Platelet Ice under Arctic Pack Ice in Winter

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- Extensive observation of platelet ice formation under Arctic winter sea ice
- Locally formed sub-ice platelet layer due to surface water mass supercooling and nucleation

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Abstract

The formation of platelet ice is well known to occur under Antarctic sea ice, where sub-ice platelet layers form from supercooled ice shelf water. In the Arctic however, platelet ice formation has not been extensively observed and its formation and morphology currently remain enigmatic. Here, we present the first comprehensive, long-term in situ observations of a decimeter thick sub-ice platelet layer under free-drifting pack ice of the Central Arctic in winter. Observations carried out with a remotely operated underwater vehicle (ROV) during the midwinter leg of the MOSAiC drift expedition, provide clear evidence of the growth of platelet ice layers from supercooled water present in the ocean mixed layer. This platelet formation takes place under all ice types present during the surveys. Oceanographic data from autonomous observing platforms lead us to the conclusion that platelet ice formation is a widespread but yet overlooked feature of Arctic winter sea ice growth.

Plain language summary

Platelet ice is a particular type of ice that consists of decimeter sized thin ice plates that grow and collect on the underside of sea ice. It is most often related to Antarctic ice shelves and forms from supercooled water with a temperature below the local freezing point. Here we present the first comprehensive observation of platelet ice formation in freely drifting pack ice in the Arctic in winter during the international drift expedition MOSAiC. We investigate its occurrence under the ice with a remotely controlled under-ice diving robot. Measurements of water temperature from automatic measurement devices distributed around the central MOSAiC ice floe show, that supercooled water and thus platelet ice occurs widely in the winter Arctic. This way of ice formation in the Arctic has been overlooked during the last century, as direct observations under winter sea ice were not available and platelet ice does not leave a clear trace in the crystal structure of Arctic ice.

1. Introduction

Platelet ice is a characteristic feature of Antarctic landfast sea ice, where supercooled ice shelf waters lead to the advection and growth of sub-ice platelet layers. They consist of loosely attached decimeter sized plate-shaped ice crystals [*Hoppmann et al.*, 2017; *Langhorne et al.*, 2015; *Smith et al.*, 2001] and can be up to several meters thick. These ice platelets form by nucleation in supercooled layers of seawater either at depth [*Dieckmann et al.*, 1986] or directly at the ice underside [*Leonard et al.*, 2006; *Mahoney et al.*, 2011] in the vicinity of large ice shelves, which provide supercooled water due to basal ice shelf melt in the water circulation of ice shelf cavities.

As ice shelves are much less common in the Arctic [*Dowdeswell and Jeffries*, 2017], observations of platelet ice in the Arctic are very rare and the processes causing its formation are poorly understood. The availability of supercooled water plays a central role for the growth of decimeter scale ice platelets [*Weeks and Ackley*, 1986]. *Jeffries et al.* [1995] presented one of the very few descriptions of platelet ice in the Arctic Ocean. Their study identified platelet ice crystals in 22 out of 57 ice cores collected in the Beaufort Sea during August and September 1992 and 1993. They suggest four different sources for supercooled water for the Arctic, two of which require the presence of ice shelves and coastal interactions and are therefore not relevant for the central Arctic Ocean. The other two include small scale “ice pump” mechanisms [*Lewis and Perkin*, 1986] and the interaction of summer meltwater with the underlying colder seawater, leading to the formation of false bottoms in under-ice melt ponds and platelet ice crystals [*Eicken*, 1994; *Martin and Kauffman*, 2006; *Notz et al.*, 2003]. *Jeffries et al.* [1995] describe platelet ice as a widespread feature in the Beaufort Sea based on their ice-core analysis. However, this is the only more detailed mention in the scientific literature. An observation from the Russian drifting stations also detected platelet ice formation caused by meltwater percolation through the summer ice cover (personal communication I. Sheikin) and an indirect observation under fast ice in summer was described by *Kirillov et al.* [2018].

Sub-ice platelet layers can be separated from more common frazil ice in such way that the geometric size of the platelet ice crystals is on the order of 1-10 cm, whereas frazil ice typically denotes the initial crystallization types in the water column during the first stages of sea-ice growth, when small disk and needle like crystals smaller than 1 cm appear on the ocean surface or float up from depth [*Weeks and Ackley*, 1986; *Zubov*, 1963]. Sub-ice platelet layers have a rather random orientation of crystal axes. This is significantly different from the skeletal layer at the bottom of growing sea ice, in which somewhat parallel oriented ice lamellae are growing into a microscale layer of constitutionally supercooled water caused by the brine expulsion during sea-water freezing [*Lofgren and Weeks*, 2017; *Rutter and Chalmers*, 1953; *Shokr and Sinha*, 2015].

No extensive direct in situ observations of platelet ice under Arctic sea ice particularly during winter are available. Anecdotal reports from divers, such as during the Tara expedition [*Ragobert et al.*, 2008] or the "Under the Pole" diving expedition [*Bardout et al.*, 2011], allude that this feature has been mostly overlooked in the Central Arctic.

Here, we present the first extensive, more systematic in situ observations of growing platelet ice layers under Arctic sea ice in winter. Dives with a remotely operated vehicle during the international Arctic drift expedition "Multidisciplinary Observatory for the Study of Arctic Climate" (MOSAiC) from January to March 2020 around 88°N (Figure 1) revealed a widespread coverage of large platelet ice crystals growing on and under the bottom of the ice.

2. Materials and Methods

2.1 Study Area

The ice floe of the MOSAiC drift experiment of the German research icebreaker Polarstern [*Knust*, 2017] consisted of a conglomerate of various ice types, out of which deformed second year ice and relatively level residual ice (first year ice grown into a remaining matrix of very rotten melted ice [*WMO*, 2014]) were the most abundant. Initial ice thicknesses during the mobilization of the drift station in the beginning of October 2019 were as little as 20-30 cm for the residual ice and around 60-80 cm for the undeformed second year ice [*Krumpen et al.*, 2020]. Ice growth until March had increased the level ice thickness to about 145 cm for the residual ice and around 200 cm for the second year ice (Figure S1). Pressure ridges with typical keel drafts of 5-7 m and maximum of 11 m characterized the deformed ice. More details about the composition and history of the MOSAiC floe can be found in *Krumpen et al.* [2020].

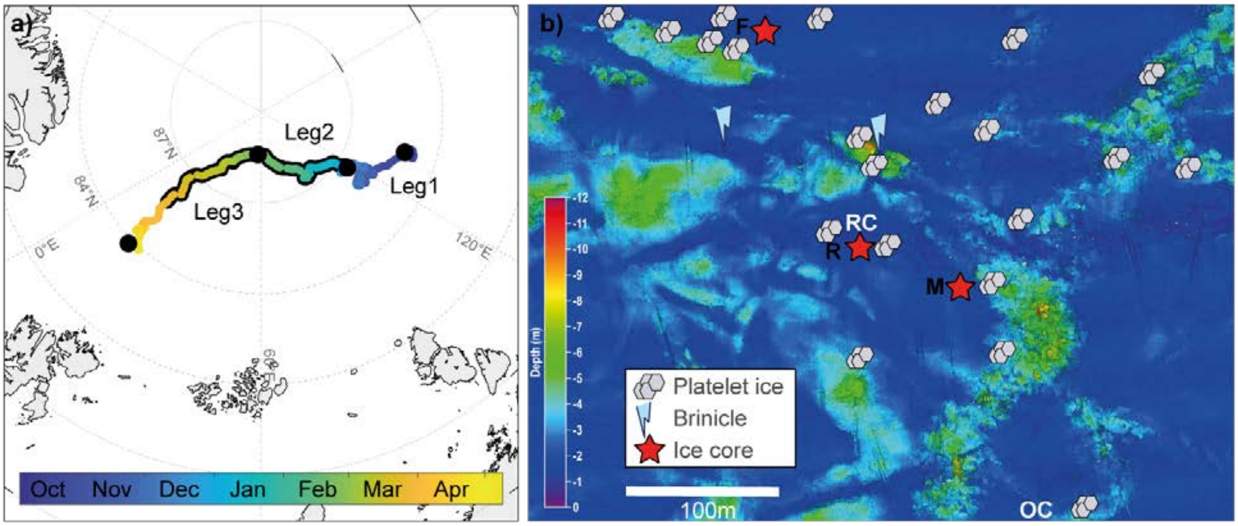

Figure 1. a) Drift track of MOSAiC floe in the Central Arctic Ocean from October 2019 to mid-May 2020. Black dots denote start and end of drift legs 1, 2 and 3, respectively. Platelet ice was observed during cruise leg 2 and 3 between 30 December 2019 and 28 March 2020 (black highlighted track). b) Map of ice draft derived from multibeam sonar with most prominent locations of platelet ice observations (grey symbols), brinicles (light blue symbols) and ice core samples (red stars). White letters indicate the position of the ROV access hole (RC) and the MSS deployment hole (OC). Black letters refer to ice cores taken at the ROV site (R), the ice mechanics site (M) and the ridge site (F).

2.2 ROV Operations

We carried out remotely operated vehicle (ROV) dives from a hole through the ice covered by a heated tent. The M500 ROV (Ocean Modules, Atvidaberg, Sweden) was equipped with a comprehensive sensor suite including cameras as well as a 240 kHz multibeam sonar [*Katlein et al.*, 2017] and provided an operating range of 300 m from the access hole. We documented platelet ice occurrences mostly with four cameras: a high definition zoom video camera (Surveyor HD, Teledyne Bowtech, Aberdeen, UK), two standard definition video cameras (L3C-720, Teledyne Bowtech, Aberdeen, UK) and a 12 megapixel still camera (Tiger Shark, Imenco AS, Haugesund, Norway).

The ROV dives covered many different sites, but several places were revisited (Figure 1b) due to repeating routine dive missions allowing for a temporal assessment of platelet ice evolution. On 15 February 2020, we towed an under-ice zooplankton net (ROVnet) with the ROV directly along the ice underside [*Wollenburg et al.*, 2019] to brush off platelet ice samples for structural analysis. In the lab, the platelets were frozen into a solid block of ice by adding sea water to the sample container, in order to later analyze the platelet ice crystal structure.

2.3 Ice Core Sampling and Analysis

We extracted ice cores in three locations (Figure 1b) where sub-ice platelet coverage had been previously confirmed by ROV imagery. We transported the ice cores into the lab on board Polarstern and then analyzed them for ice texture by preparing thin sections using the Double Microtoming Technique [*Eicken and Salganek*, 2010; *Shokr and Sinha*, 2015]. We photographed the thin sections between crossed polarizers to identify ice crystal geometric properties. To associate an approximate date of ice formation to each ice sample along the core, we used a simple ice-growth model based on the number of freezing-degree-days [*Peeken et al.*, 2018; *Pfirman et al.*, 2004], forced by the temperatures recorded by the Polarstern weather station during its drift.

2.4 Physical Oceanographic Measurements

We measured vertical and horizontal profiles of seawater conductivity, temperature, and pressure (CTD) using three independent different types of platforms. One CTD sensor was mounted on the ROV (GPCTD, SeaBird Scientific, USA), while we performed recurring deployments of a free-falling microstructure sonde (MSS 90LM, Sea and Sun Technologies, Trappenkamp, Germany) through a nearby hole in the ice (Figure 1b). In addition, several autonomous stations with CTD packages at a depth of 10 m (SBE37, SeaBird Scientific, USA) were operational in the MOSAiC distributed network at distances of 10-40 km from the central floe (Figure S2). All devices were calibrated by the manufacturers immediately before the expedition. To calculate seawater freezing temperature we applied TEOS-10 using the Gibbs Sea Water (GSW) oceanographic toolbox for MATLAB [*McDougall and Barker*, 2011].

3. Results and Discussion

3.1 Platelet Layer Morphology

We observed a 5 to 30 cm thick sub-ice platelet layer covering the ice bottom as shown in Figure 2. The ice platelets are composed of blade- or disc-shaped single ice crystals with c-axis alignment normal to the platelet surface. Most platelets were firmly attached to their substrate but very fragile to physical impact by the ROV. When observed on ropes or chains, platelet ice crystals were tightly grown through their structure (Figures 2b, S3) and not just loosely attached to the respective surface. This indicates that these platelets grew on site and have not been advected in from deeper waters or horizontally. Contrary to Antarctica, we did not find thicker layers of platelet ice accumulation [*Hoppmann et al.*, 2017; *Hunkeler et al.*, 2016], possibly due to slower platelet or faster congelation growth which allows the freezing front of the congelation ice to quickly progress downward into the platelet layer and incorporate it by congelation ice growth in between the platelet crystals [*Mahoney et al.*, 2011].

We identified crystal sizes up to 15 cm from the ROV camera footage. The maximum crystal size retrieved with the towed zooplankton net was about 9 cm, while platelet thicknesses ranged from 0.8-2.5 mm. However, due to the limited size of the sampling bottle with a diameter of 10 cm and the physical interaction of ROVnet and platelet ice structures, platelets may well have been broken during the sampling process.

Platelet ice growth depends on available crystallization nuclei. Probably due to this reason, we did not observe platelet growth on the polymer-covered thermistor strings hanging in the water column, but the complex structure of core-mantle polyamide rope or metal parts provided sufficient crystallization nuclei for platelet formation (Figures 2d, S3). This was particularly obvious also on 15 February 2020, when the ROV had been hanging for three days in 2 m water depth and was covered in up to 30 mm large platelet crystals on edges and corners, while particularly smooth plastic surfaces were unaffected by platelet growth (Figure S4).

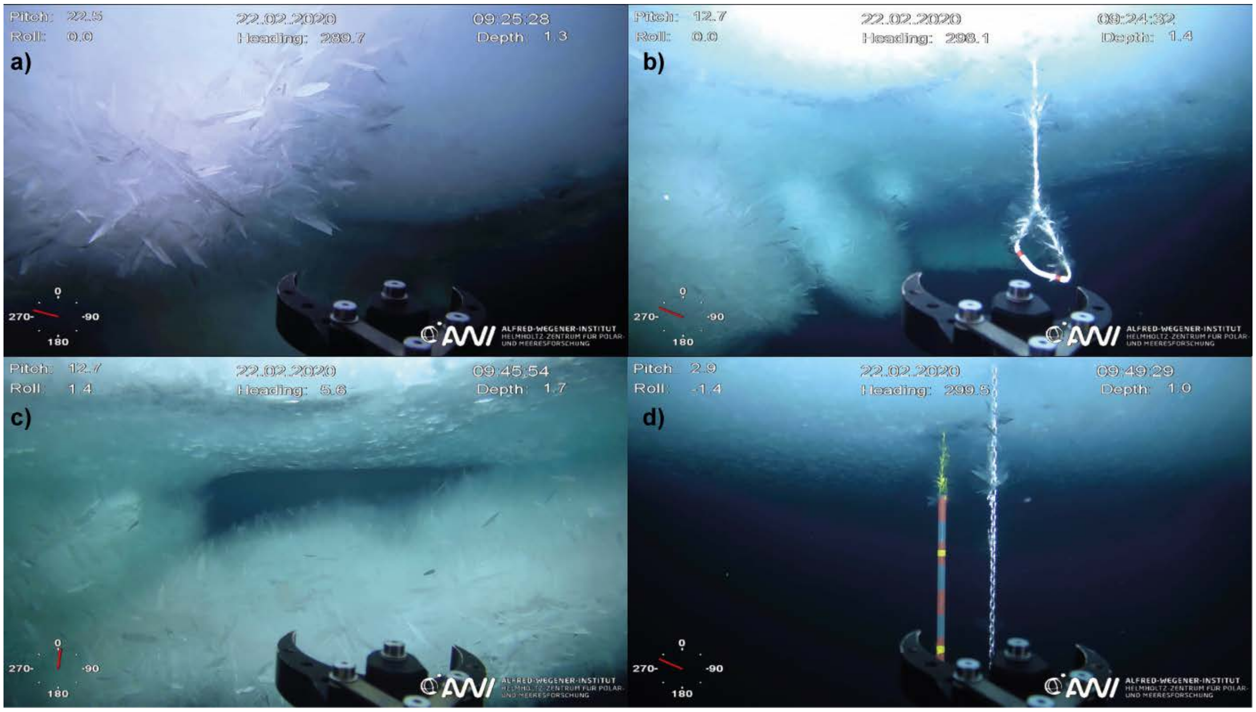

Figure 2. a) Close-up picture of platelet ice covering a ridge block. The ROV manipulator opening in the foreground is about 9 cm wide. b) Rope sling next to a pressure ridge: both, the rope and the ridge are vastly covered in ice platelets. c) Upward growing platelet ice in a ridge cavity. d) Platelet ice crystals covering the rope and chain of underwater installations. Note the lack of platelet growth on the plastic marker stick and the coverage of small platelet crystals underneath the level ice.

3.2 Spatial Distribution of Platelets

At first glance, platelet ice coverage seemed to be somewhat erratic, but with closer investigations it became apparent that platelet ice cover was ubiquitous in the entire observational range of the ROV. However, platelet ice growth was almost exclusively observed in the uppermost part of the water column, above a depth of 2-3 m. Deeper lying ridge keels, as well as deep hanging ropes and instrument installations were not found to be covered in platelet ice. Few installations exhibited a vertical gradient of platelet ice growth coverage, with the most extensive occurrence at the ice-water interface and diminishing platelet cover towards depth (Figure S5). Platelet crystals were largest (up to 15 cm) and most prominent on blocks, ridges, and edges protruding from the level ice, but at close inspection, we found also smaller scale platelet ice crystals (1-2 cm) throughout the bottom of level ice. Also these smaller platelets appeared different from ice lamellae expected in the skeletal layer. We identified no significant spatial difference in under-ice roughness (and thus platelet coverage) from acoustic backscatter derived from the multibeam sonar measurements (Figure S6).

While sheltered areas between ridge keels with low currents seemed to provide best conditions for platelet growth, we observed significant platelet growth of similar size also at locations that were completely exposed to the ice-relative currents (Figure S3). We found no direct link between platelet ice distribution and brine drainage features. Despite the occasional observation of brinicles – ice stalactites forming from the contact of descending, cold brine with seawater – we encountered them both with and without intense platelet ice cover (Figure S7).

3.3 Temporal Variability

During MOSAiC, the ROV diving schedule only allowed for a weekly cycle of repeated visits (Figure S8). Therefore, our information on the temporal variability of platelet ice occurrence is somewhat limited and less objective. However, we could identify clear differences in the amount of new platelet ice formation between different periods. These periods were characterized by excessive new crystal growth, the lack of such, or even a perceived reduction in platelet ice cover. These periods are identified in Figure 3 to investigate a link between different oceanographic conditions in the surrounding water and platelet ice formation. As the ROV sampling in the described location only started on 31 December 2019, we cannot provide a detailed assessment of the situation before. However, we observed no platelet ice during ROV dives before 6 December 2019 in a different location approximately 1 km away. We observed platelet ice for the last time during an ROV dive on 28 March 2020, after the floe had been affected by deformation and the return of sunlight. This coincides with the time, when water temperatures under the ice climbed above the local freezing point again (Figure 3c).

3.4 Supercooling

We found supercooled water, the basis for the formation of platelet ice, well below the ice-water interface, which we confirmed using three different independent measurement platforms. Temperature and salinity data from the ROV, a free-falling Microstructure Sonde (MSS), and several autonomously recording CTDs deployed at 10 m depth in 10-40 km distance from the ROV site all revealed water temperatures around 0.01-0.02 K below the respective seawater freezing point in the uppermost mixed layer (Figure 3a). This degree of supercooling is very similar to observations from the Antarctic [*Mahoney et al.*, 2011] and larger than the calibration uncertainty and uncertainties in the calculation of the local freezing point of seawater. Hence, we can confirm the existence of supercooled water several meters thick as prerequisite for platelet ice formation. Measurement uncertainties might however obscure the absolute magnitude and depth of water mass supercooling.

Within the mixed layer, the local seawater freezing point is pressure and therefore depth dependent while temperature and salinity values are approximately constant. Thus, the freezing-point departure increases towards the surface with a higher level of supercooling in the uppermost mixed layer right under the ice (Figure 3a,b). This can explain the observed decrease in platelet ice abundance below 2 m depth.

A simple hypothesis for platelet ice growth might thus be that water molecules attach to existing crystallization nuclei as soon as they are in a strong enough state of supercooling. Considering the turbulent nature of the mixed layer, where water particles get mixed up and down through the entire mixed layer at a time scale of 30 minutes [*Denman and Gargett*, 1983], they oscillate between supercooled and non-supercooled states. Thus, we hypothesize that platelet ice formation is only possible as soon as the temperature in the complete mixed layer lies below the vertically averaged seawater freezing point. This can be either achieved by excessive atmospheric cooling during the Arctic winter or due to a sudden shoaling of the mixed layer, cutting off mixing beyond a certain depth, so that suddenly most of the surface mixed layer has a temperature below the freezing point causing respective formation of platelet ice. Determining the exact nature of the processes involved in the temporally varying strength of platelet ice formation would require more targeted high temporal resolution investigations of platelet growth than could be accomplished during the rigid observational plan for MOSAiC.

However, time series of MSS and autonomous observations show that the detected levels of platelet ice were only apparent after a more temporally stable mixed layer with a depth of ~30 m had established in mid-December. Furthermore, the perceived decrease in platelet ice coverage observed in mid-February was likely linked to a passing eddy, decreasing the freezing-point departure in the upper mixed layer (Figure 3b).

Furthermore, observations of autonomous CTD sensors deployed in the distributed network at 10 to 40 km distance from the central MOSAiC floe (Figure S2) consistently show similar amounts of water mass supercooling (Figure 3c). This allows the conclusion that platelet ice formation under Arctic winter sea ice is not a local curiosity, but a widespread, overlooked feature in the Arctic Ocean.

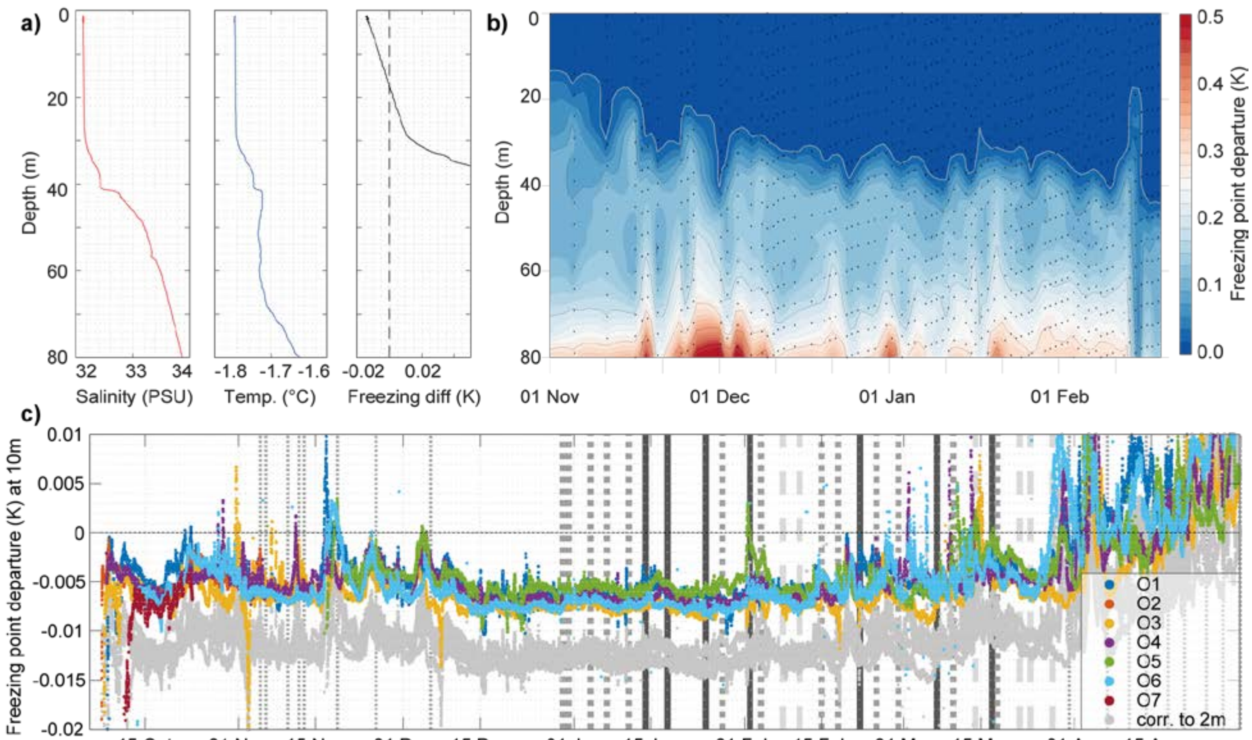

Figure 3. a) Salinity, temperature, and freezing point departure profile observed by the ROV on 22 February 2020. b) MSS time series of water temperature above the surface freezing point. Note the consistent deepening of the supercooled layer indicated in blue color. c) Time series of freezing-point departure measured in 10 m depth (and adjusted to 2 m depth in gray) from the autonomous observation stations. Vertical lines indicate platelet ice intensity observations classified as high (solid lines), normal (thick dotted lines) and low intensity (dashed lines) based on visual ROV observations. Thin dotted lines indicate ROV surveys without platelet ice observation. See supplemental figure S2 for geometric location of stations relative to the central observatory.

3.5 Persistence in Ice Core Analysis

Despite the ubiquitous occurrence of platelet ice shown in our study, there is a general lack of extensive signs of platelet ice formation in the texture of Arctic sea ice cores of the Transpolar Drift [*Tucker et al.*, 1999]. To investigate this lacking linkage, we retrieved ice cores at three locations (Figure 1b) where we had documented platelet ice beforehand with the ROV cameras. Strikingly, and in contrast to Antarctic landfast ice cores, none of the investigated ice core bottom thin sections (Figure S9) showed clear signs of incorporated platelet ice, despite the rapid congelation ice growth of 5-9 cm per week and the confirmed presence of platelets. In various places we found a few large, inclined crystals which could be interpreted as originating from platelet crystals, but none were as clear as reported in the existing literature also from the Antarctic platelet ice [*Jeffries et al.*, 1995; *Langhorne et al.*, 2015; *Leonard et al.*, 2006; *Smith et al.*, 2001].

To investigate this contradiction more closely, we analyzed the texture of the collected platelet crystals refrozen into seawater. The resulting texture (Figure S10) looks significantly different from the one described for freshwater-derived platelet ice by *Jeffries et al.* [1995]. In particular, platelet ice crystals seen from the side have a rectangular rather than triangular shape, and also many platelet crystals exhibit sub-grain boundaries which are described as absent in the work of *Jeffries et al.* [1995].

We thus have two hypotheses why these ubiquitous platelet ice crystals under Arctic winter sea ice do not seem to leave a strong record in the crystallographic texture of ice cores. First, despite their spectacular voluminous appearance, the ice platelets may actually only take up a small volume fraction, so that it is unlikely to observe multiple platelet crystals in a sub-millimeter thick ice core thin section. Second, the platelet crystals may serve as primary nucleation surfaces also for the congelation growth in a way that potentially recrystallizes platelet crystals and therefore obscures their initial origin. Both hypotheses could explain why such a widespread cover of under-ice platelet ice formation in the winter Arctic has been overlooked in the last decades of sea ice texture investigations. This is supported by the observation that moderate sub-ice platelet layers also do not necessarily leave a crystallographic record in Antarctic fast-ice [*Mahoney et al.*, 2011].

3.6 Physical, Ecological and Biogeochemical Implications

Does the presence of a thick supercooled surface layer and platelet ice strongly impact large scale energy fluxes and the thermodynamics of sea ice growth? Although these processes are not well included in numerical models of ice-ocean interaction, their integrated effects are probably well included indirectly in the respective energy flux and ice growth parametrizations. Explicit consideration will not strongly improve ice-ocean models. Considering large scale energy fluxes, platelet ice formation under Arctic sea ice in winter thus does probably not affect the thermodynamics of sea ice growth significantly. This is particularly due to the fact of Arctic platelet ice being a local seasonal phenomenon. In contrast, Antarctic platelet ice is often derived from water masses with spatially different origin and thus disrupting the local energy budget. Even though the impact may be small for ice-ocean physics, the porous, ragged structure of the platelet ice interface does affect the small scale roughness of the ice underside and will in particular affect the entrainment of water constituents, such as sediments, nutrients, or biological assemblages. One sample of sub-ice platelets retrieved with the towed ROVnet showed elevated levels of halocarbons compared to the general ice column, meaning this sub-ice platelet layer could play a role also in different biogeochemical cycles. Despite the assumed inactivity of the under-ice ecosystem during polar night, platelet ice might still serve as a substrate for algal growth and protection for under-ice macrofauna, as we observed amphipods maneuvering through the maze of crystal blades (Figure S11).

Platelet ice could also play a significant role in the poorly understood consolidation of voids e.g. in sea ice ridges, where it would be able to close large gaps faster than by pure congelation ice growth. This could explain why voids in ridge keels often appeared slushy when drilled through during MOSAiC (Figure S12).

4. Summary

During the polar night of the international drift expedition MOSAiC in 2019-2020, we observed a widespread coverage of the ice underside with a sub-ice platelet layer. These up to 15 cm large platelet ice crystals grew in situ from supercooled water of the uppermost mixed-layer, both on exposed ice features and level ice. This is the first comprehensive in situ observation of extended platelet ice formation during Arctic winter in the free-drifting ice of the Central Arctic.

Platelet ice formation has so far been overlooked as a widespread feature of ice growth during Arctic winter. Our study provides the first observational evidence for a link between platelet growth intensity, mixed layer stability and supercooling, but the detailed processes with respect to their seasonal impacts on ice-ocean interactions are yet to be understood. In particular, we were able to show that this sub-ice platelet layer does not leave a clear imprint on sea-ice texture and was thus easily overlooked in past ice core analyses (Figure S13). To improve our understanding of the involved processes, we suggest a more targeted investigation during future

Arctic winter campaigns with the goal to achieve higher temporal resolution and more objective observations of platelet crystal growth. This could be achieved by fixed underwater cameras in relation to water dynamics and thermodynamics in the mixed layer.

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