Contrasting ice formation in Arctic clouds: surface coupled vs decoupled clouds

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Abstract. In the Arctic summer of 2017 (June, 1st to July, 16th) measurements with the multiwavelength polarization lidar Polly[XT]-OCEANET, 35-GHz cloud radar of the OCEANET platform, and radiosonde measurements were conducted during cruise PS106 of the research vessel Polarstern around Svalbard. In the scope of the presented study, the influence of cloud height and surface coupling on the probability of clouds to contain and form ice is investigated. The analyzed data set shows a significant impact of the surface-coupling state on the probability of ice formation. Surface-coupled clouds, identified by a quasi-constant potential temperature profile from the surface up to liquid layer base, in the same cloud-top temperature range contain ice more frequent than decoupled clouds by a factor of up to 5 for cloud-top intervals between -7.5 and -5°C (169 vs. 31 profiles). These findings provide evidence that heterogeneous ice formation in Arctic mixed-phase clouds occurs by a factor of 2-5 more likely when the cloud layer is coupled to the surface. In turn, for cloud-top temperatures below -15°C, the frequency of ice-containing cloud profiles for coupled and decoupled conditions approached the respective curve for the Central-European site of Leipzig, Germany (51°N, 12°E). This provides further evidence that the free-tropospheric ice nucleating particles (INP) reservoir over the Arctic is controlled by continental aerosol. One possible explanation for the observation is that turbulent mixing of the air below surface-coupled clouds allows ice particles, acting as seeds for ice multiplication, or marine aerosols, acting as INP, to be transported into the cloud layer more efficiently than in the case of decoupled conditions. This hypothesis is corroborated by recent in-situ measurements of INP in the Arctic, of which much higher concentrations were found in the surface-coupled atmosphere in close vicinity to the ice shore. Using lidar measurements we also found evidence for enhanced INP number concentrations (INPC) within surface-coupled cloud-free air masses. The INPC have been estimated based on particle backscatter profiles, published freezing spectra of biogenic INP and existing parameterizations.

1 Introduction

The Arctic climate is known to change much faster compared to other regions on Earth, which is referred to as Arctic amplification (Serreze and Francis, 2006). The surface temperature anomaly of the Arctic for the year 2013 with respect to the mean of 1970 – 1999 is 2 – 3 K above the one of the mid-latitudes (Francis and Skific, 2015). As is also pointed out by Francis

and Skific (2015), this differential heating will likely have consequences for the mid-latitudinal circulation, leading to reduced zonal winds and consequently more-steady weather periods with accompanied larger regional risk of severe droughts or wet periods.

Given the possible widespread consequences of Arctic amplification, it is essential to understand the physical processes
5 leading to this rapid change. A number of different atmospheric and marine processes are currently discussed as potential sources for Arctic amplification. Nevertheless, a clear causal chain could to date not be established (Serreze and Barry, 2011; Pithan and Mauritsen, 2014; Kim et al., 2017) because the quantitative contribution of the single processes involved as well as their autocorrelation could yet not be determined. Besides the evident role of sea ice loss in the warming process, a key role in Arctic amplification is attributed to clouds (Vavrus, 2004). Kay and L'Ecuyer (2013) obtained a climatology of Arctic clouds
10 and radiation conditions for the first decade of the 21st century. They highlight the importance of clouds in the Arctic climate system but they also note that both conditions - presence as well as absence of clouds - can contribute to Arctic amplification, depending on the season and the sea ice conditions. In 2016 the German transregio initiative ArctiC Amplification: Climate Relevant Atmospheric and SurfaCe Processes, and Feedback Mechanisms (AC)³ was established to further investigate the reasons and consequences of Arctic amplification (Wendisch et al., 2019).

15 With respect to the microphysical properties of Arctic mixed-phase clouds, it is evident that an accurate representation of the latter in atmospheric models is important in order to understand and accurately simulate Arctic climate (Engström et al., 2014). Especially their longevity puts high demands on the research community. Big efforts were put into establishing model frameworks that are capable of simulating such cloud systems (Fridlind et al., 2007; Klein et al., 2009; van Diedenhoven et al., 2009; Morrison et al., 2012; Neggers et al., 2019), even in the case of single-layer clouds of low complexity. The different
20 processes involved to form and sustain supercooled liquid or mixed-phase clouds were thoroughly discussed by Morrison et al. (2012). Large-scale advection of water vapor is considered to be the prerequisite for formation and persistence of Arctic stratus decks, especially over closed ice surfaces.

In the marginal sea ice zone, the transition zone between closed ice surface and open sea, the importance of surface sources of heat and moisture in promoting cloud processes relative to in-cloud or advective sources is, however, uncertain (Harrington
25 and Olsson, 2001; Shupe et al., 2013). The subsequent microphysical evolution of the Arctic stratiform cloud decks is subject to the availability of cloud condensation nuclei (CCN) and ice nucleating particles (INP) (Stephens, 2005; Fridlind et al., 2007; Kalesse et al., 2016). At temperatures above -38°C only heterogeneous ice formation takes place, which requires the availability of such INP (Hoose and Möhler, 2012), with INP from different origin starting to be active at different temperatures. Mineral dust, e.g., starts getting active below a temperature of about -15°C (Hoose and Möhler, 2012) while sea spray aerosol INP
30 have been found to be already active at -5°C (DeMott et al., 2016). INP from biological origin are assumed to be one of the most active ones at low to moderate supercooling (Schnell and Vali, 1976; Szyrmer and Zawadzki, 1997; Murray et al., 2012; O'Sullivan et al., 2018).

Many studies report that respective INP reservoirs for Arctic clouds are mainly provided by means of long-range transport from lower latitudes (Morrison et al., 2012). An increasing number of studies, however, suggest that also local aerosol sources
35 can provide significant numbers of CCN and INP which stem from marine processes (Bigg, 1996; DeMott et al., 2016; Hart-

mann et al., 2020) or even from ship emissions or industry (Creamean et al., 2018; Thomson et al., 2018). This suggests that also Arctic clouds are subject to anthropogenic climate change (Lohmann, 2017). Wex et al. (2019) found an annual cycle in INP number concentration (INPC) at four different-land based stations in the Arctic with the largest INPC in summer. Hartmann et al. (2020) analyzed filter measurements from an Arctic airborne campaign and found the highest INPC during low

5 level flights above open leads and polynyas. Heat sensitivity of the sampled INP as well as high freezing onset hint towards biogenic origin. Low flight altitudes, a large number of open leads in the vicinity of the aircraft flight track, and detected sea salt in the aerosol samples suggest that these INP rather originate from local marine sources than long range transport.

One way of evaluating the relationship between temperature, aerosol conditions, and the efficiency of heterogeneous ice formation is the utilization of remote-sensing observations. From combined observations of cloud radar, lidar, and microwave

10 radiometer, the vertical structure and microphysical composition of clouds and precipitation over a specific site can be obtained (Illingworth et al., 2007; Shupe, 2007). For vertically and optically thin cloud layers also the application of single systems such as polarization lidar can be used to obtain the required information (Sassen, 2005; Ansmann et al., 2009). Thermodynamic properties of the atmosphere are provided by soundings or model data. Numerous studies provide evidence that the occurrence and efficiency of heterogeneous ice formation at ambient conditions depends strongly on both, temperature (Shupe, 2011;

15 Zhang et al., 2017) as well as the type and quantity of the aerosol burden at cloud level (Sassen, 2005; Seifert et al., 2010; Kanitz et al., 2011; Zhang et al., 2018).

With respect to the humidity conditions, such studies are even further constrained under the presence of layers of supercooled liquid water which is the case for the majority of cloud layers with top temperatures above -25°C (Ansmann et al., 2008; de Boer et al., 2011; Westbrook and Illingworth, 2011). Changing aerosol conditions in the Arctic have thus the potential to modify

20 the general occurrence of heterogeneous ice formation. This puts a definite requirement to advance the understanding of the current state of how heterogeneous ice formation occurs in the Arctic. First studies suggest that aerosols potentially influence the structure and microphysics of Arctic clouds. Norgren et al. (2018) show that aerosols might be responsible for the reduction in the cloud ice content in low-level Arctic mixed-phase clouds. They found that mixed-phase clouds present in a clean aerosol state have higher ice water content by a factor of 1.22 to 1.63 at cloud base than do similar clouds in cases with higher aerosol

25 loading. Jouan et al. (2014) hypothesized that emissions of SO_2 may reduce the ice nucleating properties of INP through acidification, resulting in a smaller concentration of larger ice crystals that leads to an increase in precipitation.

Clouds in general are highly variable in their occurrence and structure (Stephens, 2005). The main feature of Arctic clouds is, however, associated to the frequent occurrence of multi-layer temperature and humidity inversions which lead to the formation of temporally stable multi-level mixed-phase cloud decks (Shupe et al., 2011; Morrison et al., 2012; Verlinde et al., 2013).

30 These cloud layers are of complex macro- and microphysical structure and frequently occur at heights close to the ground which are not easily trackable. Liu et al. (2017) pointed out that space-borne remote-sensing techniques miss to detect 25 to 40% of the clouds below 500 m height and also underestimate the fraction of mixed-phase and ice clouds between the surface and 1000 m height. In turn, ground-based profiling studies from the Arctic, which rely on lidar and radar observations, usually provide reasonable data only at heights above $100 - 150$ m above ground, as it is the case for the 35-GHz cloud radar (KAZR)

35 of the U.S. Atmospheric Radiation Measurement (ARM) program of the Department of Energy (DOE) at the NSA (North

Slope of Alaska) site in Utqiaġvik (formerly known as Barrow), USA. Cloud processes that take place at lower heights can thus not thoroughly be characterized (Griesche et al., 2020).

Even though indications are given that local aerosol sources may play a role for heterogeneous ice formation, none of the studies available so far investigated any potential effects of the surface-coupling state of Arctic clouds on the frequency and

5 efficiency of ice formation. Investigation of potential effects of the surface coupling were so far restricted to bulk properties such as ice water path (IWP) or liquid water path (LWP), without referencing clearly to any relations between ice formation and temperature, or even aerosol conditions. Shupe et al. (2013) found only moderate differences in coupled versus decoupled clouds. They report that clouds which are thermodynamically linked with the surface tend to show colder temperature profiles within the cloud and slightly weaker in-cloud turbulence, yet often have higher LWP and IWP, for which they suggest as a

10 reason the additional moisture supply from below. Qiu et al. (2015) studied the occurrence of Arctic mixed-phase clouds in relation to the presence and strength of humidity and temperature inversions but they did not provide any information about the overall frequency of ice formation in the different coupling states. Similar to Qiu et al. (2015), Qiu et al. (2018) used the opportunity to study the influence of both, surface conditions and different air masses, on thermodynamic variables and on the properties of Arctic mixed-phase clouds. Due to the coastal location of the Utqiaġvik site in northern Alaska where the dataset

15 for their study was obtained, marine air masses are transported by northerly winds, while more continental air masses are transported by southerly winds. Furthermore, the Arctic mixed-phase cloud occurrence frequency was found to have a positive relationship with relative humidity with respect to ice and a negative relationship with stability. But also this study investigated mixed-phase cloud properties only. The efficiency of ice formation was not investigated. Sotiropoulou et al. (2014) provide a detailed study of the properties of coupled and decoupled Arctic clouds but found with respect to the thermodynamic phase

20 partitioning, that the IWP and LWP as well as their ratio of coupled and decoupled clouds are similar. Gierens et al. (2020) studied surface-coupling effects on mixed-phase clouds based on a two year data set from ground-based remote-sensing in Ny-Ålesund, Svalbard. They found a seasonal cycle of the coupling-state, with most coupled clouds observed during summer. The LWP in coupled clouds was roughly 40% higher compared to decoupled clouds, but only minor differences have been found in IWP. Their findings are effected by the surrounding orography of the measurement site. Glacier outflows tend to be

25 decoupled, while for clouds transported from the open sea towards Ny-Ålesund coupling was most common. The open sea west of Svalbard also might act as a local humidity and heat source. Furthermore, models have their difficulties to accurately reproduce heterogeneous ice formation in clouds. Nomokonova et al. (2019) reported in agreement with Sandvik et al. (2007) that single-layer mixed-phase clouds tend to be underestimated in models compared to results from the synergy of different ground-based instruments. Without considering any surface-coupling effects in their study, they found in a temperature regime

30 between -20 to -5°C a lower occurrence of mixed-phase clouds by the expense of pure ice clouds.

Given the indication that aerosols play a dominating role in the heterogeneous ice formation process and that Arctic clouds are frequently occurring either coupled or decoupled to the surface and corresponding local aerosol sources, it should be investigated if the characteristics of heterogeneous ice formation processes differ between coupled and decoupled clouds. The goal of this study is motivated by the need for an accurate characterization of the near-surface cloud properties and the

35 prevalent indications that the microphysical and dynamical structure of surface-coupled Arctic clouds differs from those of

decoupled clouds (Shupe et al., 2013; Qiu et al., 2015, 2018). The work is based on a comprehensive dataset of remote-sensing instruments and atmospheric soundings from an 8-week cruise of the research vessel Polarstern into the marginal ice zone between Greenland and Svalbard in May-July 2017 that was collected in the frame of (AC)[3]. By splitting this dataset into low- and high-altitude cloud layers as well as into coupled and decoupled clouds, an investigation of cloud macro- and microphysical

5 properties will be possible separately for free-tropospheric clouds, not depending on regional effects and further aerosol input, and of surface-coupled clouds, being linked to local phenomena and aerosols in the Arctic region.

The article is structured as follows. Section 2 will focus on the instrumentation and methodology used to analyze the data from the ship cruise in the Arctic summer. In Section 3 an overview of the observations will be provided and statistical evaluation of the analyzed measurements of the Arctic clouds will be presented. A detailed discussion of the findings is given in

10 Sect. 4. Section 5 summarizes and concludes this study.

2 Instrumentation and Methodology

From 1 June until 16 July 2017 cruises PS106.1 and PS106.2 (PS106 in general) of the German research vessel Polarstern took place with the goal to conduct measurements in the marginal sea ice zone north and northeast of Svalbard (Macke and Flores, 2018). Cruise PS106.1 comprised the "Physical feedbacks of Arctic boundary layer, Sea ice, Cloud and AerosoL (PASCAL)"

15 icebreaker expedition and ice floe camp, as well as the "Arctic CLoud Observations Using airborne measurements during polar Day (ACLOUD)" aircraft campaign (Wendisch et al., 2019). PASCAL as well as ACLOUD were dedicated to the investigation of processes related to Arctic amplification. During the full period of PS106, continuous remote-sensing of aerosols and clouds was performed with the OCEANET platform aboard Polarstern (Griesche et al., 2020). The suite of instruments of OCEANET operated during PS106 is listed in Table 1. Of specific interest for the underlying study are the motion-stabilized vertically

20 pointing 35-GHz cloud Doppler radar Mira-35 (Görsdorf et al., 2015; Griesche et al., 2020), the multiwavelength Raman polarization lidar Polly[XT]_Oceanet (hereafter referred to as Polly[XT]; Engelmann et al., 2016) and the microwave radiometer (MWR) HATPRO (Rose et al., 2005). Auxiliary data for the study was obtained from the regularly performed atmospheric soundings of type Vaisala RS41 which are available every 6th hour (UTC) of the day for the entire cruise.

The set of instruments deployed for this study is used to obtain information about cloud vertical extent, atmospheric ther-

25 modynamic state, phase partitioning, and ice and liquid microphysical properties. As mentioned in the introduction, the goal of this study is to investigate the phase partitioning of Arctic cloud systems with respect to their surface coupling. It was thus aspired to obtain similar statistics as it was presented before by, e.g., Ansmann et al. (2009), Seifert et al. (2010, 2015), and Kanitz et al. (2011). Kanitz et al. (2011) showed that the relationship of spatially and vertically distinct ice-containing cloud layers and cloud top temperature varies strongly by region on Earth. For the current study, however, the cloud classification

30 procedure that was applied by Kanitz et al. (2011) or similar ones such as of Seifert et al. (2010, 2015), was extended in such a way that it accounts for the long-lasting nature of Arctic cloud systems which frequently prevented the classification of distinct, vertically and temporally separated cloud layers. Hence, we now present the applied method for this data set.

Table 1. Instrumentation used in the frame of this study.

Platform			
Instrument	Type	Atmospheric parameters	Resolution
OCEANET			
Polly^{XT}	Multiwavelength Raman polarization lidar, pointed 5° off- zenith	Particle backscatter and extinction coefficient; linear depolarization ratio; water vapour mixing ratio	7.5 m; 30 s
Mira-35	35-GHz (Ka-band) motion stabilized, vertically pointing cloud radar	Vertical structure, boundaries and vertical-velocity dynamics of clouds and precipitation; contributes to cloud liquid water and ice water profiles	30 m; 3 s
HATPRO-G2	14-channel microwave radiometer	Estimated profiles of temperature and humidity; integrated water vapor and liquid water path	100 – 1000 m; 1 s
Polarstern Meteorology			
RS41	Radiosonde	Atmospheric pressure, temperature, humidity, wind vector	1 s
OceanRain			
ODM470	Optical disdrometer	Precipitation rate, type, size distribution	60 s, 128 bins 0.5 – 22 mm

2.1 Ice-containing cloud analysis

The applied procedure to identify and characterize the individual cloud profiles is illustrated in Fig. 1. Initially, the dataset is split into time intervals of 30 minutes. Using the Polly^{XT} 532 nm depolarization ratio (Fig. 2 (a)) the cloud phase was determined. In Fig. 1 (a) a simplified profile of the depolarization ratio is shown with an aerosol layer and a cloud in the background.

5 Aerosols can increase the depolarization depending on their shape. Also ice particles show an enhanced depolarization ratio due to their crystal shape. Liquid droplets on the other hand have a very low depolarization ratio. Within the liquid layer, however, the depolarization ratio increases strongly due to multiple scattering (Jimenez et al., 2020). The following classification was applied in the frame of the inspection of each individual profile: A depolarization ratio close to 0 accompanied with a strong lidar backscatter indicates the presence of spherical liquid-water droplets. If the depolarization ratio below the liquid layer is

10 very high (likely due to ice crystals falling out of the cloud) the cloud is classified as an ice-containing cloud (15-16 UTC and 17-18 UTC in Fig. 2). Otherwise, it is classified as a liquid cloud (16-17 UTC and 18-21 UTC in Fig. 2). In the presence of ice the liquid layer base height (dashed gray line in Fig. 1, gray bars in Fig. 2) is defined as the transition region in which the depolarization ratio is higher and reduces sharply with increasing height (transition region between ice particle scattering to cloud droplet scattering). In the absence of ice crystals it is the region where the lidar backscatter increases strongly with

15 height. The cloud top height cannot be determined with lidar for optically thick clouds because of the attenuation of the signal, which was frequently the case for the Arctic clouds which are subject of this study. In this case the cloud radar measurements
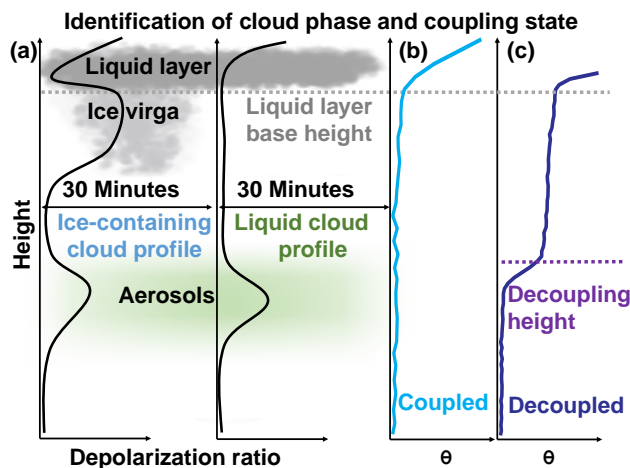
Figure 1. Sketch of the applied method: panel (a) illustrates a cloud above an aerosol layer with the according profile of the depolarization ratio. Due to the ice virga below the cloud (high depolarization) the first 30 minutes are classified as ice cloud. Without ice falling out of the cloud only the liquid layer is present (low depolarization). In the presence of ice the liquid layer base height is characterized by an strong decrease in depolarization. Within the liquid layer the depolarization increases again due to multiple scattering. In panel (b) and (c) two profiles of θ are depicted, with (b) illustrating a coupled cloud and (c) a decoupled cloud. In (c) additionally the decoupling height is marked.

are used (Fig. 2 (b)). The height in which the signal decreases sharply is defined as the cloud top height (marked in red bars Fig. 2 (b)).

The cloud-top temperature is an important parameter in the sense of this study. INP efficiency increases about an order of magnitude every 5 K (DeMott et al., 2015). Hence, the probability of ice production is highest at the cloud top where usually the
5   coldest temperature is reached within the cloud. The cloud-top temperature was obtained from the radiosondes including the knowledge of the cloud radar-derived approximate cloud top height. In theory the cloud top height should be equal to the height of the cold side of a temperature inversion as convection is very weak in the Arctic and is stopped at an inversion. Therefore, the cold side of the temperature inversion which is closest to the cloud-radar-derived cloud top height in the radiosonde data is searched for and is defined as the cloud-top temperature.

10   Cloud layers, which may be affected from a cloud layer above have been filtered from the data set. Ice crystal precipitation from the upper layer may act as ice nuclei in the lower one. The analyzed data set is corrected for this seeding effect based on cloud radar observations, which fully detect all clouds up to the tropopause. Cloud layers which are vertically closer than 1000 m to the subjacent cloud are thought to be able to influence the lower one and thus these periods have been excluded from the analysis.

15   **2.1.1   Surface coupling state**

The surface coupling state of the cloud is derived from the thermodynamic profiles of the radiosondes. Following Gierens et al. (2020) who introduced a simplified coupling algorithm from Sotiropoulou et al. (2014) we examined the profile of the
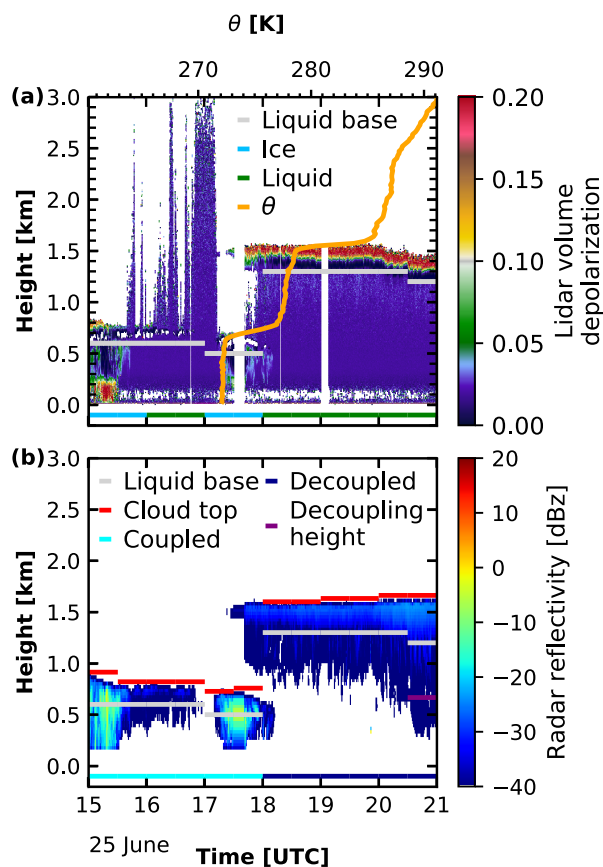
Figure 2. An example of the applied method on 25 June 2017 between $15-21$ UTC. In (a) the lidar volume depolarization is shown. Marked are also flags for liquid layer base height (grey) and cloud phase (ice: blue, liquid: green). Additionally the θ profile for the sounding launched at 17:15 UTC (orange) is plottet. In (b) the cloud radar reflectivity is depicted, together with information on the liquid base height (grey), cloud top height (red), the coupling state (cyan: coupled, dark blue: decoupled) and (if applicable) the decoupling height (purple).

potential temperature θ starting at liquid layer base down to the surface. If the difference between the cumulative mean of θ and θ exceeds 0.5 K the cloud is considered as decoupled (Fig 1 (c)) and this height in taken as the decoupling height (marked in purple in Fig 1 (c) and Fig. 2 (b)). A quasi-constant θ-profile on the other hand identifies coupled clouds (Fig 1 (b)). In Fig. 2 (a) the base of the clouds between $15-17$ UTC were too low to be decoupled ($500-600$ m). The θ-profile was nearly

5   constant until base height. From 17 UTC on, however, the liquid base height is significantly higher ($1200-1300$ m) and due to the increase in θ at roughly 700 m these clouds are defined as decoupled.

2.2 INP properties from lidar observations

As discussed in the introduction, recent studies suggest that local marine sources may significantly contribute to the INP reservoir in the Arctic, especially in the marginal ice zone. To further constrain whether the observed clouds during PS106 were influenced by such local sources we made use of cloud-free Polly^{XT} particle backscatter profiles (Baars et al., 2016).

5 These profiles have been normalized by their decoupling height. To retrieve the decoupling height for cloud free situations the above introduced surface coupling algorithm was applied for each level of the radiosonde, starting at the surface. The lowest height where the decoupling criteria was fulfilled was set as decoupling height.

Mamouri and Ansmann (2016) introduced a retrieval for INPC from lidar particle backscatter profiles. They applied the method to existing parameterizations, e.g., for desert dust (Niemand et al., 2012; DeMott et al., 2015; Ullrich et al., 2017), sea

10 salt (DeMott et al., 2016), and continental aerosol (DeMott et al., 2010). Other studies suggested that INP active at temperatures above -10°C in the Arctic are of biogenic origin. Hence the existing parameterizations have to be adjusted in a way to obtain an estimate of such INP. Gong et al. (2020) studied filter samples from the Cape Verde Atmospheric Observatory. They found INP active at temperatures above -10°C which consists likely of biological material. In their supplementary material they published freezing spectra of biological INP prior and after heating. The heating process significantly reduced the ice nucleating ability

15 of the samples. After heating the freezing onset was reduced from -7 to -11°C with a factor of 50 to 60 less INP. The resulting freezing spectrum after the heating procedure is comparable to those from mineral dust sources. Welti et al. (2018) for example analyzed filter samples also from Cabo Verde and assigned INP active below -12°C to air masses originating from the Sahara. The freezing behavior of the corresponding INP is similar to those of the heated samples from Gong et al. (2020). Hence in order estimate the number concentration of INP at -10°C we applied a scaling factor of 50 to the parameterization of mineral

20 dust from DeMott et al. (2015) to retrieve an estimate of the biogenic INP number concentration.

3 Results

3.1 Campaign overview

The investigated period covers 1548 of analyzed intervals of 30 minutes. In 87% of the time a cloud was identified and roughly 56% of the investigated clouds were identified as ice clouds. Approximately 61% of the analyzed clouds were coupled to the

25 surface whereas 39% were decoupled. 61% of the surface coupled clouds were defined as ice-containing clouds but only 48% of the decoupled clouds.

3.2 Influence of surface coupling

Following Kanitz et al. (2011) we analyzed the fraction of ice-containing clouds with respect to all observed clouds in different cloud-top temperature intervals, starting at 0°C down to below -40°C. Figure 3 (a) shows the fraction of ice-containing clouds

30 as a function of cloud-top temperature for the Arctic (blue) in contrast to findings from Leipzig (orange; Kanitz et al., 2011). Basically any cloud from both data sets with a top temperature <-25°C contained ice. In warmer clouds (cloud-top temperature
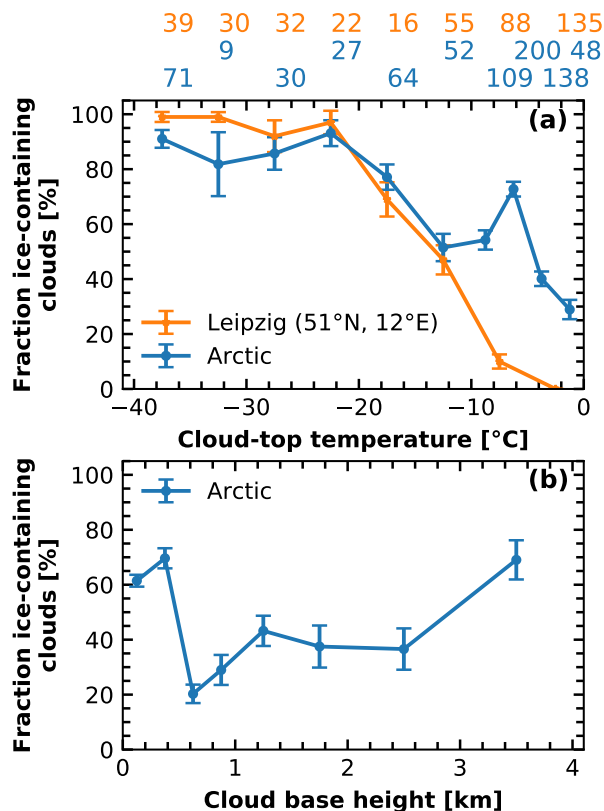
Figure 3. (a) Fraction of ice-containing clouds as a function of cloud-top temperature for the heterogeneous ice nucleation regime. Data of all clouds of the Arctic 2017 field campaign is plottet in blue. In orange the result for Leipzig from Figure 3 in Kanitz et al. (2011) is shown. The error bars show the statistical uncertainty as in Seifert et al. (2010). Temperature intervals increase with decreasing cloud-top temperature due to decreased number of data (ΔT = 2.5°C below -10°C and 5°C above -10°C). The numbers on top of the plot show the number of data for each temperature interval and the data points have been placed in the middle of the respective investigated interval. (b) Fraction of ice-containing clouds for different liquid layer base heights. Base height intervals increase with increasing liquid layer base height due to decreased number of data (Δh = 0.25 km below 1 km, 0.5 km between 1 and 2 km and 1 km above 2 km).

>-10°C) above Leipzig on the other hand usually little to no ice-containing clouds were found. For the Arctic we found a different pattern in this temperature regime. Temperatures slightly below freezing are already sufficient for ice production: Up to 70% of the investigated clouds with cloud-top temperatures above -15°C showed signals of ice. As warmer cloud-top temperatures are usually associated with lower cloud heights, in a next step we analyzed the data set in terms of liquid layer
5   base height.

Figure 3 (b) represents the fraction of ice-containing clouds as a function of liquid layer base heights (see Fig. 1) between 50 and 4000 m. In general there is a tendency of increasing fraction of ice-containing clouds with increasing base height. An increase of liquid layer base height usually is attended by an increase of cloud top height, which in turn typically goes along
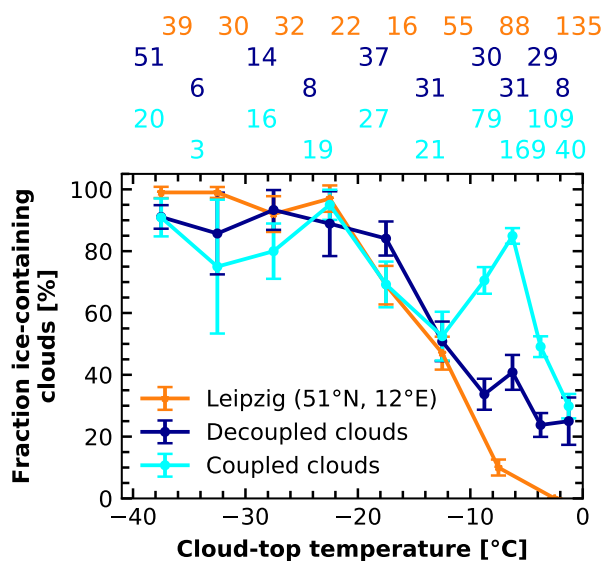
Figure 4. Same as Fig. 3 (a) with the Arctic clouds separated by their coupling state (cyan: coupled clouds, dark blue: decoupled clouds).

with a decrease of cloud-top temperature. This leads to a higher probability of ice formation, as a higher fraction of aerosols can act as possible INP. The fraction of ice-containing clouds for liquid layer base heights below 500 m, however, is also up to 70%. To further investigate if this effect may be linked to a possible INP source at the surface we separated the data set by the surface coupling state of the clouds, as described in Sect. 2. The resulting distribution for both surface coupled (cyan) and decoupled clouds (dark blue) is shown Fig. 4. Between -15 and 0°C strong coupling effects can be seen. Surface-coupled ice-containing cloud profiles compared to decoupled ones occurred more frequent by a factor of 2-5 (e.g. 169 vs. 31 profiles between -7.5 and -5°C cloud-top temperature). Their frequency of occurrence was twice as high, as is the case between -5 and -10°C. Below -15°C this effect vanished and both curves showed similar distribution as found over Leipzig. Investigating colder cloud-top temperatures the cases of surface coupled clouds reduce significantly.

4   Discussion

The separation of the Arctic cloud data set revealed the presence of surface effects on the enhancement of the occurrence of ice formation. At greater heights, lower temperatures or in the case of uncoupled clouds, however, the ice frequency statistics are similar to what is observed over nothern-hemisphere midlatitude sites. The reasons for the increase in ice forming efficiency for low and coupled clouds in the Arctic must be caused by effects resulting from the linkage to the surface (Solomon et al., 2014). A surface coupling of the cloud is accompanied with a well-mixed layer from the surface up to liquid layer base. Multiple processes were discussed in previous studies as potential candidates for explaining the observations. They will be listed and examined below. In Shupe (2011) the main reason for clouds to contain ice was expected to be near-surface diamond dust. As
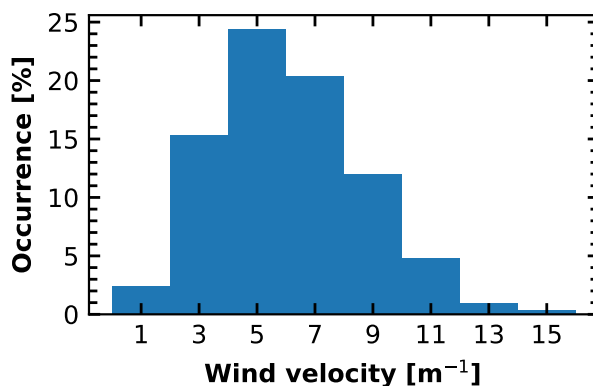
Figure 5. Histogram of the mean surface wind for any of the analyzed 30-min time interval.

this effect is strongest in winter and close to land (Intrieri and Shupe, 2004), it can be neglected as a dominating reason for the Arctic clouds during the investigated Polarstern cruise.

Also an influence of blowing snow on the results can be ruled out. As Serreze and Barry (2014) pointed out, a minimum wind speed of $15\,\mathrm{ms}^{-1}$ is needed to lift the snow even for few meters above the ground. Since the wind speed during the
5 PS106 campaign did not even reach this threshold (see Fig. 5), we are confident that blowing snow did not affect our findings. To consider also possible seeding effects from precipitating clouds above, the data set has been filtered for those (during this cruise anyway rare) situations with little to no effects on the results.

A further potential explanation is, that marine aerosol from areas of open water within the marginal sea ice zone or from open leads or polynyas may be mixed into the coupled cloud layers where they can act as ice nuclei (Burrows et al., 2013)
10 and increase the probability of ice production. Decoupling then again indicates a separation of the air masses due an inversion below liquid base. However, decoupled clouds observed above RV Polarstern may have been coupled to the surface prior approaching the measurement site. This could be an explanation why decoupled clouds still show a slightly enhanced fraction of ice-containing clouds, e.g., compared to clouds observed above Leipzig. The origin of such highly active INP needed for such an effect is still under discussion in literature. Wex et al. (2019) found the largest INPC in the Arctic in summer with
15 INP being active for temperatures up to -5°C. Hartmann et al. (2020) suggested these INP may be of biogenic origin from local marine sources such open leads or polynyas. In an attempt to narrow down possible sources for marine INP in the Arctic, Ickes et al. (2020) compared the ice nucleation ability of Arctic sea surface micro layer samples and two different predominant Arctic phytoplankton species. Even though these samples showed ice nucleating activity already under moderate supercooling conditions, no clear evidence was found that they may serve as local marine INP source.
20 To examine potential enhancement of aerosol effects on the surface-coupled clouds, we performed a lidar-based aerosol analysis for PS106. Figure 6 (a) shows profiles of the particle backscatter coefficient at 532 nm wavelength for 8 different time periods adjacent to cloud observations, when Polly$^{\mathrm{XT}}$ was able to probe cloud free air masses. The y-axis was normalized to the respective decoupling height of each individual profile. A reduction in β above the decoupling height can be seen. Following
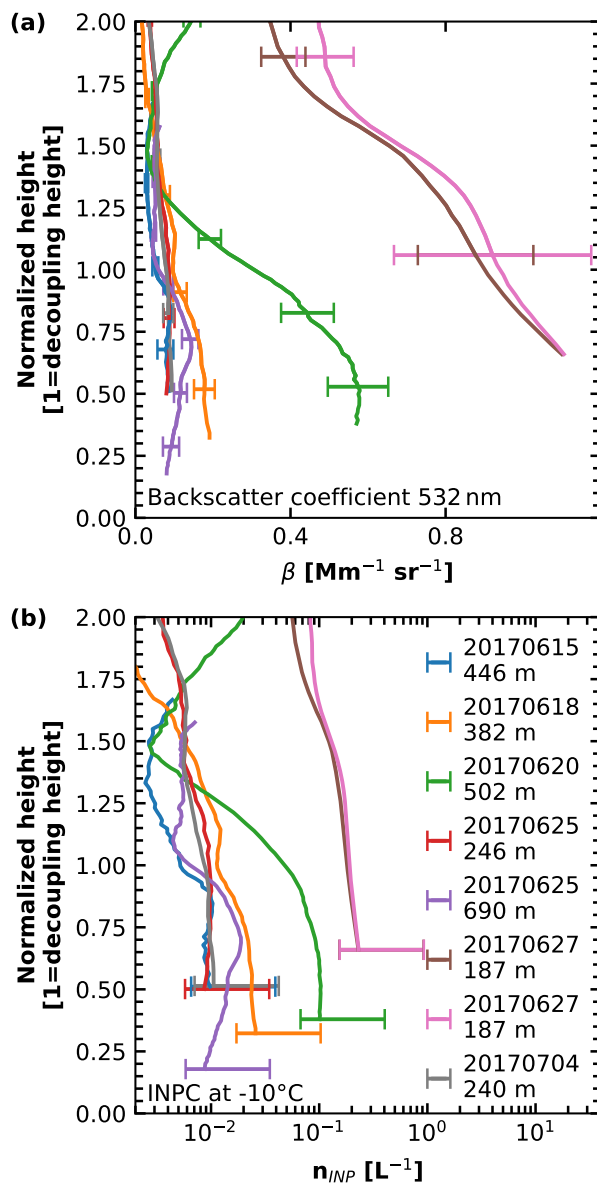
Figure 6. (a) Profiles of particle backscatter coefficient at 532 nm from Polly$^{\mathrm{XT}}$ and (b) the derived estimate of INPC. The date of the corresponding profiles is given in (b) together with the respective deoupling height.

the procedure presented in Sec. 2.2, Fig 6 (b) presents the INPC derived from the β profiles for biogenic sources at -10°. Similar as for β, higher values below than above the decoupling height have been found for the INPC for all six cases.

5 Summary & Conclusions

In this study differences in the fraction of ice-containing clouds for surface-coupled and decoupled clouds were investigated. In order to do so, lidar, cloud radar, and radiosonde observations from the RV Polarstern cruise PS106 around Svalbard in the Arctic summer 2017 were analyzed. Beside cloud-top temperature, the data show a significant dependence from the liquid layer base height and coupling state of the cloud on the probability of ice formation. Figure 4 compares the fraction of ice-containing clouds for different cloud-top temperatures for coupled and decoupled clouds. Strongest differences have been found at cloud-top temperatures slightly below freezing. Above -15°C coupled clouds contain ice more frequent by a factor of up to 5. Furthermore, the number of analyzed data is largest in this range, which underlines the significance of this statement.

In the frame of our study, we examined the potential reasons for the surface-coupling effects by means of a literature survey. However, seeding from higher ice clouds, as well as from blown snow or ice fog can be ruled out for the analyzed observation period. As a most likely explanation we found that the larger reservoir of marine ice nucleating particles in the surface-coupled marine boundary layer leads to higher freezing efficiency in the clouds which have at least their base in that layer. This conclusion is corroborated by recent in-situ based studies of the INPC which took place in close vicinity to open water surfaces in the marine Arctic boundary layer. Future studies hence should focus on the linkage between types of aerosols raised to the clouds and the fraction of ice-containing clouds in order to prove the statement. It could also be worth investigating different Arctic and Antarctic cloud datasets with respect to their distance from the marginal ice zone, open leads and polynyas. If indeed INP from marine origin control heterogeneous ice formation that strongly, a decrease of this effect with increasing distance from open water should be detectable. For a better understanding of the phenomenon also measurements in different seasons and regions of the Earth should be done to get knowledge if this effect is only characteristic for the Arctic summer.

Data availability. The lidar measurements are available by Griesche et al. (2019), the cloud radar measurements by Griesche et al. (2020). The radiosonde data is available by Schmithüsen (2017a) (PS106.1) and Schmithüsen (2017b) (PS106.2).

Author contributions. HG and KO conducted the ice-containing cloud analysis under supervision of PS. HG performed the lidar analysis under supervision of AA, PS and RE. HG, KO and PS prepared the manuscript. HG finalized the manuscript under supervision of AA, KO and PS.

Competing interests. The authors declare that they have no conflict of interest.

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