Response to Reviewer Comments

Dear Reviewer,

We sincerely thank the reviewers for their time, effort, and thoughtful comments on our manuscript. Your valuable feedback has played a crucial role in improving the quality of our work. Below, we provide a point-by-point response to address each of your comments in detail. We have carefully considered all suggestions, and where appropriate, revised the manuscript accordingly to clarify our methods and enhance the overall presentation of the study.

Please note that, due to the limitations of the current online review system, we are unable to attach the updated manuscript directly within this response. However, all suggested revisions have been incorporated, and additional adjustments have been made to further strengthen the manuscript.

Point-by-Point Responses

1. The title is heavily misleading. The paper is NOT a MSS model of the Arctic Ocean. Its merely a MSS for a fraction of the Arctic Ocean which is covered by the SAR mode of Cryosat-2. This makes the usability of the MSS very unusable for most purposes.

Response:

Thank you for your comment. We fully agree with your suggestion—the original title was indeed somewhat misleading. We have revised the title to: "SDUST2024MSS_AO: a MSS model of the ice-covered Arctic Ocean derived from CryoSat-2 SAR altimeter data". This revision more clearly defines the applicable scope of the model and helps avoid potential misunderstandings.

2. Also what is the reason for not including the SAR-in data???? or LRM data. At least this should be performed in the revised paper.

Response:

Thank you for your valuable suggestion. Our study focuses primarily on the construction of a MSS model in the ice-covered regions of the Arctic Ocean, where CryoSat-2 SAR mode data offer higher spatial resolution. In contrast, SARin and LRM mode data mainly cover the open ocean areas of the Arctic, which do not fully align with the target regions of this study. Therefore, we chose to focus on SAR mode data to improve MSS representation in sea ice-covered areas.

3. The most severe problem in its current form, is that the paper does not appear to have notice/discuss the seasonal variation of the Cryosat-2 mode mask. This means that in large fraction of the derived MSS model is not reliable as there are only data available during a fraction of the year due to the implemented mode mask.

Response:

Thank you for your valuable comment. In fact, the final coverage of the MSS model constructed in this study is largely limited to the overlapping regions observed under the seasonal variations of the CryoSat-2 mode mask. Furthermore, we applied strict temporal criteria when processing the data (as noted in Lines 187–190 of the manuscript): "To ensure accurate data calculations, each grid's time series for calculating the mean SSH must start before 2016.25 and end after 2016.25, with a minimum duration of 36 months. The black areas in Figure 3 indicate grid cells with fewer than 10 months of observational data, likely preventing a reliable calculation of mean SSH using equation (6) within these grid cells." In other words, the mean sea surface height was only calculated for grid cells with sufficiently long data coverage and an adequate number of observations. If the data volume in a certain region was too low, the mean sea surface height was not computed, thereby avoiding the impact caused by the seasonal variation of the mode mask.

4. Also, the paper does not discuss or model the large seasonal signal in the Arctic Ocean. This signal has an amplitude exceeding 10 cm in the coastal regions along the northern coast of Russia. This has a significant effect on the derived MSS model. Particularly when coupled with the seasonal data-coverage and mode mask.

Response:

Thank you for your comment, we fully agree with your point. In this study, to minimize the impact of seasonal variations on the calculation of mean sea surface height, we adopted the following formula (see line 180 in the manuscript):

$$H(t_i) = H(t_0) + \frac{dH}{dt} \cdot (t_i - t_0) + s_1 \cdot \sin(2\pi t_i) + s_2 \cdot \cos(2\pi t_i)$$

Here, t_i represents the i-th month, t_0 is the reference time, $\frac{dH}{dt}$ denotes the linear trend of SSH, and s_1 and s_2 are the fitting coefficients for seasonal variation. By introducing annual-cycle sine and cosine terms, the seasonal signals in the sea surface height data are effectively removed.

5. Also, the paper mentions the problem with melt ponds during summer but does not do anything

to handle this. This is today state of the art and implemented by several groups. Compared with the annual signal and the seasonality of the sea-ice cover and melt ponds (which only occurs roughly 1 months), this easily contaminates the MSS exceeding 10 cm in the parts of the Arctic Ocean.

Response:

Thank you for pointing out the issue regarding the influence of melt ponds during summer. In this study, we refer to the findings of Chen et al. (2022), who noted that radar waveforms struggle to distinguish between actual leads and sea ice surfaces covered with meltwater. Such misclassifications can result in overestimated sea surface heights, thereby contaminating the final MSS model. Chen et al. further analyzed the variation of δgrid values (i.e., the standard deviation of sea surface height within each grid cell) across different months. They found that δgrid values increased in June and July, mainly due to the influence of melt ponds. However, from August to October, δgrid values decreased, which they attributed to thinning sea ice. During this period, even if some melt ponds were misclassified as leads, the resulting height errors were relatively small.

Reference:

Chen, G., Zhang, Z., Rose, S. K., Andersen, O. B., Zhang, S., and Jin, T.: A new Arctic MSS model derived from combined Cryosat-2 and ICESat observations, International Journal of Digital Earth, 15, 2202-2222, https://doi.org/10.1080/17538947.2022.2153181, 2022.

6. In the abstract the author writes that their model detects the leads with a precision of 90.97%. How is this evaluated and how does this compare with other studies. Please explain. Also what is the impact of this physically in seasonal sea-ice cover.

Response:

Thank you for your suggestion. To provide a clearer presentation of how the recognition accuracy is evaluated in this study, we have revised the relevant description in Section 2.3 of the original text and added a table.

The revised content is as follows: “To improve computational efficiency and ensure the scientific rigor of the analysis, the samples in this study were deliberately categorized. For the calculation of mutual information, a balanced dataset of moderate size was constructed by randomly selecting 500 samples each from the entire lead and sea ice sample sets. For performance evaluation, in order to minimize the impact of class imbalance on metrics such as precision, recall, and F1 score, and to fully utilize the available lead samples, all 712 lead samples were selected. An equal number of 712 sea ice samples were randomly selected as a control group, resulting in a balanced test set with equal numbers of positive and negative samples, which ensures a more objective and reliable assessment of classification performance. The detailed sample division is shown in Table 1.”

Table 1. Division of sample sets.

Purpose of Sample Set	Sample Type	Number of Samples	Details
Computing mutual information (waveform feature selection)	Lead	500	Randomly selected from all lead samples
	Sea ice	500	Randomly selected from all sea ice samples
Evaluating precision, recall, and F1 score (detection performance assessment)	Lead	712 (all)	All identified lead samples used
	Sea ice	712	Randomly selected from sea ice samples to match the number of lead samples

The main reason for not comparing our results with those of other studies is the use of different baseline versions of the data, which leads to a lack of comparability between methods. CryoSat-2 data processing varies significantly across different baseline versions. For example, the echo waveform window in Baseline-B consists of 128 range bins, while Baseline-C extends this to 256 range bins (Rinne and Similä, 2016), and the Delay-Doppler processing strategy also differs (Passaro et al., 2018). These differences affect the power output of each echo and the corresponding waveform features (e.g., PP, SSD, etc.). This study uses the latest Baseline-E data product, whereas most previous studies used the earlier Baseline-B or Baseline-C data. Directly comparing the performance of methods across different baseline versions is not technically valid and would not yield scientifically sound conclusions.

Regarding the physical impact in seasonal sea-ice cover, the primary objective of this study is to construct an accurate MSS model. Acquiring a larger volume of sea surface height data is crucial for improving the model's accuracy. This research focuses on sea ice-covered regions of the Arctic Ocean, where identifying more lead observations directly contributes to enhancing the precision of the MSS model. To balance precision and recall, we adopted the F1 score as the evaluation metric. Although the precision may not be the highest, detecting more leads in sea ice-covered areas is actually beneficial for improving the accuracy of the MSS. Therefore, the proposed method plays a positive role in enhancing the reliability of sea surface modeling in regions with seasonal sea-ice cover.

Reference:

1. Rinne, E. and Similä, M.: Utilisation of CryoSat-2 SAR altimeter in operational ice charting, The Cryosphere, 10, 121-131, https://doi.org/10.5194/tc-10-121-2016, 2016.

2. Passaro, M., Müller, F. L., and Dettmering, D.: Lead detection using Cryosat-2 delay-doppler processing and Sentinel-1 SAR images, Advances in Space Research, 62, 1610-1625, http://dx.doi.org/10.1016/j.asr.2017.07.011, 2018.

7. Figure 2 is absolutely un-usable. Is this all the Icesat-2 data available? As this is what the title states. I doubt it?

Response:

Thank you for pointing out this issue. We acknowledge that the original title of Figure 2 was inaccurate, as the figure did not represent all available ICESat-2 data. To enhance the rigor, persuasiveness, and reproducibility of this study, we have updated and expanded the ICESat-2 dataset used in our analysis. Specifically, we now utilize ICESat-2 ATL07 data from the entire year of 2019, covering regions north of 67°N. This updated dataset includes 5,171 ground tracks and 65,666,695 lead observations. The spatial distribution of these data provides more comprehensive coverage of the MSS model domain and offers improved representativeness. The new distribution is illustrated in the revised Figure 2.

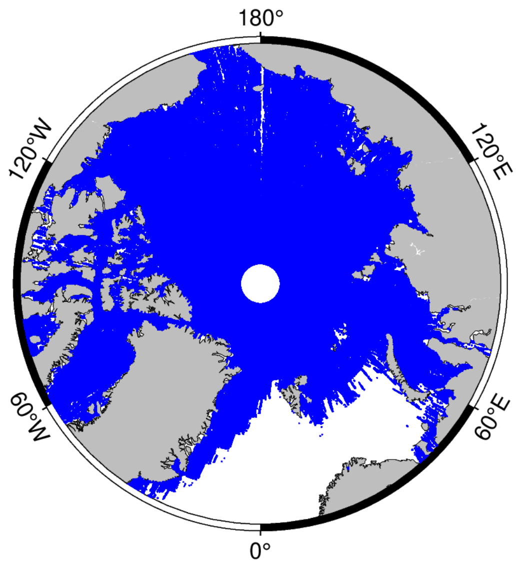

Figure 2. Spatial distribution of ICESat-2 ATL07 lead observations in 2019 north of 67°N.

Based on this updated ICESat-2 dataset, we re-evaluated the SDUST2024MSS_AO, CLS2022, DTU21, UCL13, and SDUST2020 models. The revised validation results are presented in the updated Table 6 and Figure 8.

Table 6. Differences between MSS models and ICESat-2 samples.

MSS models	Mean(m)	SD(m)
SDUST2024MSS_AO	-0.172	0.219
CLS2022	-0.069	0.302
DTU21	-0.120	0.296
UCL2013	-0.159	0.228
SDUST2020	-0.058	0.347

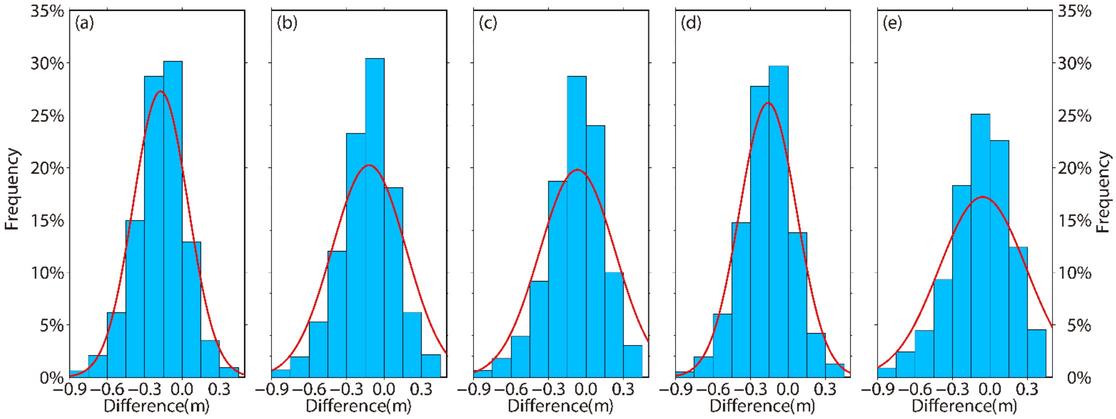

Figure 8. Histograms of the differences between ICESat-2 samples and SDUST2024MSS_AO (a), DUT21 (b), CLS2022 (c), UCL2013 (d), SDUST2020 (e), respectively.

Relevant revisions and discussions have been incorporated into the manuscript. We sincerely appreciate your valuable feedback.

8. The Comparison with ICESAT is too preliminary and consequently un-usable in its present form. The author themselves writes on line 283:

As rigorous data corrections were not applied to the ICESat-2 altimeter data systematic errors may be present.

Why did the authors not rigorous data correction prior to submitting the paper to an international journal. Actually, the results of the various models comparison of the Mean with Icesat-2 is one of the more interesting results in the paper. This entire analysis should be performed / redone in a more rigorous matter before the paper is potentially re-submitted. Also the authors should explain pro/cons of the difference wavelength and how this matters to MSS computation.

Response:

Thank you for your valuable comment. We apologize for the lack of clarity in our original description, which may have caused some misunderstanding. The ICESat-2 altimetry data used in this study are from the ATL07 product, which belongs to Level-3A data and has already undergone standard geophysical corrections (e.g., tidal corrections, dry and wet tropospheric delay corrections, etc.), making it suitable for direct use. The statement in the manuscript regarding the "rigorous data corrections were not applied to the ICESat-2 altimeter data" specifically refers to the fact that we have not performed dedicated adjustments for potential systematic biases between the ICESat-2 and CryoSat-2 measurement systems, rather than implying that the ICESat-2 data themselves were uncorrected. We have revised the relevant description in the manuscript to clarify this point.

In this study, the ICESat-2 data are primarily used for a preliminary, overall-level validation of the constructed MSS model, serving as an external reference to help assess the general consistency of the model. The comparison between the mean values of the MSS models and ICESat-2 observations is intended to provide a visual indication of consistency, rather than a quantitative accuracy assessment. Moreover, differences in observation mechanisms caused by varying wavelengths between different altimetry systems do not have a substantial impact on the accuracy or applicability of the MSS model developed here based solely on CryoSat-2 data. Given that the main focus of this work is the development of a high-resolution MSS model over the Arctic Ocean, rather than a systematic analysis of differences between altimetry systems, we believe it is unnecessary to explore this aspect in greater depth. We sincerely thank you again for your valuable feedback.

9. Finally. The authors claim that the model is likely very good. Perhaps in the regions covered by permanent SAR mode mask of CryoSat, but no proper evaluation is still to be performed. There are both Sentinel-3A/B and HY-2B data available in the region which could be applied and introduced before resubmitting the paper to an international journal once again.

Response:

Thank you for your constructive comments. In this study, we have systematically compared the constructed MSS model with several existing mainstream models, including DTU21, UCL2013, CLS2022, and SDUST2020. The relevant analysis can be found in lines 230–279 of the manuscript. It should be noted that the orbital coverage of Sentinel-3A/B and HY-2B is approximately ±82.5°, whereas CryoSat-2 extends to ±88°, resulting in a coverage difference in polar regions. Therefore, while the inclusion of Sentinel-3A/B and HY-2B data could improve the model accuracy in areas south of 82.5°N, CryoSat-2 retains an irreplaceable advantage in the high-latitude Arctic region, particularly north of 82.5°N, which is the focus of this study. In future work, we plan to further explore the integration of multi-source altimetry data to enhance the spatial coverage and accuracy of the MSS model.

Once again, we sincerely thank the reviewers for their constructive comments and insightful suggestions. We believe these revisions have significantly improved the manuscript, and we look forward to receiving your further feedback.

Best regards,

Xin Liu

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