Responses to CC2 (Arttu Jutila)

Dear Arttu Jutila,

Thank you for your valuable suggestions and the further discussions needed. We apologize for any previous misunderstandings concerning your remarks. We have made several significant revisions, as detailed in the attached document. The original comments are in black, and our replies are written in blue.

Best regards,
Yi Zhou and other co-authors.

Reply to author comment https://doi.org/10.5194/egusphere-2024-1240-AC1 by Zhou et al. for the manuscript by Zhou, Y., Wang, X., Lei, R., von Albedyll, L., Perovich, D. K., Zhang, Y., and Haas, C.: Seasonal evolution and parameterization of Arctic sea ice bulk density: results from the MOSAiC expedition and ICESat-2/ATLAS, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2024-1240, 2024.

Dear Zhou et al.,

Thank you for your response to my comment and in particular for continuing the public discussion in the spirit of The Cryosphere's interactive review process.

I am pleased to see that you have carefully considered my comments. Nevertheless, I still see some loose ends which I would like to discuss further.

First, we would like to inform that we have significantly revised and re-evaluated some results, and further details will be provided in the revised manuscript. Given that you are a major contributor to the MOSAiC airborne data and the AWI Icebird multi-sensor sea ice dataset, we respectfully invite you to participate as a co-author on the revised manuscript, subject to policy permissions. Your involvement would greatly enhance the manuscript's quality. All modifications can be found in ***Supplementary A1*** at the end.

Scales. Thank you for the very helpful additional Figure A1. While you clarify that the extraction radii for IS2 and IMBs were 50 km and 30-40 km, respectively, you have unfortunately misread my comment. I did not use the term **radius** but **diameter**, i.e. two times the radius, for a very specific reason. Let's consider a rather standard satellite data product that has data in a regular grid format where the grid cells are square-shaped with each side measuring 25 km in length. This results in a spatial scale of 25 km – not 12.5 km that would be the radius of the largest possible circle drawn within the grid cell. In your case, for example looking at Figure 3c where the IS2 ground track passes nearly directly above the center of the circle or the MOSAiC CO, you end up extracting along-track data for a length of 100 km, not 50 km. That is the largest length scale of your input data. The same principle applies to the 40-m footprint size of the AWI IceBird measurements: it is the diameter, not the radius, of the EM-Bird footprint, within which snow depth and freeboard measurements are averaged and sea-ice bulk density is eventually derived.

In your consideration of the helicopter-borne laser scanner data in Hutter et al. (2023), you state having found it temporally insufficient with only about ten days of valid data for your study period. Did you include also the approximately weekly transect flights that extend beyond the MOSAiC CO floe for a few tens of kilometers into the DN, in most cases reaching the three L-sites? They cover several buoys, including seven IMBs of your study.

Authors' response: We apologize for the misunderstanding of your comments. Considering your suggestion, we included ALS airborne data and extended the analysis to the L-site scale **(as shown in Fig. A1)**. The DN scale was defined as a spatial scale with a radius of 50 km from the CO, while the L-site scale was defined as a radius of 25 km. We then used all IMBs within the L-site scale and the corresponding IS2/ALS modal freeboards to derive the IBD **(Fig. A2)**, with more details to be provided in the revised manuscript.

Furthermore, I would like to pose you a question: which of the two has more severe effects, lack of spatial or temporal overlap? Earlier you stated that during the winter season, which is the focus of your study, there was little sea-ice dynamics influencing the study area. Temporal interpolation should not cause too many problems then. After all, you already apply it for snow density. Figure 4d even shows that the IS2 modal freeboard values are very close to the trend line.

Authors' response: We suggest that the lack of spatial overlap is more severe. Due to the strong spatial heterogeneity of sea ice, the averaged results from the buoy arrays and the measurements at the IS2/ALS scales inevitably introduce spatial scale differences. This spatial variability poses challenges for the coordination of using both the average values from the IMB array and the modal values from IS2/ALS in the hydrostatic equilibrium equation. Therefore, in the revised manuscript, we introduced a spatial scale correction term to mitigate this issue. **Please refer to our response to RC1 for details.**

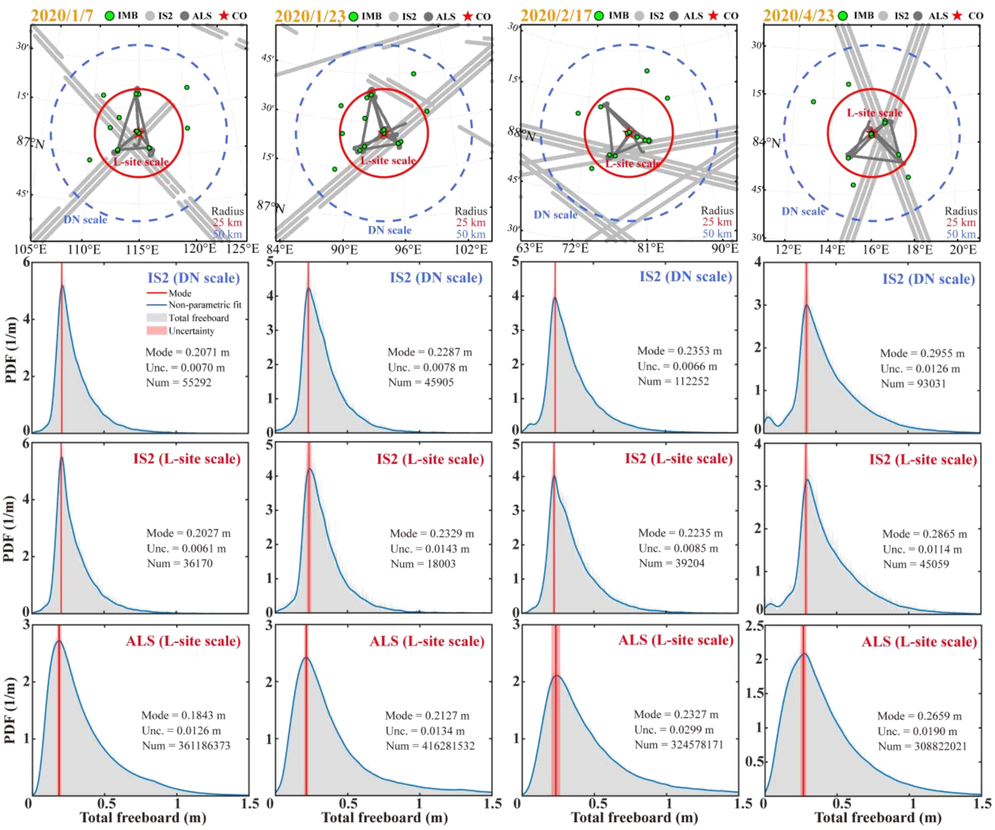

Figure A1. Distribution of IS2, ALS, and IMB array measurements, showing the cases on January 7, 2020, January 23, 2020, February 17, 2020, and April 23, 2020.

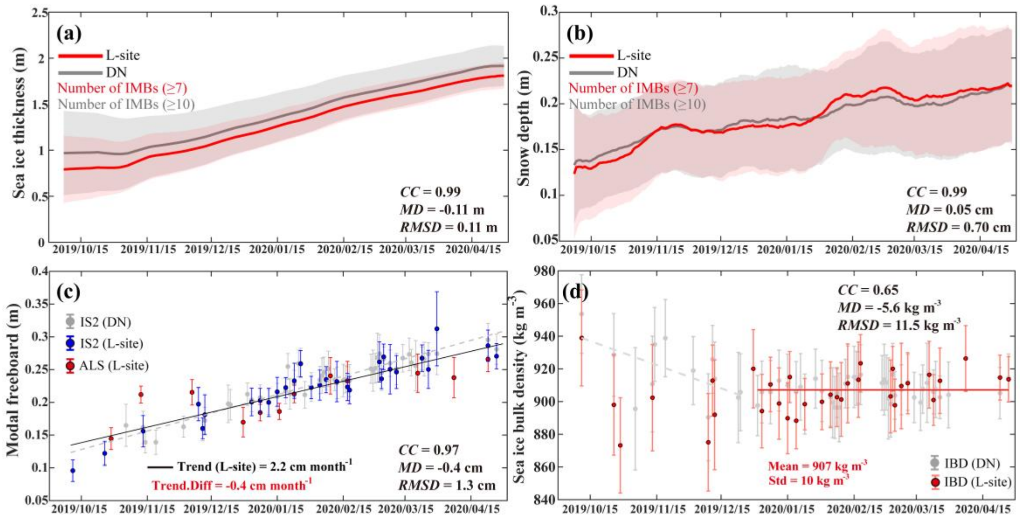

Figure A2. Comparison of L-site and DN sea ice parameters, including (a) sea ice thickness, (b) snow depth, (c) modal freeboard, and (d) sea ice bulk density. Statistical metrics include correlation coefficient (CC), mean difference (MD, L-site minus DN), and root mean square difference (RMSD).

IS2 modal freeboard. I may have been too quick previously agreeing that modal freeboard is an estimate of level ice. Coming back to it now after a while, I would like you to carefully consider the log-normal distribution and the modal value with respect to different variables. For sea-ice thickness measurements, it is indeed well-known and supported by studies that the modal value represents the most common value and the thickness of thermodynamically-grown level ice. For freeboard variables, whether it is sea-ice freeboard or snow/total freeboard, I think it is not so straight forward. In your answer to my comment, you give a long list of references very much like Koo et al. (2021), who write:

"Since the modal thickness represents the thickness of the most frequently observed ice or level ice (Farrell et al., 2012; Hansen et al., 2013; Petty et al., 2016; Rack et al., 2021; Tian et al., 2020), we estimate the thermodynamic ice growth around the buoys by using the variations in the modal thickness."

They, like many if not all the studies you referenced, first transform snow or sea-ice freeboard (depending on the sensor in question) into sea-ice thickness **with auxiliary data** using the hydrostatic equilibrium assumption before deriving the thickness distribution and its modal value. I suppose that looking only at freeboard distribution you are (1) mixing the terms snow freeboard and sea-ice freeboard and (2) "cutting corners" in your study. Are sea-ice and snow freeboards correlated with each other or with sea-ice thickness, do they always behave the same? Could a seemingly level snow freeboard conceal sea ice that is not level? A single snow freeboard value can correspond to a wide range of sea-ice thickness values depending on the snow load that cannot be deduced from laser altimetry alone. Let's consider a fixed total freeboard value of 0.3 m, approximately the derived modal value in your Figure 3c. Additionally, let's assign representative and fixed values for the densities of sea water, ice, and snow, but let snow depth vary from 0 to 0.3 m (it could be even larger for cases of negative freeboard). The sea-ice thickness values resulting from this single total freeboard value, but varying snow depth information, can vary by more than 1.5 m according to the hydrostatic equilibrium equation.

Authors' response: We fully understand your concern that the modal value of the total freeboard distribution cannot represent the average state of sea ice, as snow cover may affect the statistical properties of the sea ice fraction. However, we have not conflated the difference between total freeboard (which includes snow cover) and sea ice freeboard, and we expect that the impact of snow cover on the statistical characteristics of sea ice over scales of tens of kilometers is very limited. To demonstrate the validity of the modal value of total freeboard distribution representing the average state of total freeboard for level ice, we used the latest Icebird total freeboard data with ice surface classification labels to evaluate our method. Based on the AWI Icebird measurements from April 2017 and April 2019, we compared the modal value of the total freeboard distribution (all ice types) with the mean total freeboard of level ice **(Fig. A3)**, retaining only the results for each measurement date where the proportion of level ice exceeds 20%. Overall, the two freeboard values are very close, with all proximity values greater than 90%, demonstrating the validity of our method.

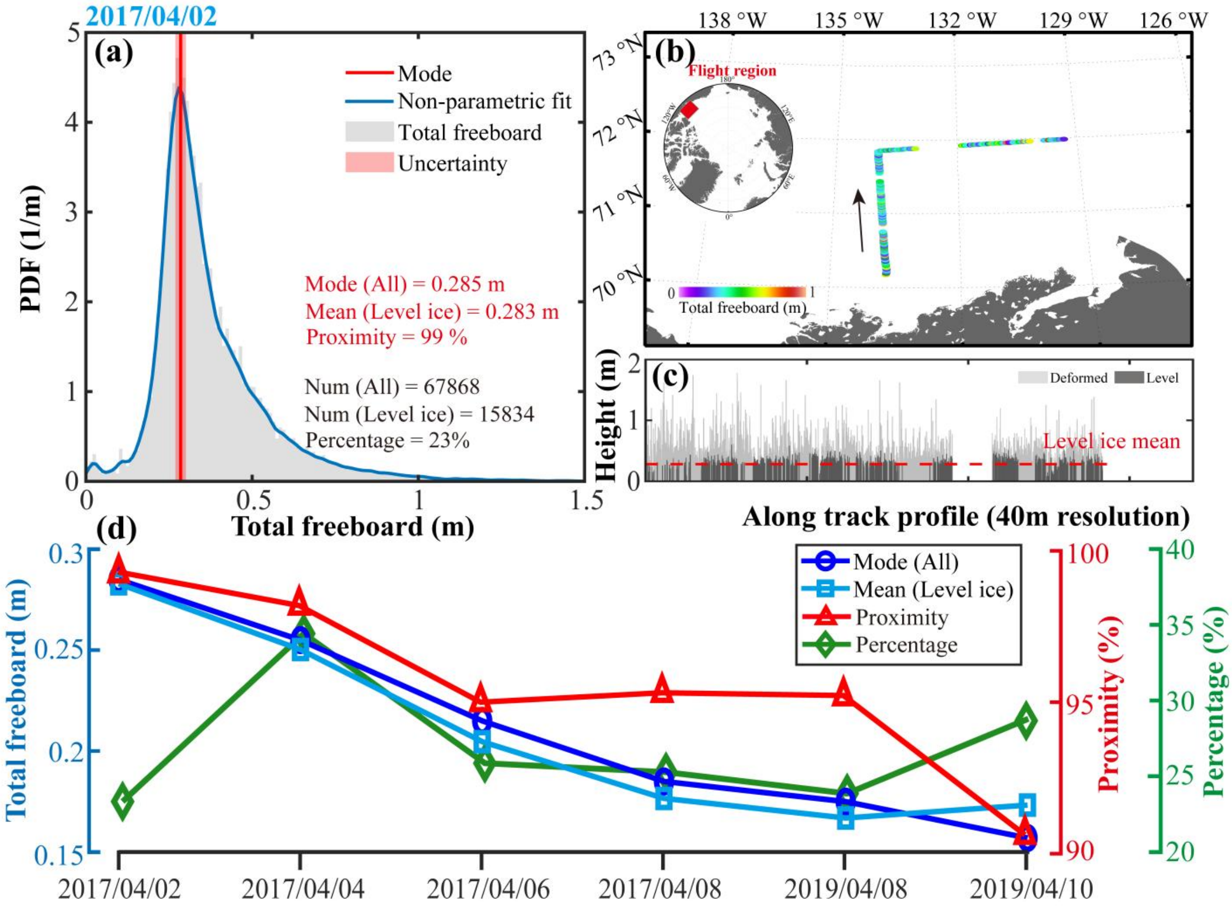

Figure A3. Comparison of the modal value of total freeboard distribution (all ice types) with the mean total freeboard of level ice from AWI Icebird measurements in 2017 and 2019. The example of 2 April 2017 shows (a) the total freeboard distribution (b) the measurement area, and (c) the total freeboard profile. (d) Results for each measurement date, including the modal freeboard, mean value for level ice, absolute relative percentage difference between the two values (proximity), and the proportion of level ice (percentage).

Snow pits. Regarding the snow pit data, I do recommend being more explicit and more detailed in the methods section. While the data descriptor paper by Macfarlane et al. (2023) states a total of 576 snow pits, you have used only a small part of that data in your analysis. In fact, from the MOSAiC snow pit snow density cutter dataset (https://doi.org/10.1594/PANGAEA.940214), I can count only 85 snow pits between 25 October 2019 and 30 April 2020. The large number of "snow pits" stems from the fact how snow pits of different complexity were defined during the expedition: even a single profile with the SnowMicroPen (SMP) instrument could count as a snow pit. In the context of your manuscript, however, this is misleading since you did not use the SMP density profiles in your analysis. Furthermore, I trust you have indeed dug deep into the MOSAiC jargon of locations: snow pit locations "FR" in January-February and "DR" in April refer to "Fort Ridge" and "David's Ridge" sites, respectively, that do not represent level ice conditions.

Authors' response: Thank you for your clarification. We will provide a detailed description of the specific snow pits used in the revised manuscript. We have reviewed the snow pit results that included ice ridges (e.g. FR and DR) and excluded these records to recalculate the snow bulk density, see panel (c) of **Figure A4.**

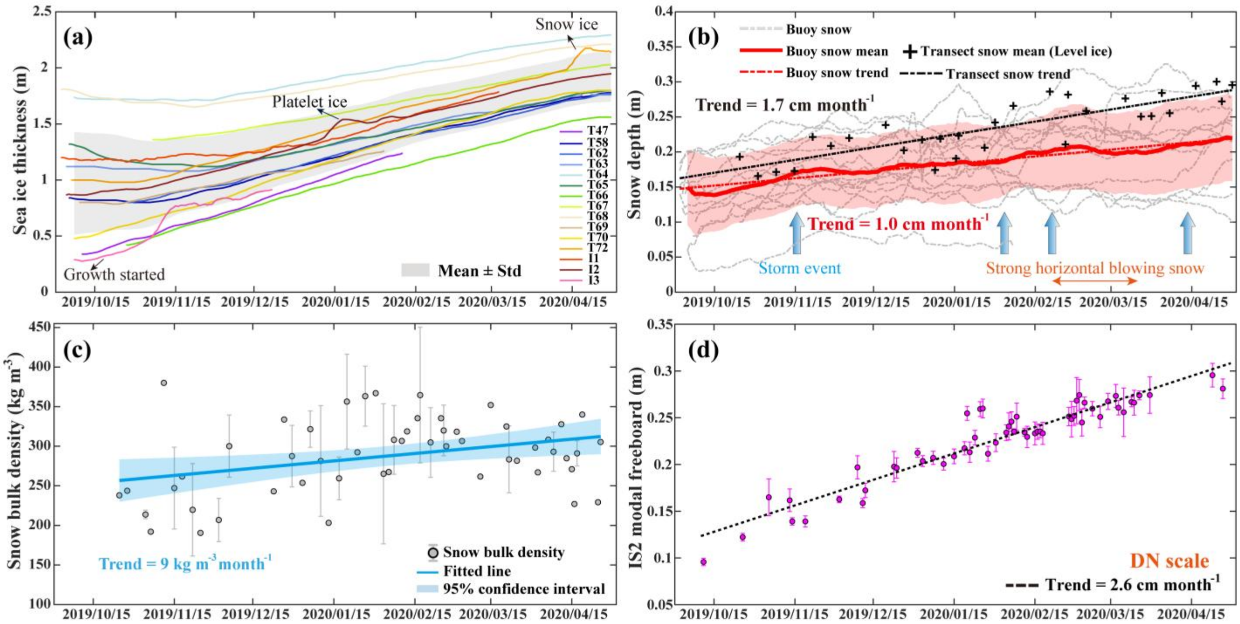

Figure A4. Variations of sea ice and snow during the MOSAiC freezing season (DN scale). (a) Sea ice thickness measurements from the IMBs. The peculiarities of T72, I2, and I3 sites (as described in the text) are indicated by black arrows. The gray shaded band indicates the mean ± standard deviation (at least 10 buoys). (b) Snow depth measurements obtained from buoys and transects. The blue arrows mark four storm events, and the yellow arrow indicates a period characterized by a strong snow drifting event, according to Wagner et al. (2022). (c) Snow bulk density derived from snow pit measurements. (d) Seasonal evolution of the IS2 modal freeboard, with uncertainties indicated by error bands.

AWI IceBird average densities. In your response you claim to have used the mean values of sea-ice bulk density from Table 3 of Jutila et al. (2022). I have now double-checked this, and while the values for SYI and MYI seem fine, I don't think this is true for FYI. Table 3 of Jutila et al. (2022) states 929.3 +/- 16.0 kg m-3 for 2017 and 925.4 +/- 17.7 kg m-3 for 2019, in addition the main text states 928.5 +/- 16.4 kg m-3 as the overall average density for FYI. However, your code snippet "Sea_ice_bulk_density.m" in Zenodo (https://doi.org/10.5281/zenodo.11055727) shows that a value of 921.4222 +/- 18.5586 kg m-3, smaller than any other FYI average value given in Jutila et al. (2022), was used for plotting Figure 5.

Authors' response: Thank you for your clarification, and we apologize for the inaccuracy values that we used. In the revised manuscript, we calculated the mean IBD of SYI and FYI, including only the level ice portions, based on the latest version of the AWI Icebird data (original resolution). The mean and standard deviation of the recalculated IBD were ~913 kg m^{-3} and 40 kg m^{-3}, respectively, and were compared with our results **(Fig. A5)**. Overall, the average IBD during the relatively stable phase of MOSAiC is very consistent with the average IBD from Icebird.

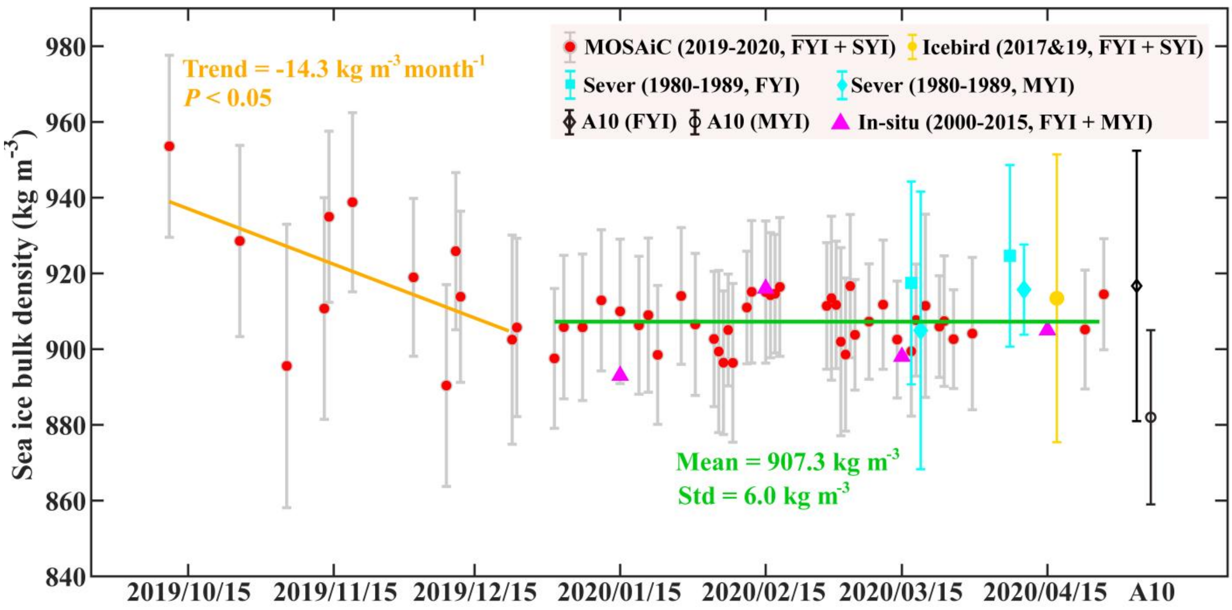

Figure A5. Seasonal evolution of IBD during the MOSAiC freezing season. The orange line indicates a significant decreasing trend in the MOSAiC IBD, while the green line indicates the mean value during a relatively stable phase. Also shown are the mean IBDs of FYI (black diamond) and MYI (black circle) from the A10 climatology (Alexandrov et al., 2010), the mean IBDs of FYI (cyan square) and MYI (diamond) estimated during the Arctic Sever expedition from 1980 to 1989 (Shi et al., 2023), the mean ice densities (FYI and MYI, purple triangle) from 2000 to 2015 based on in situ observations (Ji et al., 2021), and the mean IBD of FYI and SYI (diamond) based on AWI Icebird multi-sensor measurements in April 2017 and 2019 (Jutila et al., 2022). The underline indicates IBD results for level ice only. The gray error bars indicate the uncertainty of the MOSAiC IBD, and the other error bars indicate one standard deviation. Note that the density data from the historical measurements correspond to the month, regardless of the year.

Reference.

Alexandrov, V., Sandven, S., Wahlin, J., and Johannessen, O.: The relation between sea ice thickness and freeboard in the Arctic, The Cryosphere, 4, 373-380, 2010.

Ji, Q., Li, B., Pang, X., Zhao, X., and Lei, R.: Arctic sea ice density observation and its impact on sea ice thickness retrieval from CryoSat–2, Cold Regions Science and Technology, 181, 103177, 2021.

Jutila, A., Hendricks, S., Ricker, R., von Albedyll, L., Krumpen, T., and Haas, C.: Retrieval and parameterisation of sea-ice bulk density from airborne multi-sensor measurements, The Cryosphere, 16, 259-275, 2022.

Shi, H., Lee, S.-M., Sohn, B.-J., Gasiewski, A. J., Meier, W. N., Dybkjær, G., and Kim, S.-W.: Estimation of snow depth, sea ice thickness and bulk density, and ice freeboard in the Arctic winter by combining CryoSat-2, AVHRR, and AMSR measurements, IEEE Transactions on Geoscience and Remote Sensing, 2023. 2023.

Wagner, D. N., Shupe, M. D., Cox, C., Persson, O. G., Uttal, T., Frey, M. M., Kirchgaessner, A., Schneebeli, M., Jaggi, M., and Macfarlane, A. R.: Snowfall and snow accumulation during the MOSAiC winter and spring seasons, The Cryosphere, 16, 2022.

Supplementary A1

[Data]

a) IS2 Freeboard Data Updated to ATL10 version 6.

Kwok et al. (2023), ATLAS/ICESat-2 L3A Sea Ice Freeboard, Version 6. [Data Set]. NSIDC.(https://doi.org/10.5067/ATLAS/ATL10.006).

b) Airborne Laser Scanning (ALS) Data: Added L-site scale data during the MOSAiC freezing season.

Hutter et al. (2023), Gridded segments from helicopter-borne laser scanner during MOSAiC. [PANGAEA](https://doi.org/10.1594/PANGAEA.950339).

c) AWI IceBird Multi-Sensor Sea Ice Parameters Updated to the Latest Version

- Jutila et al. (2024), Airborne sea ice parameters during the IceBird Winter 2019 campaign in the Arctic Ocean, Version 2. [PANGAEA](https://doi.org/10.1594/PANGAEA.966057).

- Jutila et al. (2024),Airborne sea ice parameters during the PAMARCMIP2017 campaign in the Arctic Ocean, Version 2. [PANGAEA](https://doi.org/10.1594/PANGAEA.966009).

d) Core-Based Ice Density Data: Added data on sea ice density from the *Sea Ice Physics Group* during MOSAiC legs 1 to 4.

- Oggier et al. (2023), First-year sea-ice salinity, temperature, density, oxygen and hydrogen isotope composition from the main coring site (MCS-FYI) during MOSAiC legs 1 to 4 in 2019/2020. [PANGAEA](https://doi.org/10.1594/PANGAEA.956732).

- Oggier et al. (2023), Second-year sea-ice salinity, temperature, density, oxygen and hydrogen isotope composition from the main coring site (MCS-SYI) during MOSAiC legs 1 to 4 in 2019/2020. [PANGAEA](https://doi.org/10.1594/PANGAEA.959830).

[Method]

a) IS2 Modal Freeboard Calculation: In the revised manuscript, we have retained the original resolution of IS2 ATL10 v6 and no longer perform the 150-segment averaging. Additionally, we no longer use log-normal fitting to estimate modal freeboard. Instead, we directly use the average of the freeboard values corresponding to the five highest frequencies in the freeboard distribution to obtain the modal freeboard (standard deviation is used as the uncertainty for the quasi-peak region of the total freeboard distribution). The purpose of this modification is to preserve the original distribution characteristics of the data as much as possible, without imposing fitting constraints or making resolution adjustments. Moreover, we have adopted the same approach to obtain the modal ALS freeboard.

b) Modal Value Feasibility for Level Ice: The AWI Icebird dataset was utilized to assess the feasibility of our approach, which features rigorously defined ice surface classification labels. We obtained the modal freeboard from the total freeboard distribution that includes both level and rough ice, and compared it with the average total freeboard of level ice.

c) Spatial Scale Correction: We introduced a spatial scale correction term to better align buoy array data with IS2/ALS modal freeboards.

d) Added Uncertainty for IS2 Modal Freeboard: We added uncertainty to the IS2 modal freeboard by calculating the mean difference (~0.0125 m) between IS2 and reference ALS modal freeboard.

[Results]

a) Sea Ice Bulk Density (IBD) Recalculation: All IBD results have been recalculated and re-evaluated following substantial revisions.

b) Enhanced IBD Parameterizations: Additional details have been included in the IBD parameterizations to improve clarity and accuracy.

c) IBD Results at Different Scales: Besides the DN scale, IBD results have now been extended to include the L-site scale.

d) High-Precision Ice Core Density: Ice core density that we used were obtained using the high-precision hydrostatic weighing method.

e) Expanded Discussion on IBD Uncertainty: More comprehensive discussions have been added regarding the uncertainty of IBD, its seasonal variations, spatial heterogeneity, limitations, and potential applications.