Dear **Referee #2**,

Thank you for your insightful comments on manuscript tc-2019-199 “Seasonal timeline for snow-covered sea ice processes in Nunavik's Deception Bay from TerraSAR-X and time-lapse photography.” and for providing advice on how to improve it. We appreciate your time. The manuscript has been considerably reworked following your comments and those of Referee #1.

The title and objectives have been reworded to reflect our focus on the combined use of TerraSAR-X and time-lapse photography for seasonal sea ice processes monitoring. Section 2. “SAR backscattering from sea ice” has been removed. The methods and results have been re-organized, and some content has been moved to the supplementary materials. The discussion has been completely rewritten.

We reproduced your comments below (R), provided our answers (A), and detailed changes to the manuscript (M). When providing section numbers, we refer to the first version of the manuscript.

Sophie Dufour-Beauséjour, for the authors
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R1: The abstract is rather imprecise, e.g. it is claimed that Inuit’s have reported greater inter-annual variability in the seasonal ice conditions. In which way were there changes? Since when have they reported this? This information is very useful and it would have been very nice if these observations were further reported and explored within the manuscript. Why can we expect increase in solid precipitation? Over which time period? Please rewrite the abstract to focus on the main findings and points addressed within the manuscript.
A1: The abstract was rewritten to focus on the main points addressed in the manuscript.
M1:
We added examples of changes to seasonal sea ice conditions reported by Inuit:

> *“Indeed, Inuit have reported greater inter-annual variability in seasonal sea ice conditions, including later freeze-up and earlier breakup.” (in the Abstract)*

Regarding climate projections, we clarified the information:

> *“The evolution of seasonal sea ice conditions in Deception Bay is expected to continue, with 2040-2064 climate projections for the region showing shorter snow cover periods and warmer annual average temperature (Mailhot and Chaumont, 2017).” (in the Introduction)*

R2: The manuscript is very long and contain information that is well covered in other works, e.g. the sea ice evolution during the year. Please reference these works instead, and only highlight things of specific importance and relevant to the scientific work carried out within this manuscript. This would significantly shorten the manuscript, e.g. can section 2 be significantly shortened to possibly cover 1/2 page instead of the near 3 pages. The study area section can also be shortened, e.g. is the tidal range is not important for the rest of the study. Similarly, is the last paragraph in section 3 not relevant for the presented work? Please revise the work bearing in mind what you are trying to convey and new scientific findings.

A2: The literature review on SAR backscattering from sea ice was shortened: highlights relevant for the manuscript were incorporated in the Introduction and in the Discussion. This, as well as the transfer of some content to the supplementary materials (as detailed in A11), has significantly shortened the manuscript.

M2:

Section “2. SAR backscattering over snow-covered sea ice”, which presented a literature review on the seasonal evolution of C-band backscattering from first-year sea ice, was removed following your comments as well as those of Referee #1. Relevant references to the literature on this topic are now reserved for the discussion.

Information on the tidal range was removed from Section “3. Study area”.

The paragraph detailing how the relevant local authorities were consulted and gave their approval for the project is still in the manuscript, because this information serves to demonstrate that the data was acquired in a respectful manner

R3: Please expand the methods section to explain to the reader what is done in the study and how the results are achieved. E.g. define and explain why the following is calculated; first freezing degree-day, freeze-up, frost flower maximum and winter onset?

A3: The methods section was expanded to include examples and definitions, and restructured to follow the manuscript objectives.

M3:

A paragraph explaining how the methods relate to the objectives of the manuscript was added as an introduction to the methods section:

> *“The objective of combining TerraSAR-X and time-lapse photography time-series for seasonal sea ice process observation is addressed by identifying indicators relating to freeze-up, winter, and breakup process elements. [...] Sections 4.1 and 4.2 describe the indicators and how they are observed or measured from each data source. Section 4.3 then explains how photographs are compared with coincident satellite images and used to identify their features, which serves to evaluate the potential of time-lapse photography to support TerraSAR-X image interpretation.*

In the Methods, we justify why each indicator is calculated by relating it to a process element, which is itself related to a given sea ice process:

> *“For example, elements of the freeze-up process include the date on which freeze-up begins, and the day on which it ends. These process elements can be observed through time-lapse photography indicators consisting of the first day where parts of the winter ice cover are observed on the water, and the first day where the winter ice cover is complete and stable.”*

R4: According to the manuscript frost flowers could not be observed in the photographs, and as far as the reader can work out a peak in SAR backscatter values is therefore inferred to correspond to frost flowers. Though this is not again specifically stated in the methods section.

Moreover, how do you know that frost flowers were present? Could the post-freeze-up peak be related to increased sea ice thickness?

A4: We agree that the post-freeze-up peak cannot be reliably attributed to the presence of frost flowers. Indeed, frost flowers are too small to be resolved on the photographs. In general, following your comments and those of Referee #1, we now refrain from associating X-band backscattering time-series features to sea ice processes (e.g. frost flowers). Instead, the features are tracked as they are (e.g. post-freeze-up peak) throughout the Methods and Results. Potential explanations for the features based on physical processes (e.g. frost flowers, or increased sea ice thickness) are now reserved for the Discussion.

The difference between our observations of backscattering from nilas and those of the literature, which are several dBs lower, is suggested to be caused by the presence of a snow cover (snowfall was observed on the photographs). Frost flowers are cited as a possible additional source of scattering which cannot be resolved on the photographs (see excerpt below in M4). Regarding the specific case of the post-freeze-up peak, we were unable to confidently associate it with a physical process such as the presence of frost flowers or the growth of ice thickness, because of the relative lack of literature on X-band backscattering mechanisms within sea ice, particularly young sea ice in the winter. We do however offer potential explanations in the Discussion (see excerpt below in M4).

M4:

On the role frost flowers may have played in backscattering from nilas:

> *"In cold and dry snow conditions, the X-band isn't expected to penetrate significantly in the ice cover, with backscattering dominated by the presence of brine at the snow-ice interface (Nandan et al., 2016). Several factors may be intervening in backscattering from nilas. Frost flowers are known to increase the backscattering from newly formed sea ice in the C-band, an effect which may be more pronounced over thin ice; an increase of 5 dB was reported over ice 2 to 15 cm thick (Nghiem et al., 1997), and of 13 dB over 5 cm thick ice (Isleifson et al., 2014). Snow may also lead to an increase in backscattering through warming of the ice surface and brine absorption (Gill et al., 2015). In the case of our nilas observations, snow itself might be enough to explain the 3 dB difference; frost flowers may also have played a role, but cannot be observed on the photographs." (in the Discussion)*

On the mechanisms responsible for the post-freeze-up peak:

> *"The post-freeze-up peak and monotone backscattering onset are also observed in C-band time-series over sea ice (Yackel et al., 2007), but these seasonal features have been less studied than their spring counterparts (end of monotone backscattering and spring peak). Moreover, the same features in the X and C-band could well be related to different scattering mechanisms, and even to different physical processes. We limit ourselves to speculating, for the X-band data presented in this manuscript, that the increasing portion of the peak may be associated with the domination of surface scattering related to a brine-rich ice surface, potentially covered in frost flower, and that the decreasing portion may be associated with a transition to*

an absorption regime, in which the signal suffers loss in the brine-wetted and increasingly colder snow. " (in the Discussion)

R5: Why are not snow thickness information reported for any other time period than April 2017? In order to fully address the scientific topic indicated in the title of the paper information about the snow thickness is essential for the sea ice monitoring. It is unclear to the reader how are the estimates about the snow cover carried out? Photographs? Is there information about snow cover thickness and distribution? Judging by the title the manuscript should only contain information about snow-covered sea ice. Yet figures showing e.g., grease ice and pancake ice has no snow cover. Consider updating the title to reflect the sea ice included within the study. Please discus how do you expect the snow-cover to affect the results?
A5: The title of the manuscript and its objectives were reworded to better reflect the manuscript's focus on the combined use of TerraSAR-X and time-lapse photography for seasonal sea ice processes monitoring. Snow thickness measurements, performed by the authors as part of the greater Ice Monitoring project and included as context for the study site, have been updated to the entire available range of data (2015 to 2018).

The presence of a snow cover on the sea ice, which is the case for almost all the TerraSAR-X images in the time-series, is expected to play a significant role in the total backscattering and its seasonal evolution. Following freeze-up, the snow absorbs brine expelled from the new ice (Barber and Nghiem, 1999). The presence of brine in the snow is expected to restrain the interaction of the signal to the snow volume and the snow-ice surface because of absorption in the lossy brine-wetted snow (Nandan et al., 2016). Penetration in the ice cover itself is therefore small (modelled penetration depth is for the X-band VV is 2 cm in brine-wetted snow, as reported by Nandan et al., 2016). Relevant scattering mechanisms should be limited to surface and volume scattering within the snow layers and surface scattering at the snow-ice interface.
M5:
Reworded Title:

> *"Combining TerraSAR-X and time-lapse photography for seasonal sea ice monitoring: the case of Deception Bay, Nunavik" (Title)*

Reworded manuscript objectives:

> *"This article explores the use of combined TerraSAR-X and time-lapse photography time-series to observe seasonal sea ice processes, and the potential of the time-lapse photography to support TerraSAR-X interpretation. The case study is performed over three years in Nunavik's Deception Bay. A complementary objective is to describe the processes through an interannual comparison. (in the Introduction)*

Updated snow thickness data and provided details and a reference regarding the measurement method:

> *"Point thickness measurements performed in Deception Bay for the Ice Monitoring project in January-February and April-May 2016, 2017, and 2018 (Gauthier et al., 2018) ranged from 0 to 55 cm for the snow cover, and 52 to 165 cm for the ice cover. " (in the Study area)*

R6: Why is beta nought used instead of the more commonly used sigma nought? Since beta nought is used please use the symbol beta in all the figures 6, 10, 11, 12 and 16 instead of the symbol sigma.

A6: In the Methods section, it was incorrectly indicated that the TerraSAR-X data had been processed in beta-naught. The data is actually in the conventional sigma-naught, which is why the sigma symbol is used throughout the manuscript.

M6: Corrected:

> *"This workflow starts with a conversion from the digital number to radar brightness (sigma-naught) [...]." (in the Methods)*

R7: The incidence angle difference within the dataset is significant (8o), how does this affect the presented results?

A7: The seasonal features (peaks and inflexion points) were observed for all acquisition parameters, so the different incidence angles between orbits doesn't affect the results presented in the manuscript. The relative amplitude of the features did however sometimes depended on incidence angle. To discuss the effect of incidence angle, we compare the two ascending-evening orbits. Orbit 13 (empty squares) at an incidence angle of 38° and orbit 89 (black diamonds) at an incidence angle of 46° are first shown for 2017-2018 (see Fig. R2-1).

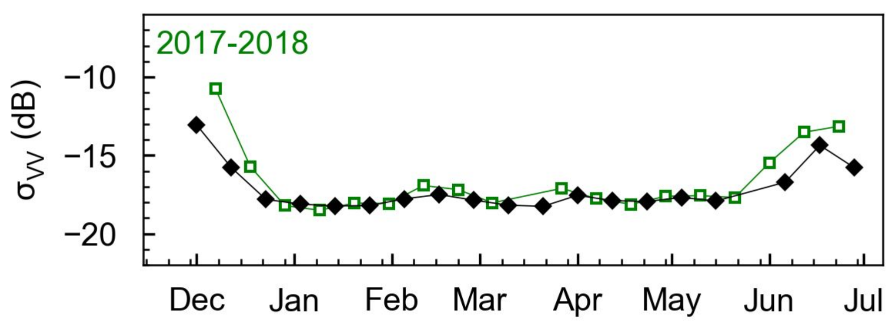

Figure R2-1: TerraSAR-X median VV backscattering plotted versus time for 2017-2018. Two orbits are shown: orbits 13 (38°, empty square) and 89 (46°, black diamond).

A small incidence angle effect can be seen on the median VV backscattering during the post-freeze-up and spring peaks. The backscattering at 38° is 1 to 3 dB higher than the backscattering at 46°. No incidence angle effect is seen in the monotone winter period. The same is observed in 2016-2017 (see Fig. R2-2). A backscattering signal which decreases with incidence angle is expected for situations dominated by surface scattering on a relatively rough surface (Ulaby et al., 1986). Surface scattering at the interfaces between dry snow, brine-wetted snow and ice is indeed expected to dominate backscattering from cold snow-covered sea ice, with a transition to mixed scattering for thicker snow covers (Gill et al., 2015). The monotone winter period where no incidence angle effect is observed might be associated with mixed scattering.

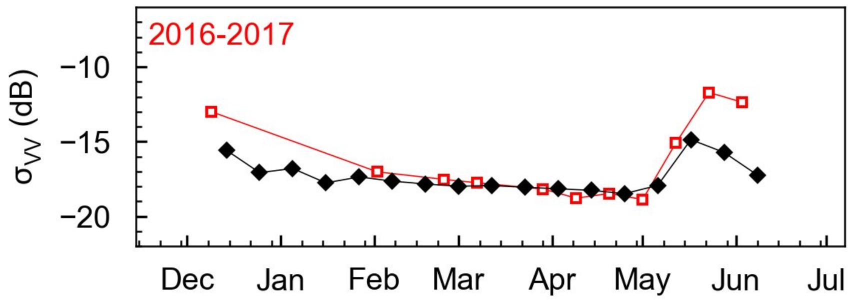

Figure R2-2: TerraSAR-X median VV backscattering plotted versus time for 2016-2017. Two orbits are shown: orbits 13 (38°, empty square) and 89 (46°, black diamond).

The effect of incidence angle is completely different in 2015-2016 however. There is an almost constant difference of 2 dB between the two orbits, with the backscattering at 38° always **lower** than the 46° backscattering (see Fig. R2-3). The freeze-up process was also different in 2015: the thermal freeze-up is expected to have produced smooth thermal ice, compared to rougher ice from nilas patches and other ice types in 2016 and 2017. We suggest that, for 2015-2016, the surface scattering at the snow-ice interface was consistently low because of a smoother ice cover, and that the total backscattering was dominated instead by volume scattering. Volume scattering may increase with incidence angle (Ulaby et al., 1986), as observed in the 2015-2016 data throughout the winter and spring.

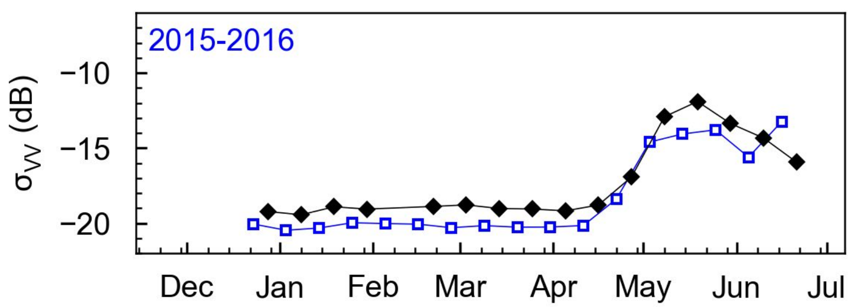

Figure R2-3: TerraSAR-X median VV backscattering plotted versus time for 2015-2016. Two orbits are shown: orbits 13 (38°, empty square) and 89 (46°, black diamond).

M7: A discussion on the effect of incidence angle has been added to the discussion:

> *"Before moving on to the spring processes, we first discuss the influence of an 8° difference between ascending orbits 13 and 89. For 2016-2017 and 2017-2018, a small incidence angle effect was seen during the post-freeze-up and spring peaks, where backscattering was 1 to 3 dB smaller at the higher incidence angle, and no effect was seen during the monotone winter period (see Fig. 9 and 12). A backscattering signal which decreases with incidence angle is expected for situations dominated by surface scattering on a relatively rough surface (Ulaby et al., 1986). In the C-band, surface scattering at the interfaces between dry snow, brine-wetted snow and ice is indeed expected to dominate for cold snow-covered sea ice, with a transition*

to mixed scattering for thicker snow covers (Gill et al., 2015). We speculate that surface scattering on the ice formed from nilas patches explains the dependence on incidence angle observed in our X-band data. 2015-2016 however presents a very different case. Backscattering at the higher incidence angle is consistently 2 dB stronger than at the lower incidence angle, throughout winter and during the spring peak (see Fig. 12). We've shown the freeze-up process to have been different that year compared to 2016 and 2017, and already suggested that the ice cover was much smoother for the 2015-2016 season. We speculate that surface scattering was consistently low that year, and that volume scattering, which Ulaby et al. (1986) have shown can increase with incidence angle, dominated instead." (in the Discussion)

R8: The fjord is given as 20 km wide (a scale bar would be nice to see in Figure 2), how much of the overall area is covered by the 15km wide TerraSAR-X images?

A8: A scale bar was added to Fig. 2, and the overlap between the study area and the TerraSAR-X image subset (a 9 km long section of the bay) is now indicated in the description of the study site and the TerraSAR-X data.

M8:

Added a scale bar to the map of Deception Bay.

Added detail on study area coverage by the TerraSAR-X images:

"Figure 2 shows the extent of the subimages, which overlaps with a 9 km long section of the bay." (in Data description)

R9: It is in the discussion stated that the sea ice observed in the ship wake was broken. How is this verified? How are wind effects accounted for in these observations? Would it be possible to include observations from these ships?

A9: Following their transit in the bay, the *MV Nunavik* and *MV Arctic* leave a track of open water and floating broken ice pieces. Because the ice cover is landfast to both shores, the track remains "open" until it has refrozen (in the winter); it is never closed by wind or currents. Ice lateral movement under the effect of the wind could be resolved on time-lapse photography, and was not observed. The refreezing of the track will depend on how much broken ice is in the open water and on the air temperature. The broken ice left in the ship's wake can be observed on time-lapse photography for the areas close to the cameras. We also observed the tracks left by the ships during winter fieldwork in Deception Bay in 2016, 2017, and 2018. During the spring, when ice-breaking transport resumes around June 1st, the tracks left by the ship are unlikely to refreeze due to warm temperatures. We speculate that the ship tracks are then left open, potentially with floating ice pieces depending on the ice and meteorological conditions. We don't have access to observations from the ships.

M9: Following the rewrite, the particular sentence which referred to broken ice left in the ship's wake is no longer in the discussion.

The effect of the wind (or absence thereof) has been added to the discussion on breakup processes:

"We speculate that the ice cover was in a more advanced state of degradation when breakup started in 2016 than in 2017. This is supported by time-lapse photography

which show that the ice cover was partly mobile (under the effect of wind or current) during breakup 2016, but mostly landfast during breakup 2017 (Movies S4-S5). In 2018's comparatively late spring, both the MV Nunavik and MV Arctic entered the bay during pond onset (on June 17th). Open water was observed along their tracks in the following days, and new cracks perpendicular to the shore appeared when the ships left the bay eight days later." (in the Discussion)

R10: It is in the manuscript stated that the X-band backscatter change is expected to be similar to the one in C-band. A suggested to corroborate this is to include Sentinel-1 images overlapping the fjord to investigate if these C-band images show the same evolution as the TerraSAR-X images. The use of Sentinel-1 may also reduce the revisit time.

A10: Following comments from Referee #1, we removed the assumption that the seasonal evolution of the X-band backscattering should be similar to that of the C-band. The question of similarity between the two bands is now reserved for the discussion.

During the Ice Monitoring project, RADARSAT-2 C-band data was acquired during winters (December to April) 2015-2016, 2016-2017, and 2017-2018, in partnership with the Canadian Ice Service. The median VV RADARSAT-2 backscattering at 36° over the same AOIs as presented in the paper is shown in Fig. R2-4, alongside TerraSAR-X data from orbit 13 at 38°. The RADARSAT-2 data was processed in the same way as the TerraSAR-X data, using the Multi-SAR-System at DLR.

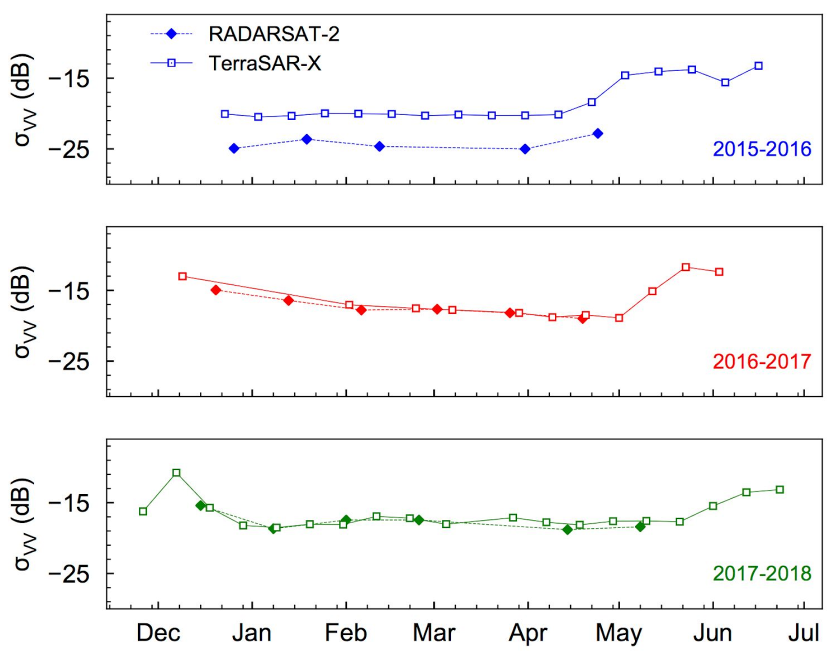

Figure R2-4: TerraSAR-X (38°) and RADARSAT-2 (36°) median VV backscattering plotted versus time. RADARSAT-2: in full diamonds and TerraSAR-X in empty squares.

The available RADARSAT-2 data closely matches the TerraSAR-X time-series for 2016-2017 and 2017-2018 monotone winter periods, as well as for the 2017 acquisition in the post-freeze-up peak. No data is available during one of the spring peaks. In 2015-2016, the monotone winter period backscattering is consistently lower in the C-band than in the X-band, by approximately 4 dB, which is probably due to differences in penetration depth. As described in A7, ice in 2015-2016 was presumably smoother than the other two years. The low signal both in X and C-band (Fig. R2-4) suggests that the ice appeared smooth at both radar frequencies. The C-band's increased penetration depth (due to a longer wavelength) might have led to increased absorption of the signal by brine inclusions in the sea ice, leading to a lower total backscattering than at the X-band.

M10: Added to the conclusion:

> *"Future work in the Ice Monitoring project will build on this characterization of seasonal processes and focus on spatial variations within the bay and comparison with similar fjords, namely Salluit and Kangiqsujuaq. It will also involve comparison of the TerraSAR-X time-series data with RADARSAT-2 time-series acquired over the same period and area." (in the Conclusion)*

R11: Rather than stating that the standard meteorological station at the airport is not used, a correlation measure between the used temperature and the airport temperature would have been beneficial. Such a comparison would also have verified the supposedly heated camera case claim, rather than a statement that the authors think that it is so. At what altitude is the temperature sensor located?

A11: We performed a correlation analysis between the camera temperature measured in Deception Bay and the airport temperature measured in Salluit, 50 km away. Everything related to the temperature measurements has been moved to a supplementary document focused on air temperature. It includes a description of the two different temperature data sources (including altitude), the data acquisition method, and a comparison of the two datasets (including the Pearson coefficient). The airport data was shown to be strongly correlated to the Deception Bay camera measurement. We therefore chose to use the airport data, despite the 50 km distance, to document how warm or cold each month was. We removed the bias modeling and correction for the camera data. Results on monthly cumulative freezing and thawing degree-days are given in the supplementary document for the airport dataset, and cited at several points in the Discussion.

M11:

Added detail to the description of the temperature data:

> *"The closest weather station to Deception Bay is located in neighboring Salluit, at the airport. Measurements at the station are taken hourly during the day, and their daily mean is available online from Environment Canada. Salluit is a Nunavik coastal community located 50 km west of Deception Bay; the airport is located 2.8 km inland at an altitude of 226 m.*
>
> *Two Reconyx PC800 Hyperfire Professional Semi Covert cameras were installed in Deception Bay as part of the CAIMAN research project. These cameras were installed*

near the study area, in front of Moosehead Island at an altitude of 22 m (series A) and on Black Point at an altitude of 33 m (series B)." (in the Supplementary)

Added a correlation analysis:

"Figure S3-2 shows the camera and airport datasets from 2015 to 2018. The camera and airport measurements showed a Pearson coefficient of 0.98 and 0.99 for the three years of the study, which proves a strong correlation despite their different locations. The camera dataset however differs from the airport's dataset with a root mean-squared-error (RMSE) of 3.9 to 4.3°C. To investigate this discrepancy, Fig. S3-2 also shows that the daily difference between the two datasets is roughly flat from September to January, and then peaks in April-May.

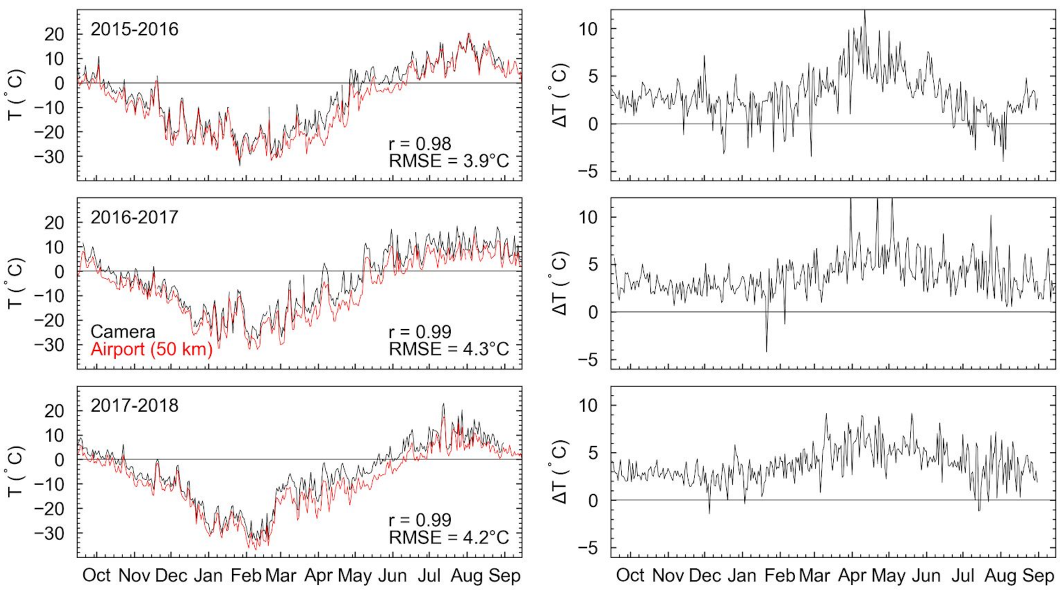

***Figure S3-2**: Left: Daily mean air temperature measured by the camera in Deception Bay (black) and at the Salluit airport (red). Right: Daily difference between the two datasets." (in the Supplementary)*

R12: As stated in the manuscript is FDD used, yet the unit used was oC, please explain? Also freezing at +3.5 oC to +4oC seems a bit high. Why is 0oC used when sea ice is investigated as it will likely freeze at -1.8oC. Are there any sea water temperature measurements?

A12: Freezing degree-days are a sum of temperatures (measured in °C). Since summation preserves units, FDDs were presented with a °C.

Freezing degree-days are a sum of freezing temperatures normalized to a positive number; freezing degree-days of 3.5 and 4.5 °C on average therefore mean that the daily temperature was roughly -4°C on average between the first freezing day of the year and the day of freeze-up, which is coherent with water freezing at -1.8°C.

While it is true that sea water freezes at slightly lower temperatures than fresh water, we chose to use the conventional definition of freezing and thawing degree-days (relative to the 0°C

mark), used by the Ouranos consortium in their climate projections for the region for instance (Mailhot and Chaumont, 2017).
No surface sea water temperature measurements were made as part of the fieldwork for this project. Temperature measurements reported in the literature were taken in September 2006 (GENIVAR, 2007) and August 2012 (GENIVAR, 2012).
M12: Added the reference to the Ouranos consortium climate projections to the description of freezing and thawing degree-days.

R13: It is mentioned in the discussion that the Deception River has warm water, please provide a temperature time series for this river or at least give some specific temperatures.
A13: No water temperature measurements were performed for Deception River, and we found no such data in the literature for the breakup period.
M13: The statement on Deception River having warm or warmer water was removed from the discussion.

R14: How do the values in e.g. Fig. 10 relate to e.g. work by Onstott 1992?
A14: We added a comparison of our results with those presented by Onstott (1992) and others.
M14: Added:

> *"Despite a difference of almost 20° in the incidence angle, our observation of -12 ± 1 dB over unidentified ice one to nine days after freeze-up (Fig. 8) is close to [...] reports by Onstott (1992) of -14.4 dB over thin first year ice (30 to 70 cm thick) in the X-band HH at 23°." (in the Discussion)*

R15: Additional comments According to the temperature records, as presented on row 254, temperatures are recorded between 11 September 2015 – 16 September 2016 and then from 18 September 2018 (?) to 31 August 2018. Please clarify.
A15: This is a mistake; the correct date ranges are 11 September 2015 – 16 September 2016 and 18 September 2016 – 31 August 2018.
M15: Corrected in the manuscript.

R16: Ibid. is not a way to reference that I've seen in this journal before. Whilst this might still be ok, many of the references where ibid. has been used are not correct and the statements that are supposed to be covered in those references are not included here. E.g. on row 129 the "white ice" term is attributed to Johansson et. al., 2017 and on row 400 correctly to WMO. Moreover, when referring to the WMO terminology please include the full reference, (WMO, 2014).
A16: We removed all uses of "ibid" and checked all citations.
M16: All uses of "ibid" were changed to in-text citations.

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