The authors would like to thank the two reviewers for the invaluable comments and suggestions to our manuscript. Below are the respective replies to each point raised in the two comments. For the comments from Reviewer #1, the comments and replies are on the following part of this page to page 3, with the original comments in *blue italic*. For those from Reviewer #2, Dr. Boutin, the comments and replies are on page 4 to page 11, and the original comments in *green italic*. Moreover, in the marked version of the revised manuscript, the revisions are highlighted also in the respective colors, and marked accordingly with 'REV1' and 'REV2'. There are also other minor corrections, which are indicated by 'REVLang' in the marked version.

Reply to comments from Reviewer #1:

The paper is concerned with the estimation of the depth of MIZ affected by the penetration of incoming ocean waves using the altimeter onboard CS2. The wave-affected sea ice regions were identified from two distinctive features of the CS2 waveform characteristics, namely the Stack standard Deviation (SSD) and the Trailing Edge Shape (TES) parameters. An inversion procedure was thus developed and applied in the MIZs of the Atlantic sector of the Arctic over 12 winters from 2010 to 2022. ICESat2 data and Sentinel-1 SAR images were used for comparison to validate the CS2 retrievals.

The paper is well-written and the inversion methodology is accurately described. Results are also discussed in comprehensive detail.

I have only a few minor remarks as suggestions for the authors:

p. 1 last row: Besides frictional processes, wave attenuation in sea ice occurs also as a result of the energy scattering among floes.

Reply: The authors appreciate the reviewer for pointing out the mechanisms of wave attenuation in the marginal ice zone. We have revised the aforementioned statement as follows:

"Furthermore, in the marginal ice zone, wave energy attenuation is predominantly governed by a diversity of processes, which can mainly focus on two mechanisms: dissipation due to interactions between ice floes and the ocean (Doble et al., 2015; Ardhuin et al., 2020; Voermans et al., 2021) and redistribution of energy through the floe-induced wave scattering (Kohout et al., 2006; Squire, 2020)."

p. 2 rows 35-40: For completeness, it would be useful to mention that spaceborne SAR can image with spatial modes able to distinguish short waves that decay within the first tens of kilometers inside the ice edge of the MIZ. These MIZ regions are

typically formed by frazil, grease, and pancake ice, which are becoming the most populated ice types in the Arctic (Wadhams et al. 2018; De Carolis et al. 2021).

Wadhams, P., Aulicino, G., Parmiggiani, F., Persson, P. O. G., & Holt, B. (2018). Pancake ice thickness mapping in the Beaufort Sea from wave dispersion observed in SAR imagery. Journal of Geophysical Research: Oceans, 123, 2213–2237. https://doi.org/10.1002/

2017JC013003

De Carolis, G., Olla, P. & De Santi, F. SAR image wave spectra to retrieve the thickness of grease-pancake sea ice using viscous wave propagation models. Sci Rep 11, 2733 (2021). https://doi.org/10.1038/s41598-021-82228-x

Reply: The author thanks the reviewer for the suggestion of adding SAR-based MIZ observations in this part of the manuscript. We have incorporated the recommended content into the manuscript as follows:

"To resolve waves in the MIZ, high-resolution satellite payloads are typically required, including various optical sensors, Synthetic Aperture Radar (SAR), and laser altimetry of ICESat-2 (IS2) (Markus et al., 2017; Horvat et al., 2020; Collard et al., 2022). These advanced payloads facilitate detailed analysis of sea ice characteristics in the MIZ, including the floe size distribution as well as the wave propagation and attenuation in ice-covered regions(Wadhams et al., 2018; De Carolis et al., 2021; Stopa et al., 2018)".

p. 7 rows 155-160: How reliable is it to use the sigma0 and its variability information in cases of extreme winds to detect the MIZ boundary?

Reply: The author thanks the reviewer's comment on the feasibility of Sigma_0 for detecting MIZ boundary. We argue that the waveform power of CryoSat-2 (CS2), which characterizes the backscatter at nadir-looking angles (<2-deg), is sufficient to detect the presence of sea ice and distinguish MIZ from open water. Among all the cases we have carried out retrieval, the CS2 waveforms all show drastically higher power on sea ice (MIZ) than the nearby ocean, no matter how strong the waves are on the ocean.

It is worth noting that: the slant-looking backscatter is not suitable for the differentiation between sea ice and open water. Under high ocean conditions, the backscatter on the open ocean is very strong and even higher than that over sea ice. However, over open water at nadir-looking angles, the backscatter mechanism is different from the Bragg-type backscatter at slant-looking angles, which is modulated

by wind and the ensuing capillary waves. On the contrary, higher winds (i.e. rougher seas) will slightly reduce the nadir-looking backscatter (instead of increasing it).

Furthermore, the backscatter is very homogeneous over the ocean (along the CS2 track) since the ocean's condition has much larger spatial scales than sea ice. However, a very large variability of backscatter is present over the sea ice-covered regions due to the backscatter being mostly determined by highly variant snow/surface conditions. To summarize, the CS2 backscatter (along with its distribution) can be used to determine the MIZ's outer boundary.

p. 9 row 200: "scanning of in the whole..." may be missing a word after "of".

Reply: The author is grateful to the reviewer for identifying the incorrect language in this sentence. It has been revised as follows:
"Second, we scan the entire range of potential value of ξ (from 0 to π, relative to the east)."

Please revise figure captions: symbols, colored lines, and boxes should be explained in more detail.

Reply: The author appreciates the reviewer's valuable feedback. We will revise the figure captions to include more detailed information of the symbols, colored lines, and boxes for better clarity and understanding. The modifications are highlighted in the revised manuscript.

Reply to comments from Dr. Boutin, Reviewer #2:

This is a review of the manuscript entitled "A 12-Year Climate Record of Wintertime Wave-Affected Marginal Ice Zones in the Atlantic Arctic based on CryoSat-2". The manuscript describes a method to retrieve the wave-affected Marginal Ice Zone (MIZ) using Cryosat- 2. After introducing the importance of the MIZ, they describe their algorithm to retrieve the inner and outer limits of the MIZ. Then, they apply this algorithm over 2 case studies and discuss their definition of the MIZ against wave detected by Sentinel-1 to evaluate their method. They pursue this evaluation using this time a comparison of their method with ICESat-2 retrieved wave-affected MIZ for collocated tracks, with a special focus on 1 case. Having gained confidence in their algorithms and assessed sources of uncertainty, they extend their study to CS2 tracks in the Atlantic Arctic for the period 2010-2022. They describe the properties of the MIZ in 3 sub-regions and find no significant trend in the MIZ width in any of these regions. Finally, they discuss other sources of uncertainty.

The manuscript is generally well-written and clear. It synthesizes a large amount of work, with a strong emphasis on the validation of the algorithm using a multiple-sensor approach. The science is sound, well-referenced, and the results are well-discussed. Therefore, I recommend this manuscript for publication after minor revisions.

Reply: The authors thank the reviewer for the comment to our work.

Minor general comments:

I would suggest restructuring section 6 to start with the discussion and end with the summary. I think that would make more sense and conclude the paper on a more "positive" note. I would also suggest concluding by adding a few sentences to give some context to the results. For instance: the dataset is now available to the public and the research community, what type of application do the authors suggest for it? Could we use it already to evaluate the MIZ extent in wave-ice coupled models? What is the next step with this dataset? For instance, is there any plan to retrieve more quantitative data from CS2 in the MIZ (floe size, wave height in ice...)? What is missing to do that? Is there any plan to extend the method to the Pacific Arctic, or Antarctica? Would it work? This conclusion does not need to answer all these questions or to provide an in-depth plan of future work, but I think giving some direction would really improve the impact of the paper.

Reply: Following the reviewer's suggestion, we have reformulated Section 6 to summarize the paper better and introduce the dataset and future work. Specifically, a new section (Sec. 6.4) titled "Summary of the dataset and outlook" is added, which

introduces the potential usage of the dataset, potential improvements to it, as well as other aspects of future works on MIZ retrieval.

I have another general comment that is more like a suggestion. The quantity of information lets me think the manuscript could be divided into two: proof of concept one (section 1 —>4) and a short result article extending section 5. That would certainly increase the impact of section 5 and benefits the authors. Now, the paper is coherent as it is and reads well despite being long, so the decision should be made by the authors.

Reply: The author appreciates the reviewer's thoughtful, constructive suggestions. In particular, we also appreciate the comment on dividing the paper into two distinct parts, with the first containing the proof of concept and the second focusing on the extended results from section 5.

After careful consideration and discussion, we have decided to keep the manuscript as a cohesive unit. Section 5, in its current form, introduces the main retrieval results of the MIZs in the Atlantic Arctic, and it is a key part of the manuscript. Furthermore, based on the dataset, we intend to carry out extended analysis as a future work, which is briefly introduced in Section 6.

Specific comments:

L1: “integral part of the ice cover”—>I am not sure what this expression means. Important part of the ice cover?

Reply: we revise it to: “an essential part of the ice cover”.

L20: I am not sure “incurred” is the right verb here.

Reply: the sentence is revised as: "Consequently, the sea ice cover undergoes complex dynamic and thermodynamic processes, promoting air-sea exchange of heat and moisture within the MIZ."

L22: Wave attenuation is a big topic and there is no real consensus on which processes (not all related to friction) dominate depending on wave and sea ice conditions. I would suggest “a diversity of processes”? On this note, I may be a bit biased, but I would suggest that a direct application of this dataset is to gain a better understanding of the processes dominating the wave attenuation by constraining the MIZ extent in wave-ice coupled model (see what Boutin et al. 2022 did with Horvat et al. 2020 dataset for instance).

Reply: The author appreciates the reviewer for the comments on the status-quo of our understanding of the wave attenuation. We have revised the aforementioned statement as follows:

“Furthermore, in the marginal ice zone, wave energy attenuation is predominantly governed by a diversity of processes, which can mainly focus on two mechanisms: dissipation due to interactions between ice floes and the ocean (Doble et al., 2015; Ardhuin et al., 2020; Voermans et al., 2021) and redistribution of energy through scattering phenomena caused by sea ice (Kohout et al., 2006; Squire, 2020).”

Besides, we express our hope to apply the new MIZ dataset to both the study of wave attenuation and the validation/intercomparison to the wave-ice coupled model. Although this target is beyond the scope of this paper, we want to mention that the wave attenuation is planned next in our future work. The more detail about the potential application of this new product is now also included in Section 6.

L23: “more important roles by inducing positive feedback” —> Asplin et al. 2012 only suggest it might be the case, but I don’t think it has been proven. I would add potentially (by potentially inducing...).

Reply: The author appreciates the reviewer's suggestion. The sentence is revised as: “MIZs play even more important roles by potentially inducing positive feedback on the sea ice cover”.

L24/25: The sentence is a bit confusing. Also, I’m a bit picky maybe but I feel “Ingvaldsen et al., 2021” is not the best reference to support the statement made here as it discusses physical and ecological changes, not really changes in human activities.

Reply: The authors are grateful to the reviewer for identifying the misleading description of this sentence. Accordingly, the sentence is revised as: “Furthermore, it is also a critical region for human activities, including fishing, tourism, and navigation, due to its distinctive oceanic and ice conditions and unique ecosystem (Palma et al.,2019).” And the new reference is added.

L32: “and the respective uncertainties” —>the phrasing is confusing here. “and are highly uncertain in the MIZ”? (I am sure there must be a reference for that)

Reply: The author is grateful to the reviewer for identifying the inappropriate language in this sentence. It has been revised as: “... are highly uncertain in the MIZ (Nose et al.,2020)”.

L66: "Furthermore, besides [...] that contain extra information of the ocean's surface." I am a bit confused by that sentence. I would recommend splitting it into shorter simpler sentences.

Reply: The sentence is divided into two shorter ones, as follows: "Furthermore, besides the traditional gated waveform power, the waveform stack describes how the backscatter radar signal for the same footprint changes with different look angles. The waveform stack also contains extra information on the ocean's surface."

L71: "However, due to the relative coarse resolution of CS2 with respect to the typical wavelengths in MIZs"—>Wavelengths is a bit ambiguous here—>(surface gravity) wave wavelengths.

Reply: We have revised it to: "the wavelength of surface gravity waves" here.

L74: "Wind waves affect the ice cover by wave/swell generation, the propagation into the ice edge, and the ensuing interaction with sea ice, including breaking the sea ice into smaller floes and the wave attenuation". This sentence is a bit confusing and needs some rephrasing. (For instance, I understand the first part as "Wind waves affect the ice cover because they can generate swells", which is not correct).

Reply: The author is grateful to the reviewer for identifying the inappropriate description of the paragraph. The following paragraph has been revised as follows: "The wind waves and swells, generated from the open ocean, propagate into the ice edge and interact with the sea ice. This process could break the sea ice into smaller floes and further attenuate the wave energy."

L82 ", waves and swells" —> swells are still waves, so maybe "wind waves and swells"?

Reply: it is revised to "wind waves and swells", which is a more precise description.

L83: I feel like these references are not the most appropriate to support the statement made here. The fact that waves get longer as they propagate has been known for a while (I'd suggest Robin, 1963, see below).

Reply: We appreciate the reviewer's suggestion for a more proper reference, and we have added the reference to the revised manuscript.

L87: on—>in ; wave—>waves

Reply: We have revised them accordingly.

L91: The authors might want to repeat the reference to Figure 1 at the start of this paragraph, it really helps the reader to look at this figure while reading the description of these quantities.

Reply: We have added the reference to Fig. 1 in the sentence: “Therefore, CS2 waveforms on the wave-affected MIZs have the following characteristics (Fig. 1)”.

L107: constitutes

Reply: it is corrected to “constitutes”.

L113: “is utilized” —> I think “is used” works better here, and in a lot of places in the rest of the manuscript.

Reply: The author thanks the reviewer for pointing out the inappropriate language in this sentence. All similar cases in the manuscript have been revised to 'is used'.

L135: I would recommend referring to a manuscript’s figure that shows such patterns (there should be one in Collard et al., 2022 for instance).

Reply: According to the reviewer’s suggestion, we have added a reference to Collard et al., (2022) to indicate these patterns.

L159—>165 I find this paragraph confusing, it could be worth re-ordering the information, maybe starting with the introduction of the physical concept (looking for individual leads as a proxy for pack ice), and then explaining how this is done in practice. I would also recommend adding a comment on this choice of defining pack ice with the presence of leads. Technically, the MIZ can be characterized by the presence of many small leads. While I understand the idea of the authors, I think it can be counter-intuitive to potential readers.

Reply: The author appreciates the reviewer's suggestion on reordering the paragraph. It has been revised as follows:

“Second, among the various waveform parameters, we adopt the SSD as the indicator to determine the along-track transition from the wave-affected part (i.e., the MIZ) to the inner ice pack. To determine the inner boundary of the MIZ, we conducted statistical tests with the distributions of SSD. Specifically, we search for the first lead waveform (available from ESA’s baseline product) in the along-track direction and record the sample-based distribution of SSD from the location of the sea ice lead to 100km in length (containing over 300 CS2 footprints). Here, the lead is a flat surface with a high speckle return, observed by CS2. Thus, the wave-affected MIZ cannot extend beyond the location of the first lead. Then, the recorded SSD distribution is used as the benchmark for further determination of the MIZ’s inner boundary.”

L200—>203. I find the description of the method to retrieve “xi” hard to follow. I would suggest rewriting it or adding a little schematic.

Reply: We add extra descriptions of the method to retrieve the angle of “xi”. The following paragraph has been revised as following:

“Second, we scan the entire range of potential value of ξ (from 0 to π, relative to the east). For each possible value of ξ, we constructed a local intersection line that separated the aforementioned local area into two parts, and computed the accumulated sea ice extent (SIE) for both sides of the intersection line. Then, we defined the final ξ as the angle under which the SIE difference of the two sides is maximum.”

L215: University

Reply: We have corrected it to “University”.

L218: “CS2 measured marked” —> I don’t understand.

Reply: In order to make it more clear, we revise it as: “The waveform power measured by CS2 increase ”.

L229: shows—>show

Reply: We have corrected it accordingly.

L230: “large... than”—>“larger .. than”

Reply: We have corrected it to: “larger .. than”.

L248: “is on the order of”—>“is of the order of”

Reply: We have corrected it accordingly, as: “is of the order of”.

Figure 5: Which green points are associated with panels d,e,f?

Reply: We have revised the figure caption as follows:

“Figure 5. Collocating SAR images from Sentinel-1 (EW mode, panel a) for the MIZ in Fig. 4 and the northern end (red box in panel a) of the CS2-retrieved MIZ shown in detail (panel b). The region with detected wave-in-ice by spectral analysis (Appendix B) on the SAR image is marked by yellow boxes (10km scale). The spectra of the Sentinel-1 backscatter map of three typical regions (green dots in panel a, for the (c)-(e) corresponding to the northernmost, the middle, and the southernmost) are shown on the right, along with the respective fitted parameters and their uncertainties in Eqs. B1. “

L329: corrected—>correctly?

Reply: We have revised it to: “correctly”.

L354: From the text, I don’t understand the reason why the swell penetration is “potentially limited”. My guess is that this is because this advected ice is thicker than locally formed one, but this is not clear in the text. Or do the authors mean that there is simply not a large band of ice (and so mechanically a narrow MIZ)? Please clarify.

Reply: We have made revisions of the paragraph to improve its clarity, as follows:

“Sea ice in NS mainly originates from within the Arctic Ocean, due to the ice advection through the transpolar drift and the interaction with the Atlantic inflow. It is usually older and thicker than the locally grown sea ice during the freeze-up season. Consequently, the swell's penetration into the ice pack is potentially limited due to higher ice thickness, and the MIZ is generally narrower in NS. ”

L424: The gridded product resolution is much coarser than the mean width of the MIZ in the Atlantic Arctic. Is it not a problem? I would recommend justifying this choice and detailing what limits the choice of finer resolutions (e.g., the sampling of CS2?).

Reply: The authors would like to make the following clarifications regarding the gridded dataset. First, the choice of the resolution of 2° (zonal) by 1° (meridional) is a trade-off of the CS2 coverage and resolution. For finer resolutions, the CS2 will potentially have insufficient coverage for every gridded location; due to that, the sampling is limited to the nadir locations of the satellite's track. Besides, along the sea ice edge, the representation of MIZ width is usually sufficient at 100 km scale (note the 100km radius for computing SIC-based MIZ width in Fig. 11). We consider the choice of 2° by 1° is proper for characterizing the presence of MIZ.

Second, and more importantly, we consider that the along-track MIZ dataset is the more essential product that we provide. Due to the highly variant nature of MIZs, the monthly or even daily product is insufficient for process-level studies, such as the wave-ice interactions. Such studies require fast and instantaneous sampling of the MIZs, for which only the along-track product is sufficient.

Here, we choose to provide the monthly gridded MIZ dataset together with the along-track product to facilitate potential usages such as climatology analysis and model evaluations.

References:

Robin, G. de Q. (1963). Ocean waves and pack ice. Polar Record, 11(73), 389–393. https://doi.org/10.1017/S003224740005350X

Boutin, G., Williams, T., Horvat, C., & Brodeau, L. (2022). Modelling the Arctic wave-affected marginal ice zone: A comparison with ICESat-2 observations. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 380(2235), 20210262. https://doi.org/10.1098/rsta.2021.0262

Reply: These references are added and referred to the revised manuscript accordingly.