Responses to RC1

We sincerely appreciate your constructive comments, which have substantially contributed to the improvement of our manuscript. We have incorporated detailed revisions based on your suggestions. The original RC1 comments are presented in *blue italics*, followed by our responses in standard black. Key points are emphasized in **bold black**; Fig. and Table denote the additional figure and table information, respectively.

The study titled "Estimating seasonal bulk density of level sea ice using the data derived from in situ and ICESat-2 synergistic observations during MOSAiC" integrates observations of snow and ice thickness from 15 ice mass balance buoys, along with snow freeboard data from ICESat-2, airborne laser altimeters, and snow density data to estimate bulk ice density for a drifting ice floe and its surroundings at various scales. It also compares these estimates with manual observations of ice density and proposes several parameterizations, primarily using ice freeboard and thickness as key parameters.

Parametrization of ice density is a valuable task, and the study provides new data and implements known concepts to derive density estimates from large scale observations. The methods are clearly described, yet some details do not allow a reproducibility. The overview of remote methods is accurate enough, while an overview of in situ measurements is quite limited. In addition, there are a lot of inconsistencies related to the description of representative ice types and ice and snow thicknesses, related to a limited usage of existing in situ observations during the described expedition.

While the study offers valuable insights into the upscaling of sea ice freeboard data during the ice drift, where measurements were limited to individual floes, there are some methodological challenges that should be considered. For instance, the ice density estimates rely on a methodology with certain limitations. Some of these issues were addressed by manually adjusting the freeboard measurements, although the rationale and approach behind this adjustment could be more clearly explained. While these adjustments resulted in more realistic density estimates, there remains significant variability in the data, similar to the previously observed seasonal fluctuations in ice density.

Given this level of variability and the presence of an adjustment parameter that heavily influences both the density values and their seasonality, it is challenging to recommend a robust parameterization based on the current data. Additionally, the assumption that the adjustment is time-independent may need further justification. As a result, it becomes difficult to fully assess the quality of the density estimates due to both the high variability and the manual adjustments made during the analysis.

Overall Reply We appreciate the reviewer's feedback on the manuscript and we have made the following improvements: 1) we clarified the regional representativeness and validity of the retrieved IBDs; 2) we added specific descriptions for the spatial scale adjustment; 3) we incorporated physical interpretations for the IBDs and developed additional parameterizations; 4) we thoroughly analyzed the uncertainties and constraints associated with the IBD process; 5) we evaluated the developed parameterizations against coring measurements from late October 2022, with a resulting relative error ranging from 0.2 to 0.9 %; 6) We estimated the pan-Arctic second-year ice bulk densities from 2010 to

2024 to demonstrate the applicability of our parameterizations; 7) we also proposed a new age-related IBD climatology, taking into account the limitations of the parameterizations.

Representativeness Indeed, our estimated IBDs represent the average condition of the ice layer as measured by the selected IMBs, as illustrated in Fig. A1. Given the considerable spatial variability in sea ice and snow thickness observed among the MOSAiC ice floes, we retract our previous statement that the results represent typical ice conditions at the DN or L-site scales. **As a result, all regional scale statements are based on the results from the buoy sites (SYI-dominated), which also motivate the so-called spatial scale adjustment.**
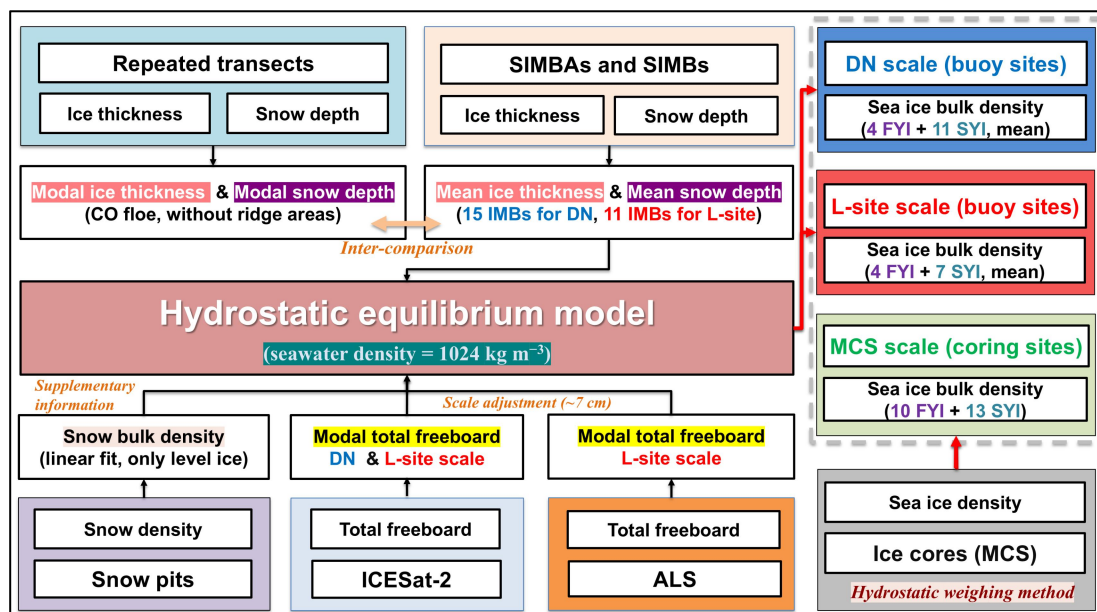

Figure A1. Flowchart of the IBD retrieval process.

Compatibility of spatially non-overlapping data The spatial scale adjustment was carefully evaluated, and the resulting values were derived from specific calculations rather than being manually determined; **we then provided additional details.** The purpose of this adjustment is to align the large-scale observations with the buoy-deployed ice layers. We explain how the correction term was derived and why it is time-independent in our response to the general comments (see details in **GC2**). Essentially, the spatially scaled modal total freeboard can be considered an approximation of the mean total freeboard across the buoy sites.

Validity, Limitations, and Uncertainties We argue that IBDs derived from buoy sites (regional) remain valuable, demonstrating relatively strong agreement with direct measurements (local) during MOSAiC, and illustrating a **general seasonal pattern** (Fig. A2, Fig. A3, and Table A1), while also falling within the range of historically reported FYI and SYI bulk densities. We discussed in **GC1** why the regional estimates were more consistent with the IBD variation of MCS-FYI ($R = 0.71$, $P < 0.01$), despite being mostly composed of SYI. We also acknowledge that the hydrostatic equilibrium method for calculating IBD has inherent limitations and challenges, as noted by Hutchings et al. (2015) and Jutila et al. (2022), primarily related to deformation- and scale-related hydrostatic equilibrium failures. Nevertheless, it remains suitable for estimating the bulk density of level sea ice over tens of kilometers under the assumption of hydrostatic equilibrium (see details in **GC3**). Due to irregular variations in

airborne and satellite trajectories, and the limitations of the buoys in capturing daily variations in mean snow depth over their deployment area, we emphasize that the retrieval method may not fully resolve synoptic-scale IBD variations, with a relatively high uncertainty of ~3 % (Fig. A4).
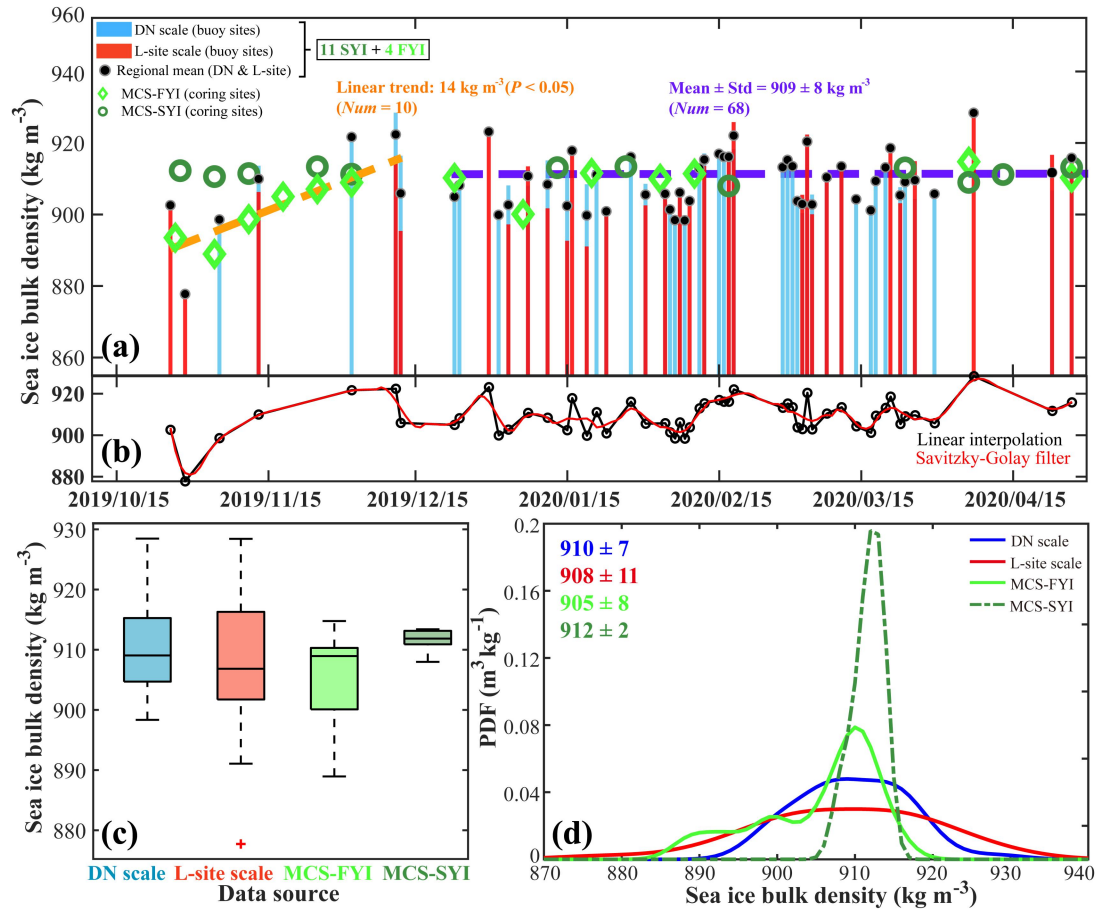

Figure A2. (a) Seasonal variation of IBD estimates at the DN (blue bars), L-site (red bars), and MCS (green symbols) scales during the MOSAiC freezing season. The black dots are the regional mean of the DN and L-site estimates. The orange dashed line represents the linear fitting from late October to early December ($R = 0.62$, $P < 0.05$) and the purple dashed line indicates the mean ± one standard deviation from late December to April. **(b)** Linear interpolation (black) and smoothing (red) of regional IBD estimates. **(c)** Box plots of all IBD estimates over the study period, showing interquartile range (IQR, Q3−Q1, boxes), median (black lines), and outliers (greater than 1.5 × IQR, red crosses). **(d)** Probability density distribution (PDF) of all IBD estimates over the study period, with labelled values showing the mean ± one standard deviation.
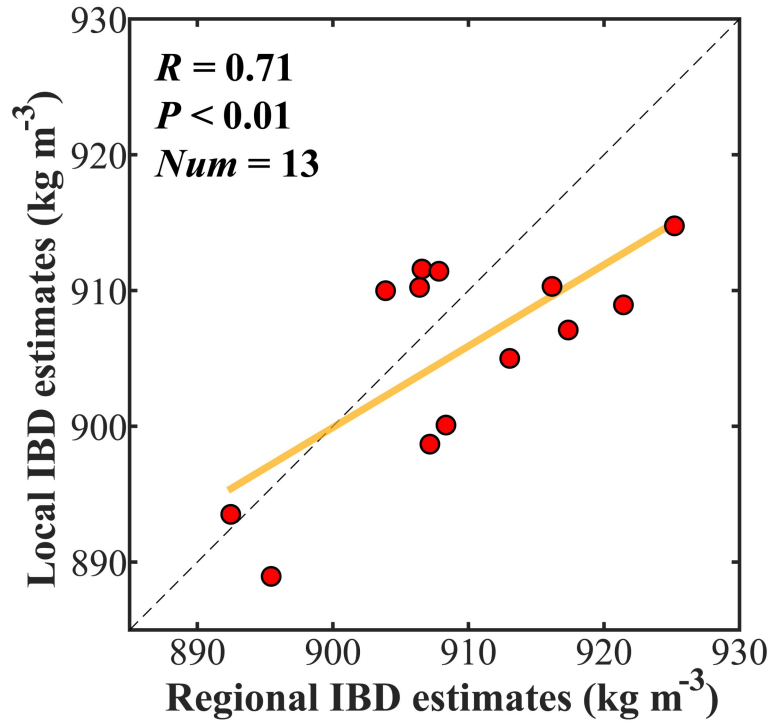
Figure A3. Scatterplot of regional versus local IBD estimates. The regional IBD represents the smoothed result derived from both DN and L-site scale estimates, while the local IBD represents the MCS-FYI. The solid orange line indicates the fitted results and the dashed black line shows the one-to-one relationship. The statistical metrics include the correlation coefficient (*R*), the statistical test *P*-value, and the total number of samples (*Num*).

Table A1. Seasonal averages of IBD at regional and local scales during the MOSAiC freezing season, where ON denotes autumn (October to November), DJF denotes winter (December to February), and MA denotes spring (March to April). Statistical information is presented as mean value (Mean), standard deviation (Std) and total number of samples (*Num*).

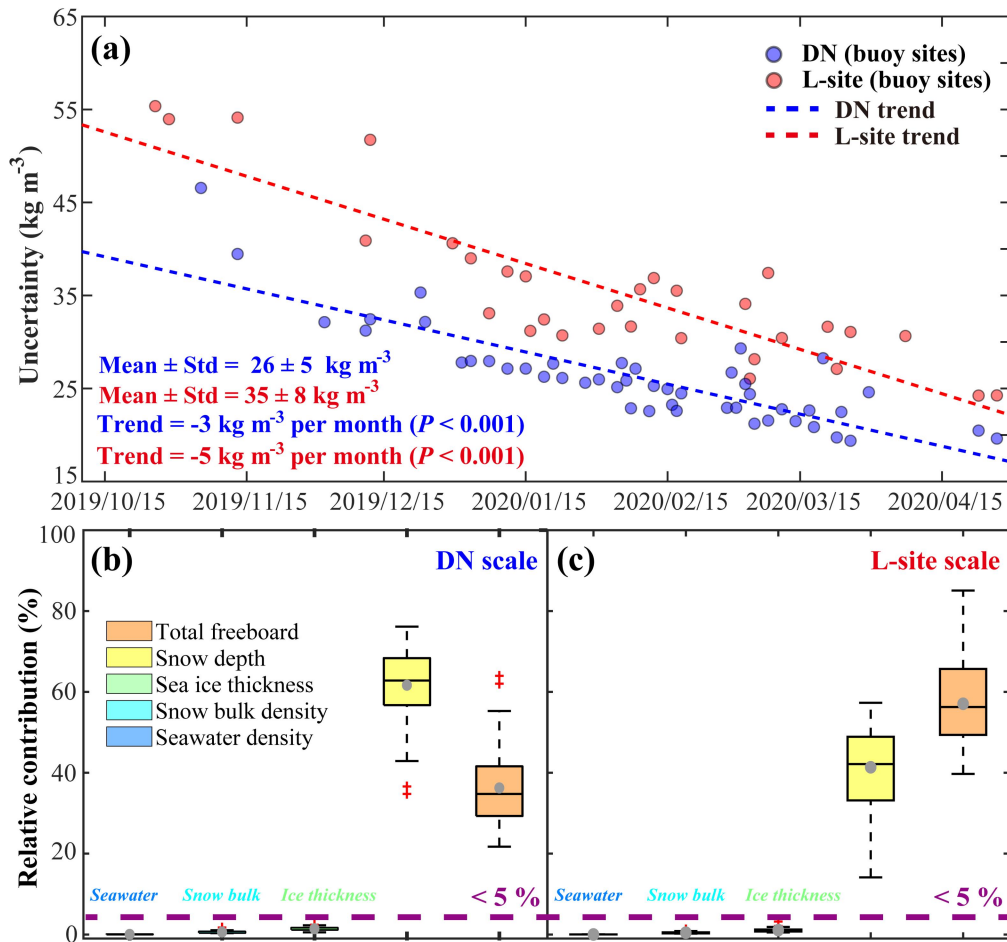| Season	DN & L-site (regional)			MCS-FYI (local)			MCS-SYI (local)		
	Mean (kg m^{-3})	Std (kg m^{-3})	*Num*	Mean (kg m^{-3})	Std (kg m^{-3})	*Num*	Mean (kg m^{-3})	Std (kg m^{-3})	*Num*
ON	900	14	5	899	8	5	912	1	4
DJF	910	9	45	909	4	6	911	3	4
MA	910	7	28	913	3	2	912	2	4

Figure A4. (a) Seasonal variation of IBD uncertainties at the DN (blue dots) and L-site (red dots) scales during the MOSAiC freezing season. Also shown are the relative contributions of uncertainties for different input parameters to the total IBD uncertainty over the study period at the **(a)** DN and **(b)** L-site scales, respectively. The boxplots depict the inter-quartile range (IQR, Q3−Q1, boxes), median (black lines), mean (grey dots), and outliers (exceeding 1.5 × IQR, red crosses).

General comments

A parameterization of sea-ice density can indeed be a valuable tool for both modelers and observers. However, I have some concerns regarding the potential usefulness of the parameterization presented here for such applications. Firstly, it is based on a methodology with significant uncertainties, which in many cases seem to exceed the actual seasonal variability of sea-ice density. Secondly, the current parameterization focuses on correlations between density and ice freeboard or thickness, without addressing important physical factors such as region, ice salinity, ice temperature, or water temperature. Since ice freeboard is inherently linked to its density, this creates a positive feedback loop. While snow may also play a role, it is less likely to directly influence ice density. Low ice freeboard can result from both high ice density and reduced thickness, complicating the interpretation. Similarly, the relationship between ice thickness and density involves multiple factors, including the region, ice age, and type, in addition to seasonal variations. Suggesting that only very thin ice has lower density seems to oversimplify the complexity of these processes. Additionally, it may be less useful to rely on ice thickness as an input parameter, as this is typically the primary goal of many remote sensing estimates rather than an available input variable.

GC1 Reply The validity of the IBD data has been discussed above and carefully addressed in **GC2** and **GC3**. We also argue that IBD variability at the sub-weekly scale does not undermine the overall correlation between IBD and other parameters. In the revision, we focus on comparing the potential IBD parameterizations derived from regional (buoy sites) and local (coring sites) estimates, for which we no longer assert absolute robustness due to inherent differences in spatial scale, measurement methods, sample sizes, and ice types.

GC1: Clarification

- We agree with the reviewer that predicting IBD from sea ice parameters alone is challenging. Given the complexity of the multiple processes and parameters influencing IBD, the primary objective of this study is to propose some **potential simple parameterizations** for predicting IBD throughout the freezing season, adapted to **contemporary ice conditions in the central Arctic**. We also would like to clarify that the samples used for the IBD parameterization **themselves have time-varying properties** such as ice porosity, temperature, salinity, thickness, and age.

- The IBD parameterization **involving sea ice thickness remains valuable** for satellite-based retrievals of sea ice thickness, as it can be combined with radar/laser freeboard-to-thickness conversion (when other parameters are known) to estimate both IBD and sea ice thickness simultaneously. We highlight that the regional IBD results are not independent of their sea ice parameters and are therefore subject to error propagation. Nevertheless, we suggest that these regional IBD parameterizations, which are **representative of the hydrostatic equilibrium-based IBD**, and the coefficients derived from observations, still provide valuable guidance for satellite retrievals of sea ice thickness based on the same principles.

Comparison of IBD parameterizations at regional and local scales reveals significant effects of spatial scale (buoy array vs. spot core sampling) and computational method (hydrostatic equilibrium vs. weighing) on the IBD parameterzation (see **Fig. A5** and **Fig. A6**). **Our potential parameterized equations for IBD at the regional scale support many of the previous findings.** *For example, Ackley et al. (1974) proposed a negative linear equation dependent on ice freeboard, Kovacs (1997) developed a power equation dependent on ice thickness, Alexandrov et al. (2010) and Shi et al. (2023) defined positive linear equations dependent on the ice freeboard-to-thickness ratio, and Jutila et al. (2022) developed a negative exponential function dependent on ice freeboard.*
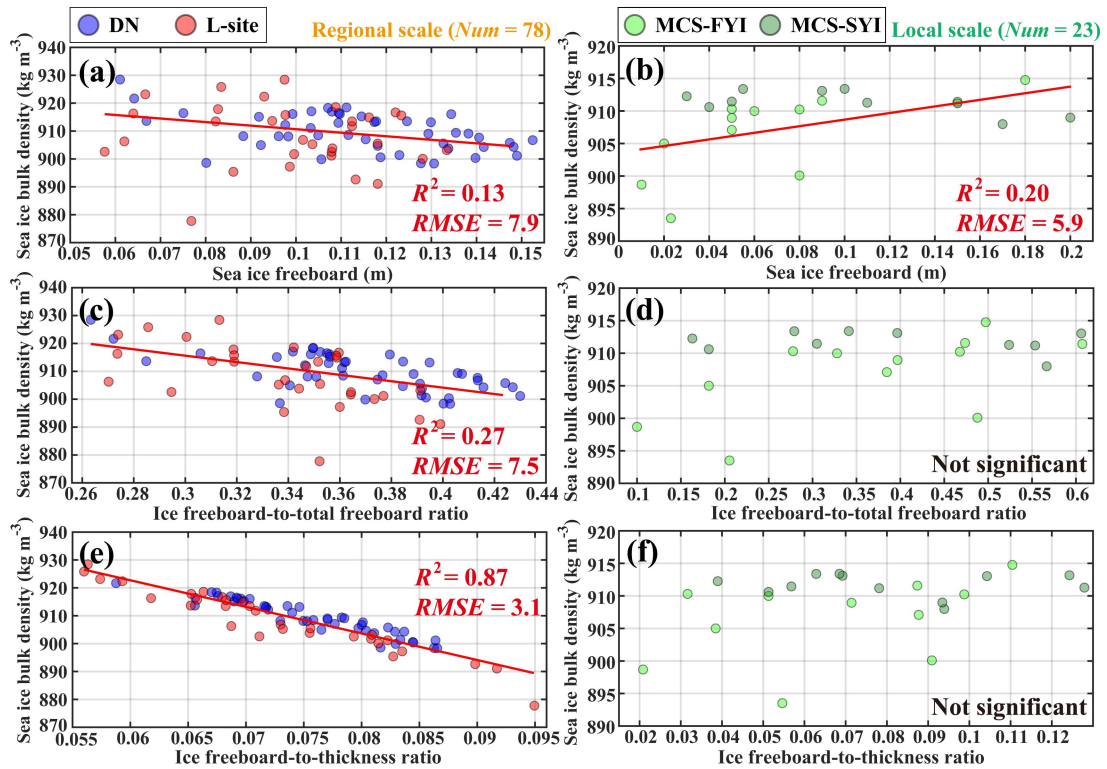

Figure A5. Potential parameterizations for IBD at the regional scale and comparison with results at the local scale, including regression models using **(a, b)** sea ice freeboard, **(c, d)** ice freeboard-to-total freeboard ratio, and **(e, f)** ice freeboard-to-thickness ratio. Each panel shows model fit metrics, including the coefficient of determination (R^2) and root mean square error (*RMSE*, unit: kg m^{-3}). The significance level for the statistical test is set at 95%. The total number of samples (*Num*) is 78 for the regional scale and 23 for the local scale.
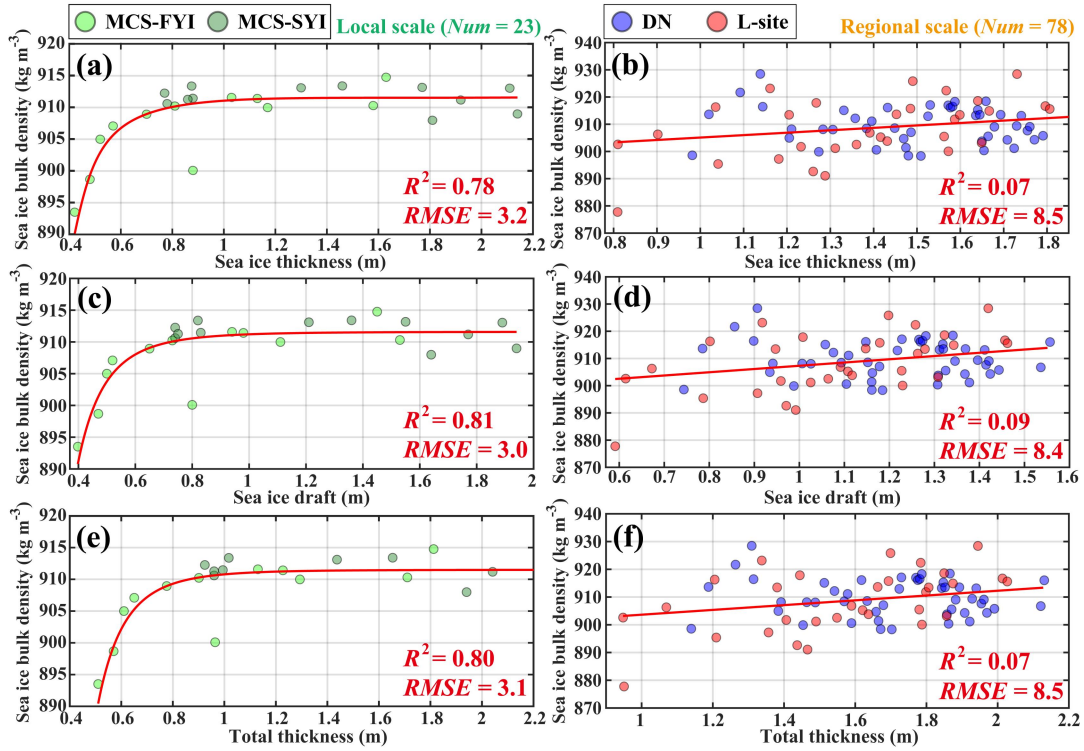
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Figure A6. Potential parameterizations for IBD at the local scale and comparison with results at the regional scale, including regression models using **(a, b)** sea ice thickness, **(c, d)** sea ice draft, and **(e, f)** total thickness. Each panel shows model fit metrics, including the coefficient of determination (R^2) and root mean square error (*RMSE*, unit: kg m^{-3}). The significance level for the statistical test is set at 95%. The total number of samples (*Num*) is 23 for the local scale and 78 for the regional scale.

GC1: Parameterization Considering Physical Factors We investigated whether physical factors could enhance the established IBD parameterizations based on sea ice parameters. Here, a multiple linear regression model was used to investigate the relationships between these variables and IBD. The analysis showed that **sea ice bulk temperature significantly improved the performance of the developed regional IBD parameterizations** (see Fig. A7 and Table A2), particularly the sea ice freeboard-dependent parameterization (R^2 improved by ~85%), while air and seawater temperatures were not helpful suggesting that they are insufficient to explain the seasonal variability of IBD. None of these multivariate regression models suffer from multicollinearity problems, with variance inflation factors (VIFs) less than 2. In contrast, the introduction of any physical factor (including sea ice bulk temperature and salinity) into the developed local IBD parameterizations did not improve their original fitting performance, possibly due to the spatial heterogeneity of ice porosity and the potentially non-linear relationship.
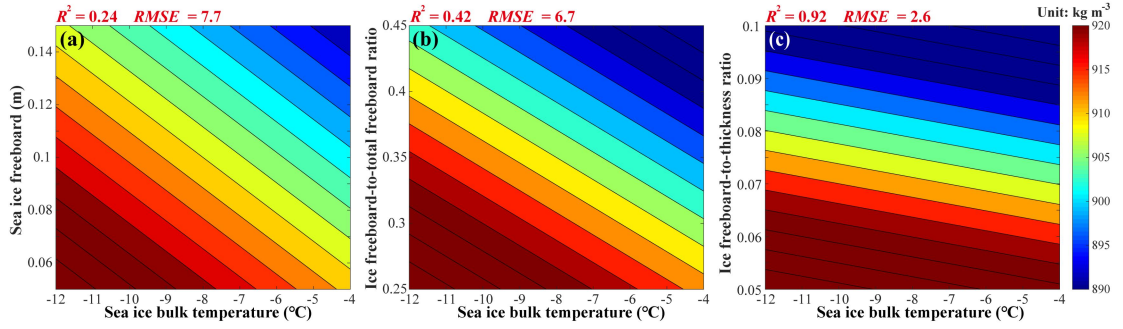

Figure A7. Potential parameterizations for IBD at the regional scale using both sea ice parameters and sea ice bulk temperature, including **(a)** sea ice freeboard and sea ice bulk temperature versus IBD, **(b)** ice freeboard-to-total freeboard ratio and sea ice bulk temperature versus IBD, **(c)** ice freeboard-to-thickness ratio and sea ice bulk temperature versus IBD. Each panel shows model fit metrics, including the coefficient of determination (R^2) and root mean square error (*RMSE*, unit: kg m^{-3}). **Note:** The significance level for the statistical test is set at 95% and the total number of samples is 78.

- **The parameterized equations for IBD at the regional scale combing both sea ice parameters and physical factors are defined as follows:**

$$\overline{\rho_i(x, y, t)} = a1 \times |\overline{\delta(x, y, t)}| + a2 \times \overline{X(x, y, t)} + a3, \tag{A1}$$

where $|\overline{\delta(x, y, t)}|$ represent the absolute value of regional sea ice bulk temperature at any given grid cell over tens of kilometers scale (x, y) and time (t). Table A2 lists the regression coefficients and their 95 % confidence intervals for Eq. (A1).

Table A2. Regression coefficients of the parameterized equations based on sea ice parameters and sea ice bulk temperature at the regional scale (kg m^{-3}), and parentheses represent 95 % confidence intervals for the regression coefficients.

$\overline{X(x, y, t)}$	Variable type	a1	a2	a3
Sea ice freeboard (m)	*Univariate*	2.1 (0.7, 3.5)	−198 (−290, −106)	913 (902, 924)
Ice freeboard-to-total freeboard ratio	*Bivariate*	2.7 (1.5, 3.8)	−155 (−197, −112)	942 (928, 956)
Ice freeboard-to-thickness ratio	*Bivariate*	1.2 (0.8, 1.6)	−967(−1036, −899)	970 (964, 976)

Figure A8 illustrates the seasonal variation in air temperature, ice bulk temperature, ice bulk salinity, and brine volume during the MOSAiC freezing season. **According to the theoretical relationship (Timco and Frederking, 1996), the recorded sea ice temperature and bulk salinity variations cannot account for the seasonality of IBD over the study period.**

- **MCS-FYI.** The significant increase in IBD during the early stages is closely related to the **significant reduction in the air fraction** (Salganik et al., 2024), as the conversion of liquid water to solid ice in closed brine pockets causes volume expansion, compressing trapped air bubbles and pushing gas into the brine solution as temperatures fall (Crabeck et al., 2016; Crabeck et al., 2019).

- **MCS-SYI.** The MCS-SYI showed a relatively stable IBD with an increase of only ~3 kg m^{-3} during the early stages, **corresponding to its relatively low thickness growth rate (~9 % per month) and low porosity** with a brine volume of ~1 to 4 % (Fig. A8) and an air fraction of ~0.8 to 1 % (Salganik et al., 2024).

- **Regional.** The regional IBD results also showed some increasing trend (~14 kg m^{-3} per month, $P < 0.05$), similar to the MCS-FYI, but the limited sample and relatively high uncertainty should be noted (average of ~30 kg m^{-3}). In this context, the mean ice thickness at the DN and L-site scales experienced monthly growth rates of ~15 and 21 %, respectively, with the majority of the buoy-monitored ice layers beginning to grow. **This also reveals the potential difference in ice properties between local (MCS-SYI) and regional (SYI-dominated buoy sites) scales.**

"In particular, Hornnes et al. (2024) found that the spatial heterogeneity of SYI porosity was much greater than that of FYI during the GoNorth expedition in October 2022, and also found similar air fractions in FYI (2.5 ± 0.5 %) and SYI cores (2.8 ± 0.5 %)."

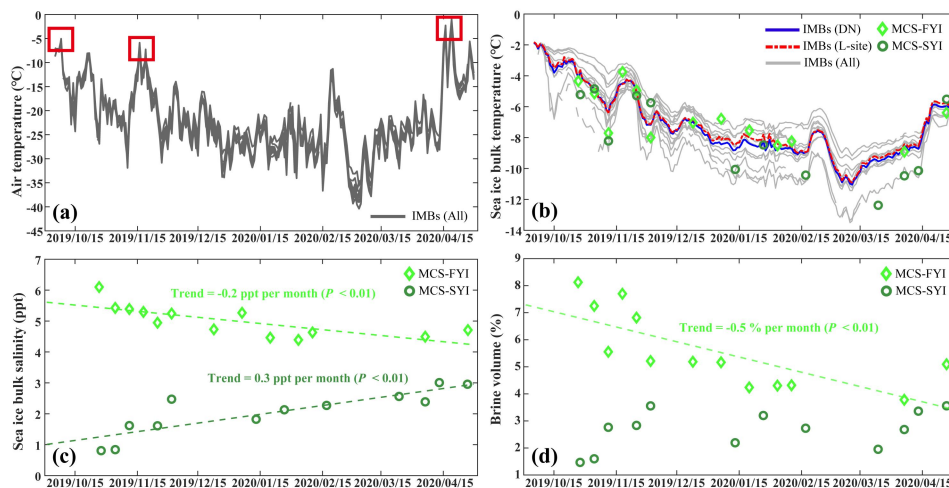**Figure A8.** Seasonal variation of **(a)** buoy-derived air temperature, **(b)** buoy-derived and core-based sea ice bulk temperature, **(c)** core-based sea ice bulk salinity, and **(d)** core-based brine volume during the MOSAiC freezing season. The red boxes in panel **(a)** mark warm air intrusion events, and the dashed line in panels **(c, d)** indicates the seasonal linear trend ($P < 0.01$).

GC1: Updating IBD Climatology

Given the limitations of the developed IBD parameterizations, we proposed a new age-related IBD climatology for the freezing season by combining the results from the Arctic Sever expedition (Alexandrov et al., 2010; Shi et al., 2023), the IceBird campaigns (Jutila et al., 2022), and the MOSAiC expedition (this study), as shown in Table A3. These age-related IBD values can serve as an updated IBD climatology for future basin-scale satellite sea ice thickness retrievals, providing an alternative to A10, with two key upgrades: **1) additional SYI information, and 2) mitigation of the potentially biased A10-MYI.**

Table A3. Age-related bulk densities of level sea ice during the freezing season derived from a combination of the Arctic Sever expedition (from 1980 to 1989), the IceBird campaigns (April 2017 and 2019), and the MOSAiC expedition (from 2019 to 2020). Uncertainty is given as the maximum difference in age-related mean IBD values across observations.

Ice age	Mean (kg m^{-3})	Standard deviation (kg m^{-3})	Uncertainty (kg m^{-3})
FYI (0–1 years)	**916.9**	7.5	20
SYI (1–2 years)	**907**	6.8	13
MYI (2+ years)	**900**	14	34

During the GoNorth Expedition in late October 2022 (Salganik et al., 2023), we used the SYI core results to evaluate the developed IBD parameterizations within their potential applicability ranges, along with the age-related IBD climatology Fig. A9). The FYI core was not selected because its ice parameters were not applicable to the proposed parameterizations (mean ice thickness of 0.31 m). We found that the regional IBD parameterizations maintain respectable accuracy compared to local direct measurements, even surpassing the results of parameterizations constructed from MOSAiC ice cores.
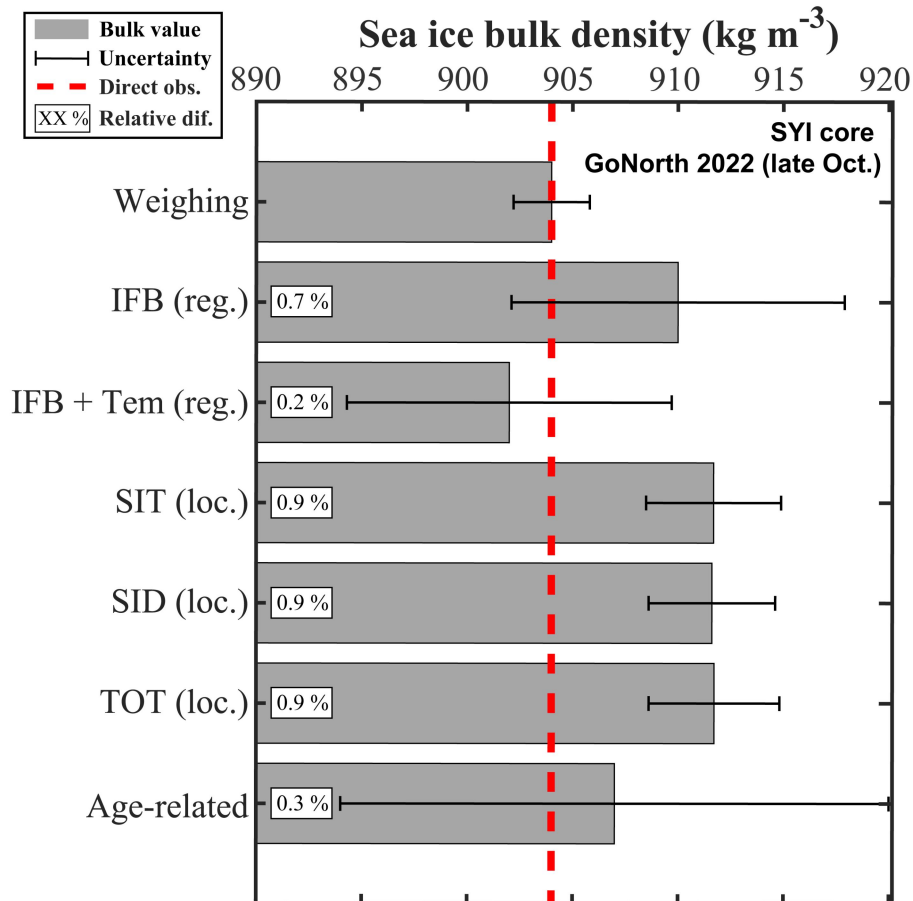

Figure A9. Evaluation of the regional and local IBD parameterizations during the GoNorth Expedition in late October 2022. The age-related IBD climatology and its uncertainty are also shown. **Note: Weighing** represents the direct measurement of IBD using the hydrostatic weighing method with an uncertainty defined as 0.2 %. **Reg.** and **Loc.** are regional and local scales, respectively. **IFB**, **Tem**, **SIT**, **SID**, and **TOT** represent ice freeboard, ice bulk temperature, ice thickness, ice draft, and total thickness, respectively. The uncertainty of the IBDs derived from the parameterizations is determined by the 95 confidence intervals of the regression coefficients.

GC1: Application

We combined AWI CS2 sea ice data, the ice age field, and regional IBD parameterizations to provide preliminary insights into the pan-Arctic monthly SYI bulk densities and their updated thicknesses during the 2010 to 2024 freezing seasons (Fig. A10). The final results are presented as averages derived from the three regional IBD parameterizations. The incorporation of the regional IBD parameterizations into the current AWI CS2 product introduce**d more realistic variations in SYI bulk densities**, leading to **systematically higher SYI thickness estimates and reducing their seasonal growth rates and interannual trends**. Future incorporation of pan-Arctic SYI bulk temperatures, along with more accurate sea ice ancillary parameters, will be more effective in retrieving SYI bulk densities. Notably, the IBD for AWI CS2 showed a gradual increase, associated with the sea ice type-weighted scheme configured to the A10 climatology used (i.e., non-physical variation).

In contrast to the increasing trend of IBD from late October to early December during MOSAiC, pan-Arctic SYI bulk densities showed a decrease (~6 kg m^{-3}) from October to November, which may be related to several factors: 1) lack of IBD samples in early October during MOSAiC (possibly main brine discharge); 2) high spatial heterogeneity of SYI porosity; 3) extrapolation of the regional parameterizations to pan-Arctic SYI; 4) inherent uncertainty in AWI CS2 sea ice parameters; 5) failure of the parameterizations for severe sea ice deformation units. **Nevertheless, the results were consistent with the expected range and evolution of SYI.**
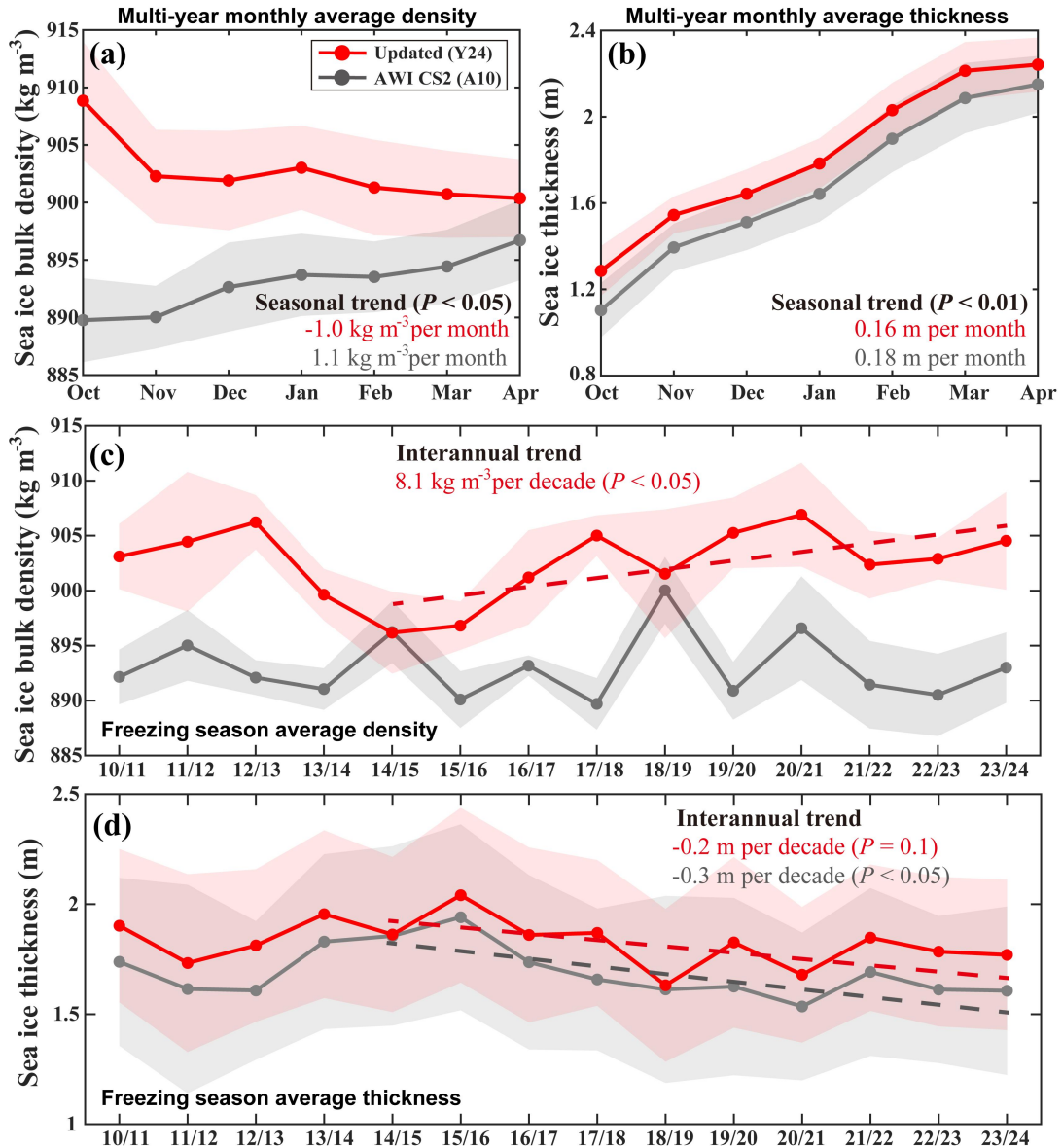
Figure A10. IBD and thickness variation of the pan-Arctic SYI during the 2010 to 2024 freezing seasons based on the AWI CryoSat-2 (AWI CS2) sea ice product, including results using our parameterizations (Y24) and the original settings (sea ice type-weighted A10 climatology). The shaded areas denote mean ± one standard deviation and dashed lines indicate linear trends with their statistical test P-values. **(a)** Multi-year monthly average estimates for IBD from October to April. **(b)** Multi-year monthly average estimates for ice thickness from October to April. **(c)** Freezing season average estimates for IBD from 2010/2011 (10/11) to 2023/2024 (23/24). **(d)** Freezing season average estimates for ice thickness from 2010/2011 (10/11) to 2023/2024 (23/24).

Another significant concern regarding the methodology of this study involves the so-called "spatial scale adjustment." First, the issue with buoys is not solely about spatial coverage or the number of buoys deployed. Rather, it arises from the fact that the buoys were installed in ice that may not be representative of the broader area. Secondly, such a substantial adjustment requires a more detailed explanation than a brief mention with a reference to supplementary materials. The adjustment of 7 cm to the freeboard, which accounts for roughly a third of the average total freeboard during the observation period, is quite significant. According to the methodology, ice freeboard is calculated as the difference between ICESat-2 snow freeboard and buoy snow thickness. Since the buoy snow thickness remains unchanged, applying a 7 cm adjustment equates to adjusting the ice freeboard by 7 cm, which corresponds to approximately 65 cm of ice thickness. This can be shown considering the initial buoy ice thickness was around 100 cm, while the modal ice thickness from electromagnetic sounding was between 40-50 cm, giving a similar difference in ice thickness, as the adjustment equivalent. Such a considerable adjustment to the interpretation of ice thickness, which ultimately impacts the density estimates, warrants a more thorough explanation of both its value and physical meaning. Additionally, it is perplexing that instead of adjusting the relatively uncertain estimates of snow and ice thickness from the buoys, the ICESat-2 and airborne laser scanner data were adjusted instead and presented in this adjusted form. This 7 cm adjustment was applied across the entire seven-month observation period, but it is not clear why this adjustment was considered time-independent. If the buoys were installed in areas with unrepresentatively thick ice, it seems unlikely that this bias in ice thickness would remain constant throughout the ice growth season. Numerous observations indicate that by the end of the cold season, initially thinner ice can grow more rapidly due to thinner snow cover, making the differences between thick and thin ice less distinguishable. Furthermore, another issue arises from the fact that buoys were installed in areas with thicker ice, which is known to correlate strongly with snow thickness. Even toward the end of the season, ice with greater surface roughness tends to accumulate more snow compared to smoother, younger ice. This raises questions about the representativeness of the snow thickness measurements from the buoys. These considerations lead to a broader question regarding the interpretation of the seasonal changes presented in the study. How might these changes be affected by the unrepresentativeness of the buoy measurements?

GC2 Reply The spatial scale adjustment is designed to compensate for systematic differences in snow depth (rather than sea ice freeboard) between buoy sites and large-scale observations, as determined by **a comprehensive intercomparison** of observations from buoy, ice core, transect, and airborne/satellite measurements during the early study period (**Table A4**, **Fig. A11**,and **Fig. A12**).

In the initial phase, a comparison of MCS-FYI, MCS-SYI, and regional measurements (Krumpen et al., 2020) indicated that snow depth was the primary contributor to the total freeboard of level sea ice, and that their sea ice freeboards were very similar, despite significant differences in their ice thicknesses (up to 0.4 m) and spatial scales (local and regional), as shown in **Table A4**. Furthermore, the initial snow and ice thickness values at the SYI-dominated buoy sites were comparable to those observed in the MCS-SYI (see **Fig. A12**). This suggests that the spatial heterogeneity of level ice freeboard between the buoy sites and the large-scale airborne/satellite measurements is likely to be small, despite the absence of direct freeboard measurements for either. A subsequent comparison of buoy snow observations at the DN and L-site scales from 5−11 October 2019 with corresponding regional transect measurements showed that buoy-derived mean snow depths (0.14 m) were **approximately 7 cm**

higher at both scales. This highlights that snow conditions on buoy-observed ice layers may not accurately reflect the magnitude of snow depths over a broader measurement area (and vice versa). However, **the seasonal trends in mean snow depth at the buoy sites were closely aligned with the modal snow depths derived from transects over the CO floe** throughout the study period (see Fig. A12), which covered a much larger area. This finding suggests that the buoys effectively captured seasonal snow accumulation over level sea ice within their deployment area. Therefore, it can be concluded that the modal total freeboard derived from airborne/satellite measurements could be systematically adjusted by approximately 7 cm to align with buoy observations.

The spatial adjustment term was further validated by using ice core data as the initial freeboard reference for the buoy sites. In this context, we calculated the adjusted value at the corresponding regional scale as the sum of two terms: 1) the absolute value of the maximum negative difference between the original modal total freeboard and buoy-derived mean snow depth (**~0.4 m**, see Fig. A11), and 2) the initial freeboard reference obtained from the FYI and SYI cores in late October, determined by weighting the FYI/SYI ratios from the corresponding buoy sites (**~0.3 m**). The buoy-derived mean ice thickness and snow depth were comparable in mid-October (initial satellite record) and late October (initial ice core record), and the timing difference is not expected to significantly impact the reference freeboards. The final adjusted values were **approximately 7 cm at both spatial scales**, which aligned with those obtained from snow depth differences between the regional transects and buoy sites. This, in turn, suggests that the spatial scale difference between the two observations results from a systematic bias in snow depth rather than sea ice freeboard. Together with the ability of the buoys to capture seasonal snow variations, we ensured that the difference between the adjusted modal total freeboard and the buoy-derived mean snow depth reasonably approximated the sea ice freeboard across the buoy sites, thereby ensuring compatibility between the buoy array and the airborne/satellite measurements used in the IBD retrieval.

Table A4. Comparison of ice conditions in different measurement domains during the early stages of the MOSAiC expedition.

Data (scale)	Time	Sea ice thickness (m)	Snow depth (m)	Total freeboard (m)	Sea ice freeboard (m)
Ice cores (MCS-FYI)	27 Oct	0.42	0.09	0.11	**0.023**
Ice cores (MCS-SYI)	28 Oct	0.77	0.15	0.18	**0.03**
Krumpen et al. (2020) (Regional transects)	5−11 Oct	0.36	0.07	0.10*	**0.03***

Note that data marked with an asterisk (*) are based on modal total freeboard derived from ALS and ICESat-2 on 11 Oct 2019. Sea ice thickness and snow depth from Krumpen et al. (2020) are weighted estimates according to daily observation samples or transect distances from 5 to 11 October 2019.
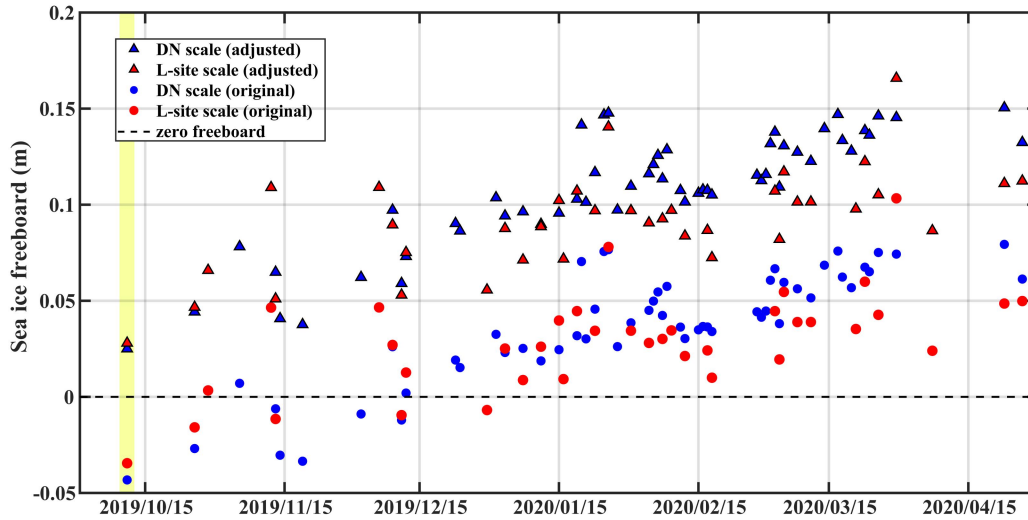
Figure A11. Seasonal variation of the approximate sea ice freeboard for buoy sites during the MOSAiC freezing season, calculated by subtracting the buoy-derived mean snow depth from the adjusted and original modal total freeboards at the DN (blue) and L-site (red) scales, respectively. The black dashed line indicates the zero sea ice freeboard, and the yellow bar highlights the maximum negative difference between the original modal total freeboard and the buoy-derived mean snow depth.
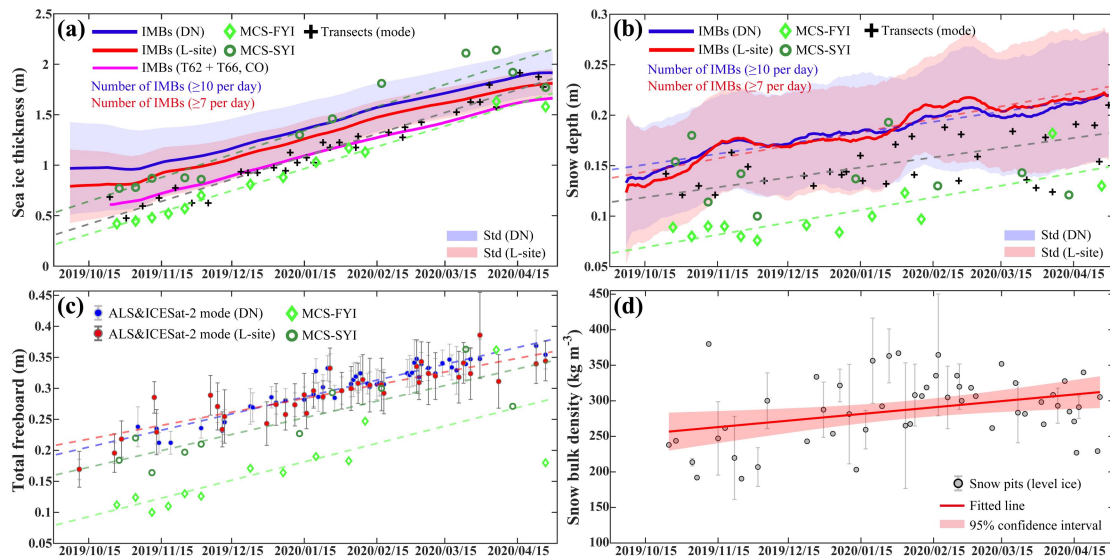

Figure A12. Seasonal variations of sea ice and snow parameters from level ice components during the MOSAiC freezing season. **(a)** Sea ice thickness measurements obtained from buoys (blue, red, and magenta lines for DN, L-site, and CO scales, respectively), transects (black crosses, mode), and ice cores (green symbols). **(b)** Snow depth measurements recorded from buoys (blue and red lines for DN and L-site scales, respectively), transects (black crosses, mode), and ice cores (green symbols). **(c)** Total freeboard measurements derived from ALS & ICESat-2 (blue and red dots for DN and L-site scales, respectively) and ice cores (green symbols). The error bars represent the uncertainties of the modal total freeboard. **(d)** Snow bulk density measurements ascertained from snow pits (grey dots), with error bars denoting one standard deviation from all daily estimates. The red line indicates a linear fit and the shaded band labels the 95 % confidence interval. **Note:** The dashed lines in panels **(a)**, **(b)**, and **(c)** represent seasonal linear trends, with all statistical *P*-values less than 0.01.

GC2: Modelled IBD

Given the relatively high uncertainties and sparse samples associated with the increasing trend of regional IBDs in the early stages, we introduced hydrostatic equilibrium-based modelled IBD estimates based on a simple trend assumption, to further elucidate the potential seasonal shifts in IBD. Specifically, we set the initial sea ice thickness, snow depth, and total freeboard in mid-October to values of 0.36, 0.07, and 0.10 m, respectively, which are expected to represent typical ice conditions for MOSAiC level ice (Table A4). We then calculated the average seasonal trends for these parameters during MOSAiC as ~0.20, 0.01 and 0.03 m per month according to Fig. A12, and extrapolated these initial values to April. Finally, using the hydrostatic equilibrium equation and the same snow bulk and seawater densities used for the regional IBD estimates, we calculated the so-called modelled IBD (Fig. A13). It should be noted that the modelled values can only indicate the approximate seasonal trends of IBD, completely filtering out possible IBD changes at daily and weekly scales. **Overall, the derived modelled values also supported the early increase trend of IBD depending on the seasonality of the different observed ice parameters during MOSAiC.**
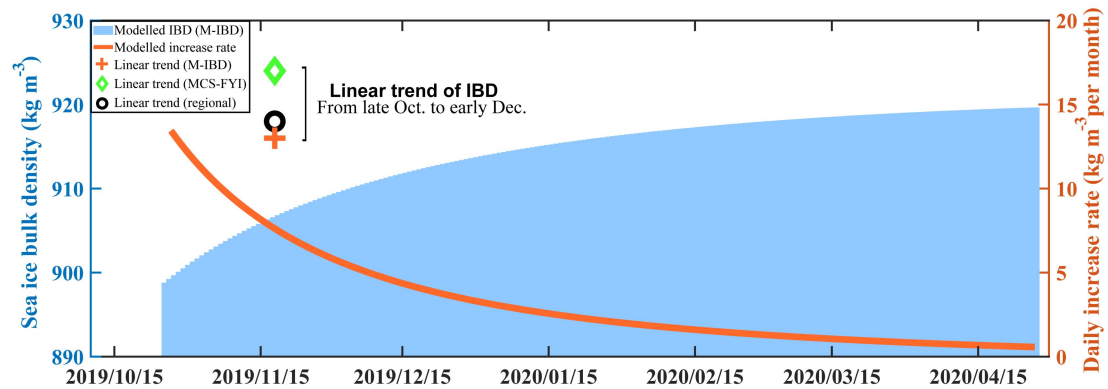

Figure A13. Hydrostatic equilibrium-based modelled IBD estimates (M-IBD) during the MOSAiC freezing season.

A third concern relates to the interpretation of in situ density measurements. Based on the abstract from the coring dataset by Oggier et al. (2023), it appears that the sea-ice density was measured at constant laboratory temperatures rather than at in situ conditions. However, this is (1) not explicitly mentioned in the study, and (2) there is no description of how density was recalculated to reflect in situ temperatures, if such a correction was applied. If this adjustment was not made, any discussion of how brine volume evolution affects sea-ice density becomes less meaningful. Furthermore, the interpretation of the measured density shows a larger standard deviation from actual weighing than from the combination of ICESat-2 freeboard data and buoy snow and ice thickness. This seems to contradict previous estimates of uncertainties in density measurements (Hutchings et al., 2015; Pustogvar and Kulyakhtin, 2016). Specifically, weighing has consistently been found to be one of the most precise methods, while density estimates based on ice freeboard and thickness measurements tend to have standard deviations several times higher—by an order of magnitude—according to Hutchings et al. (2015), even when the thickness and freeboard were measured in situ. Given this prior evidence, it is somewhat surprising that the reported standard deviations suggest the opposite pattern in this study. A clearer explanation of these discrepancies would clarify the interpretation of these measurements.

GC3 Reply Although the laboratory temperature (−15 °C) varies from the in situ temperature, Pustogvar and Kulyakhtin (2016) demonstrated that the hydrostatic weighing method effectively mitigates the density errors associated with brine drainage due to ambient temperature. Even under extreme conditions, such as a 19 % brine loss, the measurement error remains as low as 2 %, while the mass/volume method can introduce errors of up to 20 %. Specifically, the hydrostatic weighing method can effectively limit the loss of brine during ice sectioning at low laboratory temperatures compared to in situ conditions, where brine losses can be greater in warm ice. The use of kerosene coating further helps to minimize brine loss by occupying the spaces at the core interfaces, thus improving the accuracy of the measurements. Salganik et al. (2024) found little impact of brine loss on hydrostatic weighing density measurements by comparing sea ice densities reconstructed from in situ temperature and freeboard/thickness, exhibiting a similar variation pattern. **Therefore, despite measurements being conducted at a constant laboratory temperature, this method provides highly reliable and accurate results, facilitating a meaningful discussion of brine volume evolution and its impact on sea ice density.**

In the revision, we have added detailed information on ice core parameters to the text. *"The ice temperature was measured in the field using Testo 720 thermometers at 5 cm vertical intervals; ice salinity was determined from melted cores using a YSI 30 conductivity meter at 5 cm resolution; ice density was derived in the freezing laboratory at an ambient temperature of –15 °C using the hydrostatic weighing method. The temperature and density results were further interpolated to match the depth of the salinity measurements, providing a continuous density profile throughout the core sample. Then, brine volume was calculated from measured ice salinity, temperature, and density using the equations of Cox and Weeks (1983) for cold ice and Leppäranta and Manninen (1988) for ice warmer than –2 °C."*

Our regional IBD results did not show a lower standard deviation than those of direct measurements. Except in the initial stages, the standard deviation of the regional IBDs exceeded twice that of MCS-FYI and MCS-SYI. The standard deviation of all IBDs at the DN scale was comparable to that of MCS-FYI, attributable to the sample difference and the early rapid increase. Considering estimates from different seasons independently (Table A3), the standard deviation at the regional scale was significantly higher compared to that of MCS-FYI and MCS-SYI. The relatively high standard deviation of the hydrostatic equilibrium-based IBDs in Hutchings et al. (2015) can be attributed to the inclusion of both level and deformed sea ice in their measurements, with a relatively high spatial sampling resolution. This may result in a failure of the hydrostatic equilibrium assumption at the local level. In contrast, the IBD results of this study represent the average state of the level ice layers across all buoy sites, resulting in significantly lower IBD variability compared to previous studies. Moreover, our analysis is focused on spatial scales of approximately 25 and 50 km radius, which facilitates the convergence of the hydrostatic equilibrium-based IBD estimation.

For this point, the airborne observations of Jutila et al. (2022) provided a good example of the significant impact of spatial scale on IBD calculations. Based on a ~30 km airborne measurement profile, the IBDs derived from sampling at 5−6 m spatial resolution were mainly between 800 and 1000 kg m^{-3} with considerable spatial variability. When weighted averaging over the length scale of 800 m was used, the resulting IBD effectively converged to about 880 to 920 kg m^{-3}, significantly reducing the potential non-physical variability of the retrieved IBDs at 5−6 m spatial resolution. We also applied the hydrostatic equilibrium method (also known as the freeboard/draft method) to calculate the IBDs of MCS-FYI and MCS-SYI using the seawater and snow bulk densities defined in Section 2.2.3. Despite the small mean differences, the results showed **considerable variability compared to those obtained by the weighing method**, with deviations of 7 ± 35 kg m^{-3} for FYI and 1 ± 21 kg m^{-3} for SYI, further highlighting the challenges of assuming hydrostatic equilibrium at local scales.

Specific comments

Line 21: The phrasing suggests that this study considers deformations, brine, and gas inclusions in its estimates of ice density, but this does not appear to be accurate. It would be helpful to clarify this point. Impact of deformed ice, brine and air inclusions were not analysed in this study.

Reply: Agreed, and as mentioned above, we have added the analysis of physical factors. **Revised to:** *"which are influenced by factors such as the age, temperature, brine, air intrusion, and growth rate of the sea ice."*

Line 23: The term "Distributed Network scale" might not be clear to readers unfamiliar with the MOSAiC Distributed Network. Could you specify the scale or provide additional context to make it more accessible and inclusive? Line 24: The statement regarding ice density estimation is not entirely accurate. Ice density was calculated separately from a combination of buoy ice thickness and altimetry freeboard data and from ice coring data. It might be helpful to differentiate these methods more clearly.

Reply: Thanks for the suggestion. **Revised to:** *" To estimate regional IBD, we combined sea ice thickness and snow depth observations from ice mass balance buoys, snow density measurements from snow pits, together with high-resolution along-track freeboard data from airborne laser scanning (ALS) and the Ice, Cloud, and land Elevation Satellite-2 (ICESat-2), at both the Distributed Network (DN) and L-site scales (~50 km and ~25 km radius from the research vessel Polarstern).Assuming hydrostatic equilibrium, regionally averaged IBD estimates were obtained for the buoy-deployed ice layers, including 11 sites in second-year ice (SYI) and 4 sites in first-year ice (FYI). The regional IBDs were then compared and evaluated with high-precision density measurements from FYI and SYI cores, the latter representing the local ice domain revisited at the Main Coring Sites (named MCS-FYI and MCS-SYI)."*

Line 28: The assertion that MOSAiC ice floes predominantly consisted of second-year ice needs further support. (1) Several studies suggest otherwise, and (2) the term "predominantly" is vague in terms of areal fraction. Additionally, it would be useful to clarify what is meant by "MOSAiC ice floes"—how many floes are being referenced, and which ones specifically?

Reply: We apologize for the misrepresentation. As mentioned above, we actually retrieved the IBDs that are representative of the buoy-deployed ice layers, which we thoroughly revised in the text. *MOSAiC ice floes* **are defined as** ice floes within 50 km of *Polarstern*.

Line 32: The ratio of ice freeboard to ice thickness cannot serve as a direct measure of ice density since they are mathematically correlated. Density is typically used to convert ice freeboard to ice thickness. Meanwhile, such relationship may be complicated by the presence of deep snow or absence of accurate snow observations. The latter is directly related to the results of this study. Please clarify the interpretation here.

Reply: The regression coefficients derived from the statistical relationships still have value in predicting hydrostatic equilibrium-based IBD, and we emphasized that parametric fit performance does not represent absolute robustness in the text, as discussed in **GC1**. At the same time, the parameterization based on ice freeboard-to-thickness ratio can be used for the so-called radar (laser) freeboard to thickness conversion to simultaneously estimate IBD and sea ice thickness from space, which can facilitate sea ice remote sensing (see **Fig. A10**). **Revised to:** *"On this basis, we developed several potential parameterizations for regional- and local-scale IBDs that are expected to be applicable throughout the freezing season, taking into account a variety of sea ice, snow, and environmental parameters."*

Line 34: The statement that second-year ice (SYI) dominates the central Arctic Ocean contradicts existing studies, such as Tschudi et al. (2019, 10.5194/tc-14-1519-2020), which show that first-year ice (FYI) is the primary ice type in the Arctic. Could you provide more context or evidence to support this claim?

Reply: Agreed, we removed this statement.

Line 59: The referenced study from Timco and Weeks (2010) offer an overview of sea-ice properties but do not draw any specific conclusions about the heterogeneity or seasonal evolution of ice density. They only presented ice density at various temperatures (assuming zero gas volume) and discussed a broad range of density measurements without the kind of conclusions mentioned in your study. Could you clarify this?

Reply: We would like to clarify that this review do discuss the internal structure and porosity of sea ice. *Timco, G. and Weeks, W.: __A review of the engineering properties of sea ice__, Cold Regions Science and Technology, 60, 107-129, https://doi.org/10.1016/j.coldregions.2009.10.003, 2010.*

Line 63: The claim that sea ice density influences permeability, meltwater infiltration, and biogeochemistry is quite bold. The cited studies may show correlations, but it seems inaccurate to assert that density directly defines these processes. Permeability, for example, is largely governed by ice age, microstructure, and brine volume. Could this section be reframed to reflect the complexity of these relationships? Also, the term porosity is used in unconventional and inconsistent way. In most

cases it is used as equivalent to gas volume fraction (line 440), while typically it should combine both gas and brine volume fractions. Therefore, please explain how gas volume is influencing permeability.

Reply: We rephrased the sentence, and we defined the ice porosity in the text as the sum of the brine and air volume fractions. **Revised to:** "*IBD is regarded as a pivotal parameter for thermodynamic and mechanical modelling of sea ice (Ono, 1967; Wang et al., 2021) and indirectly involved in key processes such as sea ice permeability, summer meltwater infiltration, and biogeochemical cycles in the Arctic Ocean (Perovich et al., 2021; Angelopoulos et al., 2022).*"

Line 66: *If by winter you mean a period from December to February, this is not accurate statement. Most referenced measurements were collected in winter and spring.*

Reply: We rephrased the sentence. **Revised to:** "*However, the scarcity of ice core sampling, particularly in the early ice growth period, limits the spatial representativeness of core-based density measurements (Timco and Frederking, 1996; Hutchings et al., 2015).*"

Line 71: *This (small errors of weighing) was known way before the referenced publication.*

Reply: We rephrased the sentence. **Revised to:** "*In terms of measurement accuracy and uncertainty, the hydrostatic weighing method proved to be the best at capturing natural variations in ice core density and reducing sampling constraints **(Butkovich, 1955; Nakawo, 1983; Pustogvar and Kulyakhtin, 2016). ***"

Line 90: *The robustness of the parameterizations is limited by the assumption of hydrostatic equilibrium, which has been shown to be less precise (Hutchings et al., 2015). For instance, Jutila et al. (2022) propose density values above 950 kg/m³ for relatively thin ice, but such values are unrealistic, as they have not been validated by in situ measurements. How do you account for these limitations?*

Reply: We would like to clarify that Hutchings et al. (2015) studied a ~100 m transect covering a large area of deformed ice. They claimed that the unrealistic density values observed could be due to the hydrostatic equilibrium assumption being inappropriate at these length scales in deformed ice. Jutila et al. (2022) also include many deformed units, which may partly explain the potentially high density of thin ice. In contrast, our focus is exclusively on level sea ice over tens of kilometers, where the hydrostatic equilibrium assumption is still valid, as details discussed in **GC1**. This explains why the standard deviation of our IBD results is significantly smaller than that of previous studies. **Revised to:** "*potential parameterizations.*" **Added:** "*In this study, we combined sea ice thickness and snow depth data from an IMB array (15 buoys), along-track total freeboard data from ALS and ICESat-2, and snow bulk density data from snow pits to retrieve the bulk density of level sea ice over tens of kilometers suitable for the hydrostatic equilibrium assumption (Section 3.1).*"

Line 101: Most of laser scans were significantly smaller than the linear scale of tens of kilometres (Hutter et al., 10.1038/s41597-023-02565-6). Could you clarify the scale?

Reply: We clarified the measurement scale of ALS data. **Revised to:** *"Moreover, repeated airborne laser scanning (ALS) measurements yielded high-resolution along-track total freeboard data (Hutter et al., 2023a,b), uncovering sea ice elevation characteristics ranging from the local floe (< 5 km from Polarstern) to regional transects of tens of kilometers, with a total of 64 helicopter fights from September 2019 and September 2020."*

Line 132: The exclusion of melt ponds from the sampling is not straightforward, as refrozen melt ponds are a substantial part of the ice cover, covering around 20-30% area. And their smooth surface also influence the amount of snow which may accumulate above such ice type. Additionally, surface conditions are not the primary issue when it comes to hydrostatic balance. The representativeness of the ice thickness at the buoy sites is more important, and this is not adequately discussed. How does excluding ridges and deformed ice improve representativeness?

Reply: According to the buoy installation reports and initial surveys, the IMBs were indeed deployed at sites initially devoid of melt ponds. In addition, temperature profiles recorded by the IMB did not show any anomalous signals that would indicate potential refrozen melt ponds. In terms of representativeness, the buoy deployment sites successfully recorded thermodynamically driven ice growth, effectively representing the level ice features in their deployment areas (Koo et al., 2021). We also acknowledge that the buoy deployment area contained many thick SYIs, and given the heterogeneity of the MOSAiC ice floes, it is difficult to fully represent DN scale ice conditions. **Therefore, we no longer claim in the text that buoy observations are representative of DN ice conditions. Revised to:** *"The SIMBAs and SIMBs were mainly deployed on level ice, free from melt ponds, to ensure the reliability of the buoy data"*. **Added** *"In particular, buoy deployment sites have successfully recorded thermodynamically driven ice growth, effectively representing the level ice features in their deployment areas (Koo et al., 2021)."*

Line 140: You state that 27% of the buoys were in FYI and 73% in SYI, but Kortum et al. (2024, 10.5194/tc-18-2207-2024) showed equal fractions of FYI and SYI based on freeboard measurements. How was this potential unrepresentativeness of buoy sites handled? Moreover, SYI is not typically associated with ice deformation when thinner FYI is present, which may influence evolution of its areal fraction.

Reply: Our IBD results only represent the average sate across the buoy sites, as described above.

Line 141: *First, does this influence your results? Probably not. Also, exceptionally large ice growth should be quantified of important. Illustration shows that platelet ice presumably contributed to 10-20 cm ice growth which later disappeared. Is it relevant for this study?*

Reply: Agreed. **Removed** *"In particular, exceptionally large ice growth was observed at some sites (e.g., T72 and I2) due to the formation of snow-ice or platelet ice (Fig. S1). Katlein et al. (2020) provided direct evidence for platelet ice formation during MOSAiC based on remotely operated vehicle observations."*

Line 173: *There's an inconsistency here—earlier, you stated that 27% FYI was representative in an SYI-dominated area, yet here, 43% FYI is also considered representative. Meanwhile, Kortum et al. estimated this fraction as 50%. Could you clarify this discrepancy?*

Reply: Here, snow bulk density serves as an auxiliary data for IBD retrieval, with a relatively low error contribution (less than 5%). Our main objective is to extract its seasonal trend by analyzing all available snow pit data. **Revised to** *"The snow pit records used contained approximately 12 % refrozen lead, 43 % FYI, and 45 % SYI, according to the original snow pit metadata and MOSAiC ice floe characteristics (Macfarlane et al., 2021; Nicolaus et al., 2022),* ***effectively reflecting the general variability in snow properties under different ice conditions during MOSAiC.***"

Line 179: *It would be more robust to demonstrate the representativeness of the selected sites by comparing their ice thickness or freeboard with large-scale observations, rather than just stating they were selected for representativeness.*

Reply: Agreed. **Removed** *"and were sufficiently representative of the FYI and SYI properties during MOSAiC"*.

Line 182: *Please clarify what is meant by "ice porosity." What does it include?*

Reply: "Ice porosity" **replaced** with "brine volume". In this study, ice porosity was considered as the sum of brine and gas volume fractions.

Line 183: *According to Oggier et al. (2023), salinity was measured directly from the sample after weighing, not interpolated from another core. Also, could you explain how brine volume and density were estimated for the measured temperatures?*

Reply: We would like to clarify that the density values are indeed interpolated to the depth of salinity measurements, as described in Oggier et al. (2023). *"The depth estimates assume that the total length*

of all core sections is equal to the measured ice thickness. Each core section has the value of its practical salinity (14), isotopic values (16, 17, 18) (Meyer et al., 2000), as well as sea ice temperature (19) and ice density (20) interpolated to the depth of salinity measurements."

Modified and added: *"Of these, ice temperature was measured in the field using Testo 720 thermometers at 5 cm vertical intervals; ice salinity was determined from melted cores using a YSI 30 conductivity meter at 5 cm resolution; ice density was derived in the freezing laboratory at an ambient temperature of –15 °C using the hydrostatic weighing method. The temperature and density results were further interpolated to match the depth of the salinity measurements, providing a continuous density profile throughout the core sample. Then, brine volume was calculated from measured ice salinity, temperature, and density using the equations of Cox and Weeks (1983) for cold ice and Leppäranta and Manninen (1988) for ice warmer than –2 °C."*

Line 189: The statement that some cores were longer and might come from rafted ice, leading to substantially different densities, is not supported by the data from Oggier et al. (2023). Please provide evidence for this assertion.

Reply: We would like to clarify that the FYI cores from 2020-03-21 and 2020-04-14 are labelled as rafted ice. Our aim is to focus solely on the variations in ice properties under thermodynamic growth of the level ice and their comparison with regional results. **Here, we removed the statement of substantially different densities. Revised to** *"To ensure reasonable comparability of IBD estimates between ice cores and regional estimates for the level ice layer, core-based density records of rafted ice associated with ice deformation were excluded."*

Line 268: The ice pack does not consist solely of level ice. Please rephrase this statement, as ridges and deformed ice make up a substantial portion of the ice cover, as shown in transect observations. Also, how can you be certain that modal snow freeboard represents the same level ice described at the buoy sites? A simple comparison of ice thickness distribution or mean, modal and median values could be also useful. What if ice consists of both FYI and SYI level ice, with a bimodal thickness distribution, which is not seen in snow freeboard data?

Reply: *The ice pack does not consist solely of level ice.* **Revised to** *"The MOSAiC ice floes have considerable spatial heterogeneity, covering ice ridges, deformed ice, level ice, and refrozen melt ponds (Nicolaus et al., 2022). To estimate the IBD accurately, it is first needs to obtain the total freeboard that is representative of the level ice portions to ensure compatibility with the selected IMBs, which were deployed exclusively on level ice."*

Also, how can you be certain that modal snow freeboard represents the same level ice described at the buoy sites? This is why we made the spatial scale adjustment mentioned above.

A simple comparison of ice thickness distribution or mean, modal and median values could be also useful. What if ice consists of both FYI and SYI level ice, with a bimodal thickness distribution, which is not seen in snow freeboard data? We would like to clarify that based on the high-resolution IceBird airborne measurements, which include both level and deformed FYI, SYI and MYI, we found that the modal total freeboards of all ice types are very close to the mean total freeboards of the level ice fractions only (Fig. A14). In addition, the total freeboard distributions obtained from ICESat-2 and ALS both showed distinct unimodal characteristics, as did the ice thickness distributions derived from the transects. Several studies have found that the typical regional characteristics of sea ice freeboard/thickness conform to log-normal/negative exponential distributions (Haas, 2010; Farrell et al., 2011; Ricker et al., 2015; Petty et al., 2016; Landy et al., 2019; Koo et al., 2021), despite the inclusion of both deformed and level ice, as well as first-year and multi-year ice.
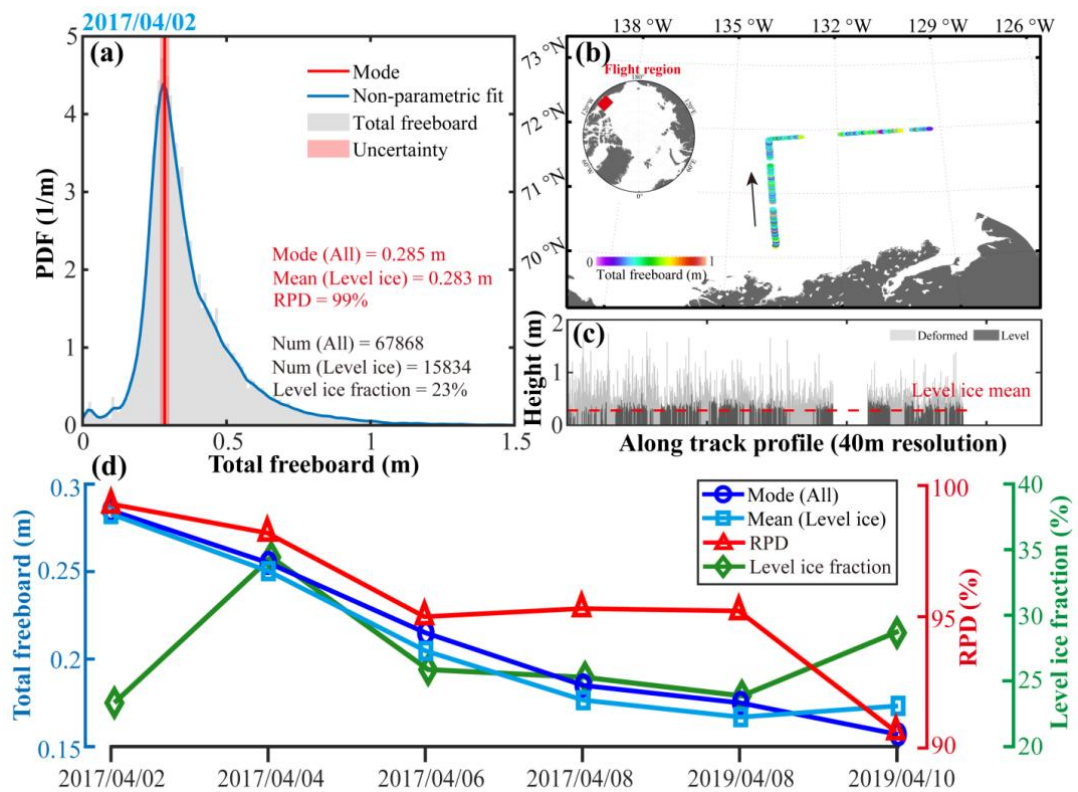

Figure A14. Comparison of the mode of the total freeboard distribution (encompassing all surface types) with the mean total freeboard of level ice, derived from AWI IceBird measurements conducted in April 2017 and April 2019. The example from 2 April 2017 illustrates: **(a)** the total freeboard distribution, **(b)** the measurement area, and **(c)** the total freeboard profile. **(d)** Results for each measurement date include the modal freeboard for all surface types, mean freeboard for level ice, and the relative percentage difference (RPD) between the two freeboard values, as well as the level ice fraction (at least 20%).

Line 287: What are "MOSAiC ice floes, type II"? Could you provide more information on this classification? If you refer to the types of uncertainties, then they are described after this part of the manuscript.

Reply: Clarified. **Revised to:** "*1) ascertaining the modal total freeboard, which is derived from the mean of the five highest frequency peaks in the total freeboard distribution, with the standard deviation quantifying the **uncertainty (Type I)** introduced by these peaks. 2) This mean difference was also considered to represent the **uncertainty (Type II)** of the modal total freeboard, stemming from the measurement methods and the spatial heterogeneity of the MOSAiC ice floes. 3) The final modal total freeboard uncertainty was then set as t**he sum of the Type I and Type II uncertainties**.*"

Line 291: The 7 cm adjustment is a significant point, yet it is only briefly mentioned. Could you explain in more detail how this value was estimated and why it was applied as a time-independent adjustment throughout the seven-month period?

Reply: We clarified this in **GC2**, see above. **Added:** "*2.2.2 Spatial scale adjustment*".

Line 294: How is this possible if you only use a single source of snow thickness from buoys? Here you attempt to match ice freeboard calculated as difference between ICESat-2 snow freeboard and snow thickness from buoys. You do not have data about large-scale snow thickness (line 314). Therefore, you lift the snow and ice freeboards together which leads to increased estimate of ice thickness which fits better the initial buoy ice thickness. From these estimates of ice freeboard and thickness you estimate the ice density. Therefore, it is not clear what do you mean by the snow depth difference between satellite and buoys sites, as second one is unknown. Similarly, this is an important assumption which cannot even be generalized for future campaigns. It deserved not to be described in supplementary materials.

Reply: We clarified this in **GC1** and **GC2.**

Line 315: While seawater density might not be the primary source of uncertainty, why not use directly measured seawater salinity and temperature from the expedition? Why was the chosen reference used instead?

Reply: The selected literature is very representative and has been widely used in the hydrostatic equilibrium equation for Arctic sea ice. We also found that the fixed value is in good agreement with the mean density estimate with the upper 10 m layer recorded by buoys and CTDs during MOSAiC (Hoppmann et al., 2022). In the range of their estimated densities (~1023.5 to 1026.5 kg m⁻³), the effect on our IBD results does not exceed 0.5 kg m⁻³ (0.05 %). **Overall, the use of representative value remains valid.**

Line 317: Again, more evidence is needed to support the claim that the MOSAiC Distributed Network (DN) was dominated by SYI. How this is possible when the measured by ICESat-2 snow freeboard in autumn was close to 10 cm? Was it representative for SYI, especially SYI similar to ice where buoys were installed? Because buoys had ice freeboard around 10 cm and snow thickness of 13 cm, giving the snow freeboard way above 10 cm.

Reply: Please refer to our answers in the **GC2. Revised to:** *"This method provides an estimate of the regional bulk density of level sea ice mixed with SYI (11 buoy sites) and FYI (4 buoy sites)."*

Line 318: Krumpen et al. (2020, 10.5194/tc-14-2173-2020) report that the modal ice thickness in L-sites was only 40-50 cm, significantly thinner than at buoy sites. Why is this discrepancy not addressed?

Reply: We addressed this in **GC2**. We highlighted in the text the significant differences in thickness and snow depth of level sea ice between the buoy sites and earlier transects during MOSAiC.

Line 359: The ice thickness range of 0.6–2.0 m is stated as representative for level ice, yet Krumpen reports much thinner modal thicknesses. Early transects from Itkin et al. (2023,10.1525/elementa.2022.00048) also mainly show modal ice thickness around 0.5 m. Could you provide clarification on this?

Reply: Agreed. **Revised to:** *"The mean ice thicknesses recorded by the buoys at the DN and L-site scales were 1.41 ± 0.32 and 1.30 ± 0.33 m, respectively (Fig. 5a and Table 2), whereas the average values for individual buoys ranged from ~0.6 to 2 m (Fig. S1). Due to their deployment strategy, buoy-derived sea ice thicknesses were generally thicker than the regional transects in the early stages (Krumpen et al., 2020, Table 1)"*

Line 370: Arbitrary selection of coring sites does not necessarily make them representative in terms of ice thickness. This should be better supported.

Reply: We removed that statement.

Line 375: You obtain level ice freeboard using modal values of snow freeboard. Why is a different approach applied here to the transect snow thickness? Itkin et al. (2023) showed a snow thickness distribution with initial modal snow thickness around 10 cm. Similarly, the initial snow thickness above

level ice in their paper is also close to 10 cm. Therefore, what is the meaning of the initial average 24 cm from transects?

Reply: We recalculated the modal snow depths for the transects and reported the differences with the buoys, see **Fig. A12**.

Line 377: It appears that specific conditions at the coring sites resulted in shifting the ICESat-2 freeboard upwards. However, ICESat-2 and ALS initially showed freeboards close to 10-15 cm, suggesting the buoys were in areas with unrepresentative snow thickness. Could this be clarified?

Reply: We highlighted and clarified in the text the differences in ice conditions between buoy sites and large-scale observations, which accounts for the spatial scale adjustment, see **GC2**. **Revised to** *"The snow depths from the transects (mode), MCS-FYI, and MCS-SYI were generally thinner than the buoy array observations, with mean values of 0.15 ± 0.02 , 0.10 ± 0.03, and 0.14 ± 0.03 m, respectively, further suggesting that thicker level ice tends to accumulate thicker snow."*

Line 384: This is a misinterpretation of the study from Itkin et al. (2023) You claim that buoy snow depth was close to transects. Yet, in the Fig. 9 of Itkin et al. (2023) the shown snow depth above level ice is below 10 cm.

Reply: We would like to clarify that our conclusion is that the buoys have similar seasonal snow depth trends to the transects, not their snow depth magnitudes. **Revised to** *" Throughout the freezing season, the regional buoy averages, as well as the transects and MCS-FYI, all exhibited significant trends of increasing snow depth, ranging from 0.010 to 0.013 m per month (Table 2)."* **Original text:** *"buoy array measurements are sufficiently representative **to capture seasonal snow accumulation on level ice over a wider area"**.*

Line 437: You mention that the DN is dominated by SYI, but later state that MOSAiC ice floes were predominantly FYI. This contradicts previous observations (e.g., Guo et al., 10.5194/tc-17-1279-2023; Kortum et al.). Could you clarify what exactly is being referred to as "MOSAiC ice floes"?

Reply: We no longer claim that any of the IBD results represent MOSAiC ice floes (which we denote as a 50 km radius centred on Polarstern), but simply the buoy-deployed ice layers, as detailed in GC1 and **GC2**. **Revised to** *"The regional IBD estimates, including both DN and L-site scales, **reflect the ice properties at the corresponding buoy deployment sites**, instead of the ice conditions over the entire regional range for DN or L-site scales."*

Line 437: Your estimate of ice density includes 7 cm freeboard adjustment; how can you discuss these minor differences between measured FYI and SYI density considering buoy method uncertainty close to 50 kg/m³? Moreover, there is not any clear difference in winter FYI and SYI density based on weighing. How can potential difference in several kg/m³ can support whether FYI or SYI was dominating the area of investigations? You are saying that 910 kg/m³ is closer to 912 kg/m³, while 908 is closer to 905 kg/m³? A difference in 2 kg/m³ is beyond measuring uncertainties and spatial variability even for the best performing methods to measure ice density. No such claims can be made. Finally, it is not correct to average FYI density for the whole period of observation, as it includes a period of lower densities in autumn. If you exclude those lower values from the average value of 905 kg/m³, would you be able to see any measurable difference between two ice types?

Reply: We fully revised this. **Revised to** *"The mean IBD values estimated at the DN, L-site, MCS-FYI, and MCS-SYI scales were 910 ± 7, 908 ± 11, 905 ± 8, and 912 ± 2 kg m^{-3}, respectively. The recorded bulk densities of FYI and SYI cores were not obviously different except in the early stages."*

Line 443: in line 437 you claim that DN is dominated by SYI, while here you claim that MOSAiC ice floes were predominantly FYI. What are MOSAiC ice floes? This contradicts many other observations (Guo et al., Kortum et al.). MOSAiC Central Observatory was one of the thickest floes in the area with the largest SYI fraction, unlike surroundings (Krumpen et al., 2020), which is opposite to the presented claims.

Reply: We removed this statement. As mentioned above, our regional IBD results only represent the physical properties of buoy-deployed ice layers (dominated by SYI).

Line 446: What is the basis of the claim of substantial sub-weekly ice density variability. This is a clear artefact of spatial variability of ICESat-2 tracks and corresponding freeboards which has nearly nothing to do with ice density changes.

Reply: We acknowledge that trajectory changes in ALS/IS2 can introduce non-physical variations in modal total freeboard that affect the derived IBD. It is also critical to note that the covariation between ALS/IS2 modal freeboard and buoy-derived mean snow depth demonstrates high consistency, which may also be attributable to variations in snow depth (**Fig. A15**). **Added:** *"Due to the irregular variations in airborne and satellite trajectories and the limitations of the buoys in capturing daily variations of mean snow depth over their deployment area, it must be emphasized that the retrieval method may not be able to fully resolve synoptic scale IBD variations and thus introduce some non-physical signals, which is a major challenge for estimating IBD using spatially non-overlapping data."*
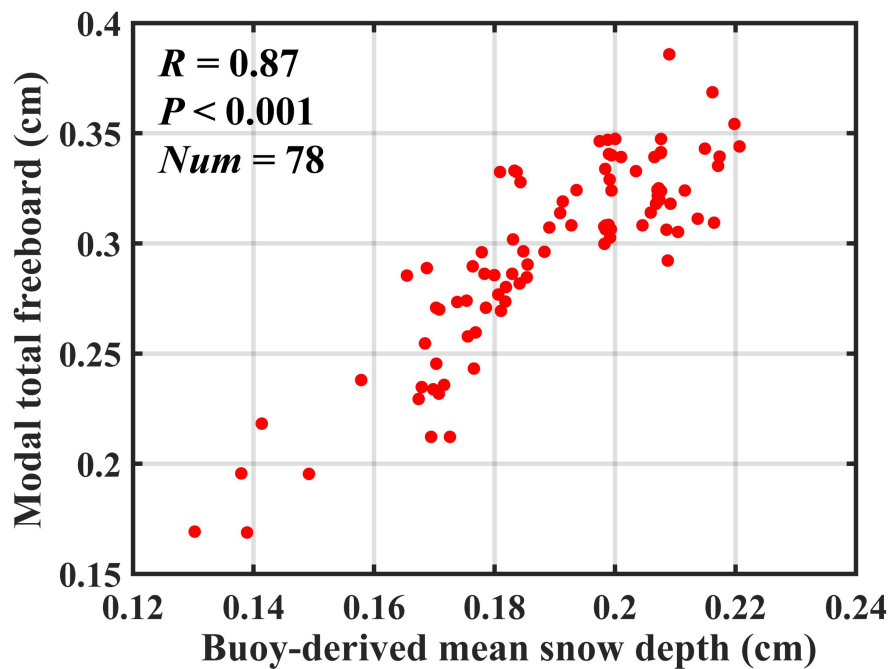
Figure A15. Buoy-derived mean snow depth versus airborne/satellite-derived modal total freeboard during the MOSAiC freezing season at both DN and L site scales.

Line 448: You are saying that FYI had newly formed SYI fractions at the ice bottom? What does it mean?

Reply: Remove this statement and we added the sea ice bulk salinity and brine volume data. **Revised to** *"The bulk salinity of MCS-SYI, on the other hand, showed an increasing trend of 0.3 ppt per month, which is closely associated with the formation of new ice layers at the base"*

Line 451: First, which layers are you referring to? These layers may contain more brine than which other layers? For FYI, how is it possible, if ice is gradually getting colder and less saline upon ice growth? The brine volume is easy to estimate, and it was estimated in several publications, there is no need for such speculations. And, following the modelling study from Griewank and Notz (2008), brine volume is decreasing in Autumn, contributing to decreasing density if gas is not considered. And if you discuss SYI, there were no new layer under SYI in autumn, only in winter, which can be clearly seen in Fig. 4a. Only since cold winter month, SYI with larger snow and ice thickness may have a substantial thickness gain.

Reply: As answered in **GC1**, we re-analyzed the seasonal variations in IBD, which were attributed to gas reduction, decreasing bulk temperatures, and rapid growth of the sea ice over the same period.

Line 461: What does it mean? There is a clear relationship between temperature, salinity, and brine volume which explain why saltier FYI has a stronger vertical gradient of brine volume. Also, most of SYI formed under the remaining 0.5 m at the surface is a new ice, with its physical properties close to FYI. Therefore, there is no surprise that FYI and SYI are eventually becoming more similar. Homogenization is a too broad description of these processes.

Reply: Remove this statement. We added analyses of the seasonal evolution of sea ice bulk temperature, bulk salinity, and brine volume (see Fig. A8).

Line 462: What is the evidence for these claims? You do not present ice salinities in this study. But if you check FYI bulk salinity from Oggier et al. (2023), it has decreasing trend very similar to the broadly used parametrization from Kovacs (1996, 10.21236/ada312027). Also, please explain in more detail the suggested process behind the initial density decrease. If you consider only brine, desalination leads to decrease of brine volume and corresponding density decrease, that is correct. But it cannot be significant only due to brine, the absolute values are less than 5 kg/m³. One can estimate brine volumes from the measured salinity and temperature and draw the same conclusion. Yet, the observed density change is much larger, and it was increasing, not decreasing (Fig. 5a).

Reply: As answered in **GC1**, we re-analysed the seasonal variations in IBD, which were attributed to gas reduction, decreasing bulk temperatures, and rapid growth of the sea ice over the same period.

Line 466: This is an example of overfitting. Density estimates from ICESat-2 has a large spread of around 30 kg/m³. The increasing trend in autumn is barely based on a single data point in Fig. 5a.

Reply: We combined the regional IBD estimates from late Oct. To early Dec. with a statistical test P value of less than 0.05 and an *R* of 0.62, so there was no overfitting (see Fig. A2). For more details, please refer to **Overall Reply**. We also acknowledge the relatively high uncertainty and small sample in the early stages and therefore additionally introduced the so-called modelled IBD values (see Fig. A13).

Line 498: Can you explain more specifically what is the mentioned scale-related density variability? You cover different areas in DN and L-site scales, but there is no clear difference between them following Fig. 5a. Also, the mean values are nearly identical, but this would not be possible without in situ measurements, providing less uncertain estimates. And what supports the well-known importance of ice density for ice thickness retrieval but based purely on your measurements? How do you validate thickness estimates?

Reply: In the revised version, we highlighted the scale-related density variability between the MCS-SYI and regional buoy sites (SYI dominated). We argue that the regional IBD results are still of

value to the sea ice remote sensing community, which was attempted in the MOSAiC observations after A10 (Sever) and J22 (IceBird), albeit with significant challenges. The supplementary validation of the parameterization and its preliminary application across the pan-Arctic SYI have provided us with considerable confidence, please refer to **GC1**.

Line 520: *Repeating this statement doesn't make it more evident. Without scale adjustment, the density estimate from ICESat-2, and buoys not only show an opposite decreasing seasonal trend to in situ measurements, but they also give unrealistic density values above 950 kg/m³. Therefore, it is not clear why this difference in correlation should be compared between different methods.*

Reply: Removed.

Line 548: *Previously, it was mentioned that seasonality of ice density is significant. Yet, none of the suggested parameters are related to seasons.* **Ice thickness has a large range from thin ice in Atlantic sector to thick ice in Pacific sector during the same sampling time.** *Therefore, ice freeboard cannot be an accurate factor related to the seasonality of ice density.*

Reply: As we mentioned above, the samples used for IBD parameterization themselves exhibited time-varying properties, such as ice porosity, temperature, salinity, thickness, and age. Therefore, we suggest that IBDs estimated from the parameterizations are still capable of exhibiting potential seasonal variations, as shown in **Fig. A10**. We also added the sea ice bulk temperature to enhance the model interpretability. Following the potential applicability ranges, spatial scales and sea ice types of the parameterizations, we suggest that it is still possible to reasonably predict IBD for different thicker and thinner ice layers in the same season.

Line 580: *What is the basis of this claim? A typical modal ice thickness is around 1.7 m (Sumata et al., 2023) which includes both FYI and SYI. Why FYI cannot have 0.8-1.8 m thickness, only SYI? Also, there is a substantial difference in ice thicknesses wit thinner FYI in the start of Transpolar Drift and older ice closer to Canadian coast, where ice thickness is also typically larger than 0.8-1.8 m.*

Reply: We removed this statement.

Line 627: *If you claim that L-site ice was FYI and SYI, while DN was mainly SYI, why then snow freeboard from ICESat-2 and ALS showed such a great agreement despite ALS covering only a relatively small area around MOSAiC ice floe? Also, if most of ice was SYI, why ice density seasonality is close to the FYI in situ measurements, not SYI with no seasonality?*

Reply: Removed. In fact, the modal total freeboard derived from ICESat-2 at the DN scale, ICESat-2 at the L-site scale, and ALS at the L-site scale are similar to each other. In the revised version, we only highlighted that the results represent buoy-deployed ice layers, as described above. We attribute the proximity of SYI-dominated regional IBDs to FYI field measurements to the high spatial heterogeneity of SYI, as detailed in **GC1**.

Line 675: The study from Kovacs does not properly describe methodology of density measurements. You describe it as "theoretical equation", what does it mean? There is a few better documented ice density reports, why this specific study was used?

Reply: We removed this statement. The K97 parameterization has been used in several sea ice thickness retrievals (Kwok and Cunningham, 2015), so it is worth comparing our parameterizations with K97 to identify uncertainties, especially since K97 has opposite characteristics to the MOSAiC coring results.

Line 680: What is the basis for such claims? There are in situ measurements of ice density for relatively thin ice (20-30 cm), and those values are mostly around 900-910 kg/m³ (10.1016/0165-232X(95)00007-X), which is close to MOSAiC values. Also, MOSAiC ice was quite thin, around 40 cm. Sampling ice thinner than 30 cm is typically considered unsafe, and there is a very short time when ice is that thin in Central Arctic, as thin ice growth exponentially faster.

Reply: Removed.

Line 682: Similarly, why a method based on substantial adjustments to be able to get realistic estimates of ice density can support limitations of more accurate method, based on measurements of ice density? What exactly was done to support this statement?

Reply: We clarified this statement. **Revised to** *"Overall, we emphasize that the IBD parameterization based on sampling from individual points has the spatial representativeness-related limitations for the application to satellite sea ice thickness retrievals. In contrast, the regional IBD parameterisations are helpful in adapting to satellite footprint scales, but have relatively high uncertainties compared to direct measurements."*

Line 697: The was not any seasonality in SYI density estimates. A strong seasonality and corresponding dependence of ice density from its thickness was only observed for FYI. Therefore, why the parametrization based on FYI measurements can optimize retrieval of SYI? This should be better explained.

Reply: As discussed above, the IBD differences between SYI-dominated buoy sites and local SYI cores suggest a possible high degree of spatial heterogeneity in SYI porosity. Thus, the parameterizations derived from the SYI-dominated buoy sites are still capable of exhibiting seasonal variations for IBD. This, in turn, illustrates the impact of spatial scale. *In particular, Hornnes et al. (2024) found that the spatial heterogeneity of SYI porosity was much greater than that of FYI during the GoNorth expedition in October 2022, and also found similar air fractions in FYI (2.5 ± 0.5 %) and SYI cores (2.8 ± 0.5 %).*

Line 707: This is generally surprising that SYI is treated as a separate ice type from FYI. Maybe it could be reasonable many years ago, but for MOSAiC observations with SYI having low-salinity remnant layer below 40-80 cm (Oggier et al., 2023), most of SYI thickness by the end of winter is FYI grown under SYI, which may have density values like pure FYI. Since all such data is available, it is worth discussing. In brief, MOSAiC SYI was much closer to FYI than SYI sampled by Jutila et al., with at least two times higher thicknesses.

Reply: We argue that the physical properties of SYI after experiencing summer melt generally differ significantly from those of FYI, such as bulk salinity, brine volume, and thickness, and therefore remain worth distinguishing, also shown in Salganik et al. (2024). We agree with the reviewer's mention of *low-salinity remnant layer* and added descriptions of ice core salinity and brine volume accordingly. We also highlighted the difference between SYI during MOSAiC and J22.

Line 734: You previously mentioned that without scale adjustments your estimates would be 50 kg/m³, therefore you should explain how this bias should be removed for future analysis prior to providing parametrization based on adjusted estimates.

Reply: We added suggestions on how to overcome methodological challenges in the future.

Line 738: You haven't provided a strong proof that the provided parametrization with a strong seasonality in autumn is related to SYI, not FYI. Observations suggest that this is different.

Reply: We would like to clarify that the regional IBDs derived from buoy sites predominantly featuring SYI indeed exhibited variations similar to those observed in MCS-FYI. By setting representative regional values and applying a trend assumption, an early growth trend in IBD was also observed. Consequently, we believe this is related to the spatial heterogeneity of SYI porosity, which has been well-documented by Hornnes et al. (2024).

Line 742: It is generally looks impossible that estimates from hydrostatic balance have smaller standard deviations than measurements from weighing. First, even in situ measurements of freeboard and thickness give much higher deviations of density as described by Hutchings et al. (10.3189/2015AoG69A814) Second, density of separate layers of ice should not be compared with bulk density.

Reply: Please see our specific answers in **GC3** for more details.

Line 743: This is one of the most inconsistent claims throughout the whole paper. Can you say specifically what exactly was dominated by FYI and SYI and provide some evidence for this.

Reply: We comprehensively revised the manuscript to clarify that the IBD results pertain solely to the ice layers where the buoys were deployed. The spatial scale adjustment was made to align the modal total freeboard derived from ALS/IS2 with the buoy sites. Therefore, interpretations for IBD that primarily involve SYI are justified and reasonable.

Line 748: The assertion that warm air intrusions substantially influenced future changes in ice density evolution is significant but not discussed earlier in the text. Could this be elaborated?

Reply: Added discussion related to sea ice permeability.

Line 756: The criticism of in situ density measurements requires more analysis. How can 15 buoys at the fixed sites capture a broader picture better than around 40 coring events at slightly different sites? Additionally, how does the smaller uncertainty from weighing lead to challenges, as this seems counterintuitive?

Reply: In our revisions, we no longer claim superiority of any methods or parameterizations. Instead, we focus on comparing the difference between the regional (buoy sites, hydrostatic equilibrium method) and local results (coring sites, weighing). Please see our specific answers in **GC1** and **CG3** for more details.

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"Our ultimate goal is to advance sea ice remote sensing; despite the methodological challenges, we have at least considered all available observational data and potential solutions for implementation."

- Snow depth and sea ice thickness data derived from SIMBA buoy measurements are available from PANGAEA: https://doi.org/10.1594/PANGAEA.938244
- Snow depth, sea ice thickness, air temperature, sea ice bulk temperature, and seawater temperature data derived from SIMB buoy measurements are available from the Arctic Data Center: https://doi.org/10.18739/A20Z70Z01 (added)
- Snow depth and sea ice thickness data from repeated transects are available from PANGAEA: https://doi.org/10.1594/PANGAEA.937781
- Total thickness data measured using the GEM-2 from repeated transects are available from PANGAEA: https://doi.org/10.1594/PANGAEA.943666
- Snow pit data collected during the MOSAiC expedition are available from PANGAEA: https://doi.org/10.1594/PANGAEA.940214
- Snow pit raw data collected during the MOSAiC expedition are available from PANGAEA: https://doi.org/10.1594/PANGAEA.935934
- Total freeboard data obtained from airborne laser scanning measurements during MOSAiC are available from PANGAEA: https://doi.org/10.1594/PANGAEA.950896
- Ice core data collected from the MOSAiC Main Coring Sites are available from PANGAEA: https://doi.org/10.1594/PANGAEA.956732(MCS-FYI) (added temperature, salinity, and brine volume)
  https://doi.org/10.1594/PANGAEA.959830 (MCS-SYI) (added temperature, salinity, and brine volume)
- Ice core data collected during the GoNorth expedition in late October 2022 are available from PANGAEA: https://doi.org/10.1594/PANGAEA.962567 (added)
- ICESat-2 ATL10 total freeboard data (version 6, latest version) are available from NSIDC: https://doi.org/10.5067/ATLAS/ATL10.006
- AWI IceBird airborne multi-sensor sea ice data (version 2, latest version) collected in April 2017 and 2019 are available from PANGAEA: https://doi.org/10.1594/PANGAEA.966009 (April 2017) and https://doi.org/10.1594/PANGAEA.966057 (April 2019).
- AWI CryoSat-2 gridded sea ice product from 2010 to 2024 (v2p6, latest version) are available from AWI: ftp://ftp.awi.de/sea_ice/product/cryosat2/v2p6/nh/ (added)
- Weekly gridded sea ice age data are available from NSIDC (version 4, latest version): https://doi.org/10.5067/UTAV7490FEPB (added)
  https://doi.org/10.5067/2XXGZY3DUGNQ (quick look)
- Temperature profiles derived from SIMBA T47 are available from PANGAEA: https://doi.pangaea.de/10.1594/PANGAEA.940387 (added)
- Temperature profiles derived from SIMBA T58 are available from PANGAEA: https://doi.pangaea.de/10.1594/PANGAEA.940393 (added)
- Temperature profiles derived from SIMBA T62 are available from PANGAEA: https://dx.doi.org/10.1594/PANGAEA.940231 (added)
- Temperature profiles derived from SIMBA T63 are available from PANGAEA: https://doi.pangaea.de/10.1594/PANGAEA.940593 (added)
- Temperature profiles derived from SIMBA T64 are available from PANGAEA: