From Bright Windows to Dark Spots: The Evolution of Melt Pond Optical Properties during Refreezing

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Key Points:

- Thicker snow cover may develop on refrozen melt ponds compared to bare sea ice due to their recessed topography
- Light transmittance through melt ponds can be lower than through bare sea ice
- Reduced light transmittance impacts sea ice energy balance and growth and the distribution of under-ice algae

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Abstract

The evolution of melt ponds on Arctic sea ice has a large impact on the surface energy balance and the ice-associated ecosystem. Melt ponds are considered as bright windows to the ocean, because they transmit more solar radiation into the ocean than bare ice, also during freeze-up. Here we present results from under-ice radiation measurements close to the North Pole during summer 2018 using a remotely operated vehicle in combination with ice and snow measurements. Our results reveal that light transmittance of melt ponds is lower compared to bare ice once covered by the first snow. Results from a radiative transfer model suggest that refrozen melt ponds with a snow cover (> 0.04 m) lead to lower light transmittance than adjacent bare ice. This has implications on autumn ecosystem activity and thermodynamical ice growth, because it reduces the solar heat input to the Arctic Ocean in September by >50%.

Plain Language Summary

Arctic sea ice is covered with melt ponds during summer. These ponds control most of the sunlight and energy that enters the ice-ocean system. The light availability underneath Arctic sea ice with lots of melt ponds is usually much higher than underneath bare ice, also during autumn when the surface refreezes again. Using a robot operated underneath the sea ice close to the North Pole in summer 2018, we discovered a situation where less light was available beneath refrozen melt ponds. We found that the main reason for this opposing behavior is a thicker snow cover on the

refrozen pond surface compared to bare ice. This is a surprising finding, because it contradicts the established theory and how it is described in most computer models and theories. It has consequences for our understanding of the ice-associated ecosystem (organisms that live in and under sea ice). It also changes the mass and energy balance of central Arctic sea ice during summer-autumn transition when new sea ice starts forming.

1 Introduction

Melt ponds play a key role for the surface energy budget (Nicolaus et al., 2012) and the mass balance of sea ice (Flocco et al., 2015), as well as for the ice- and ocean-associated ecosystem (Arrigo, 2014). During summer, the areal fraction of melt ponds on Arctic first-year ice is up to 53% and 20-38% on multi-year ice (Webster et al., 2015; Nicolaus et al., 2012; Fetterer and Untersteiner, 1998). The fraction of the ponds has also been observed to increase (Schröder et al., 2014; Rösel and Kaleschke, 2012). The amount of radiation that is reflected back to the atmosphere is significantly reduced for melt ponds compared to bare ice (e.g., Nicolaus et al, 2012). Instead, a considerable amount of radiation is absorbed by and transmitted through melt ponds (e.g., Katlein et al., 2015; Nicolaus et al., 2012; Ehn et al., 2011; Light et al., 2008; 2015). Consequently, the ice underlying the melt ponds warms and can thin faster than bare ice (Flocco et al., 2015; Hanson, 1965; Untersteiner, 1961).

The translucent melt ponds are often considered as bright windows in Arctic sea ice, even during autumn when their surface refreezes. The formation and occurrence of under-ice phytoplankton blooms are highly dependent on snow and sea ice conditions and, thus, on the under-ice light field (Ardyna et al., 2020). An Arctic-wide increase in the occurrence of the blooms was partly explained by the increasing fraction of melt ponds (Horvat et al., 2017). Lee et al., 2015 showed that ice algal masses accumulate in and under refrozen melt ponds that favor higher light availability. They argue that algal accumulations in autumn can provide an important food source for higher trophic animals before and during winter.

Our study shows that the light availability under melt ponds can be less than under adjacent bare ice after snow fall starts in autumn. Using data collected in the Central Arctic close to the geographic North Pole during the transition from summer to autumn in 2018, we investigate the effect of snow accumulated on the refrozen melt ponds on the under-ice light availability. We compare two datasets that represent the summer and autumn conditions, which mainly consist of snow depth and ice thickness measurements, along with aerial images and under-ice transmittance data from a remotely operated vehicle (ROV). We apply a radiative transfer model to calculate an estimate for the snow accumulation threshold necessary for the light level to be lower under melt ponds compared to bare ice.

2 Materials and Methods

2.1 Study Site

The data presented in this study were collected during the Arctic Ocean 2018 MOCCHA – ACAS – ICE campaign (short: AO18) onboard the Swedish icebreaker *Oden*. During this campaign, a temporary ice camp was set up on drifting, ponded multi-year ice close to the geographic North Pole between 14 August and 14 September 2018. Snow depth, total sea ice thickness (ice thickness plus snow depth) and transmitted irradiance were measured in an area of approximately 100 m x 100 m (Figure 1). Marker poles (M0 to M23) were deployed under the ice to facilitate ROV navigation and to obtain a better co-location of the data. The mean ice thickness of bare ice was

1.9 m and of the ice underlying the melt ponds 1.7 m (Table S2). Melt ponds were on average 0.3 m deep. Here we focus on two main datasets: measurements performed between 17 and 24 August represented summer conditions which were characterized by open or only slightly refrozen melt ponds and no snow cover, whereas measurements performed between 13 and 14 September represented autumn conditions which were characterized by refrozen and snow-covered melt ponds.

2.2 Under-Ice Transmittance

Horizontal transects of under-ice spectral irradiance were measured by a RAMSES-ACC hyper-spectral radiometer (TriOS GmbH, Rastede, Germany). The radiometer was mounted on a M500 ROV (Ocean Modules, Åtvidaberg, Sweden, Katlein et al., 2017). The ROV was lowered into the water through a 2 x 2 m hole in the ice covered by a tent next to the (pristine) study area.

The light transmittance was calculated by wavelength-integrating the transmitted irradiance from 350 to 920 nm and normalizing by the incident downwelling planar irradiance recorded by an upward-looking reference sensor at the surface. The data were filtered for ROV pitch, roll and depth, and noise was filtered from the spectra. Using the photosynthetically active radiation (400 to 700 nm) did not lead to qualitatively different results and conclusions in this work, and is thus not further considered here.

For under-ice navigation, the ROV was equipped with an acoustic long baseline positioning system (Pinpoint 1500 Linkquest, San Diego, CA, USA). We manually post-processed the ROV position to remove distortions caused by calibration uncertainties.

2.3 Snow Depth and Sea Ice Thickness

Snow depth point measurements with a horizontal spacing of 1 to 3 m and an accuracy of 0.01 m were obtained using a Magna Probe (Snow-Hydro, Fairbanks, AK, USA, Sturm and Holmgren, 2018). The GPS position of each measurement was recorded by an integrated GPS with an accuracy of 2.5 m (Sturm and Holmgren, 2018).

Total (sea ice plus snow) thickness was determined using a ground-based electromagnetic induction sounding device (GEM-2, Geophex Ltd, Raleigh, NC, USA, Hunkeler et al., 2015) using the in-phase signal at a frequency of 18.33 kHz. The GEM-2 was placed on a sledge and dragged across the study area in a grid pattern at the very end of the campaign. The accuracy of the total thickness measurements is ± 0.1 m (Hunkeler et al., 2015). Finally, ice thickness was calculated from total thickness by subtracting the (interpolated) snow depths. GPS positions of snow depth and ice thickness measurements were subsequently corrected for ice drift using GPS recorders placed at the acoustic transponder locations to enable co-location with the transmittance measurements.

In addition, in situ snow depth, ice thickness, draft, freeboard, and melt pond depth were measured in drill holes at the marker locations using a tape measure on 17 August.

2.4 Aerial Images

Oblique aerial images were obtained during a helicopter flight on 23 August (summer) and by a drone on 13 September (autumn). Those were used to retrieve the geographic coordinates of the melt ponds. The images were corrected for camera perspective and georeferenced using the marker locations measured by a terrestrial laser scanner (VZ-400i, RIEGL, Horn, Austria). Melt ponds in the image were detected using a simple threshold criterion. All pixels within the study area where mean(R,G,B) < 70 + 0.5 · B (Katlein et al., 2015) were classified as melt ponds, with R, G, B representing the integer values of the respective channels of the RGB color space (R=700 nm, G=525 nm, B=450 nm). We added a 2 m buffer by image dilation to account for horizontal light spreading (Ehn et al., 2011) and uncertainties of the ROV position.

2.5 Radiative Transfer Model

We modelled under-ice broadband transmittance using the radiative transfer model DORT2002 version 3.0 (Edström, 2005; Katlein et al., 2021). The model uses a discrete ordinate model geometry and is implemented in the MATLAB™ software. The ice geometry was approximated by three layers each for bare ice and melt ponds (Table S1): The bare ice consisted of the interior sea ice underlying a surface scattering layer (SSL) with a freshly fallen snow layer of varying thickness on top. The melt ponds consisted of interior sea ice underlying the melt pond overlain by a snow layer of varying thickness. For simplicity, the situation without any snow will be referred to as “summer” conditions whereas the snow covered scenario is referred to as “autumn” conditions. We used typical inherent optical properties for multi-year ice (Katlein et al., 2021; Perron et al., 2021).

3 Results and Discussion

3.1 Evolution of Surface and Optical Properties in the Transition from Summer to Autumn

Figure 1 illustrates the distribution of melt ponds and bare ice, as well as the magnitude and spatial variability of under-ice transmittance during the transition from summer to autumn in the study area.

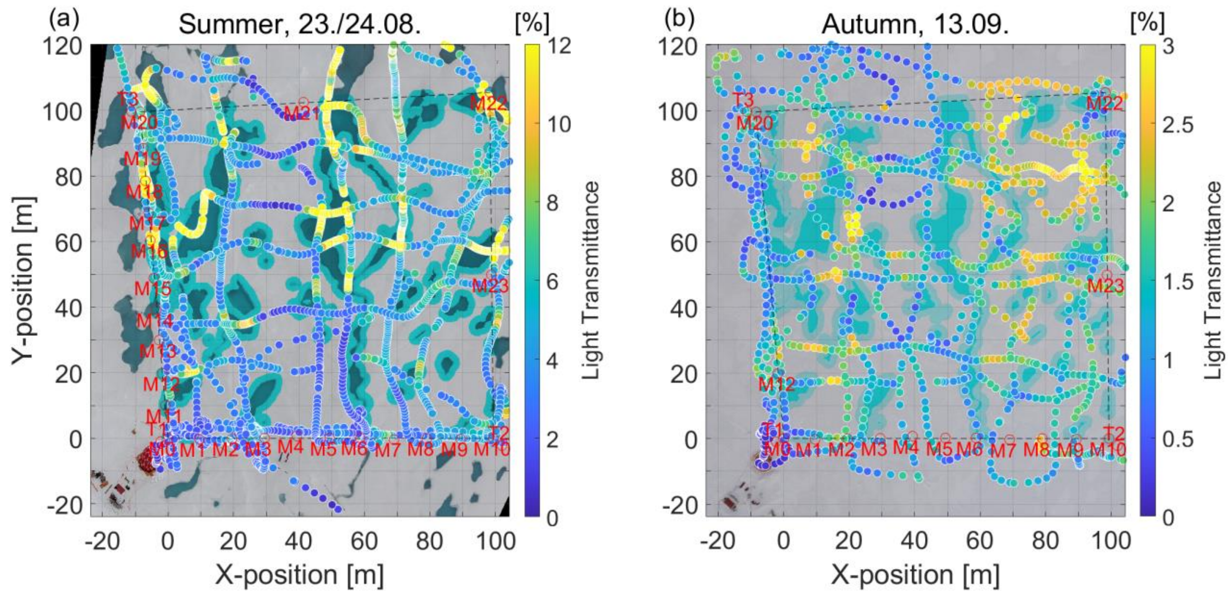

Figure 1: Light transmittance through ponded sea ice during the transition from (a) summer to (b) autumn. The data show ROV-based radiation measurements under (a) open melts ponds and (b) refrozen and snow-covered ponds. The background images are orthorectified aerial images acquired during (a) a low altitude helicopter flight and (b) a drone flight. Pixels within the study area that were classified as melt pond and used for further analysis are colored in blue. The melt ponds in (b) were refrozen and snow-covered but marked blue for illustration purposes. The edges around the melt ponds in (a) and (b) were dilated by a buffer of about 2 m. This area is indicated by a brighter blue. Red labels indicate the marker (M) and transponder locations (T). The ROV tent and control hut are visible on the lower left corners of the images. Note the different range in transmittance in (a) and (b).

On 23 August, the melt ponds were generally still open but in parts slightly refrozen at the surface (Figures 1a and S1a). The mean and maximum transmittances of ponds (8.9% and 23.2%, respectively) were significantly higher than those of bare ice (4.1% and 15.5%, see also Figure 1a and Table S2) on 24 August. Histograms showed a bi-modal transmittance distribution of ponds and bare ice combined (Figure S2a). The distribution also showed a characteristic long tail for ponds, indicating high spatial variability and different properties of the ponds. This distribution is typical for Arctic summer sea ice and results from the formation and development of the melt ponds (Katlein et al., 2015; 2019; Nicolaus et al., 2012; Schanke et al., 2021). The magnitudes of transmittance are similar to observations from Nicolaus et al. (2012) in the same region in August 2011. The maximum transmittance of the melt ponds also agrees to values found by Katlein et al. (2019).

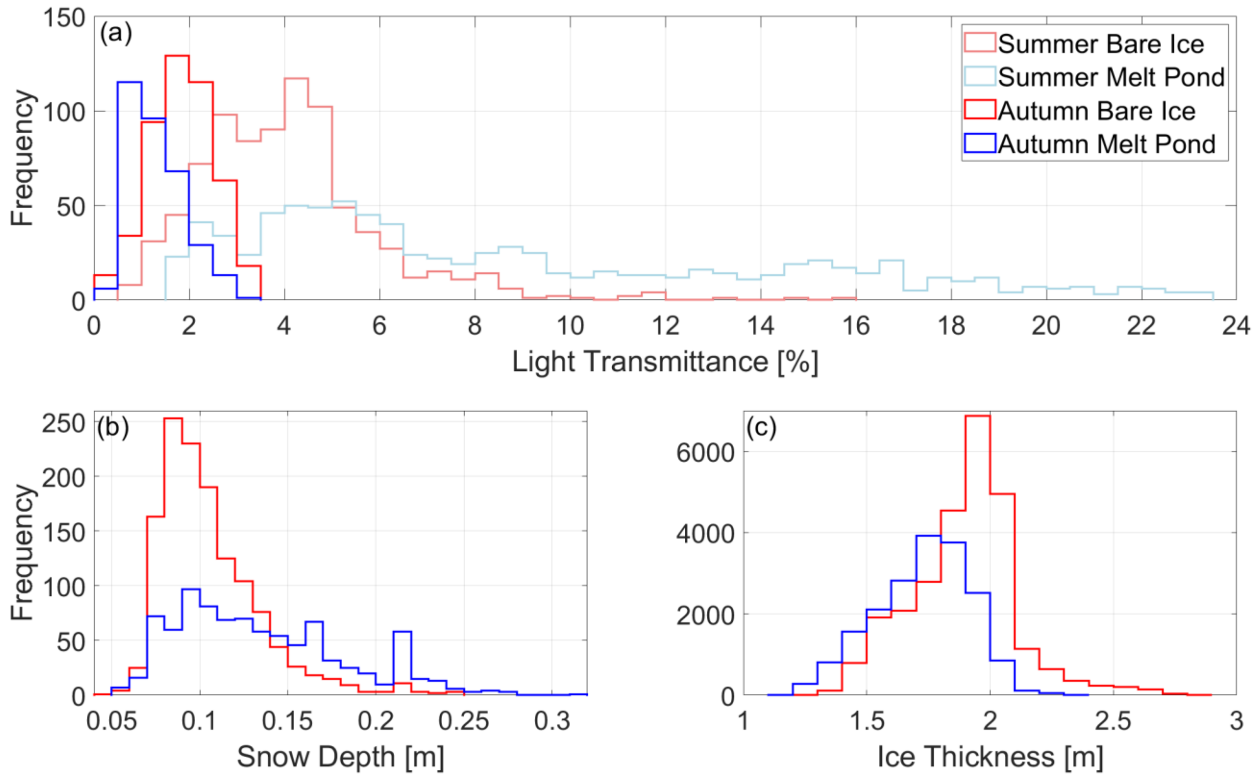

Figure 2: Histograms of measured (a) light transmittance, (b) snow depth, and (c) ice thickness of melt ponds and bare ice.

After freeze-up, the surface of the melt ponds was refrozen and a snow cover accumulated on top of it as well as on bare ice (Figure 1b). The transmittance of both melt ponds and bare ice decreased due to new snow (Figures 1 and S2, Table S2). The spatial variability in the transmittance of both melt ponds and bare ice was significantly reduced in autumn while the long tail of the high transmittances diminished, with very few observations higher than 3% (Figures 2a and S2, Table S2). In summer, approximately 80% (25%) of the transmittance measurements were higher than 3% (9%) while in autumn only 1% (0%). This can be explained by stronger and more frequent snow fall events that started to occur from 28 August (Vüllers et al., 2021).

Lee et al. (2011) describe that melt ponds remain bright windows of Arctic sea ice also in autumn, after refreezing. This implies that the transmittance of melt ponds ice remains higher than that of bare ice. Katlein et al. (2019) showed that the bi-modal structure of transmittance during summer is conserved even during the first weeks of freeze-up in mid of September. They further suggest that the transmittances of both melt ponds and bare ice decrease gradually and equally in the transition from summer to autumn.

In contrast to those results, we observed the opposite behaviour: the mean transmittance of melt ponds (1.3 %) was lower than that of bare ice (1.8 %) in autumn (Figures 1b and 2a, Table S2). The transmittance distribution showed two distinct modes of 1.0% and 2.0% associated with melt ponds and bare ice, respectively (Figure 2a, Table S2). This opposing behaviour is explained by the higher mean snow depth (0.14 m) on melt ponds compared to that on bare ice (0.11 m) (Figure 2b, Table S2). On the melt ponds, higher snow depths were also much more frequently measured than on bare ice (modes of 0.17 and 0.22 m, Figure 2b).

The melt ponds and their recessed topographic position induce a rougher ice surface compared to adjacent bare ice (Figure S1, Fetterer & Untersteiner, 1998). Thus, they provide a catchment area for snow. The passage of low-pressure systems between 29 August and 15 September brought precipitation accompanied by strong winds with speeds up to 13 ms^{-1} (Vüllers et al., 2019). As a result, snow was re-distributed towards and caught by the refrozen melt ponds and their edges, leading to the higher snow accumulation on the ponds.

Despite the reversal of the magnitude in the transmittance of melt ponds and bare ice, the spatial variability remained during autumn (Figure 1). This suggests that the spatial variability was still coupled to the ponds after snow accumulation and re-distribution and most likely also persisted into winter.

The transmittance of ridged ice with thicknesses up to 2.8 m was naturally still lower than that of the melt ponds (Figures S3b and 1b). Those measurements are included in the bare ice data and are represented in the tail of larger ice thicknesses in the histogram (Figure 2c).

This study provides first quantitative observations of lower light transmittance of melt ponds than of bare ice in autumn due to higher snow depths on the ponds. Major implications on the ice-associated ecosystem and the energy and mass balance of the sea ice arise from those observations:

Lee et al. (2011) proposed that the soft refrozen surface of open melt ponds that are in connection with the ocean provides a fertile habitat for biomass in autumn. They pointed out that the biomass accumulated under the refrozen melt ponds serves as an important food source for higher trophic animals during the transition from autumn to winter and further into winter. However, as presented here, a snow cover significantly reduces the light availability in and under melt ponds in autumn, suggesting a limited suitability as habitat in terms of available light. Those observations lend support to a study by Lange et al. (2017), who found higher biomass values underneath hummocks on multi-year ice compared to adjacent level ice. Lange et al. (2017) attributed the differences in biomass accumulation to increased light availability under the hummocks resulting from a very thin or absent snow cover. Our results and those of Lange et al. (2017) suggest that light conditions under sea ice in spring can already be initialized by melt pond coverage and snow distribution during autumn and may persist throughout winter.
Further, due to the common assumption that there is more light available under melt ponds than under bare ice also during autumn, processes and magnitudes of carbon uptake and biomass accumulation in models, might need to be adjusted with respect to our new observations.

Arndt and Nicolaus (2014) developed a parameterization to quantify the annual solar heat input through Arctic sea ice. For their calculations in autumn, they use for transmittances of melt ponds the fivefold (500%) of that of bare ice. However, our results showed that the modal transmittance of melt ponds is only half (50%) of that of bare ice once covered by the first snow (Table S2). Using the parameterization from Arndt and Nicolaus (2014), their constant summer mean melt pond fraction for multi-year ice of 29% (Rösel et al., 2012), their estimate for the solar heat input into the ocean in September of 0.69×10^{19} J, their transmittance of melt ponds on multi-year ice of 0.4%, but the ratio of transmittances between melt ponds and bare ice as presented in the present study, the solar heat input would decrease by 61%. Even though the solar heat input in September is low compared to May-August (e.g., Perovich et al., 2011; Arndt and Nicolaus, 2014), the results of reduced light transmittance of snow-covered melt ponds compared to that of bare ice, should be incorporated in future solar heat input calculations. In this regard, our results might also impact the heat stored in the upper ocean, the interior sea ice structure, as well as internal and basal melting.

The implications of our results on the sea ice mass balance are related to the insulating effect of the snow cover. As a consequence, reduced thermodynamic ice growth, delayed freeze-up of the liquid melt pond, and induced bottom roughness are expected.

The refrozen surface of the melt ponds alone reduces the heat release from the ocean through the ice towards the atmosphere (Flocco et al., 2015). This hampers ice growth at both water-ice interfaces of the refreezing pond, as well as between the sea ice bottom and the ocean in the transition from autumn to winter. This can result in a delay of the complete freeze-up of the pond by up to 60 days (Flocco et al., 2015). A thinner ice cover is more vulnerable to dynamic and warming events. The presence of a snow cover on top of the refrozen pond surface is expected to amplify those effects. As a result of the reduced thermodynamic growth of the sea ice underlying melt ponds compared to bare ice, a generally rougher bottom topography might result, affecting the mass, momentum, heat, and salt fluxes at the sea ice-ocean interface.

The exact evolution of the optical properties of melt ponds during refreezing depends on the sequence of weather events. Whether or not more snow accumulates on the refrozen melt ponds than on adjacent bare ice is governed by the wind speed and snow drift regime during and after the snow fall, by the snow properties, and by the roughness of the refrozen surface. Falling and deposited snow needs to be re-distributed before it can accumulate on the topographically recessed and rougher pond surface. Wet and heavy snow sticks easier to the refrozen surface of melt ponds and better resists erosion by wind than low density snow. Further, on very flat, dry and smooth nilas, snow might not accumulate that much compared to surfaces that froze under turbulent conditions and that exhibit a rougher and wetter surface where snow can more easily deposit (Sturm et al., 2002).

3.2 Radiative Transfer Model

For the effect described above, it is of interest to quantify the threshold snow depth that is necessary to decrease the transmittance of melt ponds below that of bare ice. In order to determine this threshold depth, we used the radiative transfer model DORT2002. For the situation without snow (summer), both the simulated transmittances of melt ponds and bare ice (9% and 4%, respectively) were very similar to our observations (8.9% and 4.1%, respectively, Figure 3, Table S2).

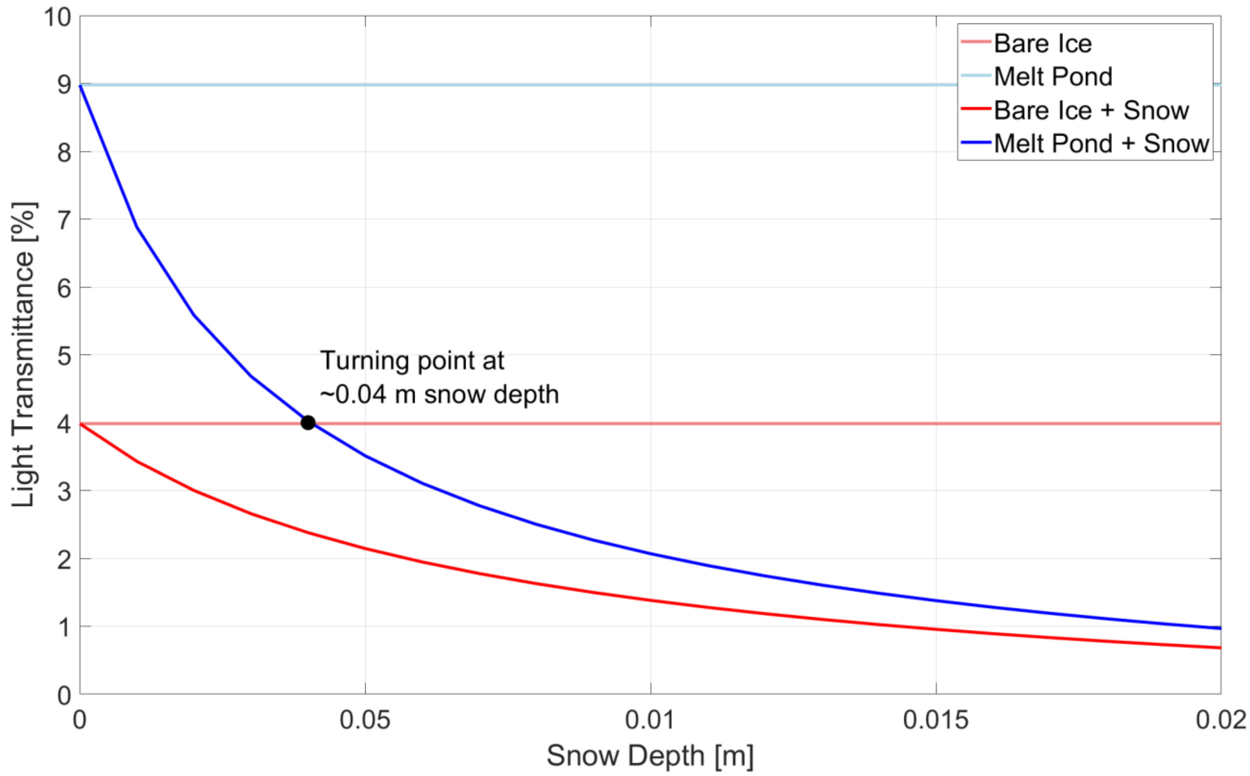

Figure 3: Simulated light transmittance depending on the snow depth as modelled by DORT2002 for four cases: bare ice (light red), melt ponds (light blue), snow-covered bare ice (red), and snow-covered melt ponds (blue).

Incorporating an increasing snow cover from 0 to 0.04 m (autumn), our results yielded an exponential decrease in the transmittances of both melt ponds and bare ice (Figure 3). For a snow depth of approximately 0.04 m the transmittance of the melt ponds becomes lower than that of snow-free, bare ice (Figure 3). This is in agreement with the observations presented earlier in this study which showed that the transmittance of melt ponds was lower than that of bare ice for a 0.03 m higher mean snow depth on the ponds (Table S2).

In our simulations, the influence of the thin ice lid on the melt ponds on the transmittance was neglected, as they were only partially existing, as for typical Arctic summer sea ice these are very translucent and scattering is small (Lu et al., 2018), indicated by their blue-green color (Figure 1a).

5 Summary

We measured light transmittance under a ponded sea ice floe in the transition from summer to autumn using a ROV together with snow depth and ice thickness and used a radiative transfer model to quantify a threshold snow depth. Those measurements showed that melt ponds cannot be universally considered as bright windows of Arctic autumn sea ice. The transmittance of refrozen melt ponds on Arctic sea ice during autumn can become lower than that of adjacent bare ice. The reason for that is a 0.03 - 0.04 m thicker snow cover that accumulate on the ponds due to their recessed topographic position compared to bare ice. This conclusion has consequences for the ice-associated ecosystem, the thermodynamic sea ice growth and the energy budget. Algae might not dwell as much under the darker melt ponds and we speculate that the snow cover on top of the refrozen ponds hampers ice growth due to its insulating effect and, thus, induces increased bottom roughness.

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Data availability

All data presented in this study are publicly available under the following DOIs:

ROV: https://doi.org/10.1594/PANGAEA.925698

Magna Probe and GEM2: DOI generation is currently in progress

Aerial images: https://doi.org/10.5281/zenodo.5119094

Competing interest

The authors declare that they have no conflict of interest.

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