**Figure 5: Vertical profile of the cloud phase determined by the DARDAR retrieval algorithm for a satellite validation situation encountered during POLARCAT 2008 campaign (Mioche et al., 2017). The black line shows the aircraft flight track.**

In order to evaluate the DARDAR cloud retrieval, the DARDAR cloud products along the flight track are compared to the asymmetry parameter ( $g$ ) values determined from the Polar Nephelometer (PN) in situ measurements. The method consists in oversampling the DARDAR products to match the PN resolution (around 80 m horizontal).

Cloud detection is first investigated by comparing the DARDAR cloud detection algorithm (i.e. all classes including a cloud type) along the flight tracks to the in situ Polar Nephelometer measurements considered as the cloud/no cloud occurrence reference. The comparisons are summarized in Table 2 where the statistics of co-occurrences are displayed. A very good agreement is observed between DARDAR and in situ measurements both for cloud and clear sky cloud detection. 91 % of the clear sky events and 86 % of the cloudy pixels match with the PN measurements. The false detections can be explained by changes in the cloud structure (cloud top and base heights, dissipation) between the satellite overpass time and the aircraft measurements time (delay up to 85 minutes). Most of the undefined DARDAR class actually corresponds to clouds (60 %). In particular, this occurs at low-levels, where DARDAR retrievals are strongly impacted by the attenuation of the lidar laser beam by liquid layers as well as the contamination by radar ground echoes. This assumption is strengthened by Fig. 5 showing that the undefined DARDAR pixels (brown) are mostly localized close to the surface.

DARDAR class	PN (reference)	
	No cloud	Cloud
Clear sky	91 %	9 %
Cloud	14 %	86 %
Undefined	40 %	60 %

**Table 2: Statistics of the cloud detection validation.**

The cloud phase retrieval is also evaluated by comparison with PN in situ measurements.  $g$ -values of 0.80 and 0.83 are chosen to define the thresholds between the ice, mixed and liquid phases (Jourdan et al., 2010). The quantitative and statistical approach is provided on Figure 6 where the frequencies of occurrence of  $g$ -values are displayed for the three main phase classes derived from DARDAR cloud type classification. From these histograms, the “validation scores” are summarized in Table 3.

The  $g$ -values distribution corresponding to the mixing of ice and supercooled water DARDAR phase (green, hereafter called mixing class) is centred on 0.85. Nearly 90 % of the DARDAR mixing class is associated with a liquid phase according to PN ( $g > 0.83$ ). The remaining pixels are distributed more or less equally among the “in situ” ice and mixed phase (6 % and 5 % respectively). The ice DARDAR class (blue) distribution exhibits two modes: the main one around 0.74, and the second around 0.84. The statistics scores show that 61 % of the observations corresponding to ice DARDAR class are validated by PN data. The remaining DARDAR “ice” pixels are distributed among the “in situ” mixed (15 %) and liquid (24 %) phases. Finally, the distribution of the supercooled water class (red) shows that 67 % of the DARDAR pixels detected as “supercooled water only” are validated by the in situ measurements while 24 % correspond to an “in situ” mixed phase. The remaining 9 % corresponds to an ice phase. However, the number of DARDAR pixels concerning this class is limited and thus might not be representative, leading to difficulties to draw conclusions.

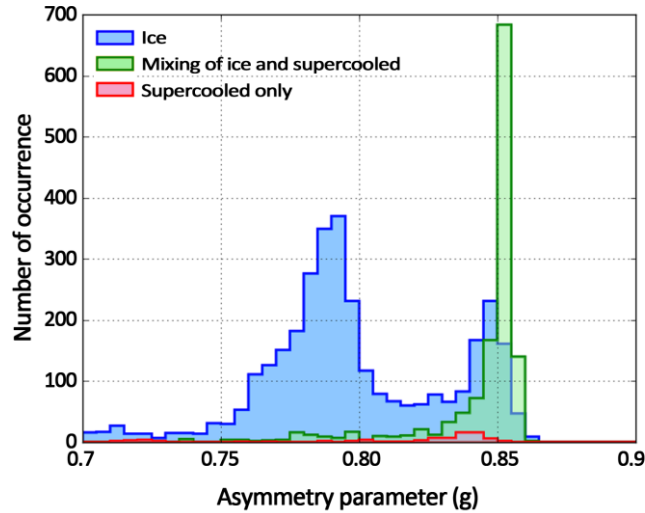


Figure 6: Frequencies of occurrence of the asymmetry parameter from PN according to the DARDAR cloud phase retrieval in color (Mioche et al., 2017).

DARDAR retrieval	PN (reference)		
	Ice phase ( $0.75 < g < 0.80$ )	Mixed phase ( $0.80 < g < 0.83$ )	Liquid phase ( $g > 0.83$ )
Ice	61 %	15 %	24 %
Mixing of ice and supercooled water	6 %	5 %	89 %
Supercooled water only	9 %	24 %	67 %

Table 3: Statistics of cloud phase retrieval validation.

The differences of time and space observation scales between in situ and satellite measurements may explain the main misclassifications of DARDAR pixels. Indeed, in situ measurements account for the small scale inhomogeneities of the liquid and ice occurrences as they document with accuracy and at high spatial resolution the cloud thermodynamic phase. On the opposite, satellite products are more representative of an averaged cloud phase since their spatial resolution is coarser (one order of magnitude lower than in situ measurements). Therefore, a pixel classified as ice by DARDAR could correspond to a mixture of several small sequences or pockets of ice and supercooled liquid droplets, as shown by previous in situ measurement studies (cf. section 4.1). On the contrary, mixed cloud layers optically dominated by supercooled water droplets could be considered as a liquid phase by the PN measurements while the radar could still detect the presence of a few ice crystals. These differences of detection techniques could be responsible for the disagreement between in situ and satellite mixed-phase class.

Additionally, the aircraft sampling time may differ from the actual satellite overpass time. During this delay, cloud top and base altitudes and the cloud layer thickness may vary and could contribute to the discrepancies observed between DARDAR and PN classification. For instance, this could explain the misclassification of 24 % of the DARDAR pixels of the “ice” class that should belong to the “liquid phase” according to the PN measurements ( $g > 0.83$ ). Physical assumptions considered in DARDAR algorithm, such as the supercooled liquid layer thickness can also influence the retrievals of the cloud phase. The liquid layer is set to have a maximum thickness of 300 m (Delanoë and Hogan, 2010) whereas aircraft measurements have clearly shown that within MPC this liquid layer can be thicker than 300 m. This 300m threshold correspond to the fully attenuation of the CALIOP laser beam meaning that DARDAR is not able to detect the liquid phase beyond this thickness. Since most of the misclassified pixels occur in the lower part of the liquid layer, this could be a plausible explanation for the observed disagreement.

We recall that the results presented here have been made by oversampling the satellite observations to match the in situ measurements resolution. A Similar work has been performed averaging the PN data on the same

resolution grid as DARDAR products (pixel size of 1700 m and 60 m horizontal and vertical respectively, corresponding to approximately 17 in situ data points) and it is quite remarkable that the results are very similar for the two methods, both in terms of cloud/no cloud detection and for the cloud phase product. These comparisons illustrate the impact of sampling resolution on the cloud detection and cloud phase retrievals. Sub-pixel representativity of the spaceborne observations can be assessed showing that the satellite detection of cloudy pixels is consistent with higher spatial resolution in situ cloud measurements. Finally, these findings also highlight that the characterization of the horizontal and vertical variability of MPC thermodynamical phase at different observation scales, is still needed.

## 6. Conclusion

The investigation of Arctic mixed-phase clouds (MPC) is of primary importance to improve their representation in numerical models and thus improve the accuracy of the Arctic climate modelling and global climate predictions. In particular, the liquid-ice partitioning, ice crystals and liquid droplets properties (number, size, shape, mass), formation and growth processes and interactions with aerosols and radiation need to be assessed.

Observations from satellites can be used to study Arctic clouds at a regional scale. In particular, the new satellite active remote sensing measurements from CALIPSO and CloudSat have greatly improved the accuracy of observations from space compared to the previous passive remote sensing measurements. The assessment of the seasonal, spatial and vertical variability of Arctic MPC became possible. Main results (Cesana et al., 2012; Mioche et al., 2015) highlighted that MPC are present all year long in the Arctic, with important spatial and seasonal variability. The Arctic Atlantic side (region around Barents and Greenland Seas) exhibits high and almost constant occurrence of MPC throughout the year with higher frequency than the Arctic average. On the contrary, regions of Central Arctic Ocean and Pacific side (region around Northern Alaska, Barents and Chukchi Seas) exhibit a clear seasonal variability, with low MPC occurrences during winter and spring, and larger occurrences in summer and autumn. The vertical distribution of MPC showed that most of the MPC are present below 3 km, except during summer where these clouds are frequently observed at mid-altitudes (3-6 km). This seasonal and vertical variability of MPC at regional scale are related to the influence of the North Atlantic Ocean and with the melting of sea ice. The Atlantic Ocean provides heat and moisture necessary to the formation of MPC in the Greenland and Barents Seas regions all along the year. The open water resulting from the melting of sea ice from spring to autumn allows the transport of heat and moisture from the North Atlantic Ocean to the Central Arctic Ocean and Pacific side, promoting the formation of MPC in this region during these seasons.

However, active remote sensing retrieval algorithms need to be evaluated and validated. Moreover, observations from space are known to be biased close to the surface (< 2km). Ground-based and airborne remote sensing can provide accurate cloud measurements at low level altitude. High spatial and temporal resolution measurements are also needed to study microphysical properties and processes. Therefore, even though they remain very local in time and space, airborne in situ measurements offer the high resolution needed to accurately characterize cloud particles properties and microphysical processes.

Since the 90's, numerous major field experiments involving in situ cloud airborne measurements have been carried out. Based on these measurements, properties of liquid droplets and ice crystals within MPC (number, size, shape, mass) and main processes responsible for their formation, growth and persistence can be investigated. These campaigns datasets combined with modelling studies give an insight of the main processes involved in the MPC life cycle.

In particular, the main findings highlighted from in situ airborne measurements concerning Arctic MPC can be summarized as follow:

- Liquid droplets result from the activation of CCN particles at cloud base. They grow during their ascent towards the cloud top. Temperature inversion at cloud top limits the vertical development of MPC by entrainment of dry air and evaporation of a part of the cloud droplets. If humidity inversion occurs at cloud top, it can counteract this effect by providing moisture and prevent the evaporation of droplets.
- Ice crystals are formed by heterogeneous ice nucleation processes or, under specific thermodynamical conditions, by secondary ice formation processes. Ice crystals can grow through riming, condensational (including Wegener-Bergeron-Findeisen process) and aggregation processes, depending of the supercooled liquid amount available, humidity (supersaturation) conditions and dynamical conditions. Consequently to these numerous processes, ice crystal properties does not exhibit specific vertical variability and are almost uniformly distributed into MPC.



- The formation and growth of ice crystals and the subsequent precipitation efficiency depend strongly on the liquid phase and aerosols properties. In cases of polluted situations (from mid-latitude long-range transport), a higher concentration of aerosols (and thus CCN) results in a large number of small liquid droplets and reduce the formation of the ice phase, its growth efficiency, and thus its precipitation ability. Moreover, this reduction of the precipitation efficiency may help to maintain the liquid phase and the MPC longevity since droplets are less consumed by ice crystals, resulting in a positive cloud feedback.
- As a result of the interaction processes between ice and liquid phases, it has been shown that Arctic MPC exhibit a liquid water fraction increasing with decreasing temperature into the cloud, contrary to mixed-phase clouds at lower latitudes. That means that specific parameterizations for Arctic MPC are needed to improve modelling.
- There is a strong optical signature of the liquid water fraction and shape of ice crystals within the MPC layers with possible impacts on remote sensing retrievals and radiative properties. This confirms the importance of deriving equivalent microphysical models based on a limited set of free parameters (roughness, mixture of idealized particle habits, and aspect ratio of ice crystals) that reproduce the main optical and features of the cloud layers

At last, in situ measurements are very useful to validate remote sensing observations. We showed that, when they are collocated with satellite observations such as the CloudSat radar and CALIOP lidar measurements, they can be used to evaluate retrieval algorithms. Validation works in terms of cloud detection and thermodynamical phase highlighted a general good accuracy of the retrieval products. Nevertheless, some issues have been identified regarding the retrieval of the supercooled water phase, which is mostly confounded with the mixing of ice and supercooled water class. The retrieval of the ice phase also presents some misclassifications as some part of the retrieved ice pixels is actually liquid water. These issues may be mainly attributed to the difference in resolution between satellite and in situ observations which have a better ability to detect the heterogeneities (sequences of liquid and ice) of mixed phase at small scale compared to large scale (satellite resolution). Finally, these results also highlighted the need to link large and small scale observations (and allow to investigate the sub-pixel representativity of satellite observations).

In conclusion, the synergy of satellite active remote sensing observation and in situ airborne cloud measurements performed in the Arctic region constitute a great step forward in the characterization of the macrophysical, microphysical and optical properties of low-level MPC and the understanding of the large and small scale processes governing their life cycle, as well as their interactions with aerosols and radiation. This is important to mitigate biases of the modelling and parameterizations of cloud properties and radiative impact.

However all the radiative-dynamical-microphysical process interactions and feedbacks controlling the liquid to ice conversion, the precipitation rates and the MPC maintenance remain complex and need to be better assessed. Many challenges and unanswered questions remain to understand the MPC life cycle and to improve the accuracy of the retrieval algorithm and their representation in global and regional models. More multi scale modelling studies constrained by larger comprehensive datasets are needed to unravel the web of interactions between processes occurring in MPC. Measurements planned during the ALOUD (Arctic Cloud Observations Using airborne measurements during polar Day, 2017) campaign or the international initiative MOSAiC (Multidisciplinary drifting Observatory for the Study of Arctic Climate, 2020) in the Central Arctic Basin ice pack should provide an accurate dataset to improve our process-level understanding of MPC clouds. Ship-based, airborne, ground-based measurements coupled with satellite observations over sea ice and open ocean will be used to estimate the role of Arctic MPC on the amplified climate change occurring in the Arctic region.

## Figure captions

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