Responses to RC2

<u>1. No explanation of why backscatter from ice bottom would remain coherent during growth</u>
The speckle offset tracking technique requires that the scattering surface remains coherent between image acquisitions. However, in the case of scattering from the bottom of a growing floating ice cover, the radar is seeing an entirely new surface at each acquisition and I therefore see no reason why the speckle would remain consistent over timespans of 12 days. The authors need to provide more explanation of how the scattering characteristics of the underside of the sea ice (if indeed that is where the signal is coming from) would remain constant as new ice forms below each previously imaged surface.

The offset tracking algorithm seeks the peak in the 2D cross-correlation between master and slave images. This peak does not have to be large (which corresponds to high coherence), but it has to be distinct (i.e. distinct global maximum). This can be achieved by using a very large window when computing the 2D cross-correlation. In our study, this is achieved by a search window of 256x64 pixels. The resolution of Sentinel-1 SAR data is about 2.3x13.9 m, so the search window is ~596x888 m or 0.5 km^2. We claim that the predominant scattering over the area of 0.5 km^2 comes from the ice/water interface. This is, however, not the only scattering surface in 0.5 km^2 resolution cell. Other scattering surfaces are at various ice depths (depending on the salinity of individual 2.3x13.9 m pixels), but they do not add up to a synchronous response. The synchronous response from the ice/water interface produces a global maximum of 2D cross-correlation. The peak in the 2D cross-correlation function produced by a large search window is small but distinct. For example, Figure S1 shows the 2D cross-correlation features by applying a small window of 64x64 pixels and a large window of 256x256 pixels for the same central pixel. As shown, a small search window (left) produces a number of peaks. Some of them correspond to the reflections from the air/ice interface that capture motions at the surface. When a large window is used (right), only one distinct peak remains. See also next comment for additional details.

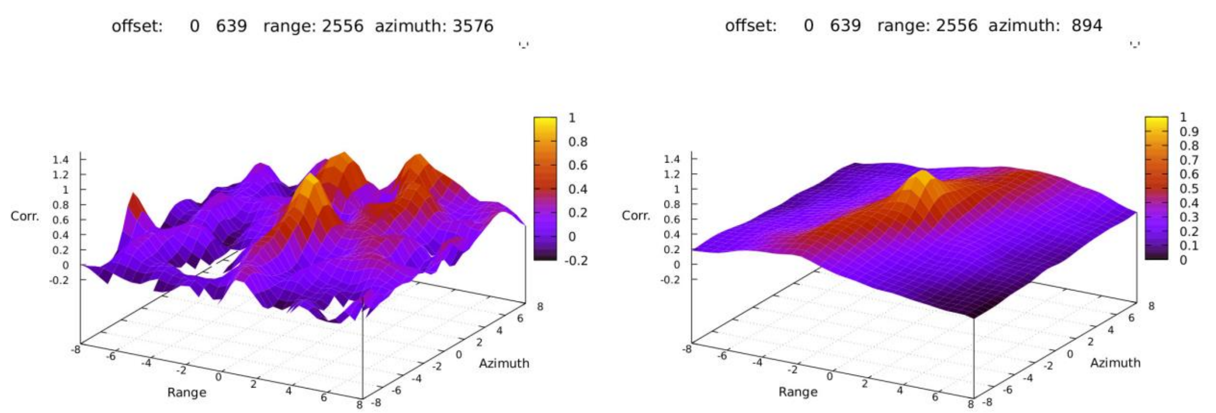


Figure S1. 2D cross-correlation plots calculated with a small window (left) and a large window (right)

<u>2. Inadequately supported assumption that ice bottom is source of SAR backscatter</u>
The authors assume that the SAR signal from the stabilized floating landfast ice is coming from the ice-water interface. The basis of this assumption is the low-backscatter signature of presumed bottomfast ice nearby and the presence of low-salinity ice in this region reported by MacDonald et al (1995). However, none of ice sampled by MacDonald et al was completely fresh and most contained a significant seawater fraction. Moreover, close inspection of the SAR intensity imagery (Fig 3d,e) shows linear spatial patterns typically associated with surface roughness features. It therefore seems likely that some fraction of the

microwave energy returned from the ice is coming from its upper surface and volume. This has a significant bearing on the interpretation of the SPO results, but is not discussed in the manuscript.

In our previous response, we explained why scattering at ice/water interface is captured by the offset tracking algorithm. This is not the only scattering mechanism present in SAR image, other scattering from the air/ice interface and at various ice depths are also present. But, this scattering does not add up to a coherent response over an area of 0.5 km^2 (i.e., window size for computing 2D cross-correlation in this study). Figure S2 shows the true-color composite of the Beaufort Sea, just north of the Mackenzie River Delta as observed by the MODIS. The brown and tan river sediments discolored the water and hinted at the extent of the outflow. It can be seen that freshwater discharged by rivers in this region propagates far from the shore affecting sea surface temperature (Nghiem et al., 2014), which supports our claim of lower salinity. MacDonald et al. (1995) confirmed from GI-1 and PI-1 stations near the shallow shore that the ice core samples are mostly composed of freshwater (e.g., freshwater ice/total ice=1.71 m/1.72 m for GI-1) and the salinity is maintained close to 0 after mid-November (see its Figure 12). Stevens (2011) also confirmed that pore water salinity measurements (e.g., drilling sites BH01-BH05) are close to 0 up to ~ 5m depth below ice surface.

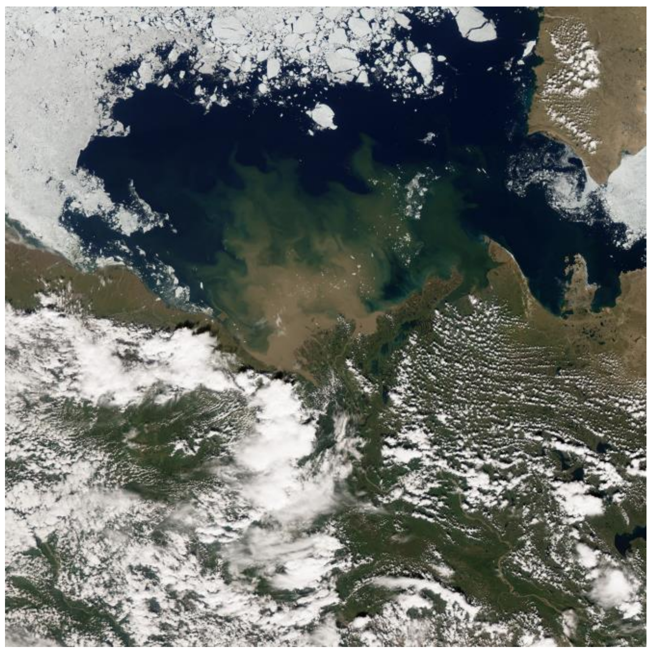


Figure S2

The radar backscattering from floating freshwater ice (green arrows in Figure 3c) is very strong compared to bottomfast ice (orange arrows in Figure 3c). If backscattering is from upper surface and volume, this cannot explain the difference between floating freshwater ice and bottomfast ice because both surfaces are not largely different. These are from different backscattering processes from ice-water interface (i.e. strong reflection) and ice-ground interface (i.e., absorption into ground). This was explained in lines 113-120 with references. Also, this was confirmed by GPR measurements in the Mackenzie Delta (Sevens et al., 2011).

In addition, we performed an additional case study to further confirm that scattering occurs at ice/water interface. For this we used archived 2 m resolution RADARSAT-2 ascending and descending SAR data acquired about 100 km east of our study area (still in the delta of Mackenzie river) during 20181021-20190321. We used identical processing with a large window size of 256x256 pixels, which corresponds to 512x512 m or 0.26 km^2 in this case. The linear deformation rate map is colour-coded for vertical motion and is shown as vectors for horizontal motion (Figure S3). This image (time-series is not shown here) shows similar responses from multiple frozen lakes and from the coastal sea ice. The horizontal motion from the coastal sea ice is also in the similar direction. The only feasible explanation of the similar signal observed over closed lakes (no water level change) and the sea is the growth of ice, especially when supported by a time-series analysis that shows a steady increase. The sea level remains nearly constant and does not show any downward trend during this time period. Previous studies of lake ice demonstrated that SAR backscratching occurs at ice/water interface (van der Sanden et al., 2013).

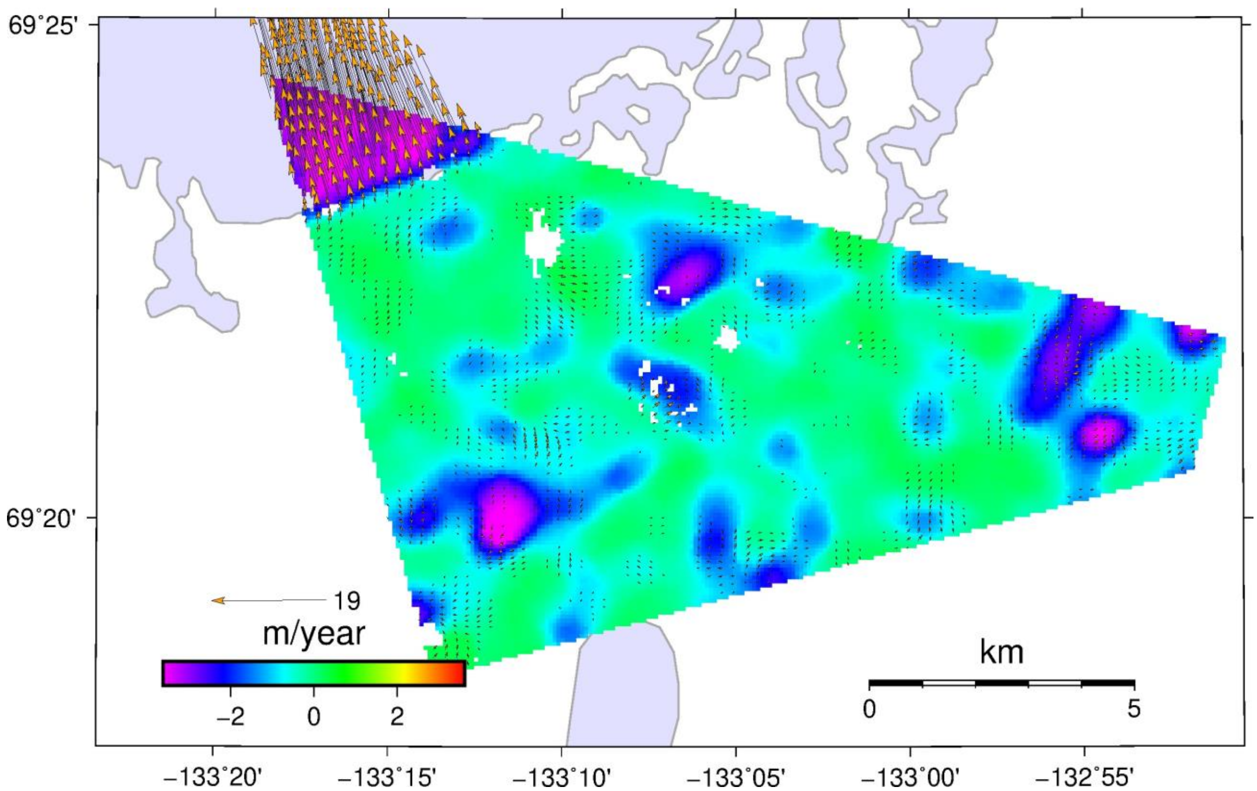


Figure S3

<u>3. Elevation increase due to ridging is unlikely to be detectable with this method</u>

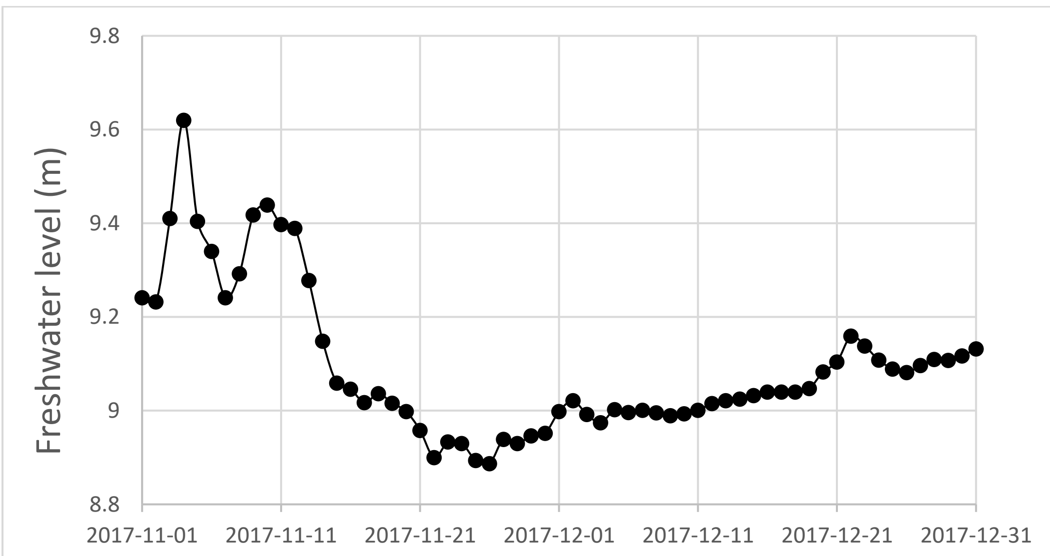
The authors attribute positive vertical ice surface motion to be the result of pressure ridging. This explanation sounds highly unlikely since any such ridging would dramatically change the surface scattering characteristics of the ice such that coherence would be lost between image acquisitions. This is similar to the problem of maintaining coherence from the ice bottom during thermodynamic growth, but a more extreme example of surface change.

We support an observation that ridging dramatically changes the surface scattering. However, this change is spatially gradual. It can be seen in Figures 4g-4i of the manuscript that the signal to noise ratio (SNR) decreases around ridges. Therefore, we can only map displacements until the peak of 2D cross-correlation is distinct and can be found by the offset tracking algorithm. The spatial coverage of our measurements is sufficient to observe the presence of ridging, but unfortunately not sufficient to fully describe it.

4. No discussion of vertical motion due to changes in local water level

I was surprised that the authors failed to consider other sources of vertical motion, besides ice growth and ridging. A far more likely source of vertical motion is variation in local sea level due to tides, winds, currents and river discharge. The authors clearly state that the discharge from the Mackenzie River continues to decrease between January and April, but fail to consider that this might lead to a decrease in water level near the Delta. This is a far more likely explanation for the negative vertical motion at locations LFI 1-3 that does not require the radar to penetrate the ice or for speckle to remain consistent from a growing ice bottom.

We discussed about the local freshwater and seawater level (lines 165-168) and ruled them out as insignificant. The local freshwater level had decreased until late November, but rather had increased since December as shown in Figure S4. For example, during 20171126-20180113 showing the largest downward motion up to ~1.5 m (Fig. 6e), the local freshwater level increased more than 0.2 m. Furthermore, the local sea water level shows small fluctuations between ±0.3m during the SAR acquisitions, not a consistently decreasing pattern. Thus, both freshwater and seawater levels do not affect the consistent downward vertical motions.



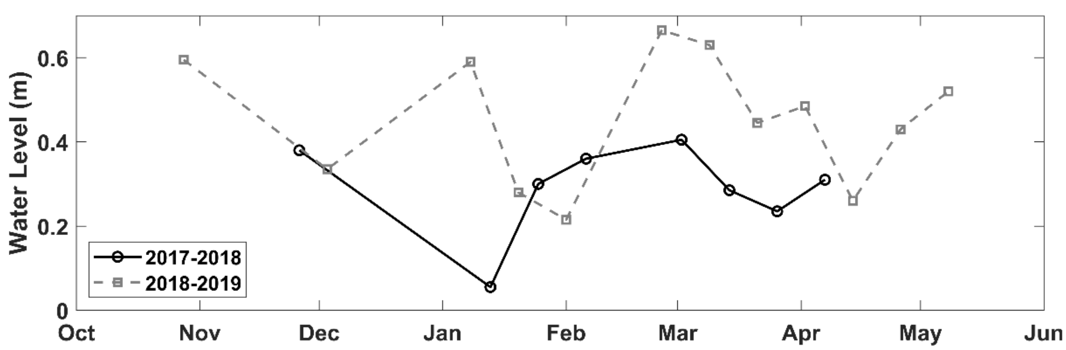


Figure S4. Local freshwater level (upper, from 10MC011 station at 69° 01´ N, 135° 30´ W) and local seawater level (lower, from Tuktoyaktuk station at 69° 43´ N, 132° 99´ W).

5. Interpretation of river current-induced horizontal motion is unsupported

The text repeatedly makes a connection between offshore motion of the landfast ice near the Mackenzie Delta and the direction of river discharge toward the Beaufort Sea (e.g., lines 137-139; lines 155-157; and line 193). However, I find this an unlikely explanation and the only supporting evidence the authors provide is that the discharge in winter is non-zero. If the authors wish to strengthen their claim that any offshore motion of the landfast ice caused by river outflow, they should estimate the likely basal stress on the ice and describe a likely mechanism by which this could fracture and displace the ice.

Most of the landfast ice near the Mackenzie Delta is floating ice as shown in Figures 1 and 3. We agree, however, the amount of freshwater discharge is very low during November to March, so it is not enough to explain the horizontal displacements. We analyzed wind statistics over the same periods and confirmed the direction of the horizontal displacements of drifting landfast ice agrees to the wind direction. In particular, the distinct northwest displacements (about -40° or 320° in Figure 5d, North is 0°) are largely affected by the strong SE wind from the Mackenzie Delta (about 120~150° in Figure S5d). Also, the horizontal displacements during 20180125-20180206 (Figure 5b) and 20180206-20180302 (Figure 5c) were affected by the strong W and WNW winds (Figures S5b and S5c). In addition, Lewis and Hutchings (2019) reported that the Eastern Coastal flaw lead is open and very active by the Beaufort Gyre motion moving from east to west. This largely affects the drift sea ice motions and the horizontal displacements towards east. The figure of wind statistics will be added after Figure 5. Wind and ocean current effects will be discussed in the revised manuscript.

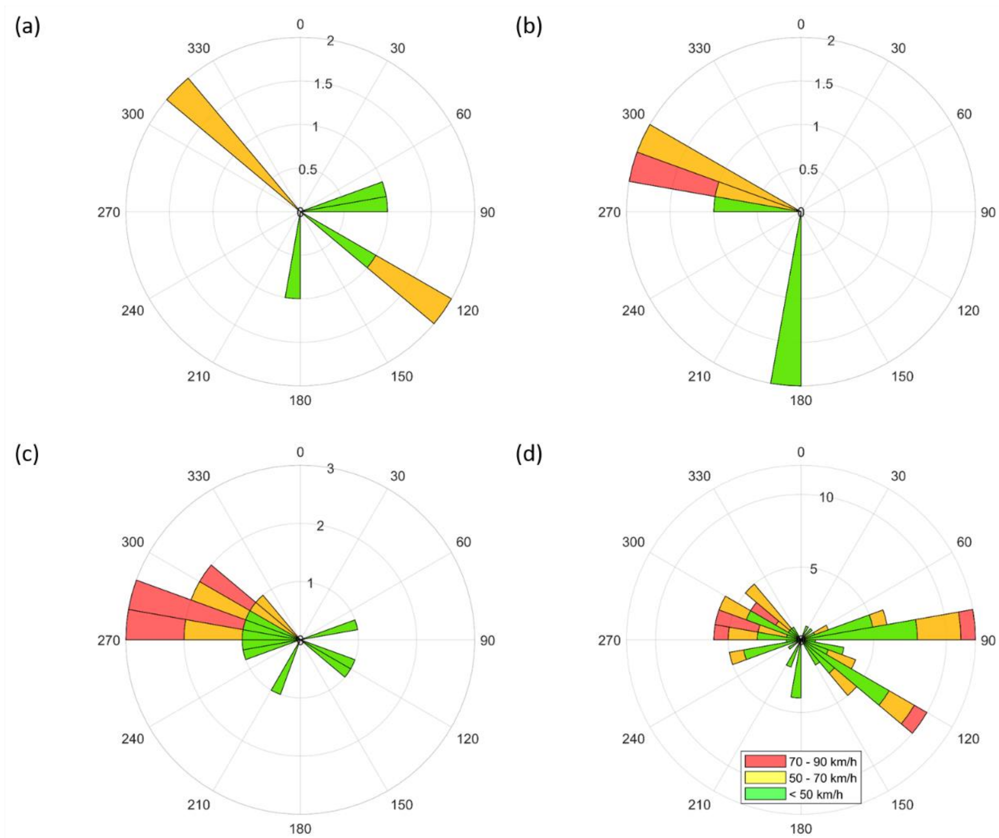


Figure S5. Wind statistics (Pelly Island station). (a) 20180113-20180125. (b) 20180125-20180206. (c) 20180206-20180302. (d) 20171126-20180407. North is 0°

References

Nghiem, S. V., Hall, D. K., Rigor, I. G., Li, P., and Neumann, G.: Effects of Mackenzie River discharge and bathymetry on sea ice in the Beaufort Sea. Geophysical Research Letters, 41(3), 873–879. https://doi.org/10.1002/2013GL058956, 2014.

Macdonald, R. W., Paton, D. W., and Carmack, E. C.: The freshwater budget and under-ice spreading of Mackenzie River water in the Canadian Beaufort Sea based on salinity and 18O/16O measurements in water and ice. J. Geophys. Res., 100(C1), 895-919, https://doi.org/10.1029/94JC02700, 1995.

Stevens, C. W.: Controls on Seasonal Ground Freezing and Permafrost in the Near-shore Zone of the Mackenzie Delta, NWT, Canada. PhD thesis, University of Calgary, https://doi.org/10.11575/PRISM/15339, 2011.

Stevens, C. W., Moorman, B. J., Solomon, S. M., and Hugenholtz, C. H.: Mapping subsurface conditions within the near-shore zone of an Arctic delta using ground penetrating radar. Cold regions science and technology, 56(1), 30-38, https://doi.org/10.1016/j.coldregions.2008.09.005, 2009.

van der Sanden, J. J., Drouin, H., and Bian, Y. : Repeat pass InSAR observations of river and lake ice cover: a preliminary evaluation of information content. Proceedings of the CGU HS Committee on River Ice Processes and the Environment (CRIPE) 17th Workshop on River Ice, 258-271. 2013.

Lewis, B. J. and Hutchings, J. K.: Leads and associated sea ice drift in the Beaufort Sea in winter. Journal of Geophysical Research: Oceans, 124(5), 3411-3427, https://doi.org/10.1029/2018JC014898, 2019.