

Reply to reviewer 1.2 (Report #1 13.09.2026)

In the following, we address all reviewer comments point-by-point. The reviewer comments are shown in black, the author responses are shown in green and changes to the manuscript are shown in orange.

The authors have addressed several first-round comments, and I am very appreciative of the authors' work and efforts. The manuscript now presents uncertainties connected to deposition modelling and to measurement errors.

We thank the reviewer for taking the time to assess our revised manuscript. We are pleased that the previous revisions have addressed most of their concerns. We have carefully considered the remaining comments and provide our responses below.

In addition, we have expanded the Copernicus Marine Service attribution in the Figure 1 caption as requested by Polina Shvedko.

If I understand correctly, the Emerson parameterization was preferred over Zhang because it showed a better agreement with observations, although this improved agreement was mostly demonstrated over vegetated surfaces (while constraints over smooth ice and open water surfaces are lacking in this regard). The authors report very large deposition modelling errors (median absolute difference between deposition fluxes from the two parameterizations is $0.62 \times 10^6 \text{ m}^2\text{s}^{-1}$ and non-negligible measurement errors (median $0.07 \times 10^6 \text{ m}^2\text{s}^{-1}$, with a 95th percentile of $0.26 \times 10^6 \text{ m}^2\text{s}^{-1}$). Given uncertainties this large, I wonder whether the estimated emission signals are statistically distinguishable from zero once measurement and model uncertainties are propagated. Without a rigorous uncertainty analysis, the main conclusions remain provisional.

We acknowledge that the uncertainties of the deposition model are large, and quantifying the uncertainties of the deposition model is beyond the scope of our study. The median absolute difference between deposition fluxes from the two parameterizations of $0.62 \times 10^6 \text{ m}^2\text{s}^{-1}$ falls within the expected range of model uncertainty, as deviations of one to two orders of magnitude are considered typical when comparing state-of-the-art size-resolved particle deposition models and measurements (Petroff and Zhang, 2010; Emerson et al., 2020). When propagating this value of $0.62 \times 10^6 \text{ m}^2\text{s}^{-1}$ as an estimate of the model uncertainty into an uncertainty analysis together with the sampling error after Finkelstein and Sims (2001) and the random error due to limited counting statistics according to Buzorius et al. (2003) yields 95 % confidence intervals that cross zero for the inferred emission strengths in all cases when the measured fluxes are negative, i.e., measured net deposition fluxes.

In cases of measured net emission fluxes, the inferred emission strength (which is the measured flux minus the modelled deposition flux) will always be more positive than the measured flux because the modelled deposition flux is negative by definition. Therefore,

independent of any uncertainty of the modelled flux, the inferred emission strength is significantly different from zero when the 95 % confidence interval of the measured net emission flux does not cross zero. This is the case in 29 % of the observed net emission intervals. This information has been added to the revised manuscript.

Line 480-484: For measured net emission fluxes, the inferred emission strength is always more positive than the measured flux, because the modeled deposition flux is negative by definition. Therefore, independent of uncertainty in the magnitude of the modeled deposition flux, a positive inferred emission strength is statistically significant when the 95% confidence interval of the measured net emission flux does not cross zero. This criterion was met in 29% of intervals with measured net emissions.

The manuscript could be considered as a research article if the authors can demonstrate that the key results are statistically significant after propagating the reported errors. This should include at least confidence intervals for reported fluxes and inferred emissions (major revision). Furthermore, this analysis should include other tests, e.g., test of whether fluxes differ significantly from zero across different surface type and weather events, or whether surface-type differences are significant.

We thank the reviewer for this comment. To calculate confidence intervals for the reported fluxes, we estimate the random uncertainty due to limited counting statistics following Buzorius et al. (2003), using the mean particle concentration, particle sample flow rate, standard deviation of vertical wind velocity and 20-minute averaging time. We propagate this instrumental error and the sampling error according to Finkelstein and Sims (2001) using the root sum of squares method. We then use the resulting total propagated random uncertainty on the 95% significance level to classify the measured particle fluxes in Figures 6b, 9a and 10a in the revised manuscript. When the 95% confidence intervals of individual 20-minute flux values include zero, the flux values are now shown in grey. As already mentioned above, we acknowledge the substantial errors associated with modelling dry deposition and the small fraction of statistically significant inferred emission strengths.

We retain fluxes when 95% confidence intervals include zero in the summary statistics. Excluding them would preferentially remove small net fluxes and artificially distort the reported statistics to more extreme values. Independent of the associated uncertainty, a net flux close to zero may simply reflect a balance of particle emission and deposition. We have also added the interquartile ranges, defined by the 25th and 75th percentiles, alongside the reported median values in the revised manuscript in order to indicate the spread of the flux values. When discussing individual fluxes, we now state whether the estimated 95% confidence intervals exclude zero.

We also compared particle fluxes across the surface and blowing snow categories, and used the Mann-Whitney U test to explore whether the median flux values are significantly different between these categories. The median values between closed ice with blowing snow and leads

were significantly different ($p = 0.044$), and the median values between closed ice with blowing snow and open water were highly significantly different ($p = 0.002$). However, these tests were performed under the simplifying assumption that the 20-minute flux values are independent. We therefore regard the results as exploratory and do not use them to claim statistically significant differences between surface types in the manuscript. Instead, we report the median values, interquartile ranges and the relative frequency distributions (Figure 9) of particle fluxes.

Line 230-235: The random uncertainty due to limited counting statistics was estimated from the mean particle concentration, the particle sample flow rate, the standard deviation of vertical wind velocity, and the 20-minute averaging time following Buzorius et al. (2003). To combine these two error contributions, the sampling error following Finkelstein and Sims (2001) and the random uncertainty due to limited counting statistics following Buzorius et al. (2003) were propagated using the root sum of squares method.

Line 359-360: Among the 20-minute intervals with particle fluxes significantly different from zero at the 95% confidence level, 53% showed net deposition.

Line 462-465: Comparing fluxes for which the 95% confidence intervals exclude zero (colored bars) with fluxes for which the intervals include zero (grey bars) shows that the majority of fluxes close to zero fall into the latter group. The qualitative pattern is similar in both cases. Negative fluxes predominate over closed ice, while both positive and negative fluxes occur over leads and open water.

Line 557-558: Among the intervals when 95% confidence intervals excluded zero, 53% showed net deposition.

Line 563-564: The resulting net emission fluxes reached $0.98 \times 10^6 \text{ m}^{-2} \text{ s}^{-1}$ (95% confidence interval excluding zero), much higher than the net deposition fluxes.

Line 568-569: The magnitude of these inferred emissions remains subject to substantial deposition modelling errors.

If the authors prefer not to perform this analysis, I believe their dataset remains valuable and should be published as a measurement report, after acknowledging the large uncertainties that currently prevent definitive conclusions, and after restructuring the article according to the journal's editorial requirements.

We acknowledge very large uncertainties associated with the modeled deposition fluxes that prevent definitive quantification of the inferred emissions strengths. However, we also show a considerable number of measured particle fluxes for which the flux direction can be determined on a 95% confidence level, indicating that both net particle emission and net particle deposition periods occur, with a slight predominance of net particle deposition. Even though we do not present statistically significant differences of particle flux statistics for

different surface types, we present and discuss rather unexpected net particle emission events over closed ice surfaces, including statistically significant positive flux values. Most previous studies on eddy covariance particle fluxes in the Arctic associate local particle emission with water surfaces. Our findings of extended and pronounced net particle emission over closed ice surfaces provide substantially new results with clear implications for the turbulent surface-atmosphere exchange of particles underpinning the potential of blowing snow as a local particle source in the Arctic.

As an additional note, the authors mention “random uncertainty” (L227-232), but it is unclear what this actually means (I’m assuming this is the random sampling error estimated via Finkelstein-Sims, but it should be specified). Furthermore, other systematic uncertainties are mentioned or quantified separately throughout the manuscript (on top of modelling and measurements errors) – estimating their contribution to the total propagated uncertainty would contribute substantially to the additional analysis required for publication as a research article.

We thank the reviewer for pointing out this ambiguity. In lines 227–232, “random uncertainty” indeed refers to the sampling error estimated after Finkelstein and Sims (2001). We have replaced “random uncertainty” with “sampling error” in this passage to make this explicit. We also combined the sampling error following Finkelstein and Sims (2001) with the random uncertainty due to limited counting statistics following Buzorius et al. (2003) using the root sum of squares method. We refer to the result of combining these two contributions as the “combined uncertainty” throughout the revised manuscript.

Line 225-230: The sampling error of the particle fluxes was estimated following Finkelstein and Sims (2001). This approach considers the temporal autocorrelation of turbulence and estimates the number of statistically independent turbulent eddies contributing to each 20-minute flux measurement. Consequently, the sampling error after Finkelstein and Sims (2001) reflects the expected variability in the flux estimate resulting from the finite sampling period and the number of independent turbulent events. The median sampling error of the measured particle fluxes following Finkelstein and Sims (2001) was $0.7 \times 10^6 \text{ m}^{-2} \text{ s}^{-1}$. In extreme cases, this sampling error may be $0.26 \times 10^6 \text{ m}^{-2} \text{ s}^{-1}$ (95th percentile).

Line 473-478: However, the median magnitude of these negative inferred emission strengths ($-0.05 \times 10^6 \text{ m}^{-2} \text{ s}^{-1}$) was smaller than the combined uncertainty ($0.07 \times 10^6 \text{ m}^{-2} \text{ s}^{-1}$) of the sampling error following Finkelstein and Sims (2001) and the random uncertainty due to limited counting statistics according to Buzorius et al. (2003). Furthermore, 57% of the negative inferred emission flux values were smaller than the combined uncertainty of the corresponding particle flux measurements. This indicates that most negative inferred emission fluxes are within the uncertainty of the particle flux measurements.

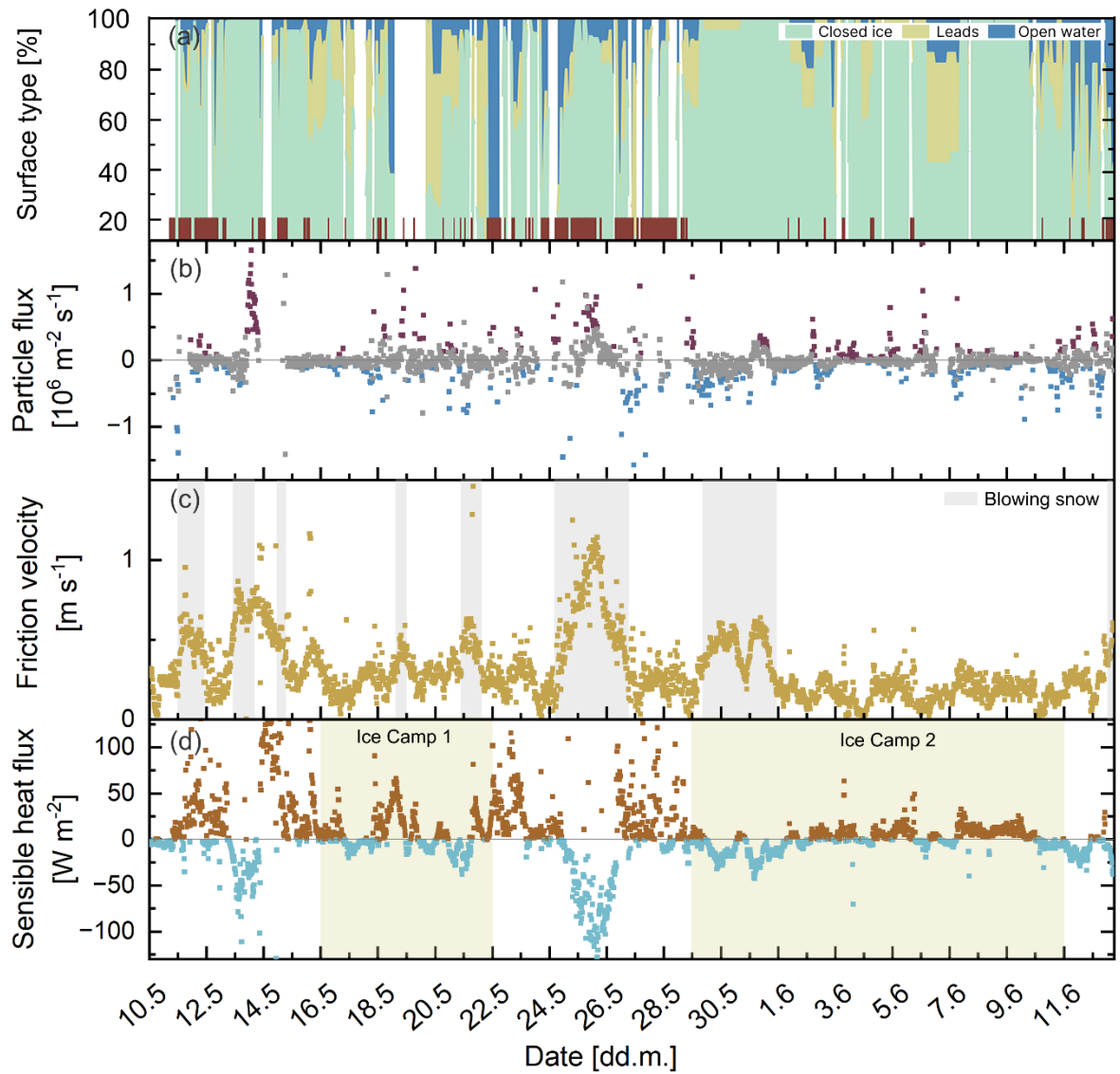


Figure 6. Overview of the surface types, particle and sensible heat fluxes, as well as the friction velocity for the entire measurement period, from 10 May to 12 June 2023. The top panel (a) shows the hourly distribution of the three surface types: closed ice (turquoise), leads (beige), and open water (blue). Periods with ship speeds ≥ 1 kn are indicated in red. The second panel (b) shows the particle flux (in $10^6 \text{ m}^{-2} \text{ s}^{-1}$) evaluated in 20-minute intervals (red squares indicate net particle emission, blue squares indicate net particle deposition, and **grey squares indicate fluxes when 95% confidence intervals include zero**). The third panel (c) shows the friction velocity (u^* , in m s^{-1}) in beige, and the high wind speed events are shown in grey. The bottom panel (d) shows the sensible heat flux (W m^{-2}) evaluated in 20-minute intervals and the periods of the two ice camps (beige shading).

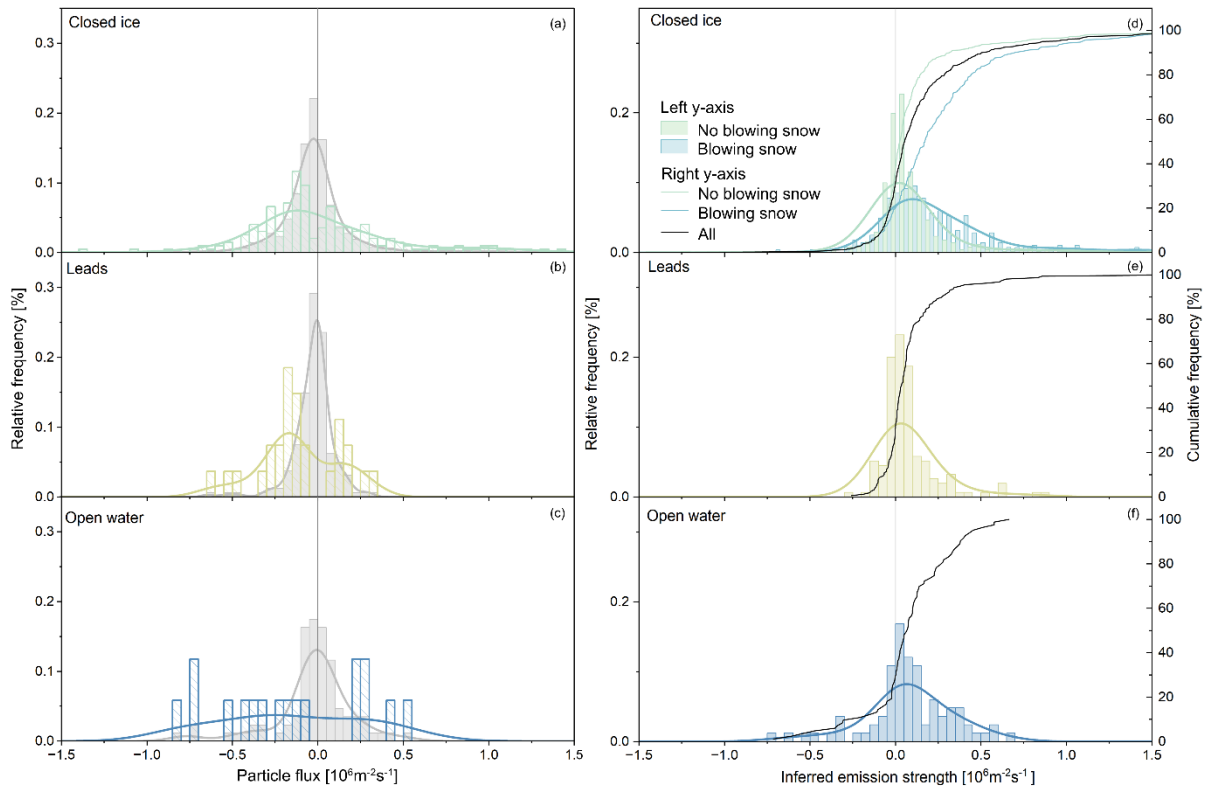


Figure 9. The left panels (a-c) show the relative frequency distributions of particle number fluxes (in $10^6 \text{ m}^{-2} \text{ s}^{-1}$) for the three surface types: (a) closed ice, (b) leads, and (c) open water. **Colored bars represent fluxes when 95% confidence intervals exclude zero, whereas grey bars represent fluxes when 95% confidence intervals include zero.** The vertical grey line indicates zero flux, separating net particle deposition from net particle emission. Only stationary periods with ship speed ≤ 1 kn are included. The bold curves show the kernel density estimation. The right panels (d-f) show relative and cumulative frequency distributions of inferred emission strength (in $10^6 \text{ m}^{-2} \text{ s}^{-1}$) for the three surface types: (d) closed ice, (e) leads, and (f) open water. The distributions are derived from observed particle fluxes and modeled deposition velocities, shown separately for periods without potential blowing snow (green) and with potential blowing snow (blue), depending on the blowing snow threshold. The bold curves show the kernel density estimation. The left y-axis (histograms) shows the number of observations, while the right y-axis shows the cumulative frequency distributions for no potential blowing snow (green line), potential blowing snow (blue line), and all observations (black line).

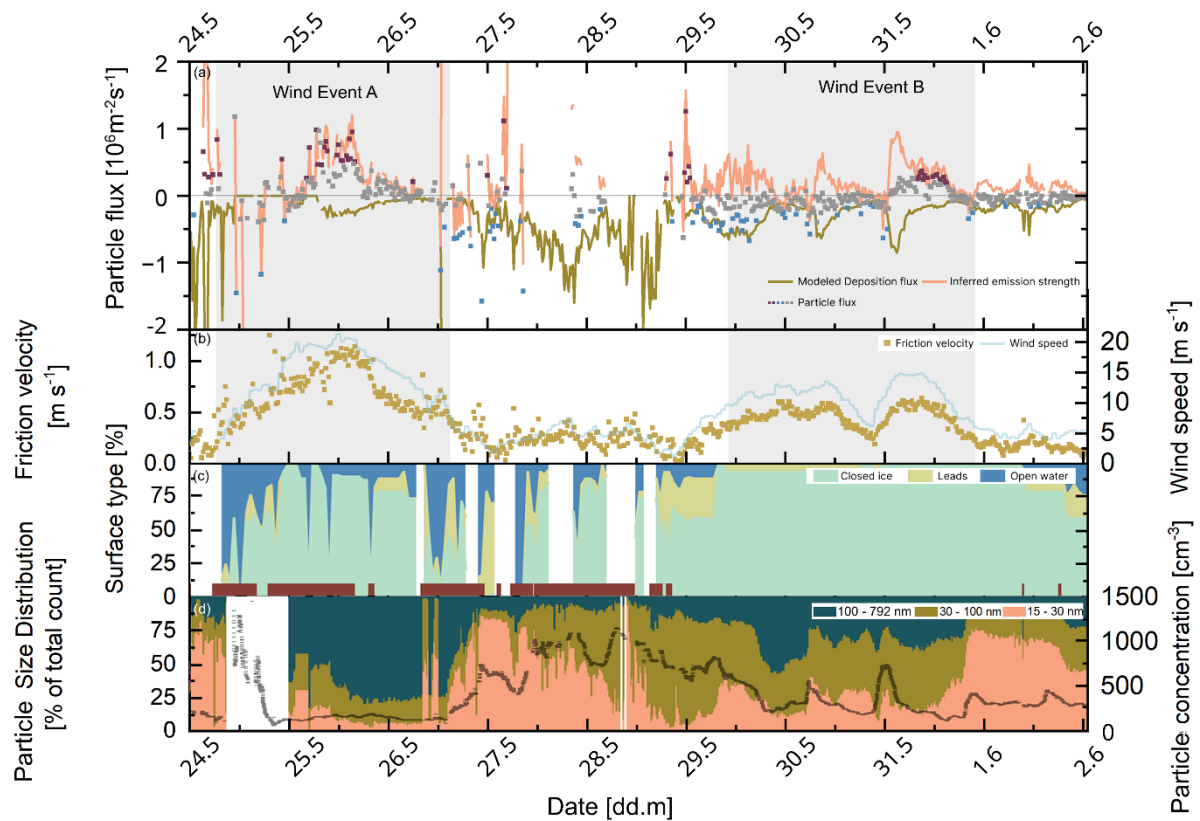


Figure 10. (a) Particle fluxes (red squares indicate net particle emission, blue squares indicate net particle deposition, and grey squares indicate fluxes when 95% confidence intervals include zero), modeled deposition flux (dark beige), and inferred emission strength (salmon-colored) from 24 May to 2 June evaluated in 20-minute intervals (in $10^6 \text{ m}^{-2} \text{ s}^{-1}$). Panel (b) shows the friction velocity (u^* , beige, in m s^{-1}) and wind speed (light blue, in m s^{-1}). The grey shading in (a, b) shows the time periods when the threshold for blowing snow is exceeded. Panel (c) shows the hourly distribution of the three surface types: closed ice (turquoise), leads (beige), and open water (blue). Periods with ship speeds ≥ 1 kn are indicated in red. (d) Particle size fractions from 15 to 792 nm in three accumulated groups (left y-axis, in % of total particle number concentration) measured with a DMPS on the fourth deck of Oden and total particle number concentration (cm^{-3}), measured with an MCPC at the foremast (black symbols; right y-axis).

References:

Buzorius, G., Rannik, , Nilsson, E. D., Vesala, T., and Kulmala, M.: Analysis of measurement techniques to determine dry deposition velocities of aerosol particles with diameters less than 100 nm, *Journal of Aerosol Science*, 34, 747–764, [https://doi.org/10.1016/S0021-8502\(03\)00025-9](https://doi.org/10.1016/S0021-8502(03)00025-9), 2003.

Emerson, E. W., Hodshire, A. L., DeBolt, H. M., Bilsback, K. R., Pierce, J. R., McMeeking, G. R., and Farmer, D. K.: Revisiting particle dry deposition and its role in radiative effect estimates,

Proceedings of the National Academy of Sciences of the United States of America, 117, 26 076–26 082, <https://doi.org/10.1073/pnas.2014761117>, 2020.

Finkelstein, P. L. and Sims, P. F.: Sampling error in eddy correlation flux measurements, *Journal of Geophysical Research: Atmospheres*, 106, 3503–3509, <https://doi.org/10.1029/2000JD900731>, 2001.

Petroff, A. and Zhang, L.: Development and validation of a size-resolved particle dry deposition scheme for application in aerosol transport models, *Geoscientific Model Development*, 3, 753–769, <https://doi.org/10.5194/gmd-3-753-2010>, 2010.