Answers to Referee #1

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This is a review of the paper entitled Linking the evolution of floe sizes to the sea-ice deformation history using SAR imagery by Hutter and Bitz. The study utilises SAR imagery to track the deformation of consolidated Arctic sea ice over successive days, corresponding to the temporal resolution of the imagery. Floe chord distributions (FCDs) are measured over defined regions of interest (ROIs) using a random sampling approach, as has been used in previous studies (e.g., Rothrock and Thorndike, JGR, 1984). Rigorous statistical analyses are conducted to translate FCDs into floe size distributions (FSDs), demonstrating that a numerical inverse method outperforms an analytical approach when compared against known FSDs.
Overall, I quite enjoyed reading this paper and consider it to be of high quality, with clear writing, careful analysis, and well-justified claims. I also find the novelty of the FSD parameterisation of large-scale sea-ice deformation to be of significant interest to the sea-ice modelling community, as mechanisms to constrain floe sizes in the consolidated ice cover are currently missing from state-of-the-art sea-ice models. The presentation of results and figures is also of a very high standard. Therefore, I recommend that this paper be published following minor revisions.
We thank the anonymous referee #1 for the positive and constructive feedback for our manuscript. Please find our answers to the minor and specific comments along with suggested changes to the manuscript below.

Minor comment—Sampling of large floes

My only minor comment concerns the sampling of floes that may partially lie within the observation domain (i.e., floes cut off by the edge of the ROI).
Line 255 reads: "*Note that we also consider the first and last segment as valid chords, even if the segment is cut short by the ROI boundary*." I would like the authors to clarify whether, in the case of a floe partially captured by these segments, strong divergence could cause the floe to move further out of the ROI, resulting in a perceived decrease in floe chord length without an actual change in floe size. I could also imagine that including these cut-off chords may be particularly impact large floes (>~ 10 km), which are somewhat comparable to the ROI size (50x50 km), and also the floe sizes that exhibit the largest reductions in size via deformation (e.g., Fig 9). Similarly, could this segmentation choice be contributing to the abundance of small floes, for example the peak near zero in Figs. 3(d)? I do not consider this a major methodological issue, but some clarification around this choice would be appreciated.
In our analysis we track the boundary of our ROIs using the drift derived from the SAR images. Since the boundary of the ROI moves with the ice, no floes leave the ROI due to deformation

and advection. In case of divergent ice motion the size of the ROI increases, but covers the same ice area and the same floes (or parts of floes if they are only partially covered by the ROI). Due to the coarser resolution of the SAR drift estimates, the advected ROI boundary might not perfectly resolve the motion of floes smaller than the drift product's resolution (700m) that are located on the ROI boundary. The displacement of larger floes, however, is tracked accurately. Therefore, the portion of a large floe within the ROI does not change between the consecutive images in our analysis. Therefore, the observed changes in the abundance of large floes result from fracturing of these floe portions, which results in the observed increase in small floes. Please also note that in the statistical conversion of FCD to FSD, we especially consider also large floes that are only partly covered by the ROI when constructing the conditional probability F(c; d).

Specific comments

L23: "*Besides lateral melting and freezing along floe edges, which leads to erosion and growth of small floes...*" Does this sentence mean that ice floes cannot increase in floe size from lateral growth and that the new ice produced prefers to create new floes?

We agree that the wording is misleading. Floes of all sizes increase size by lateral growth. Additional new ice is frozen as pan-cake ice in the smallest floe size bin. We modified the sentence above for clarification to:

"*Besides lateral melting and freezing along floe edges, which alters the sizes of floes…*"

L146: "*... distinguish only the two classes of ice and open water*" Was frazil or grease ice ever problematic for the classification of open water?

New ice, like frazil and grease, is typically smoother than the thicker surrounding ice and has a lower backscatter signal in Sentinel's C-band SAR (Johansson et al., 2017). These instances would be classified in our analysis as open water, since the pixel backscatter value is lower than the average local backscatter representative of thicker ice. This identification as "open water" and therefore floe boundary is reasonable as the frazil and grease ice would not constitute a stable bound between two rigid floes. However, in the manual adjustment of the ice-ocean mask thresholds, we have not come across any scene with areas of frazil and grease ice that we expect to impact the presented results.

Figure 2: I appreciate the effort taken into all of the plots, they are of very high quality. One question I had here was, from the images (Fig. 2a), the number of floe chords increases with the number of fracture lines in the ice cover (since more segmentations occur). However, I don't think it immediately clear how this is translated to a FSD, rather it appears to be a measure of the deformation of the sea ice (which models should still incorporate), but it doesn't look like what a reader may expect using the standard (and somewhat idealised) definition of the FSD ('collection of distinct floes'). Nothing really to change here, just a thought.

It is true that a more fractured scene would have a higher number of segmentations and that the distribution of segments would necessarily increase for smaller segments. All panels in Figure 2a have the same amount of fracture since they are for a single day. However, if we were to compare two scenes from different days but with the same number of lines, the one with more fracture would translate to a higher FSD.

L311 "*Hereby, the floes are allowed to only partially lay within the box and to overlap with other floes by up to 5 pixels*" Does this mean that this threshold is applied to both floes that are lying partially within the box and the overlapping floes? I think it's only applied to the overlapping floes, but maybe revise this sentence for clarity.
You are correct that the threshold is only applied to the overlapping floes. We split both sentences for clarity:
"Hereby, the floes are allowed to only partially lay within the box. Floes are also allowed to overlap with other floes by up to 5 pixels."

L324: "*Contact between small floes results in longer chords measured, which neither method can dissect and therefore both attribute these medium size chords to the presence of medium size floes leading to an overestimation of medium size floe sizes*" I find this sentence a bit clunky, maybe revise it's structure.
We agree and reformulate to:
"Contact between small floes results in "merged" medium-sized chords measured. Neither method can separate these "merged" chords, so both misattribute them to medium-sized floes, causing an overestimation in that size range."

L402: "*... while the majority of ROIs is undergoing convergent ice motion*" Shouldn't this be "are" not "is"?
Corrected

L423: "*... we observe general patterns depended on the mode of deformation*" Should this read "we observe that general patterns depended on the mode of deformation"?
We agree that the current wording needs clarification and we modified it to:
"On top of this chaotic spread driven by local ice conditions, general patterns emerge when grouping by the mode of deformation."

Figure 3: I like the analysis of Figure 3/§3.2.3, I think it provides novel data of floe geometries and appears to be rigorously estimated. I also find the general "egg" shape to be interesting.
We appreciate your positive feedback.

L433: "*... size floes (300 m ≤ d ≤ 10 km) following the general intuition that convergent ice motion facilitates coagulation of smaller floes*" Does this mean that coagulation is preferential towards such medium size floes?
In our analysis of convergent states, we observe two opposing processes that shape the FSD, coagulation and fracturing. Fracturing reduces the amount of large floes and increases the amount of small and medium size floes. Coagulation reduces the amount of small and medium floes and increases the amount of large floes. Determining the exact individual footprints of both processes from our data is not straightforward and we can only get a hint by grouping ROI by convergence rate. For low convergence rates, we observe also a reduction of small floes suggesting that both small and medium size floes are coagulated. In strong convergent events, however, fracture occurs simultaneously to coagulation outbalancing the reduction of small floes

and resulting in the FSD changes in Fig.8. We modified the test accordingly to make this clear: *“For convergent ice motion, we find significantly lower changes in the number density of floe chords. The observed redistribution becomes clearer when converted to floe sizes. The amount of large floes ($d \gtrsim 10$ km) increases alongside a reduction of medium size floes (300 m $\lesssim d \lesssim 10$ km) following the general intuition that convergent ice motion facilitates coagulation of smaller floes to larger ones. This process also takes place at lower convergence rates**, where in addition to medium size floes also small floes ($d \gtrsim 300$ m) contribute to coagulation.** The strong convergent states, which are averaged in Fig. 8, however, show an additional increase in small floes ($d \gtrsim 300$ m), a clear sign of ice fracturing in compressive ice states accompanied by strong shear motion taking place simultaneously with a closing of the ice cover described above.”*

L435: "*Fig. 8, however, show an additional increase in small floes (d ≥ 300 m), ...*" This should be "(d ≤ 300 m)"?
Corrected

L501: "*in Eq. (12)-(14)*" should be Eq. (12–14).
Corrected

L555: "*However, the observed redistributions for convergent ice motion are more diverse, which partly could be explained by fact that our processing chain does not fully resolve boundaries of floes between floes in full contact with each other.*" While, I understand the increased difficulty in understanding change in FSD during convergence events, I think that the data is quite interesting. I would like to see future work (since it is probably out of scope) explaining this regime since the authors' mention that can result in both increases and decreases in floe sizes (i.e., from coagulation or fracture of floes, respectively).
We agree with the referee that FSD changes in convergent events are very interesting and should be explored in future work. We discussed the shortcomings of our processing chain for that direction and recommend to use DEM simulations instead to fully resolve fracture, ridging and coagulation. Nevertheless, the data used in this study will be published once the manuscript is accepted for anyone interested to study these effects more closely in our data.

References

- Johansson, A. M., Brekke, C., Spreen, G., & King, J. A. (2018). X-, C-, and L-band SAR signatures of newly formed sea ice in Arctic leads during winter and spring. Remote Sensing of Environment, 204, 162–180. https://doi.org/10.1016/j.rse.2017.10.032

Answers to Referee #2

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The article presents a novel method for characterizing the winter sea ice floe size distribution (FSD) from SAR imagery and linking changes in the FSD to sea ice deformation. The topic is highly relevant for sea ice model development as well as for better understanding the properties of sea ice in winter. The article is very thorough and the visualizations are clear, and thus I recommend publication after minor revisions.
We are very grateful for the positive feedback to our manuscript. We address your raised comments below.

Minor comments

L22: "*deformation of the horizontal ice velocity*" – is it not sea ice deformation inferred from the ice velocity? The phrasing seems odd to me.
Agreed, we rephrase the fracture description to:
*"Overall, three groups of processes drive the evolution of the FSD: thermodynamics, interaction with ocean surface waves, and **mechanical fracture from horizontal ice deformation**;"*

L75-78: it would help to see where in the Arctic the images come from
We agree that this could be helpful for readers not that familiar with the MOSAiC expedition and produced an overview figure for the appendix:

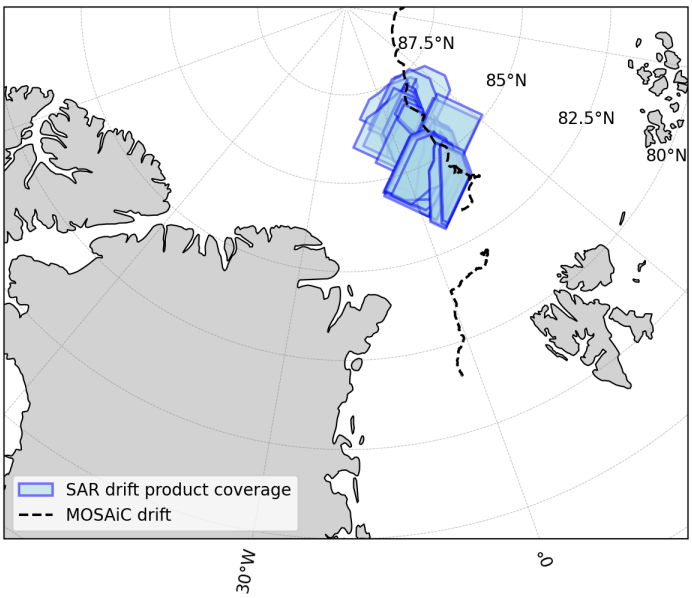


Fig A1: *Overview of the spatial location of all SAR scenes analyzed in this study. Sentinel SAR images were cropped to 400 x 400 square kilometer area centered around Polarstern, following the spatial coverage of the SAR drift product (von Albedyl & Hutter, 2023) used in this study. The dashed line shows the passive drift track during MOSAiC. In this study we only use SAR images between March 13 and May 31, 2020.*

L82: It would be helpful to provide a brief recap of the derivation of the drift vectors here, so that the reader doesn't need to look up the PANGAEA page to know what method was used.
We extended the description of the drift data with a sentence highlighting the algorithm used: *"The ice drift between consecutive SAR images was previously calculated with a feature tracking method for the MOSAiC campaign (Krumpen et al., 2021).* ***The algorithm of Thomas et al. (2008, 2011) and Hollands and Dierking (2011) was applied to HH-polarized Sentinel-1 scenes with a 50-m pixel resolution and a typical temporal spacing of one day, yielding drift fields on a regular 700-m grid from which divergence, convergence, and shear were computed as spatial derivatives.*** *The complete dataset for SAR-derived ice drift and deformation is available at von Albedyll and Hutter (2023)."*

L95: "binary images of 125 m" The highest MODIS band resolution is 250 m, perhaps 250 m resolution is what is meant here?
Thank you for catching this typo, we corrected it.

L101: Check style guide for vessel names
Done, corrected to ship name in italic: "RV *Polarstern*"

L172: note explicitly what definition you are using for the deformation and shear (either by reference or in the appendix if there is not room in the manuscript).
We added the used definitions into the sentence.

L345: I note that the regime change is happening at about 1/2 the size of the ROI. Have you investigated the sensitivity of the results to the ROI size?
The floe size, at which the change in FSD flips sign, is related to the size of the ROI, since the size of the largest possibly observed floes depend on the ROI size. In an ROI of 50x50km^2 no floes larger than 50km can be observed. Assuming power-law distributed floe sizes, a larger ROI could also include larger floes that could be fractured, potentially shifting the regime transition to larger floe sizes. In Sections 4.3 and 4.4 we discuss that the unchanged floe size d_0 is not a free parameter, but can be derived from the ice area conservation constraints and depends on ROI size, divergence rate and the present FSD. Besides these analysis, we have not studied FSD in different ROI sizes and rather aimed to align our ROI size with the resolution of climate models currently using the prognostic FSD parameterization.

L410: In fitting the power law exponent, how do you choose the minimum and maximum floe sizes?
The power law fit is performed over the full floe size and chord range. We added this information to the caption of Figure 7.

L415: Indeed, you may wish to explicitly mention prior observations of seasonality in the FSD slope.

We agree and added a reference to prior studies on the seasonality of the power-law exponent in the modified test:

“A seasonal dependence of the FSD slope is well documented, with steeper exponents in fragmented summer conditions and shallower exponents in consolidated winter pack ice (Stern et al., 2018a). Our shallow exponent is therefore consistent with the winter conditions analyzed here, in contrast to the summer conditions studied in most previous studies.“

References

- Hollands, T., & Dierking, W. (2011). Performance of a multiscale correlation algorithm for the estimation of sea-ice drift from SAR images: initial results. *Annals of Glaciology*, *52*(57), 311–317. https://doi.org/10.3189/172756411795931462
- Thomas, M., Geiger, C. A., & Kambhamettu, C. (2008). High resolution (400 m) motion characterization of sea ice using ERS-1 SAR imagery. *Cold Regions Science and Technology*, *52*(2), 207–223. https://doi.org/10.1016/j.coldregions.2007.06.006
- Thomas, M., Kambhamettu, C., & Geiger, C. A. (2011). Motion Tracking of Discontinuous Sea Ice. *IEEE Transactions on Geoscience and Remote Sensing*, *49*(12), 5064–5079. https://doi.org/10.1109/tgrs.2011.2158005