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Geophysical Research Letters

RESEARCH LETTER
10.1029/2022GL098207

Strong Ocean/Sea-Ice Contrasts Observed in Satellite-Derived Ice Crystal Number Concentrations in Arctic Ice Boundary-Layer Clouds

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Key Points:

- New ice microphysics from active satellite instruments enable large-scale analysis of Arctic boundary-layer clouds
- Ice crystal numbers are enhanced over sea ice compared to open ocean at temperatures above −10°C
- This difference is most pronounced in clouds south of 70°N through all the temperature range

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Papakonstantinou-Presvelou, I., Sourdeval, O., & Quaas, J. (2022). Strong ocean/sea-ice contrasts observed in satellite-derived ice crystal number concentrations in Arctic ice boundary-layer clouds. *Geophysical Research Letters*, *49*, e2022GL098207. https://doi.org/10.1029/2022GL098207

Received 4 FEB 2022
Accepted 21 JUN 2022

Abstract The Arctic climate changes at a faster rate than the rest of the globe. Boundary-layer clouds may play an important role in this change. At temperatures below 0°C, mixed-phase clouds exist and their phase and longevity is influenced by the abundance of ice crystals, which in turn is a function of aerosols serving as ice nucleating particles (INPs). Previous in situ studies suggested a local source of INPs due to biological activity over open ocean. Here we investigate ice crystal concentrations in clouds below 2 km at a large scale, by exploiting a newly developed data set—DARDAR-Nice—retrieved from active satellite remote sensing. The data set spans from 2006 to 2016. Contrary to previous expectation, we find that at a given latitude and temperature, there are more ice crystals over sea ice than over open ocean. This enhancement is particularly found in clouds south of 70°N, and also at temperatures between 0°C and −10°C.

Plain Language Summary The Arctic region is particularly affected by climate change, its warming is 2–3 times larger than global average during recent decades. One of the contributors to this "Arctic Amplification" may be the Arctic clouds and in particular the mixed phase type, where ice and supercooled liquid coexist at temperatures lower than 0°C. Aerosols play a significant role in cloud formation, since without the presence of some effective particles, the ice crystals could not form at all at temperatures between 0°C and roughly −40°C. In this study, we use a new satellite data set which provides an important cloud quantity, the amount of ice crystals in the clouds. Although this data set is limited to pure ice clouds, it can prove useful for understanding the behavior of Arctic clouds. What we find here is that Arctic low-level clouds show larger quantities of ice crystals over sea ice than over ocean and we think that this can be attributed to the amount and type of aerosols related to each surface. This finding contradicts a previous hypothesis, which stated that more ice crystals would possibly form over ocean because of the presence of highly ice effective aerosols there.

1. Introduction

Clouds constitute an important component of the climate system, since they influence both the radiative budget and the atmospheric water balance (Stephens, 2005), that is, the energy and water cycles. Cloud formation is inherently connected to the presence of aerosols. In particular, cloud droplets and ice crystals form on aerosols that serve as cloud condensation nuclei (CCN) and ice nucleating particles (INPs), respectively. As a consequence, anthropogenic aerosol emissions exert an effective climate forcing due to aerosol-cloud interactions, contributing one of the largest uncertainties in our knowledge of anthropogenic climate change (Boucher et al., 2013; Forster et al., 2021; Szopa et al., 2021).

In the present study, we are especially interested in clouds forming in the Arctic region and their relation to INPs as potentially emitted from surface sources. Arctic clouds are involved in a complex interplay of processes and feedbacks and play a role in the enhanced Arctic warming (Pithan & Mauritsen, 2014). This warming, about 2–3 times stronger than the rest of the world, is commonly referred to as Arctic Amplification (Serreze & Barry, 2011; Wendisch et al., 2017). Although much effort has already been invested during the previous decades, aiming to disentangle the causes of this phenomenon, its main contributions are not yet fully understood. As a result, more studies toward this direction are needed, to fill the knowledge gaps in our perspective of the complex Arctic climate system. Here we consider the idea that Arctic boundary layer clouds may change their radiative impact over time due to the influence of aerosol. Specifically, there are hypotheses that local sources of INPs in the Arctic may change due to the global increase in atmospheric temperature and the corollary sea ice retreat, which will lead to increased aerosol emissions from the exposed ocean surfaces (Browse et al., 2014; Gilgen et al., 2018).

Several studies in the past have investigated ice clouds and the factors determining ice crystal formation. At very cold temperatures, below −38°C, ice crystals are formed either homogeneously by the spontaneous freezing of haze particles or supercooled droplets, or heterogeneously with the aid of solid aerosols, so called INPs (Heymsfield et al., 2017). Homogeneous nucleation is effective at high atmospheric supersaturation and is the main mechanism in this temperature regime (Kanji et al., 2017). At warmer temperatures, above −38°C, homogeneous nucleation is not possible anymore and ice can only form heterogeneously on ice-active aerosols. These aerosols are very important for the formation and lifetime of ice-containing clouds in the regime where without INPs present, supercooled liquid clouds would exist. Such mixed-phase clouds are prevalent in the Arctic boundary layer (de Boer et al., 2009; Morrison et al., 2012; Shupe, 2011; Shupe et al., 2006).

Depending on the temperature, different types of INPs are able to nucleate ice. According to Hoose and Möhler (2012), mineral dust is an important source of ice nuclei at lower temperatures, while some bioaerosols are highly effective in forming ice at relatively warm temperatures (roughly above −10°C). Biological INPs can be for example, bacteria, fungi, pollen, lichen, viruses, phytoplankton or diatoms (Kanji et al., 2017), but also thawing permafrost has been recently found to be a potential source of biological INPs (Creamean et al., 2020). Moreover, it has been suggested by previous studies that a marine source of INPs can be associated with sea spray (DeMott et al., 2016) and is able to determine the ice nuclei concentrations in remote environments (Burrows et al., 2013; Wilson et al., 2015). In addition, McCluskey et al. (2017, 2018) linked sea spray aerosols in remote oceanic environments to organic material and suggested biological aerosols as important contributors to INP populations in these regions.

In the Arctic several measurement campaigns have taken place that included measurements of INPs. A source of highly ice-active INPs in Arctic water surfaces has been previously reported (Irish et al., 2017, 2019; Wilson et al., 2015). Creamean et al. (2018) performed measurements during spring 2017 in an Arctic oilfield location and found high concentrations of INPs efficient at or above −15°C. Wex et al. (2019) using ground-based filter samples, also observed INPs which can nucleate ice at temperatures as warm as −5°C during the Arctic summer. The authors hinted at a potentially biogenic nature of INPs, although no explicit source was identified in this study. Hartmann et al. (2020) using airborne samples, found INPs with similar onset freezing temperatures, which originated from the Arctic winter marine boundary layer. Following on, Hartmann et al. (2021) found a correlation between Arctic INP populations in the sea surface microlayer and the air, suggesting a local biogenic marine source as the likely origin.

Some of the aforementioned studies suggest the presence of marine aerosols in the Arctic, originating from the open ocean, that are particularly effective as INPs. However, the Arctic Ocean does not consist of an open water surface only, but it contains a large part of frozen surface (sea ice), the extent of which is highly variable. Other studies connect the sea ice covered ocean and its variability to sources of INPs. Irish et al. (2017) studied INPs in the sea surface microlayer and bulk seawater and found a strong negative correlation between salinity and freezing temperatures, suggesting that in areas subject to sea ice melting (less saline waters), the temperatures allowing cloud droplets to freeze are higher and thus more INPs can be present. According to Zeppenfeld et al. (2019) the sea surface microlayer of the marginal ice zone and that of melt ponds is indicative of high ice nucleating activity. In addition, other microorganisms such as ice algal aggregates or sea ice diatoms, which can accumulate in and below the sea ice and melt ponds and float into the water during the melting season (Assmy et al., 2013; Boetius et al., 2015; Fernández-Méndez et al., 2014) may also play an important role as INPs. As a result, even though there are clues on the marine origin of INPs, it is not yet quite clear whether they originate entirely from the open ocean or they are also connected to sea ice melting processes. Here we consider the hypothesis that ice-effective marine INPs coming from the open ocean may have an impact on the ice microphysics of Arctic clouds.

Although the presence of INPs is critical to cloud ice formation, it is not the only factor determining the ice crystal number in clouds. The atmospheric conditions also play an important role in transferring the particles into the cloud layer. There are several studies in the Arctic dealing with coupling conditions of clouds (Gierens et al., 2020; Griesche et al., 2021; Sotiropoulou et al., 2014) and turbulence (Egerer et al., 2021). Gierens et al. (2020) studied Arctic mixed-phase clouds and concluded that surface coupling is an important factor for their persistence and properties. Griesche et al. (2021) investigated Arctic clouds with regard to coupling conditions and found that more ice particles are detected in coupled clouds at warm temperatures, suggesting a surface source of INPs which can be mixed into the cloud when the boundary layer is coupled. Thus, given the potential

influence that the boundary layer state indirectly has on cloud nucleation, we decided to investigate also this aspect during this study.

A main question arising is whether such results from campaigns are valid at a large scale, that is, whether one can find a widespread impact on the microphysical structure of Arctic clouds. Such a large-scale analysis is now possible thanks to a new data set of satellite-retrieved ice crystal number concentrations (N_i) (Section 2.1; Sourdeval et al., 2018), a key measure to link ice clouds to their aerosol environment. In this study, we are exploring the N_i in Arctic ice clouds over open ocean in comparison to sea ice, for the time-period 2006–2016. We are focusing on the temperature range where INPs are important (heterogeneous nucleation regime; 0°C until −38°C) and at the lower part of the troposphere, in order to emphasize the relation to the surface aerosols. What is more, we are examining the atmospheric conditions that favor the transfer of surface aerosols to the base of the clouds to reduce uncertainty. Our goal is to provide some insight on the large-scale picture of boundary-layer ice clouds in the Arctic and the possible connection to the aerosols there.

2. Data

2.1. DARDAR-Nice

DARDAR-Nice is a data set retrieving ice crystal number concentrations (N_i) and was based on the radar/lidar (DARDAR) algorithm developed by Delanoë and Hogan (2010). It combines lidar and radar information to extract the particle size distributions of ice crystals. Based on DARDAR, Sourdeval et al. (2018) created a number concentrations retrieval product. Lidar measurements originate from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP; Winker et al., 2003) on-board CALIPSO satellite, while radar measurements come from the Cloud Profiling Radar (CPR; Stephens et al., 2018) on-board CloudSat. It should be noted that since 2011, CPR has operated in a daylight-only operations mode, affecting some cloud retrieval properties, such as snowfall (Milani & Wood, 2021). The data are provided with a 1.7 km footprint and a vertical resolution of 60 m. This product has been thoroughly evaluated against recent in-situ measurements in Krämer et al. (2020) and Sourdeval et al. (2018) and was further used to investigate the controls on the N_i by Gryspeerdt et al. (2018).

For the purpose of this study we used Level-2 (L2) data, starting from June 2006 until the end of 2016. The data provide ice crystal number concentration profiles along the satellite's track, but also thermodynamic variables, for example, temperature and pressure. These profiles originate from the ECMWF-AUX data set, which contains ECMWF state variables interpolated into each CPR's vertical bin (Delanoë & Hogan, 2010). The data concern either pure ice clouds or mixed-phase, where ice is mixed with or below supercooled liquid water droplets. The data also offer some information on precipitation, which we did not take into account during this study. It should be noted that mixed-phase conditions, occurring mostly between 0°C and −40°C, are considered to be less trustworthy and should be handled with great attention when it comes to interpretation (Sourdeval et al., 2018), because the lidar signal is quickly extinguished by liquid droplets and microphysical assumptions in the algorithm do not properly treat such mixtures. DARDAR-Nice reports ice crystal numbers by integrating the size distribution starting from two different lower cut-off sizes, distinguishing those that are larger than 5 and 100 μm (here denoted as $N_{i,5\mu m}$ and $N_{i,100\mu m}$), respectively. A larger cut-off size leads to a more reliable retrieval, but fails to account for a large fraction of ice crystals in an air volume (Sourdeval et al., 2018). In order to relate the number concentrations of ice crystals to the underlying surface, another satellite data set which retrieves sea ice concentration was necessary, which will be further discussed in the next section.

2.2. AMSR-E/AMSR2 Sea Ice Concentration

The Arctic region comprises, beyond land and open ocean, a large portion of sea ice covered surface. The sea ice itself is a variable quantity, being subject to seasonal and inter-annual changes, and depending on its thickness and position it can impact the Arctic radiative balance and Arctic environment, for example, the water vapor and clouds (Wendisch et al., 2017). Here we make use of the product developed by the Institute of Environmental Physics (IUP) of the University of Bremen, which retrieves sea ice concentration on a daily basis for the Arctic region (Melsheimer & Spreen, 2019, 2020).

This data set was based on the application of the ARTIST Sea Ice Algorithm (ASI; Spreen et al., 2008) on microwave radiometer data. It has a resolution of 6.25 km on a north polar stereographic grid and its time period overlaps

with that of DARDAR-Nice. The data were obtained from two instruments; the AMSR-E (Advanced Microwave Scanning Radiometer for EOS) and its successor AMSR2. According to Melsheimer and Spreen (2019, 2020), despite the change of the measuring instrument in 2011–2012, all data have been processed in the exact same settings.

3. Method

3.1. Constraint of Clouds

In our analysis we are interested in ice clouds with tops below 2 km in order to account for low-level boundary layer clouds. This limit could be further expanded to a higher one, for example, 3 km, but we found that the result is not sensitive to this increase of sample size (not shown). When referring to ice clouds here, we mean ice crystals that were retrieved inside cloud layers, identified as consisting purely of ice by the DARDAR algorithm. The definition of an ice layer we use is the same as in DARDAR-Nice, namely a certain profile of number concentrations that is vertically separated by another one by at least 480 m. Ice coexisting with supercooled water or lying below it (denoted as mixed-phase in DARDAR-Nice) was excluded from our analysis, due to high uncertainty of those retrievals (Sourdeval et al., 2018). In addition, a limitation exists at the lower part of the atmosphere due to the CloudSat radar's blind zone between 1.2 km and the ground surface (Maahn et al., 2014). As a consequence, we use retrievals that are only constrained by the lidar instrument below this height.

The focus of this study is on the ice phase of clouds and in particular on the heterogeneous nucleation regime, where the ice formation requires the presence of INPs in the atmosphere to form onto (above −38°C). For this reason, we classified the ice crystal numbers into four distinct subfreezing temperature classes of 10°C each. In this temperature range however, the N_i retrievals have to be carefully interpreted, due to the assumption of a monomodal particle size distribution in small ice crystals (Sourdeval et al., 2018). In order to avoid sedimentation of ice crystals from higher levels of the cloud or even another higher cloud, our analysis contains only single-layer clouds. In this way, we aim to limit ice formation processes such as secondary ice production (Field et al., 2017; Korolev & Leisner, 2020; Yano & Phillips, 2011) or seeder-feeder processes. Moreover, following Gryspeerdt et al. (2018) we selected only the top layers of cloud profiles, defined as the upper 120 m of a certain profile, to avoid issues with ice crystals falling from above.

3.2. Coupling/Decoupling

If there is an aerosol emission source at the surface, it is not certain to which degree some of the aerosols will eventually reach the cloud to nucleate ice. Atmospheric conditions, and especially the stability of the atmospheric layer below the cloud, play a large role on the transfer of aerosols to the cloud base. A useful measure to determine the stability conditions is the potential temperature θ (Gierens et al., 2020; Griesche et al., 2021; Sotiropoulou et al., 2014). For its derivation we used the temperature and pressure information from the ECMWF-AUX data, included in the DARDAR-Nice data set.

For each profile we determined a stability index, which in turn was used to categorize clouds in coupled and decoupled cases. The index was calculated using a rather simple approach, as the θ-difference between the cloud base and the ground surface (Goren et al., 2018). According to Tjernström et al. (2021), the model used for the reanalysis from which we take the temperature profiles shows a warm bias close to the surface and a cold bias close to 2 km. This means a seemingly steeper lapse rate than in reality, and as a result more decoupled clouds would be misidentified as coupled ones, while some coupled clouds could not be identified at all. In addition, Sotiropoulou et al. (2016) reported a likely underestimation of decoupled clouds in the ECMWF forecast model. As a consequence, we set a limit of 0.1 K to limit the coupled cases and −0.5 K to account for interpolation errors in the thermodynamic variables. Where this difference was less than 0.1 K, then turbulence and vertical mixing are present in the boundary layer, leading to coupling between the cloud and the surface. On the other hand, where the difference was greater than 0.1 K, the boundary layer is characterized by stability, the vertical motions are suppressed and the cloud is decoupled from the surface.

3.3. Analysis of the N_i

Different kinds of aerosols are emitted into the atmosphere, depending on the surface type (e.g., land, ocean). For this reason, we distinguished the ice crystal numbers with respect to the underlying surface. Two main surface types are discussed; sea ice and open ocean. Clouds occurring over land are not studied here. By sea ice we mean the area where sea ice concentration exceeds 80%, a limit which corresponds to the definition by the World Meteorological Organization as "close ice" (JCOMM Expert Team on Sea Ice, 2014), while open ocean refers to the completely ice-free area, namely where sea ice concentration equals to zero. Since the datasets used here were neither in the same spatial nor temporal resolution, it was necessary to perform spatial interpolation and time-averaging of N_i, to correspond with the AMSRE/2 resolutions. In particular, the satellite swath footprints from DARDAR-Nice were aggregated into the AMSRE (6.25 km) grid and daily averages were calculated for the cases of more than one overpasses during the same day.

The daily ice crystal concentrations related to each surface, were further analyzed in terms of seasonality and regionality. The Arctic was divided into five equal parallel zones (per 5°) north of 60°N. It is important to note here, that the geographical area covered by each zone decreases with latitude. In addition, the region from 80°N northward only covers the latitudes up to around 82°N, due to the maximum possible latitude the satellite can reach in the polar regions. The time-period was sliced into two main seasons; cold (boreal winter, autumn) and warm (boreal spring, summer). This particular choice of seasons was made after examining each season separately (especially winter and summer) and when taking into account the seasonal cycle of sea ice melting (approximately from April until September) to make sure that the results are not impacted by this season aggregation. The result (not shown) was that where sufficient data were available, the conclusions remained the same. However, for a more narrow definition of the summer season, not enough data at low temperatures was available.

From the daily N_i distributions, we determined the medians and their 95% confidence intervals. The confidence intervals were calculated using a nonparametric bootstrapping technique by using random resampling with replacement. Since we aim at a comparison of the mean behavior of the ice crystals over sea ice and ocean, in the following sections we present and discuss only the medians along with their confidence intervals, rather than the full N_i distributions. According to DARDAR-Nice, clouds consisting purely of ice account approximately for the 36% of below 2 km single-layer clouds over water surfaces (ice and ocean) in the cold season and 27% in the warm season.

4. Results

The results of the analysis are shown in Figure 1. As documented earlier, albeit with a focus on high-altitude clouds (Sourdeval et al., 2018), N_i is increasing as temperature decreases. The absolute numbers vary from $\mathcal{O}(1\,\mathrm{L}^{-1})$ above temperatures of −10°C to $\mathcal{O}(10\,\mathrm{L}^{-1})$. The concentrations within given temperature classes do not change very much with latitude.

Figure 1 depicts ice crystal numbers over sea ice and open ocean. A larger concentration of ice crystals ($N_{i,5\mu m}$) over sea ice is observed in the lower latitudes of the Arctic (60°N–70°N), forming a positive difference between sea ice and ocean in both seasons (cold & warm). This difference tends to increase with decreasing temperature during the warm season. A higher concentration over sea ice is not always observed at higher latitudes (north of 70°N). In warm temperatures (0°C to −10°C) larger $N_{i,5\mu m}$ still persist over sea ice, but these differences become smaller or even close to zero as the temperature drops and even sometimes a positive difference over ocean is formed.

Clouds separated based on coupling conditions are given in the Supporting Information. Coupled clouds (see Figure S1 in Supporting Information S1) show higher concentrations than in Figure 1 over both surfaces at all latitudes and almost all temperature bins (with some exceptions below −20°C that are about equal). Also, the differences between sea ice and ocean are higher for coupled clouds as compared to Figure 1 at latitudes lower than 70°N. Decoupled clouds (see Figure S2 in Supporting Information S1) show mostly lower concentrations over both surfaces than in Figure 1, except for some cases which are equal at high latitudes.

Larger ice crystals, with a minimum size of 100 μm($N_{i,100\mu m}$), have a similar behavior to that presented in Figure 1 (not shown). However, the concentrations of large ice crystals are—as expected—much lower. Furthermore,

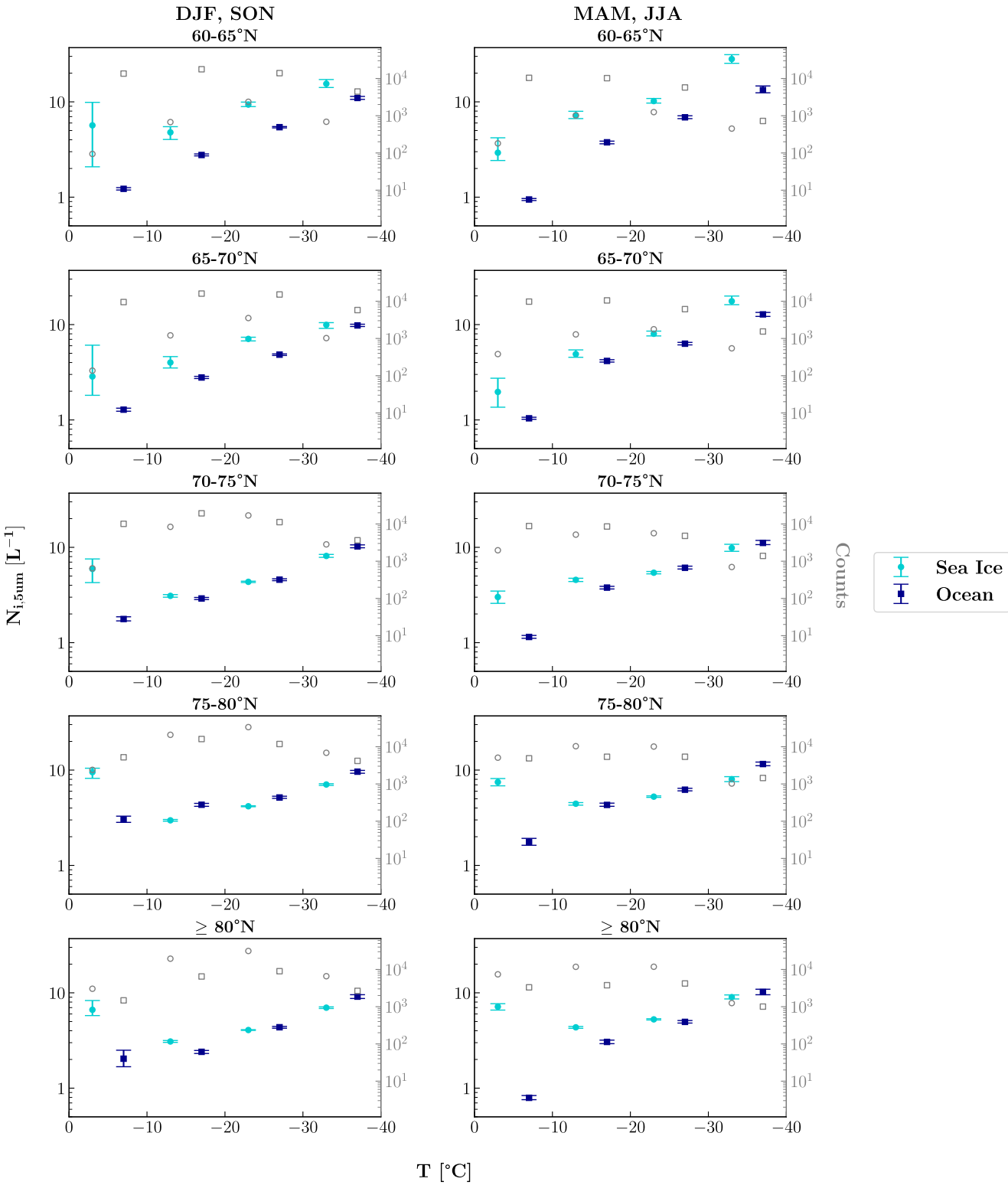

Figure 1. Medians of distributions of daily number concentrations of ice crystals that are larger than 5 μm (in L^{-1}; left *y*-axis) as a function of temperature for the time period 2006–2016. The temperature scale (*x*-axis) is not continuous; it comprises distinct temperature bins of 10°C each. The temperature offset between each consecutive point is artificial and introduced only for readability of the plot. Different colors indicate the surfaces over which these clouds exist; sea ice (in turquoise) and open ocean (in blue). Two different seasons are presented (cold: DJF, SON and warm: MAM, JJA) and five geographical regions (latitude belts). The 95% confidence intervals are displayed as the error bars. The numbers of samples used to calculate the medians are shown in gray (right *y*-axis).

DARDAR-Nice detected also, except for the pure mixed-phase cloud layers, some cases of ice with supercooled water existing lower into the same cloud layer. Even though the typical structure of clouds in the Arctic consists of a supercooled liquid top with ice below, we decided to investigate the impact to our analysis by additionally incorporating those cases, without using the actual mixed-phase layers. The main outcome didn't change very much (not shown). However, a distinction from what was presented above can be spotted at warmer temperatures (above −10°C), where the differences between N_i over sea ice and ocean are quite smaller, that is, of the order of 0.1 L^{-1}.

5. Discussion and Conclusion

Ice nucleating particles, being the seed of the ice phase between 0°C and roughly −40°C, are one of the factors controlling the ice crystal number in clouds. INP numbers are relatively low, albeit with a strong variability (10^{-6} to 10^{-1} L^{-1}) at warm temperatures (above −10°C), while increasing between −10°C and −25°C (10^{-5} to 10^{2} L^{-1}) and especially below −25°C (10–10^{3} L^{-1}) (Petters & Wright, 2015). Hartmann et al. (2020, 2021) and Wex et al. (2019) report similar or lower numbers from measurements in the Arctic.

The DARDAR-Nice ice crystal concentrations analyzed here are of the order of 1 L^{-1} at temperatures between 0°C and −10°C, at or above the upper limit of the range of in situ measurements for INPs. In contrast, the number concentrations are comparable with in situ measurements between −20°C and −25°C. In colder temperatures (below −30°C) the values for N_i retrieved by DARDAR-Nice are even lower than the range of observed INPs.

Our analysis shows surprisingly a tendency of more ice crystals over the sea ice than over the ocean, contradicting our previous expectation. This is seen quite consistently at warmer temperatures, independently of the season, region and coupling conditions, but it is particularly visible in the low latitudes of the Arctic. These regions concern mostly coastal areas, close to the sea ice edge and land, where the sea ice varies greatly throughout the year and the INP sources can be diverse. Toward northern latitudes, long-range transport of aerosols could also play a role where the concentrations are similar, but this still cannot explain why the concentrations over sea ice appear higher at the warmer temperature range.

There are three main reasons we could suspect as probable causes for this difference:

1. local source of INPs over sea ice;
2. blowing of snow;
3. secondary ice production.

A local source of INPs could be related to the sea ice melting and refreezing processes. Melt ponds developing on sea ice can be responsible for the release of new particles into the atmosphere (Dall'Osto et al., 2017), with potentially high ice nucleating ability (Zeppenfeld et al., 2019). Such particles could contain biological/organic material that is considered as highly efficient INP. However, Held et al. (2011) measuring particle fluxes over ice/open leads within the Arctic, found that while there was a source from open leads it was insufficient to explain the observed changes in aerosol concentration. Also, these processes are bound mostly to the melt season and therefore they cannot explain the differences during the winter season. Frost flowers growing on top of young sea ice may also result in the production of aerosols. However, since frost flowers are highly saline structures, the aerosols emitted are mostly sea salt aerosols (Hara et al., 2017; Rankin et al., 2000; Rankin & Wolff, 2003; Xu et al., 2016), that are not efficient INPs.

Blowing snow from the ground has also been found to be responsible for seeding cold clouds (Geerts et al., 2011, 2015; Vali et al., 2012). At snow covered surfaces, such as the high latitudes, under strong wind and updraft conditions, ice fractures may be able to reach low-level clouds and facilitate the nucleation process (Yang & Yau, 2008). Nevertheless, blowing snow is usually effective up to 1 m from the ground (Schmidt, 1982) and most of these studies consider mountainous regions and orographic clouds, where this mechanism is more crucial. Also, this mechanism is possible only during winter when the surface is frozen and is limited to relatively high wind conditions.

Secondary ice production over sea ice, for example, ice break up due to collisions, could also play a role, in particular in low updraft variability and relatively warm temperature conditions (Sotiropoulou et al., 2020). However, secondary ice production requires liquid presence in the cloud. Our separate analysis (not shown)

including the layers that contain some supercooled liquid shows that when mixed-phase processes are present, the differences between ice crystal concentrations over sea ice and ocean are dampened at warm temperatures, which might mean that the secondary ice production is not so important in determining this difference. However, the data analysis alone does not allow to attribute the identified differences between sea ice and ocean presented above, calling for model studies that are planned for the future.

Even though these results give a first impression, from a large-scale perspective, of the ice crystal formation over different surfaces in the Arctic, there is still some uncertainty related to the cloud type studied here. This analysis is limited to boundary-layer ice clouds. The prevalent cloud type in the Arctic boundary layer are mixed-phase clouds with a supercooled liquid layer on top (Morrison et al., 2012; Shupe et al., 2006; Shupe & Intrieri, 2004). For such clouds N_i unfortunately cannot be studied even from the new active satellite remote sensing product. This restriction could lead to a potential source of bias, since ice clouds are possibly at the decaying stage of their evolution and occur under specific conditions. However, the pure ice clouds analyzed here account approximately for the 36% of single-layer clouds below 2 km over water surfaces in the cold season and 27% in the warm season. Another study by Grenier et al. (2009) which also studies thin ice clouds from CloudSat and CALIPSO during January 2007, reports cloud cover percentages for single-layer ice clouds that can reach from ∼30% over the Kara Sea to ∼55% over the Beaufort Sea. Therefore, the clouds consisting purely of ice are still instructive for the problem studied here.

Future observational and modeling studies are needed to corroborate the results presented here. However, our results suggest that in a warming world with retreating sea ice, boundary-layer clouds in the mixed-phase temperature regime will contain less ice crystals, with implications for local climate change.

Data Availability Statement

The DARDAR-Nice data used for the study of ice crystal number concentrations are available from the AERIS ICARE data center via https://doi.org/10.25326/09 and can be provided upon request (Sourdeval, Gryspeerdt, Krämer, Goren, Delanoë, Afchine, Hemmer & Quaas, 2018). The AMSR-E and AMSR2 ASI Sea Ice Concentration datasets used here to distinguish the Arctic surface conditions are publicly available through PANGAEA—Data Publisher for Earth & Environmental Science via https://doi.org/10.1594/PANGAEA.919777 and https://doi.org/10.1594/PANGAEA.898399, respectively, (Melsheimer & Spreen, 2019, 2020).

Acknowledgments
This work would not be possible without the valuable contributions by groups with different expertise. The authors thank Gunnar Spreen and Kristian Melsheimer, who provided them with the AMSRE/2 data set and for their guidance on its proper use. The authors also thank Linlu Mei, Matthew Shupe, and Ann Fridlind for productive discussions on aerosols and clouds in the Arctic. Special thanks to Sebastian Zeppenfeld for providing useful comments and feedback on the manuscript. The authors gratefully acknowledge the funding by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation)—Projektnummer 268020496—TRR 172, within the Transregional Collaborative Research Center "ArctiC Amplification: Climate Relevant Atmospheric and SurfaCe Processes, and Feedback Mechanisms (AC)3" and appreciate the support and contribution by the (AC)^3 community. The authors further acknowledge funding by the European Union via its Horizon 2020 project FORCeS (GA 821205). Open Access funding enabled and organized by Projekt DEAL.

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