Dear **Referee #1**,

Thank you for your insightful comments on the manuscript 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 #2.

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.

SDB

Anonymous Referee #1

R1: My major concern with this paper now is how authors have justified the similarity in the backscatter evolution of X-band and C-band. See Line 485 under section 7.2. "The TerraSAR-X backscattering time-series presented in this article exhibits the same seasonal evolution as that of the C-band (Sect. 2), which was expected due to the spectral proximity of both bands." This sentence reads like the author already knew about the results and as an afterthought. This has lead to authors more or less assuming the scattering mechanisms during the seasonal evolution (like that with C-band), based on past literature. This is scientifically misleading. If there was similarity in scattering mechanisms at two different frequencies, our scientific community wouldn't have launched TerraSAR-X and RADARSAT-2 (for e.g.).
A1: All assumptions of similarity between both bands have been removed from the manuscript. Comparison of the X-band data with the literature on C-band is now reserved for the discussion.
M1:
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 #2. Relevant references to the literature on this topic are now reserved for the discussion.
In the Methods, the seasonal features consistently observed throughout the acquisition parameters and years of the study are no longer associated to physical processes or mechanisms:

> *"Recurring seasonal features in all X-band VV median backscattering time-series acquired during this study include two peaks separated by a monotone period. From this, four indicators were derived: the post-freeze-up peak (I), the beginning (II) and*

end (III) of the monotone period, and the spring peak (IV). Examples are shown in Fig. 4 for two different years and orbits, chosen for their clarity.

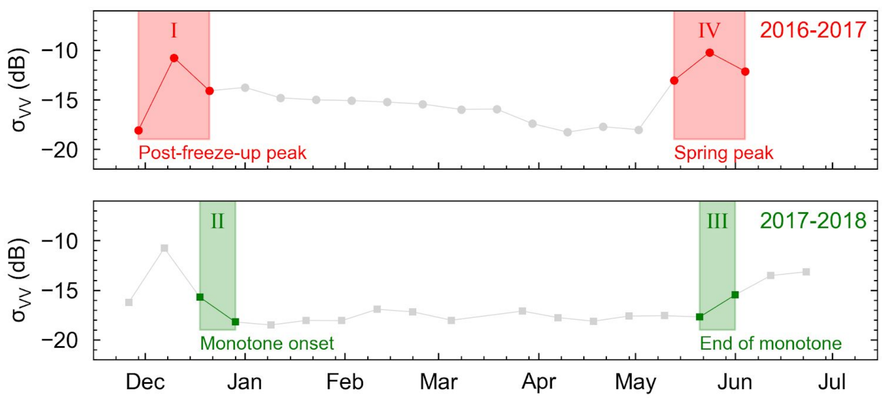

***Figure 4**: Examples of change detection in TerraSAR-X VV median backscattering. Peak detection for orbit 21 in 2016-2017 (top), and inflexion detection for orbit 13 in 2017-2018 (bottom).”*

(in the Methods)

In the Discussion, each seasonal feature is examined in terms of potential scattering mechanisms.

“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 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 a dispersion regime, in which the signal suffers loss in the brine-wetted and increasingly colder snow. ” (in the Discussion)

R2: a) Although the objective of this manuscript was to focus more on how X-band SAR can be used to provide the first-baseline signature of X-band VV backscatter. However, the majority of the paper is about analyses from time-lapse photographs and very little focus was given to analyzing the SAR signature section. I would suggest using the SAR images as the focal point of analysis (with snow/sea-ice geophysical explanation of changes in VV backscatter), ’supported’ by time-lapse photography.

A2: The manuscript title and objectives were reworded to clarify the focus of the work, which is on the combined use of TerraSAR-X and time-lapse photography time-series for the seasonal monitoring of sea ice processes. Both observational tools are uniquely qualified for remote applications, for instance in polar regions, and are often used as stand-alone tools. However, they provide access to different aspects of the environment they observe, and have different strengths (e.g. photography allows for hourly acquisitions, but with a limited view, while SAR remote sensing has a wide and precise spatial coverage, but with fewer acquisitions). We chose to give equal importance to the two data sources to explore their complementarity. The manuscript has been reworked to focus on this objective. The Methods and Discussion sections have been reorganized in the following way: first, each data source is treated as a stand-alone monitoring tool, and second, the two data sources are co-interpreted.

M2:

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)*

The Methods have been expanded and reorganized to clarify our parallel use of photograph interpretation and TerraSAR-X image interpretation, and their co-interpretation:

> *"[...] 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 enhance TerraSAR-X image interpretation." (in the Methods)*

The Discussion has been rewritten:

> *"The use of TerraSAR-X and time-lapse photography time-series for seasonal monitoring of sea ice processes is first discussed for each data source as a stand-alone monitoring tool (Sect. 6.1), and then for their combination (Sect. 6.2). This discussion focuses on three aspects of sea ice processes which are accessible with these tools: temporal, spatial, and spectral. Section 6.3 then discusses seasonal sea ice processes observed using combined TerraSAR-X and time-lapse photography time-series." (in the Discussion)*

R3: b) how they classified ice types (what method) from the TerraSAR-X images, based on beta-naught values? What is the advantage of using beta-naught over traditional sigma-naught? The authors may be reminded that the scattering mechanisms discussed in this paper (mostly based on previous literature) are applicable for sigma-naught values (significantly dependent on polarization). Therefore, substantial justification should be provided on why beta-naught values are used. And if they are, how does the scattering mechanisms change?

A3: 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. Ice type classification was performed based on photograph interpretation (see R4 and answers).

M3: Corrected:

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

R4: c) The interesting part is how authors easily interpret different ice types (grease ice, nilas, pancake ice, and grey-white ice) without any geophysical explanation (or the least scattering mechanism) justifying the backscatter occurrence from these ice types. This needs to be clarified. Although the authors have demonstrated diversity in VV (figure 10) for different ice types, the authors should demonstrate the proof of how they classified or interpreted them as these 'specific' ice types.

A4: Ice type identification was performed based on photograph interpretation, by following the WMO nomenclature (WMO, 2014). Ice type backscattering signature was extracted by co-interpreting the photographs and satellite images. This has been clarified in the Methods. Specifically, grease ice, nilas, and pancake ice types were observed on the photographs. Since grey-white ice is essentially characterized by its thickness, we removed the identification of this type of ice and instead refer to ice less than two weeks old as "unidentified ice".

M4:

In the Methods, a section is reserved to describe remote sensing and photograph co-interpretation, with examples:

> *"TerraSAR-X images were interpreted spatially using coincident photographs taken from the shore. Observed features include open water areas or leads and different ice types. Figure 6 shows two examples. At the top, nilas, pancake ice and grease ice are observed on the photographs during the 2017 freeze-up process, and then identified on a coincident TerraSAR-X image from 26 November.*

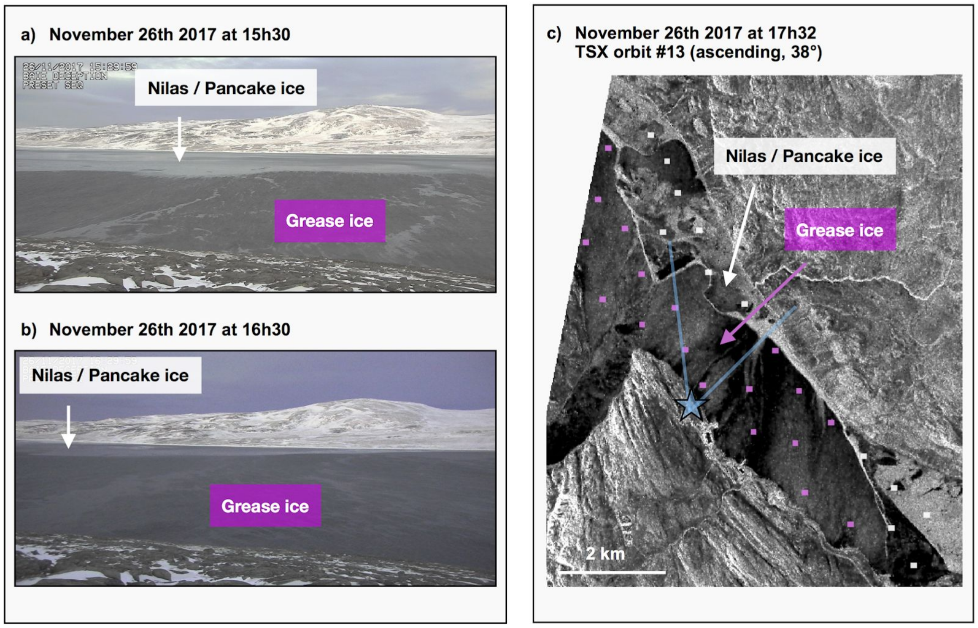

Figure 6*: Coincident time-lapse photography and TerraSAR-X image during the 2017 freeze-up process. On the image, camera location and fields of view are identified in blue. The TerraSAR-X VV image, grey-scaled from -19 to -5 dB, is from orbit 13. AOIs are color-coded according to the identified ice type, prior to backscattering signature extraction." (in the Methods)*

In the Results, backscattering data is presented for ice types identified from photographs and for unidentified young ice less than two weeks old:

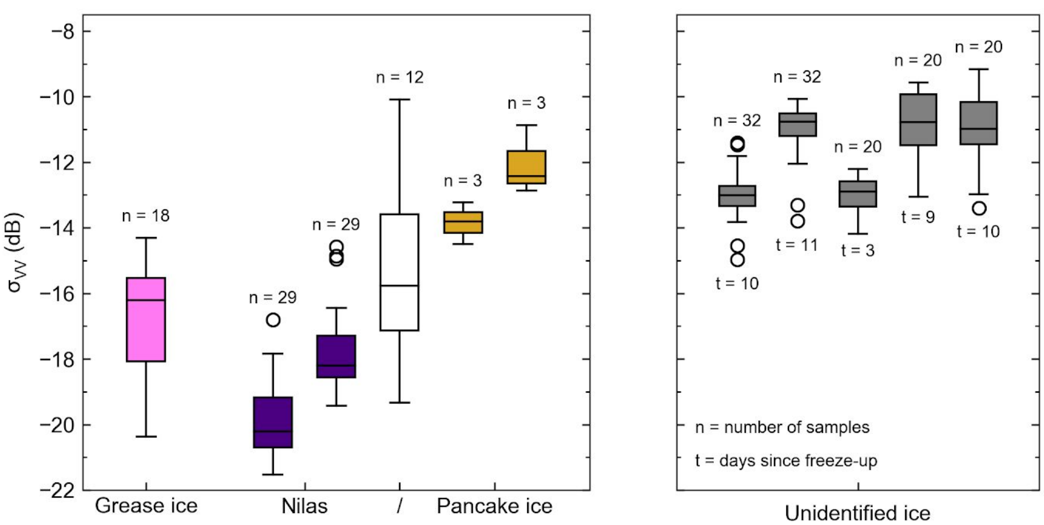

Figure 8*: TerraSAR-X median VV backscattering values observed over AOIs of ice types identified from time-lapse photography in 2016 and 2017. The number of median values used (n) is written above each box. Outliers are plotted as empty white circles. Left: Grease ice (pink) was observed on the orbit 13 image from 26 November 2017. Nilas (dark purple) was observed on 28 and 29 November 2016 in orbits 13 and 21,*

respectively. A mix of nilas and pancake ice (white) was observed on 26 November 2017 in orbit 13. Pancake ice (yellow) was observed on 28 and 29 November 2016 in orbits 13 and 21. Right: Unidentified young ice (grey) was observed on 9 and 10 December 2016 in orbits 13 and 21, as well as on 1, 7 and 8 December 2017 in orbits 89, 13, and 21. The number of days since the freeze-up date (t) is written below each box. (in the Results)

R5: For another example, the authors talk about 'frost flower maximum' which causes the first X-band inflection point. But the authors do not provide any proof of frost flower formation.

A5: 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.

M5: As described in our answer to R1 (above), association of seasonal features (e.g. post-freeze-up peak) to physical processes and scattering mechanisms has been removed from the Methods and Results, and is instead reserved for the Discussion, when possible.

R5: d) The third missing point of this paper is the lack of scattering mechanism explanation (mostly assumptions and backing up from past literature on C-band now) or sometimes explaining without any clarity in this regard. The authors should explain what they observe from the VV backscatter, based on the incidence angle range used in this study (and if they have in situ observations of snow and sea ice properties) and NOT based on agreeing with that they see from the SAR imagery, against past literature (using different incidence angle ranges from C-band imagery).

A5: Following your comments and those of Referee #2, we added some discussion on the effect of the incidence angle range used in the study. In the absence of in situ observations (given the focus of this paper on the combined use of two remote observation tools), definitive explanation of the scattering mechanisms is not possible. We however provide hypotheses for the mechanisms responsible for the seasonal features, which are more or less involved depending on the available literature (e.g. it is harder to speculate on mechanisms causing the post-freeze-peak than on those associated with melting and ponding).

M5:

The discussion was rewritten and includes segments on the scattering mechanisms for each seasonal process (examples are M1, M6). To avoid the logical fallacies you identified in your comments (e.g. X-band = C-band, or "cause of C-band feature" = "cause of X-band feature"), they are structured as follows:

1. Description, from the results, of an X-band feature
2. Existence, from the literature, of a seasonnaly coincident similar feature in the C-band (ex. inflexion point, peak)
3. Description, from the literature, of scattering mechanisms and snow or sea ice processes explaining this C-band feature
4. Discussion, from speculation, on how these mechanisms may translate or not to the X-band, in the event of these snow or sea ice processes

Added a discussion on incidence angle:

"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)

R6: e) If the authors haven't noticed, one advantage of the X-band signature time series across three years is its utility to detect melt and pond onset from SAR images (which is always challenging) and how varied the dates are for these three years. The authors, if interested should consider using this application as a tool to improve this manuscript. In addition to freeze-up and break up, another application in which the science community and also local communities are interested in how the timing of melt and ponding changes and how it can be effectively detected from SAR images. Just a suggestion for improvement.

A6: A discussion on the mechanisms which may reasonably explain the link between spring features (end of monotone backscattering and spring peak) and spring processes (melt onset and pond onset) has been added.

M6:

The end of monotone backscattering in the X-band was explained as follows:

"Monotone X-band backscattering was observed every winter of the study, for all incidence angles and acquisition times, before a systematic springtime increase in backscattering. In the C-band, monotone backscattering is also observed in the winter, ending with melt onset brought on by warmer air temperatures (Yackel et al., 2007). Mechanisms which may increase C-band backscattering from snow-covered sea ice include surface scattering from the brine-wetted layer at the bottom of the snowpack (Nandan et al., 2016), volume scattering on brine inclusions enlarged by an increase in temperature (Barber and Nghiem, 1999), and surface scattering on wet snow (Gill et al., 2015; Yackel et al., 2007) accumulated at the top of the snowpack due to above-zero temperatures and solar radiation (Gogineni et al., 1992; Kim et al., 1984). We speculate that the X-band is susceptible to all of these C-band mechanisms, with

an emphasis on surface scattering due to its lower penetration depth (Nandan et al., 2016), and attribute the end of X-band monotone backscattering to melt onset." (in the Discussion)

The spring peak in the X-band was explained as follows:

"Springtime backscattering was seen to eventually peak in all TerraSAR-X datasets (Fig. 12), although one series featured more than one maximum (orbit 13, 2015-2016), another none (orbit 13, 2017-2018), and an apparent mismatch between maximum location in the 2015-2016 data. In the C-band, springtime peaking of the backscattering is attributed (Yackel et al., 2007; Barber et al., 1995) to the transition from the pendular regime, where water is held in the snowpack (Scharien et al., 2012), to the funicular regime where meltwater drains downward (Scharien et al., 2012), flushing out brine (Barber et al., 1995), and potentially refreezing (Gogineni et al., 1992). Mechanisms which may decrease the C-band backscattering following this transition are attributed to a decrease in the dielectric properties of the snowpack following water drainage (Yackel et al., 2007). We speculate that the decrease in the X-band springtime backscattering is also caused by pond onset, and associated with increased penetration in the snowpack after water has drained out of it." (in the Discussion)

R7: Overall, if the authors would like to stick with the objective to provide a baseline understanding of X-band signature evolution, here are my suggestions

a) Even though data for all three years are available, use signatures from one year as the baseline and study the evolution of the X-band signature. That would be your baseline (which should also include describing the X-band scattering mechanisms).

b) With lack of in situ snow and sea ice observations of geophysical properties, the authors have the freedom to speculate the scattering mechanisms (never a drawback, and always room for improvements) instead of blind conviction.

c) Once the baseline signature is explained for one season, use it to differentiate different core regimes changes in the region. For eg. Table 3 shows differences in winter onset, melt onset and pond onset from SAR images for all three years. Use this info as a strong point to showcase the utility of X-band to effectively detect these changes (which can be then integrated into talking about the importance for local communities).

d) Use time-lapse photographs more as an ancillary data to explain the X-band signature evolution, and not the other way. Remember what your primary objective is.

A7: As described in A2, we chose to focus on the objective of combining TerraSAR-X and time-lapse photography time-series for seasonal monitoring of sea ice processes. The focus is therefore now less on the seasonal evolution of the X-band signal from sea ice, but rather on sea ice process monitoring through a combination of the two data sources.

The language was adapted throughout the manuscript to remove assumptions regarding scattering mechanisms and instead provide hypothetical explanations (see examples in M5 and M6).

M7: See M2, M5 and M6.

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