General Comments

The study provides valuable insights into the seasonal dynamics of sea ice floes in the Weddell Sea using high-resolution data from ICESat-2. The use of altimetry to quantify floe chord and freeboard thickness distributions, as well as lead width and vertical floe roundness, adds a crucial dimension to understanding sea ice behavior and its regional variations. This study contributes to the development of floe-resolving models by offering detailed diagnostics of sea ice processes. However, I have several concerns regarding the usage of the ICESat-2 datasets and the clarity of the methodology. Therefore, I recommend that the paper undergo major revisions before it can be considered for publication.

Thank you for your review and for recognizing the advances made by our work.

Here are my major comments:

1. I'm not sure if the manuscript presents enough innovative methodologies/findings since many previous publications have already used altimeters, including CryoSat-2 and EnviSat, to derive floe chord distribution (Horvat et al., 2019) and lead-to-floe (Tilling et al., 2019). Additionally, it is unclear whether the results might depend on the specific ATL 07/10 version.

We certainly acknowledge that several past studies have developed methodologies and estimated floe characteristics from altimetry. For example, Horvat et al. (2019) explored the spatial and temporal changes in FCD for the Arctic Ocean using CryoSat-2; Tilling et al. (2019) used CryoSat-2 to help validate the coarser measurements of Envisat in the Arctic Ocean for floe size and thickness; Petty et al. (2021) assessed the ability to use ICESat-2 to extract floe and lead characteristics in both hemispheres; Farrell et al. (2020) discussed the topography of sea ice using ICESat-2. We cite these papers and others in the introduction.

Here, our primary focus was to better understand the seasonal cycle of sea ice within the perennial ice pack of the Weddell Sea at finer scales than has previously been done, and connect these fine scales inferences to the larger-scale behavior of the pack, as inferred from coarser satellite measurements. In the process of studying the behavior of floes and leads within this region, we developed some novel metrics (e.g. floe roundness and lead spacing) that we argue are useful in characterizing the properties of the pack, and could therefore be applied to other regions in future work. It was nevertheless not our main intent to develop new methodologies for processing altimeter data.

Our main novel scientific findings are as follows:

1. The seasonality of the FCD is tied to the melt/freeze cycle, in both the west and south Weddell Sea, despite their substantial differences in ice types.

2. By contrast, the seasonality of the fITD suggests mirrored behavior during the melt season despite the total freeboard thickness having a similar phasing between these two regions.

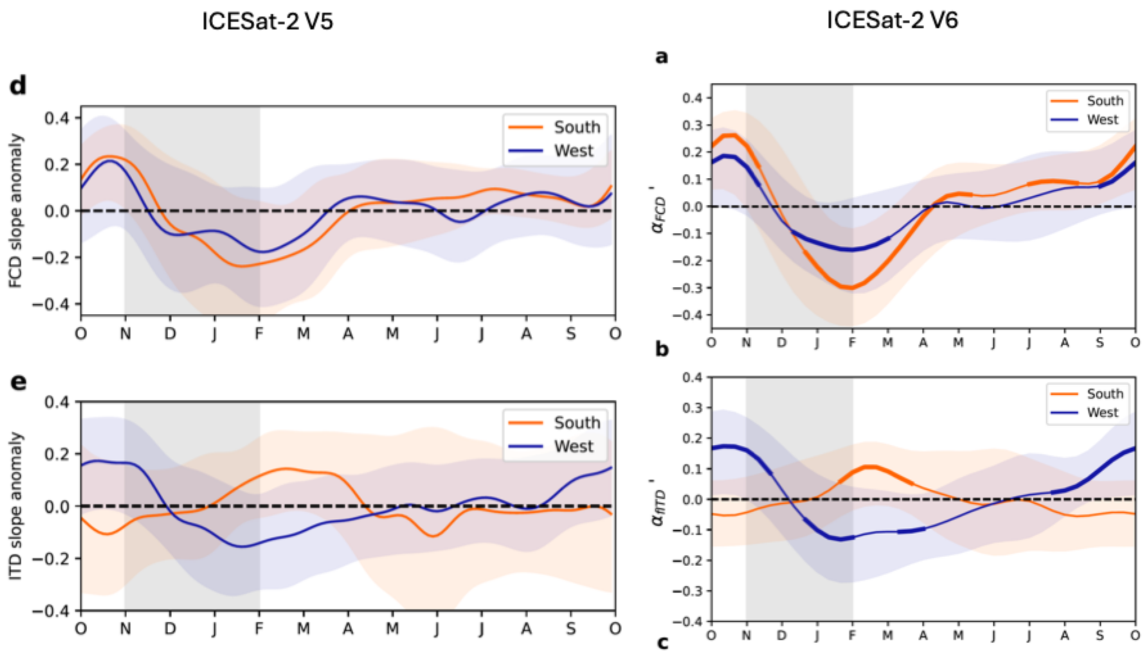
3. There is a positive correlation between sea ice freeboard thickness and floe chord length (ie. larger floes tend to be thicker). This correlation is observed throughout the year.

4. Smaller floes are rounder than larger ones. The mean roundness of floes increases during the melt season.

We believe these results deepen our understanding of sea ice behavior at fine scales and over the seasonal cycle. This new understanding could then help test and calibrate floe-aware sea ice models.

We have modified the first paragraph of the discussion to reflect the primary focus of our work on building scientific understanding rather than the systematic development of new methodologies. Moreover, the key points above are summarized in the abstract and the conclusions.

Regarding the ICESat-2 version, we use the latest version of the ATL07/10 product (v.6), as it includes the latest processing algorithms published by the ICESat-2 team. In an earlier iteration of the paper, we had used v.5, but since that version has now been supplanted by v.6, we choose to focus on the latter. Note that our main results did not change substantially when switching from v.5 to v.6 (see results below for FCD and fITD). It is beyond the scope of this study to perform a comprehensive assessment across the various versions of the ICESat-2 product .



2. The introduction mentions that “The perennial extent of Antarctic sea ice is small compared to the seasonal portion of the pack…” and the manuscript primarily addresses perennial ice. Clarify how the study’s focus on perennial ice informs the basin-wide behavior of the pack as stated in Line 74.

We agree that our study only provides inferences within the perennial sea ice region. We have changed this line to:

‘This work uses the ICESat-2 altimeter product to examine the seasonality of the perennial sea ice zone in the Weddell Sea and explore the utility of floe-level metrics in interpreting the larger-scale behavior of the pack.’

3. I don't quite follow the application of floe-derived metrics for model diagnostic evaluation since ICESat-2 and freeboard ice thickness distribution here is snow freeboard, not directly the ice thickness or ice freeboard. This means the snow freeboard needs to be converted with snow information to have potential sea ice process applications. It’s unclear how we can use this knowledge—is it just a product-based ice diagnostic study?

The freeboard information provided by ICESat-2 includes the snow layer and ice above sea level. We acknowledge the limitation of not separating the contributions between snow and ice (as detailed within the Discussion and the Conclusions sections of the paper). Performing this separation is difficult at the fine scales considered here, because it requires high-resolution information about snowfall, compaction, flooding and redistribution by winds, which is currently not available at the floe scale. We therefore focus purely on freeboard thickness to avoid introducing biases related to these uncertain snow-related processes. This is still a useful quantity, since it has been shown that data assimilation and model validation can be performed with sea ice freeboard (see for example Sievers et al., 2023). It would be the subject of follow-up work to examine snow versus ice contributions, by combining ICESat-2 with other datasets. We have added a note about the potential for data assimilation on Line 400.

Moreover, the inferences in this work pertaining to the LWD, FCD and lead spacing do not depend on conversion between snow and ice fractions.

[Sievers, I., Rasmussen, T. A., & Stenseng, L. (2023). Assimilating CryoSat-2 freeboard to improve Arctic sea ice thickness estimates. The Cryosphere Discussions, 2023, 1-23.]

4. I'm not clear how you define distributions such as floe chord distribution or freeboard ice thickness distribution in which temporal or spatial windows. While the floe chord length is defined by the distance between ice segments by each beam, what exactly is the floe chord distribution?

The FCD and fITD are calculated over time windows (chunks) of 3 days, and aggregated between all the floes detected within each region (south and west), respectively. We consider the full time period (Oct 2018-2022). Note that we tried chunks, varying from 2 to 10 days, and did not find substantial differences in our results. We have added the relevant information on Lines 199-203.

A floe chord is defined as the distance between two consecutive lead edges. The FCD is defined as the number of floes binned over chord lengths. We evaluate it for each region separately. We have added the following text on Line 172:

'The FCD is defined as the count of individual floes binned over their respective chord lengths (Fig. 3 (a)). Aggregated over the full study period (October 2018 - October 2022), …'

And the following on Line 178-179.

'The fITD is evaluated as the count of individual ICESat-2 segments binned over their respective freeboard thickness (Fig. 3 (b)). Aggregating data over the full study period, …'

5. I appreciate the use of different methods in lead detection from ICESat-2 for the sensitivity test, but since the sensitivities are all based on ICESat-2 data, how about using one case to show the lead bias or validate the lead detection from a different data source, such as SAR? How does the systematic bias in lead detection affect the distribution slope changes in the results?

Comparisons between floe chord lengths derived from ICESat-2 and imagery have been performed by several studies, including Koo et al. (2023), Petty et al. (2021) and Farrell et al. (2020). Koo et al. (2023) investigate the effects of the different lead detection algorithms used in this work, and place them in the context of leads derived from imagery in the Ross Sea. The authors find that different techniques work better for different scenarios, and that there is no one technique that always results in more accurate classification than the others. In some instances, sea ice is misclassified as a lead, while in others the opposite occurs. In some cases, the distinction may actually be ambiguous from the imagery itself, especially in the presence of thin nilas. Given that our study spans several sea ice regimes, it is difficult to robustly establish the sign and magnitude of any potential systematic, as those could vary in time and in space. Performing an additional single case study would not allow us to quantify the biases over all the regimes we consider here, as it would necessarily be limited in time and space.

Instead, performing a thorough analysis regarding the seasonal evolution of FCD and LWD using SAR imagery and comparing with our results would be valuable. However, this would require a considerable number of images, taken over the full span of the study period and region, along with a validated floe segmentation algorithm and a robust assessment of uncertainties. This would be a separate study in itself and is beyond the scope of this work.

Detailed comments:

1. Line 89: What corrections were made in the previously uncorrected ice type product?

The corrections pertain to the MYI concentration, as described in Melsheimer et al. (2023). We did not perform these corrections ourselves - instead they were performed as part of the study in Melsheimer et al. (2023), from which we sourced the MICIT data used in our work.

In brief, Melsheimer et al. (2023) apply two types of correction to the MYI concentration: (1) temperature-based, and (2) drift-based. The temperature correction considers the fact that melting may lead to some MYI appearing as FYI in its scattering properties. The correction reclassifies FYI to MYI based on whether warm enough surface air temperatures were observed in the satellite record. The drift correction uses the fact that by definition, no new MYI can be generated after the end of the melt season. Therefore, MYI should only be found within regions where it may have realistically drifted after that period. The drift correction uses a sea ice drift product to delimit these regions, and reclassify MYI outside these regions as non-MYI.

In the paper, we now provide a comparison between the corrected and uncorrected versions of the MYI product in Fig. A1. This figure shows that the two products compare well in the two regions of interest. We keep the uncorrected version in the main paper because the corrected version does not provide data between November and March, and because it does not provide further decomposition into FYI and YI.

2. Line 93: How did you complement the daily ice type with monthly ICESat-2 and weekly ice motion data? More details are needed here.

Apologies for the confusing phrasing. We use ice type data, ICESat-2 and motion data, separately. We did not combine them. We have now rephrased this to: 'Additionally, we use gridded sea ice freeboard…'

3. Figure 2: Are Figures 2c and 2d calculated based on the Weddell Sea or the Antarctic basin scale?

They are calculated based on the South and West regions shown in Fig. 2a and b. This is specified in the caption.

4. Figure 3: Are the results here based on all seasons during the period of 2018-2022?

Yes. We have added this line to the caption of Fig. 3: 'Floe-scale properties aggregated over all the ICESat-2 data collected between October 2018 and October 2022.'

5. Line 194: It might not be feasible to describe this as "inter-annual variability" given it is only four years of data. The sample is scarce in terms of defining inter-annual variability.

We removed the term 'inter-annual variability' and replaced it with 'the variability over the four years considered' or simply 'variability' throughout the text.

6. Line 196: Based on Figure 4(b), is there statistically significant anti-correlation? Only sometimes in January and March do they share significant correlation instead of the whole season. How do you explain this anti-correlation?

We agree that we cannot statistically determine whether alpha_ITD' is anti-correlated between the two regions for the seasonal cycle, especially as the signal in the west is only significant between February to August approximately. We have changed the phrasing to:

'Unlike the FCD, the seasonality of the fITD slope is not consistently in phase between the southern and western regions of the sea ice cover (Fig. 4 (b)).'

In the discussion, we suggest that the potential mirrored behavior may be due to the differential effects of thermodynamics versus dynamics in controlling ice thickness within the two regions. This would however need to be assessed with more observational data in the coming years or using model.

7. Line 254: How can we trust the lead spacing from lead detection based on ICESat-2? Figure A3 shows huge differences in those spacings from different algorithms, especially over the west region. How does this affect the results in Figure 5b?

There are indeed differences in the absolute values of lead spacing for different lead definitions. Nevertheless, the following patterns are consistent between them:

- The lead spacing is generally smaller in the south than in the west
- The lead spacing tends to decrease between July and October, increase from January to April and increase from April to July.

These are the points we comment on within the text (Section 3.3). There, we write the following regarding the sensitivity to lead definitions:

'Characterizing leads using a freeboard threshold instead of the identification provided by ICESat-2 can reduce the seasonality in the lead width spacing signal (Fig. A3). This may be due to the misidentification of thin ice as leads, especially near areas of widely distributed thin ice (Koo et al. 2023). Nevertheless, the seasonal trend in lead width spacing remains consistent across lead definitions.'

Regarding the effect of lead definitions on Fig. 5b, we have added a panel to Fig A2 that investigates the sensitivity of alpha_LWD' to the lead definition. We find that the phasing does differ with the different lead definitions, but broadly alpha_LWD' tends to be negative between December and February and positive between May and July.

We made a note of this on Lines 244-245.

8. Figure 6: Where are the 'plus' symbols in the plot?

This was a typo. We have fixed it.

9. Equation (1): What do $d\hat{x}$ and $\hat{p}(\hat{x})d\hat{x}$ mean, and what is the temporal/spatial scale you used to derive the vertical roundness values?

$\hat{x}$ is the normalized distance along a floe chord and $\hat{p}(\hat{x})$ is the corresponding freeboard height profile along the floe. We have added that information after Eq. (1).

In Fig 7a, we consider all the floes across both regions and all months to derive the roundness. In Fig 7b, we consider each month and the regions individually. This is specified in the corresponding caption.

10. Figure 7b: I'm curious about how to interpret the differences between the west and south regions in their features of vertical roundness.

It is difficult to thoroughly assess the differences between the two regions here because the seasonal variations in vertical roundness for the western regions remains within the year-to-year variability. This would be something to consider for future work with more years of data.

11. Line 300: Which basin-scale are you referring to: the Weddell Sea or the Antarctic basin?

Apologies for the confusion. We meant the perennial sea ice pack. We have changed this to: 'In spite of these regional differences, the seasonality of the FCD is consistent between the western and southern portions of the pack and is in phase with the asymmetric melt/freeze cycle over the perennial sea ice pack (Section 3.2)'.

12. Figure A2: Should be "'Freeboard height threshold at 1 cm' and 'Freeboard height threshold at 2 cm'."

Corrected.

Reference

Horvat, C., Roach, L.A., Tilling, R., Bitz, C.M., Fox-Kemper, B., Guider, C., Hill, K., Ridout, A. and Shepherd, A., 2019. Estimating the sea ice floe size distribution using satellite altimetry: theory, climatology, and model comparison. The Cryosphere, 13(11), pp.2869-2885.

Tilling, R., Ridout, A. and Shepherd, A., 2019. Assessing the impact of lead and floe sampling on Arctic sea ice thickness estimates from Envisat and CryoSat-2. Journal of Geophysical Research: Oceans, 124(11), pp.7473-7485.