Grounded ridge detection and characterization along the Alaskan Arctic coastline using ICESat-2 surface height retrievals

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Review

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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.

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?

2. <u>Uncertainties in keel depth and water depth are discussed but under-utilized</u>

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.

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 (H_L), which "is computed as the mode of the h_c height distribution in 25 km along-track segments", where h_c 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.

4. <u>Some further discussion of local variations in sea level may be required</u>

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, h_c, to derive the height of level ice, h_L, (as described by Duncan and Farrell, 2022) may be counterproductive for the purpose of estimating sail height of grounded ridges.

5. <u>GEBCO data are of questionable reliability in shallow water</u>

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 bathmetry 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.

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.

7. <u>Some more careful reading of Mahoney et al (2007a, as cited in the text) may be required</u>

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.

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).

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 Mahoney et 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.

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.

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.

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.

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

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