Grounded ridge detection and characterization along the Alaska Arctic coastline using ICESat-2 surface height retrievals
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Responses in blue text.

Summary

This manuscript presents an analysis of the distribution of grounded sea ridges near the Alaska coast in the Chukchi and Beaufort Seas based on a combination of ridge sail heights derived from ICESat-2 altimetry data and GEBCO bathymetry data. The approach can be boiled down to 3 key steps. First, the individual ridges are identified and their sail heights determined using ICESat-2/ATLAS geolocated photon height (ATL03) data following the University of Maryland Ridge Detection Algorithm (Duncan and Farrell, 2022). Second, the range of likely keel depths associated with each ridge sail is estimated using sail height/deel depth ratios derived data reported by Strub-Klein and Sudom (2012). Lastly, grounded ridges are identified as those with keel depths exceeding the water depth at their location. The result of this approach is an impressively high fidelity picture of grounding locations within the landfast ice during the 2021-22 winter that suggests grounded ridges for in deeper water in the Beaufort Sea than the Chukchi, but overall the vast majority of grounded ridges are found in waters less than 15 m deep.

Overall, I enjoyed reading this paper and I believe the work will make a valuable contribution to our understanding of landfast stability and sea ice / seafloor interaction. However, in preparing this review I identified several concerns relating to a lack of methodological detail, missing discussion of relevant physical processes, under-utilization of uncertainty calculations, and perhaps an incomplete reading of some of the cited literature. Being quite familiar with landfast ice in this region, I find the sparsity of grounded ridges near the 20-m isobath surprising, particularly in the Beaufort Sea, and in its current form, I feel the manuscript leaves me with too many questions to take such surprising results at face Value.

I want to stress that I would very much like to see this work published. I don't think any of my concerns should be too difficult to address, and once they are, I would be feel more comfortable about accepting the authors finding regarding the water depth distribution of grounded ridges. I have provided detailed comments below explaining my concerns and I have attempted to make constructive recommendations for improving the manuscript.

We thank the reviewer for their kind words and helpful comments which we address individually below in blue text:

Major Comments

1. Why are the keel/sail ratios different from those reported by Strub-Klein and Sudom?

The principle findings of this manuscript critically depend on the ratio between sail height and keel depth. I am therefore surprised to see no discussion regarding the difference between the ratios determined via the linear regressions illustrated in Figure 3 and those reported by Strub-Klein and Sudom. For the Chukchi Sea, the authors find a linear regression with a slope of 3.37 and confidence intervals with slopes of 2.92 and 3.82, while Strub-Klein and Sudom report a mean ratio of 3.92. In the Beaufort Sea, the difference is greater with Fig 3 showing a regression slope of 3.49 and confidence interval slopes of 2.74 and 4.25 while Strub-Klein and Sudom report a mean value of 4.72. Given the significance of these ratios in the determining the apparent presence or absence of grounded features, I feel these differences should be discussed in some depth. For example, how many more grounded features would be identified beyond the 10 m isobath if the authors used Strub-Klein and Sudom's Ratios?

We had used a first-order polynomial fit to the sail heights/keel depths in order to account for the thickness of undeformed ice: using a consistent ratio can introduce errors in smaller ridges. That said, those small ridges are (a) likely to be filtered out given the requirement to exceed 0.7m height above modal surface level that comes from the UMD-RDA, and (b) unlikely to be grounded ridges anyways. We have re-run the analysis, using the mean ratios identified in Strub-Klein and Sudom ratios and accounted for the variability in keel/sail ratios in the observations by using a full standard deviation for the range of values. Our new ratios reflect the 3.92 and 4.72 sail:keel ratios for Chukchi and Beaufort seas, with standard deviations of 1.99 and 1.78 respectively. We treat the three ratios for each basin (mean - SD, mean, mean + SD) as 'high', 'medium', and 'low' confidence keel depths respectively.

All of the figures throughout the paper have been updated based on these updated keel depth ratios.

2. Uncertainties in keel depth and water depth are discussed but under-utilized

The authors list a number of sources of uncertainty that could affect their findings and on lines 131-132, the text states "These uncertainties are acknowledged in this study and the results are interpreted accordingly". I commend the authors for including confidence intervals on many of their figures, but the only subsequent reference to them is on lines 382-383 where the text reads "For ridges where the whole 95% confidence interval (indicated by the purple shading) intersects the sea floor, and the features remain persistent between two dates, we can detect grounded ridges with some certainty". Aside from this brief and rather qualitative statement, I can find no other indication that the confidence intervals are taken into account when identifying grounded ridges. As a result, the principal way in which the authors account for uncertainties in keel depth and bathymetry appears to be simply acknowledging their existence and the occasional use of qualifying terms like "potential" and "possible" when referring to the identification of grounded ridges. Instead, I encourage the authors to consider assigning some quantitative level uncertainty to each grounded feature based on the degree of overlap between the confidence intervals for keel depth and bathymetry. At the least, the authors need to clarify whether or not the confidence intervals play any role in the identification of the grounded ridges illustrated in Figure 10.

Thank you for this feedback: we have re-run the analysis detecting grounded ridges from keel depth estimates as described above. We use the three ratios for each basin (mean - SD, mean, mean + SD) as 'high', 'medium', and 'low' confidence keel depths respectively. A lower than average keel:sail ratio would result in a shallower keel draft, so ridges calculated using this ratio that intersect the interpolated bathymetric line are the most likely to really be grounded ridges. Without validation surveys of the bathymetric depths in the area or the keel:sail ratios in near-shore ice, quantifying the uncertainty in ridge detection is somewhat arbitrary. We feel using the 'high', 'medium', and 'low' designations accounts for the uncertainty in keel depth without artificially quantifying uncertainty when there are too many unknowns.

Figure 10 is updated to include these 'high', 'medium', and 'low' likelihood grounded ridges.

3. <u>Some additional clarification regarding derivation of sail height would be useful</u>
The text states that sail heights are measured relative to the surrounding undeformed ice, the freeboard of which is estimated based on a freezing degree day model. However, there is no specific explanation regarding how the surrounding undeformed ice is defined or identified. Duncan and Farrell refer to height of the local level ice surface (*HL*), which "is computed as the mode of the hc height distribution in 25 km along-track segments", where hc is the height of the sea ice surface above the mean sea surface, corrected for tides and atmospheric conditions. These are important details for interpreting the results presented in this manuscript and I feel they should be included in the text so that the reader does not have to search a separate publication. I would also like to see an explanation of how these 25-km track segments are treated at the coast. Specifically, are they are truncated at the coastline and, if so, what effect might this have on the derivation of level ice height and, therefore, ridge sail heights? Please also see comment 4 about the impact of sea level variations on sail height measurement for grounded ridges.

The processing algorithm presented in Duncan and Farrell excludes ice near shore in order to have the 25-km segments not risk intersecting the coast. For this study, we omit that step of the processing algorithm in order to get the near-shore ice surface heights. The local level ice surface calculated by the the UMD-RDA without that step in near-shore areas do not align with expected ice surface heights, so we do the following:

1. Find the modal surface height along the ICESat-2 track in the 4km closest to shore. This is to determine the `level ice height` in the region in which most ridging would occur.
2. Estimate the `thickness of undeformed sea ice` based on the date of observation and a FDD model using available weather station data.
3. Estimate the `level ice freeboard` using a buoyancy ratio of 917 kg/m3 : 1025 kg/m3. *
4. Set `sea surface height` to be the height of the freeboard below the modal ice height we calculated in step 1.
5. The sail height is then the `measured ice surface height` minus the `level ice height` plus the `level ice freeboard`.

We have added an additional figure to the methods section and revised the text accordingly to better illustrate the process we use to extract sail height, float level, and keel depth estimates from the surface elevation measurements.

* This likely slightly underestimates the height of the freeboard (sea ice tends to be slightly lower density than pure ice), which means this algorithm is more likely to slightly undercount grounded ridges, especially in areas with significant snow cover.

4. Some further discussion of local variations in sea level may be required

Although line 129 makes references to a 20-cm tidal range near Utqiagvik and acknowledges this can be a significant fraction of the water depth, I feel further discussion is required. First, I feel the text should recognize that wind-driven variations in sea level are much greater that than the tidal amplitude and can exceed 1 m (e.g. Mahoney et al, 2007b as cited in the manuscript). More significantly however, variations in sea level don't just affect water depth. They can have a much greater effect of the estimation of keel depth due to the way in which sail heights of grounded ridges are measured. Unlike floating ice, the height of grounded ridges relative to the surrounding ice will vary with local sea level and I think this is a more likely explanation than changes in snow depth for the "slight changes in the best estimate keel depths" noted on line 258. For example, the sails of grounded ridges will appear lower when the sea level (and the surrounding non-grounded ice) rises. This would have then have an amplified effect on the estimated keel depth: a 20-cm rise in sea level would reduce the sail heights of grounded ridges by 20 cm, which would then reduce the estimated keel depths by more than 60 cm, depending on the keel/sail ratio used. Hence, the number of grounded ridges could be significantly underestimated if the ridge sails were measured during a surge in local sea level and the authors might consider correcting their sail heights to account for the dynamic topography of the ocean. In effect, the use of the corrected sea ice height, hc, to derive the height of level ice, hL , (as described by Duncan and Farrell, 2022) may be counterproductive for the purpose of estimating sail height of grounded ridges.

We addressed tidal range because of the possibility of having consistently biased height measurements in a region if ICESat-2 overflight timing lined up with a particularly high or low tide. We are adding discussion of wind-driven changes in local sea level and the impact that would have on the estimates to the manuscript in the Bathymetry section of the Methods, and to our Limitations section.

A wind-driven surge in local sea level that drives the level ice up around a grounded ridge would likely result in this algorithm missing that ridge. With wind-driven variations in sea level height fairly random in time, we do not expect that would cause a systematic bias in under-detecting ridge heights in a particular area. With ground tracks spread across the Alaska Arctic each day for the five month period of this study, there are likely cases where both sea level is elevated compared to a grounded ridge and where it is depressed compared to a grounded ridge.

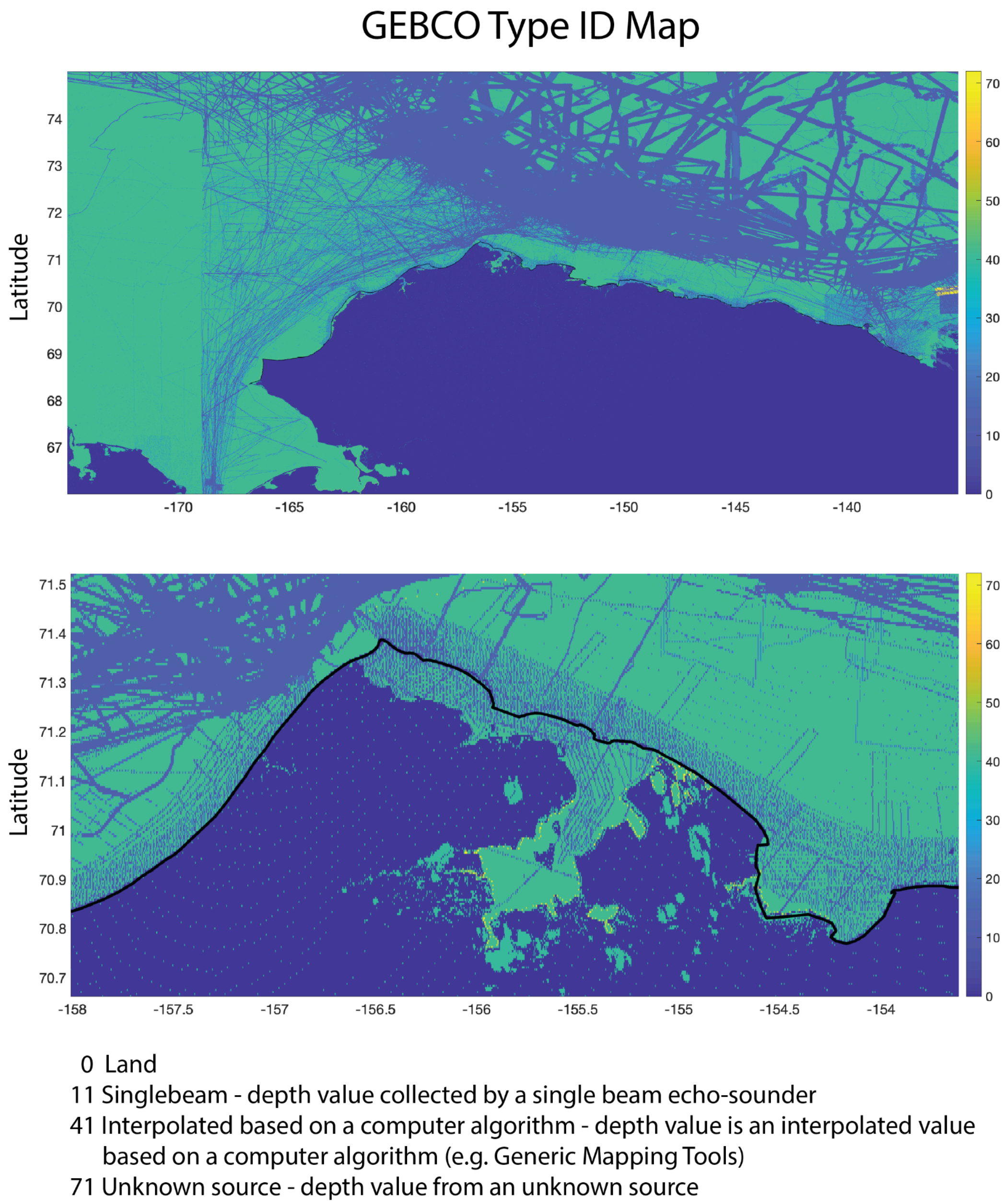
The idea of correcting sail heights for dynamic topography of the ocean is an interesting one, and one we would like to pursue further in a future study. From the relative surface height measurements alone, it is unclear which are grounded ridges where the surrounding level ice is elevated versus smaller ridges which do not extend deep enough to be grounded. For tracks where we have reliable retrievals of surface height over shore though, it would be possible to account for the dynamic height and more systematically study the impact of short-term sea level variation on ridge grounding. This would be outside the scope of this paper, but certainly an interesting idea to pursue.

5. GEBCO data are of questionable reliability in shallow water

Given the sparsity of sounding points in shallow water and the year-to-year variability of the bathymetry in these regions, I am somewhat skeptical of the validity of using GEBCO bathymetric data all the way up to the coastline. The GEBCO Type Identifier (TID) Grid, available with GEBCO bathymetry data, show that broad areas of the Alaska coast shallower than ~5 m are coded with the value 41 which indicates the bathymetry values are “Interpolated based on a computer algorithm”. I would therefore recommend the authors exercise more caution when identifying grounded features in shallow water. The authors already exclude features in water shallower than the level ice drafter, but I don’t understand the rationale for this (see comment 6). Instead, I recommend the authors establish a shallow-water cut-off value, based on the GEBCO TID Grid. This value might vary regionally according to the density of sounding points used in the GEBCO grid, but this would provide a data-driven rationale for excluding ridges in shallow water. Also, under the topic of bathymetric uncertainty, I don’t understand how the orange areas in Figures 4-7 were derived. Line 209 states “The orange shading represents positional uncertainty in the bathymetry line”, but the width of the orange shading would suggest that the positional uncertainty is on the order of hundreds of meters, which seems too high.

In the 2024 GEBCO product, the TID Grid does not identify shallow water areas as consistently interpolated (Type 41). We have included in this response a map of type identifiers both across northern Alaska and in the area around Utqiagvik and Elson Lagoon (following page). There are singlebeam depth measurements (Type 11) in shallow water (≤ 2 m) including in lagoon areas. GEBCO does not establish a shallow-water cutoff.

That said, there certainly are issues with depth estimates at shallow water depths. In re-running the analysis we implement a general shallow water cutoff at 3m depth. This is in part due to the uncertainty in shallow water measurements, but generally to exclude features inside the lagoon areas. The orange bars in the original version of figures 4-7 reflected the 500m spatial resolution of the GEBCO product. We have removed these and instead address issues regarding the coarse spatial resolution of the GEBCO product in the discussion.



6. <u>Exclusion of ridges in water shallower than draft of undeformed ice seems unnecessary</u>

I don't understand the rationale for excluding ridges in water shallower than the draft of undeformed ice. For such ridges to exist at the location, they must have become grounded at some stage when the ice was thinner. Hence, excluding ridges based in undeformed ice draft creates the possibility of a scenario in which a ridge is counted as grounded on one day, but excluded the next. I would therefore discourage the authors from excluding features on this basis and instead simply apply a shallow water cut-off as explained in comment 5.

We implement a shallow water cutoff of 3m to distinguish grounded ridges from bottom-fast ice along the coastline. Without a shallow water cutoff in the GEBCO product to use, we found that 3m excluded features inside lagoon areas and rubble on beaches without excluding too many grounded ridges. Using 5m for the shallow water cutoff excluded a lot more high-likelihood grounded ridges and seemed too high an arbitrary threshold given the data available.

7. Some more careful reading of Mahoney et al (2007a, as cited in the text) may be required
The text makes many references to the work of Mahoney et al (2007a), which I feel mischaracterize what is written in the cited work. For example, on line 308, the text states "Mahoney et al. (2007a) assumes a sail width of 100 m for grounded ridges", but this is a rather inaccurate description of what was written in that paper. For the purposes of estimating the possible spatial density of grounded ridges, Mahoney et al assumed that the keels of ridges deep enough to become grounded were on the order of 100m wide. This is not the same as assuming grounded ridge sails are 100 m wide.

We thank the reviewer for clarification on Mahoney et al.'s results. We removed the reference to Mahoney et al. (2007a) from this paragraph so as to not misrepresent that work and instead reference the ridge width statistics presented in SKS 2012.

Similarly, line 315 begins with the statement "Mahoney et al. (2007a) suggested grounded ridges discontinuously pin the landfast ice edge, roughly every 30 km". In this case, I feel the authors are taking what is written in the cited article somewhat out of context. Instead, Mahoney et al. wrote that grounded ridges would be spaced approximately every 30 km if the thickness distribution of landfast ice was the same as that measured offshore in the drifting pack ice. And they go on to note that grounded ridges are observed more closely spaced than this, suggesting that they are produced through "in-situ" grounding process (i.e. like those illustrated in Figure 1 of this manuscript).

Thank you for this clarification, we have revised the discussion around the frequency of grounded ridges observed in the tracks:

Our results suggest, on average, 1.9 and 2.5 medium-confidence grounded ridges per ICESat-2 ground track in the Chukchi and Beaufort regions respectively (with ranges of 0.4 - 5.1 and 0.5 - 6 .7 between high and low confidence ridges in the two basins). Given these tracks pass over an effectively random sampling of coastal Arctic sea ice, and that there are on average >1 ridge per track, we can infer that any along-shore section of ice is likely grounded by at least one ridge, though there are certainly some places without any grounded ridges (approximately 16% of ICESat-2 surface height profiles examined contained no grounded ridges at any confidence level, and 40% had no high-confidence grounded ridges). We also find that the average high confidence grounded ridge location was 23 % and 17% of the distance between the coastline and landfast ice edge in the Chukchi and Beaufort Sea regions, respectively. Together, this suggests that coastal sea ice is regularly supported by frequent grounded ridges in the shallow water (< 10 m depth) and infrequent grounded ridges in the deeper stamuki zone. This is a higher spatial density in the shallow water zone than in pack ice (Mahoney et al 2007a), which would suggest a combination of in situ ridge formation and advected ridges getting stuck in shallow waters.

Lastly, on line 320, the text claims “Mahoney et al. (2007a) assumes that these grounded ridge features are located close to the SLIE”, but I again feel this does not accurately represent what Mahoneyet al. wrote. Rather than making any general assumption that grounded ridges are located close to the SLIE, they identify "nodes" where the SLIE occurs most commonly and suggest that these correspond to the location of interannually recurring grounded features. Additionally, I recommend the authors consider citing Mahoney et al's more recent 2014 paper, which expands on the discussion of these nodes and provides photographic documentation of a grounded ridge in the location of a node that happens to be very close to the location of line C in Figure 2. I also feel that some further discussion of the location of the nodes identified by Mahoney et al in relation to the distribution of grounded features shown in Figure 10 would be a valuable addition to the text.

We have added further reference to Mahoney et al.,’s 2014 discussion of nodes in the landfast ice in the discussion. Thank you for sharing the shapefile for the locations of nodes identified in Mahoney et al. 2014 – we have added these to the updated version of Figure 10. Figure 10 will be further revised to include three subsets with zoomed-in views of areas around three of the nodes (near longitudes -162, -155, and - 148). The text will be revised to include this additional discussion:

Nodes from Mahoney et al., 2014 are included in the map on Figure 10, representing locations in which the landfast ice edge is statistically more likely to occur. Within each location, we find grounded ridges detected from our algorithm. In some nodes (e.g., the node at -162 longitude, closest to Point Lay, inset A), we see a cluster of grounded ridges, including high-confidence grounded ridges, at the landfast ice edge, pinning that edge in place but not providing any support for an extended SLIE. In other nodes (e.g., the node at -155 longitude, close to Point Barrow, inset B), relatively few grounded ridges are close to the landfast ice edge, and they are all low-confidence detections. This suggests that the local ice dynamics support a more extensive SLIE. The node at -148 longitude (near Prudhoe Bay, inset C) shows a combination of these behaviors with many grounded ridges close to the ice edge at the west end, but a larger SLIE at the east end.

Minor comments

Line 9 (and throughout the text): The word “Alaskan” is a noun referring to someone from Alaska. When used an adjective, the correct term is Alaska.

This will be corrected throughout the text.

Figure 1: This figure illustrates one of two ways in which a sea ice ridge can become grounded. The other way involves advection of a deep-keeled ridge into shallow water. Mahoney et al (2007b as cited in the manuscript) speculate that the latter is more likely to create a gouge in the seafloor and is therefore more significant for stabilizing the landfast ice. The authors may wish to acknowledge both ways of creating a grounded ridge and the differences between them.

We acknowledge the advection of deep-keeled ridges in the text, but agree that this can be more explicit and have updated the introduction accordingly. We have added an alternate development track in Figure 1 to make this mechanism more clear, and we have added discussion throughout the manuscript to better reflect this mechanism.

Figure 2: Why did the authors select these ICESat-2 tracks? Had they selected tracks that intersected the coast closer to Utqiagvik, they could fallen within the footprint of UAF's sea ice radar and there's a good chance that they would have intersected whaling trails where sea ice thickness has been routinely measured since 2007 (https://arctic-aok.org/data-sources/whaling-trail-mapping/). These data are both reference could have provided useful validation for the thickness of level ice in the region. Also, why is Line C truncated before the 20m isobath? From several years of observations, the landfast ice in this region is commonly anchored by grounded ridges just beyond the end of Line C.

These tracks were picked for showing a variety of sample ridge conditions, as part of the initial case study. Cloud cover/precipitation can prevent surface height retrievals, and these three tracks had very few segments of missing data in the regions around Utqiagvik for ground tracks both in January and April of that year. There are not available tracks with full coverage in both January and April that are closer to the Utqiagvik sea ice radar during the 2021-2022 winter. We do have a pair of tracks from December and March, but the December track is prior to the formation of grounded ridges.

There are a few single tracks (without repeat) that intersect the sea ice radar area. Grounded ridges detected in the sea ice radar area are approximately 1.2km from shore: this is consistent with the persistent features in the sea ice radar. It is harder to see those features in individual images in the sea ice radar (more apparent in the video animation), so we are not going to put an ice radar image in the paper, but we have added discussion to section 4.1 (Detection of Grounded ridge features) describing this additional means of validation.

We have updated the figure for Line C beyond the 20m isobath. In the January track, there are no further grounded ridges beyond what was shown in the prior version. In April, there is one ridge at 14km from shore that barely intersects the bathymetry line for the largest keel:sail ratio estimate ('low' confidence ridge) at 16m bathymetric depth. We have updated the discussion accordingly.

The whaling trail mapping effort has a lot of potential for a larger validation study of this approach: while we were only able to process a single year of the ICESat-2 data for this project, we hope to secure funding for a larger effort covering more years and more area. Working with the local community for detailed sail height measurements (and any keel geometry information) would be an important part of that.

Lines 265-267: There are multiple assertions here that should be supported by references. I think I know what the authors mean by the "classic" ridge, but I have a suspicion that its classic status derives from simplifications adopted in many illustrations of coastal ice over the years together with a bias in the early literature toward ridges in the Beaufort Sea. Also, can the authors provide a reference supporting the "prevalance of shear" on the Chukchi Side of Point

Barrow? The climatological prevailing wind is from the east, with creates a lot more divergence than shear and a lot less shear than on the Beaufort side of Pot Barrow

We reviewed the sea ice radar animations for the 2021-2022 winter: while there isn't overlap with the ice radar field of view and the ICESat-2 track, the radar does indicate the direction of pack ice movement during the periods of interest. We have changed the description in this section to be more specific about the dynamics at work here:

The spatial resolution of the SAR imagery poses a challenge for unambiguous interpretation of grounded ridges and is an insufficient tool by itself for determining where exactly ridge features form or for characterizing their geometry. The nearby Utqiagvik Sea Ice Radar (UAF, 2022a) shows pack ice motion towards the east/north-east, resulting in a compressive ridge building event on February 22, 2022. This ice motion, combined with the existing land-fast ice in the area, creates ridges that are not necessarily parallel to shore. We measure ridge width using the distance from shore, so a ridge that is not parallel to shore will overestimate the ridge width. While the field of view of the radar does not overlap with this track, the orientation of the bright patches in the SAR imagery near ridge 3 (forming between Feb 18 and Mar 2) at an angle relative to shore is consistent with the ridges visible in the Utqiagvik sea ice radar from that period.

Line 337-338: The reasoning behind this explanation in the final sentence of this paragraph is not clear to me. If grounded ridges in the same water depth are higher in the Beaufort Sea than in the Chukchi, this means the ice is piled higher above the waterline in the Beaufort. I can envision a few mechanisms that might cause such a difference (for example in-situ grounding vs advection of deep-keeled ridges in shallow water) and how they might relate to coastal aspect or parent ice thickness, but I feel most readers would benefit from further explanation.

We appreciate this feedback and have added additional explanation to the text:

In the Beaufort Sea, grounded ridges at the same bathymetric depth tend to be slightly taller than those in the Chukchi region. This difference in ridge height may be attributed to a combination of factors, including shoreline orientation relative to predominant ice drift, the thickness of the parent ice floe, and the processes by which grounded ridges form. Drift patterns in the Beaufort region bring thicker ice closer to the shoreline on a trajectory roughly perpendicular to shore. This increases the likelihood of advection of deep-keeled ridges from the pack ice into shallow waters.