# Responses to Community Comment (Dr. Arttu Jutila)

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Dear Dr. Arttu Jutila,

Thank you for your constructive comments. We will address your insights with comprehensive clarifications and revisions throughout our manuscript. We have outlined the original comments in black with our planned responses highlighted in blue. Kindly refer to the attached document.

Best regards,
Yi Zhou and other co-authors.

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Dear Zhou et al.,
Dear handling editor,

The competing interests policy of The Cryosphere prohibits me from acting as an official referee for this manuscript due to recent collaborations with some of the coauthors. Therefore, I am posting this comment as a member of the scientific community to discuss some matters related to it.

In the manuscript by Zhou et al., now under peer-review process and public discussion, sea-ice bulk density is derived using the hydrostatic equilibrium equation and values of modal total freeboard from the satellite laser altimeter ICESat-2, mean snow depth and sea-ice thickness from 15 autonomous ice mass-balance buoys (IMB) deployed within the MOSAiC Distributed Network (DN), and mean snow density from snow pit measurements conducted in the MOSAiC Central Observatory (CO) from October 2019 to April 2020.

In 2022, I have authored a paper in The Cryosphere on the same general topic, sea-ice bulk density, using a similar approach but simultaneous airborne multi-sensor measurements from the AWI IceBird program:

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, https://doi.org/10.5194/tc-16-259-2022, 2022.

This work is referenced many times and data originating from this study are used in the manuscript by Zhou et al.

First, I want to inform that there is a recently published new version of the AWI IceBird airborne sea-ice parameter dataset. In the new version, the quality flag identifying level and deformed ice has been rectified.

Jutila, A., Hendricks, S., Ricker, R., von Albedyll, L., and Haas, C.: Airborne sea ice parameters during the IceBird Winter 2019 campaign in the Arctic Ocean, Version 2, https://doi.org/10.1594/PANGAEA.966057, 2024.

Jutila, A., Hendricks, S., Ricker, R., von Albedyll, L., and Haas, C.: Airborne sea ice parameters during the PAMARCMIP2017 campaign in the Arctic Ocean, Version 2, https://doi.org/10.1594/PANGAEA.966009, 2024.

**Authors' response:** We appreciate your clarification. We will incorporate the latest version of the AWI IceBird dataset and describe it in Section 2.1.

Regarding the study of Zhou et al., I would like to raise general concerns and perhaps some misunderstandings of my paper. The general points are the following:

**Spatial scales.** While the presented study broadens the knowledge with the aspect of seasonal evolution of remotely sensed sea-ice bulk density, I am concerned about the different magnitudes of spatial scales utilized in the derivation. More specifically, you use total freeboard from the ICESat-2 satellite laser altimeter orbits extracted within a circle around the CO that has a diameter of 100 km; snow depth and sea-ice thickness derived from 15 autonomous IMBs in the DN within circle around the CO that has a diameter of 70 km (in the beginning of the drift, but how about later after being affected by sea-ice dynamics for months?) while the data are inherently point measurements; and snow density derived from snow pit measurements within the CO that extends over an area with a diameter of only few hundred meters while the data are inherently point measurements. None of these data sources have real spatial overlap with each other. This effectively diminishes the study to use ice-type-averaged values (not far from Alexandrov et al.'s (2010) multi-year ice density derivation with climatological values from literature) as the measurements are not from the same piece of ice - not even remotely.

**Authors' response:** Thank you for your insightful comments on spatial scales. We will add the discussion on the uncertainties involved in matching datasets across different spatial scales in the revised manuscript. *However, there are some misconceptions about spatial scales that we need to clarify.*

**Buoy deployment sites (relatively stable)**

To begin with, we would like to clarify that the radius used for extracting **modal freeboard** data from ICESat-2 (IS2) orbits around the Central Observatory (CO) was **50 km**, **not 100 km**. Furthermore, the autonomous Ice Mass Balance Buoys (**IMBs**) in the Distributed Network (DN) provided measurements within a radius of **30-40 km** from the CO, **rather than 70 km**, and none of them are in the wider coverage of *Extended Network* (Krumpen et al., 2020; Lei et al., 2022; Rabe et al., 2024). It is also important to note that our main study period covers the freezing season from October to April. During this period, the buoy deployment areas are less influenced by sea ice dynamics, which significantly intensify from early summer onwards (Krumpen et al., 2021; von Albedyll et al., 2022). All selected buoys were located within a 50 km radius of the CO throughout the study period, as shown in Fig. A1.

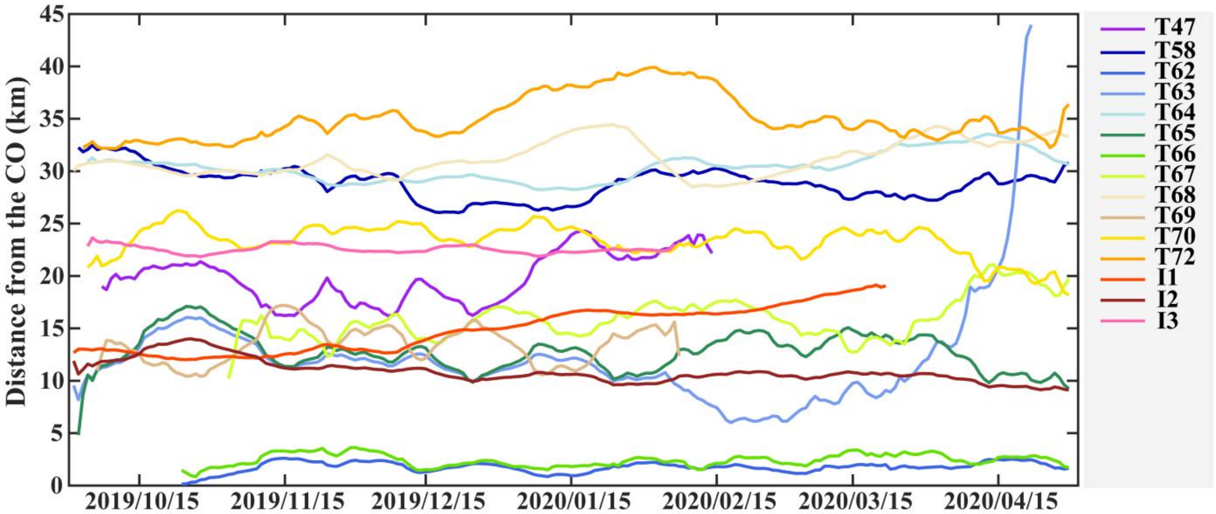

**Fig. A1.** Distance of all selected buoy sites from the CO during the MOSAiC freezing season.

## Spatial representation, not spatial overlap

We acknowledge that the measurements from the IMB array, the IS2 tracks, and the snow bulk density data do not spatially overlap. Instead, our study emphasizes spatial representation over direct overlap for the study region of kilometers to tens of kilometers. Given the challenges of acquiring multi-sensor data with sufficient temporal coverage during the freezing season, our approach combines MOSAiC and IS2 data to track the seasonal evolution of sea ice bulk density. This method aims to reasonably represent the average conditions of the MOSAiC ice floes at the 50 km scale (or DN scale), focusing on the representativeness of data, considering the spatial heterogeneity of ice thickness and snow thickness, rather than their spatial concurrence.

## Spatial compatibility of the buoy array and IS2

Despite the IMB array consisting solely of point measurements from 15 buoys, of which at least 10 are operational continuously, we are confident in their ability to effectively represent the sea ice thickness and snow depth for level ice across the MOSAiC DN scale. Supporting evidence from numerous recent studies within the MOSAiC expedition underscores the robustness of our buoy deployment strategy. These studies showed good agreement between buoy data and more extensive airborne or transect measurements, which capture a broader range of observations (Koo et al., 2021; Krumpen et al., 2021; Rabe et al., 2024; von Albedyll et al., 2022).

We adopted a modal approach to analyze IS2 orbit data within a 50 km radius around the CO, focusing on the log-normal distribution of Arctic sea ice freeboard, well-supported by extensive research (Farrell et al., 2011; Haas, 2010; Hansen et al., 2013; Koo et al., 2021; Landy et al., 2019; Petty et al., 2016; Ricker et al., 2015; Tian et al., 2020; von Albedyll et al., 2022). The mode, representing the most common level ice freeboard and excluding deformed ice (at least statistically significant), correlates closely with thermodynamic ice growth (Koo et al., 2021; Ricker et al., 2015), providing a reliable level ice estimate within the MOSAiC DN. Despite spatial and temporal variabilities, our method uses over 15,000 daily freeboard segments, ensuring reliable and statistically robust results.

## Expected phenomena

More importantly, we have identified a statistically significant decreasing trend in sea ice bulk density during the early freezing season (Fig. 5), thus providing some evidence for the seasonal evolution of sea ice bulk density, which is consistent with both the expected phenomenon (i.e., desalination processes) and the results reported in previous studies (Hutchings et al., 2015; Petrich and Eicken, 2017; Pustogvar and Kulyakhtin, 2016; Timco and Frederking, 1996).

## Snow bulk density from the MOSAiC CO

All snow pit measurements in our study were conducted on level ice, excluding the period when ice ridges were sampled (Macfarlane et al., 2023). Despite spatial heterogeneity and the resulting uncertainties, our analysis shows that the data from a single floe reliably represent the snow's metamorphic processes on level ice, essential for understanding changes in sea ice bulk density during the freezing season (see Fig. 4c). We also acknowledge that observations of snow pits originating from individual ice floe (MOSAiC CO) may limit spatial representativeness. However, based on the results of on-site investigations of several ice floes at the MOSAiC DN scale, at least at the initial stage, the snow depth of MOSAiC CO, relative to other ice floes, has no special abnormal characteristics, and can be considered representative for the snow state at the MOSAiC DN scale.

Leaving aside the issue of spatial scale, we have also quantified the uncertainties related to various input parameters in the calculation of sea ice bulk density. The relative contribution of snow bulk density to total uncertainty is around 1.7%, significantly less than that from total freeboard (50%) and snow depth (47%). Also, the estimated uncertainty in snow bulk density is about 20-30 kg $m^{-3}$, close to the representative value of 34 kg $m^{-3}$ (King et al., 2020).

In addition, using the term “local-scale” with data originating extending 100 km, when local is generally understood as < 1 km, definitely raised my eyebrows throughout the manuscript.
**Authors’ response:** Defining a study area of tens of kilometers as a local scale may not be reasonable. We will revise this terminology to ensure that the expression is not misleading.

Why was ICESat-2 ATL10 rev5 used when rev6 is available? Actually, why not use the publicly available, more local MOSAiC helicopterborne laser scanner data by Hutter et al. (2023), which you also cite in the manuscript? I think that could be a feasible option to explore and it would back up better the local-scale aspect of this study. At this point, however, I must point out that I was involved in collecting and processing said data, too.
**Authors’ response:** Indeed, when we finished the analysis, ATL10 V6 had not been released. Now, with some updated data processing, we have found that the updates in rev6 have minimal impact on our modal freeboard estimates, with changes of around 1-3%. This slight variation does not significantly impact the sea ice bulk density results. We commit to updating the ice bulk density to ATL10 rev6 for the final version to incorporate these improvements and ensure the most accurate data representation.
https://nsidc.org/sites/default/files/documents/user-guide/atl10-v006-userguide.pdf

As mentioned above, we focus on matching the buoy array (a sufficient number of IMBs) with all available freeboard data within the MOSAiC DN range. We considered using airborne data, but found it insufficient—only valid observations from about ten days were available, offering limited insights into seasonal variations due to inadequate statistical sampling. Additionally, while there are more airborne records for the CO floe, the corresponding IMB data are too sparse for reliable spatial matching and confident bulk density calculations at this scale. In the revision, we will combine thses airborne data to consolidate our conclusion.

Level ice. You state that the chosen IMBs were deployed on level ice. I agree that this is a correct approach, to consider level ice only. However, the publicly available deployment documents for the buoys T63, T65, T70, and I1 indicate that ridged ice was already in close vicinity during deployment.

**Authors' response:** We acknowledge that the deployment sites of buoys T63, T65, T70, and I1 were close to ridged ice. However, our analysis shows that the increase in sea ice thickness was consistent and smooth, indicative of thermodynamic growth typical of level ice, as detailed in Fig. 4a. This suggests that the nearby ridged ice did not significantly impact the thermodynamic-growth characteristics for the level ice with the buoy deployments. We will increase our discussion to address these questions, mainly by comparing and analyzing the accumulation of snow at the buoy deployments sits and the growth rate of sea ice.

How was it ensured that ICESat-2 data was considered over level ice only? How long are the data segments, did they include only level data? While the modal value of the log-normal fitted freeboard is an estimate of the thermodynamically grown sea ice, it does not strictly exclude e.g. thin sea ice that has deformed and gained the same freeboard as thermodynamically grown undeformed sea ice.

**Authors' response:** We extracted level ice freeboards from over 15,000 IS2 freeboard segments within the MOSAiC DN scale, which includes a broad range of ice conditions. Our methodology did not exclusively filter for level ice; rather, it involved analyzing the entire freeboard distribution to isolate the level ice component, i.e. to determine the modal feature of the freeboard frequency distribution. While we recognize that deformed thin ice can influence the data, the statistical analysis at the 50 km scale ensures that such variations do not substantially impact the representation of level ice freeboards.

How about snow pits, have you considered that pressure ridge sites were sampled on MOSAiC, too? Level ice tends to have thinner snowpack with larger temperature gradients that lead to snow metamorphism affecting the snow density profile.

**Authors' response:** All snow pit measurements in this study was conducted on level ice, and we will clarify this in the revision.

When comparing your data to the AWI IceBird dataset, did you choose measurements on level ice only quality flag? I would suggest doing so, and in that case also using the updated version of the dataset.

**Authors' response:** We agree with your suggestion and will update the dataset in the revised manuscript, ensuring that only the level ice component is used for comparisons.

More specific comments:

L62ff: Alexandrov et al. (2010) did not use airborne multi-sensor data. They used ground-based drill-hole measurements achieved through landing airplanes on the sea ice in the 1980s (Soviet Sever expeditions). So far, I am not aware of any other study utilizing airborne multi-sensor measurements to derive sea-ice bulk density than Jutila et al. (2022).

**Authors' response:** Thanks to your clarification, we will rewrite the sentence.

L79ff: While Shi et al. (2023) have more recently argued the point, it was mentioned earlier in Jutila et al. (2022), to which also Shi et al. (2023) refer.

**Authors' response:** We apologize for the oversight regarding the details in your paper, and we will rewrite the sentence to include the insights of both Jutila et al. (2022) and Shi et al. (2023) in A10.

L179ff: Sea-ice freeboard and thickness are found to follow log-normal or exponential distribution, but does total freeboard behave the same? And how about on the 100 km scale?

**Authors' response:** First, the spatial scale of our study is 50 km. We will describe in detail the substantial evidence supporting the log-normal distribution of sea ice freeboard and thickness over tens of kilometers, including both in situ and airborne measurements.

L232ff: Both your snow depth and sea-ice thickness measurements come from the IMBs. Therefore, are their uncertainties not independent and the assumption thus wrong?

**Authors' response:** Although both sea ice thickness and snow depth data are sourced from IMBs, due to the independence of their respective observations, we consider the resulting uncertainties to be independent.

L244ff: Were any other formulations than first and second order polynomials investigated?

**Authors' response:** We explored both negative exponential and second order polynomial models to describe the relationship between univariate parameters and sea ice bulk density. As we found similar performance in both, we decided to use first and second order polynomials for formal consistency between univariate and bivariate parameterizations.

Figure 5 & L313ff: Which values are you using for the three J22 data points? To my eyes, they do not match the values from Table 3 in Jutila et al. (2022) that list the average bulk densities on 800 m spatial scale. Or did you perhaps derive those values from the nominal resolution datasets? Did you use all values or only the level ice ones? Furthermore, I recommend using the same marker shape for the same ice type, adding citations also to the main text, and explaining the acronym "J22" (now only on L361).

**Authors' response:** We used the mean values provided in Table 3 of Jutila et al. (2022). We agree with your suggestions and will make the modifications.

L480ff: The data consists of several profiles covering a total distance of more than 3000 km (3410 km). Surveyed sea ice was primarily first-year ice (100 % in 2017) and multi-year ice, with only very little second-year ice. While you mention the spatial resolution of the data, I also think it's important to distinguish between the nominal measurement spacing (5-6 m) and the footprint size (40 m) of the measurement.

**Authors' response:** Thanks for the clarification, we will add this description in the revised version.

L493ff & Figure 10: Jutila et al. (2022) applied inverse-uncertainty weighted mean, not inverse distance. Are all ice types included in this analysis, also level ice and first-year ice, even though you're targeting to analyze rough and older ice? The AWI IceBird airborne sea-ice parameter datasets can easily distinguish different ice types using the provided quality flags.

**Authors' response:** We will correct the method description; this was a typo for which we apologise. In the revised manuscript, we will perform a more detailed analysis of ice types using the new version of the AWI IceBird dataset.

L523ff: The "new approach proposed in this study to determine [ice bulk density] at the basin scale using satellite altimetry data" is not new as this capability has been previously demonstrated in Jutila et al. (2022). If you mean using satellite altimetry data in your approach to determine sea-ice bulk density (together with ground-based point measurements), you need to present and discuss the effect of different scales for the reasons brought up earlier. The study also seems to highlight the parameterization applying the ice draft-to-thickness ratio, but there is no current or planned satellite mission that can directly observe sea-ice draft, thickness, nor their ratio.

**Authors' response:** We agree with your suggestion and will incorporate a discussion on how the differences in spatial scales affect sea ice bulk density retrieval. While no satellite missions currently or planned can directly observe sea ice draft and thickness, we will explore coupling the draught-to-thickness ratio with the hydrostatic equilibrium equation. This method will enable the simultaneous estimation of sea ice thickness and bulk density using satellite-measured freeboard and supplementary snow load data.

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