Response to Referees

Comments from Referee #1:

General comments

This manuscript presents a valuable pan-Arctic analysis of winter lead fraction and lead-size statistics derived from ICESat-2, using two complementary products (ATL07 and ATL10). The topic is timely and relevant, and the results (spatial patterns, regional interannual variability, and lead-size scaling behaviour) will be of broad interest. I have several comments that would improve clarity and strengthen the ATL07–ATL10 comparison and the interpretation of the power-law results.

We thank the referee for their time and valuable comments to improve our manuscript. In the following point-to-point response, we detail the revisions made to address their comments. Line and figure numbers refer to the revised manuscript with changes highlighted.

Specific comments

1. Sect. 2 (ATL07 vs ATL10 comparability; ice concentration filtering):

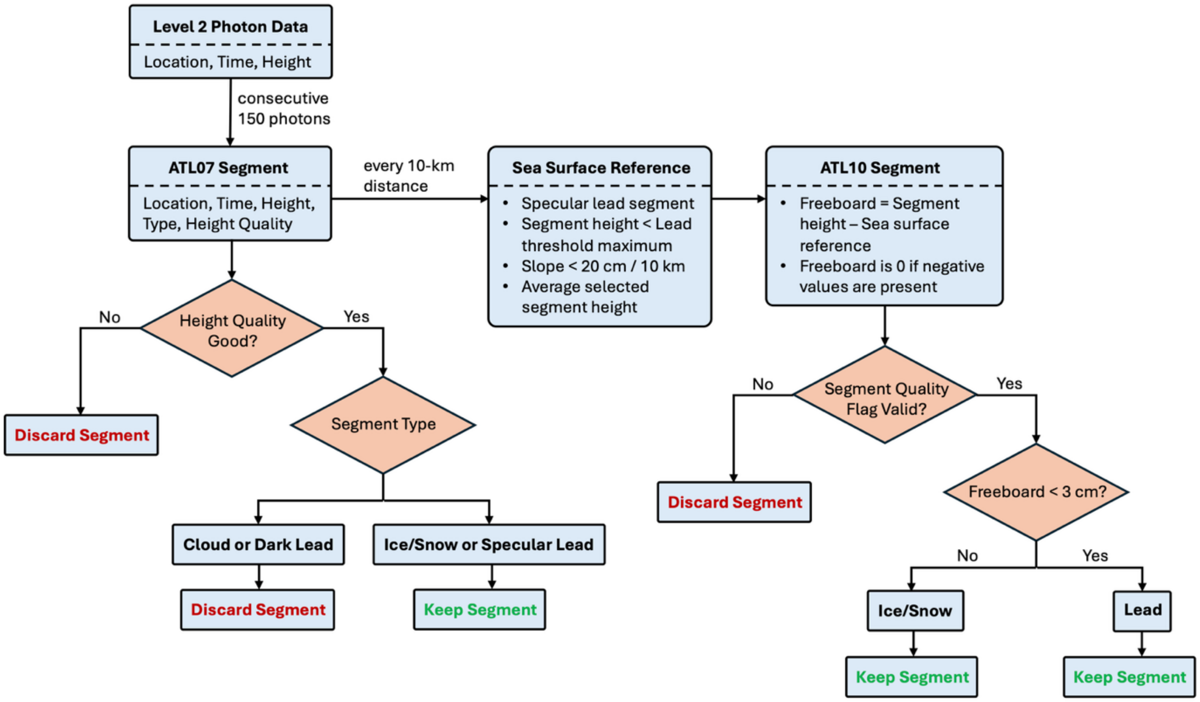
The manuscript applies different sea-ice concentration filters for ATL07 and ATL10 (and the products have different lead definitions). Perhaps discuss how the differing concentration masks could influence the ATL07–ATL10 comparison (e.g., particularly near the ice edge and in marginal seas)

We added text in Line 60 to outline the influence of the different masks used in these two products, and the detection methods: "Methodological differences in lead detection between the two products contribute to the differences in both lead classification and total counts. The ice concentration filtering excludes portions of the ice edge where lead fractions are expected to be highest. As a result, leads near the ice edge are absent from both products, with ATL10 missing a larger portion due to its more restrictive filter."

2. Sects. 2.1–2.2 (methods clarity):

The processing description would benefit from a flow chart alongside the text; this would help readers follow the differences between the ATL07 and ATL10 workflows and provide a nice visual summary.

We added the following flow chart to visualize the processing steps described in section 2.1 and 2.2. We added the following sentence in Line 64: "Major data processing steps are shown in Figure 1."



3. Definition of "climatological wintertime lead fraction" (p7):

Formally define what is meant by the "climatological wintertime lead fraction" (e.g., is the climatology computed by pooling all winter observations across years in each grid cell).

We added the definition to the first sentence of section 4.1.1 which now reads "Climatological wintertime lead fraction L_f^{clim}, calculated using all segments across the Arctic in each grid cell following equation (1), shows ..."

4. Sect. 4.1.2 (power-law / scaling context):

The power-law analysis is interesting and could be better contextualised within the broader literature on geometric scaling in sea ice (while being clear about differences between lead-size and floe-size statistics). The discussion could reference, for example:

o Stern, H. L. (2018). On reconciling disparate studies of the sea-ice floe size distribution. Elementa: Science of the Anthropocene, 6, 49. https://doi.org/10.1525/elementa.304

o Stern, H. L., et al. (2018). Seasonal evolution of the sea-ice floe size distribution in the Beaufort and Chukchi seas. Elementa: Science of the Anthropocene, 6, 48. https://doi.org/10.1525/elementa.305

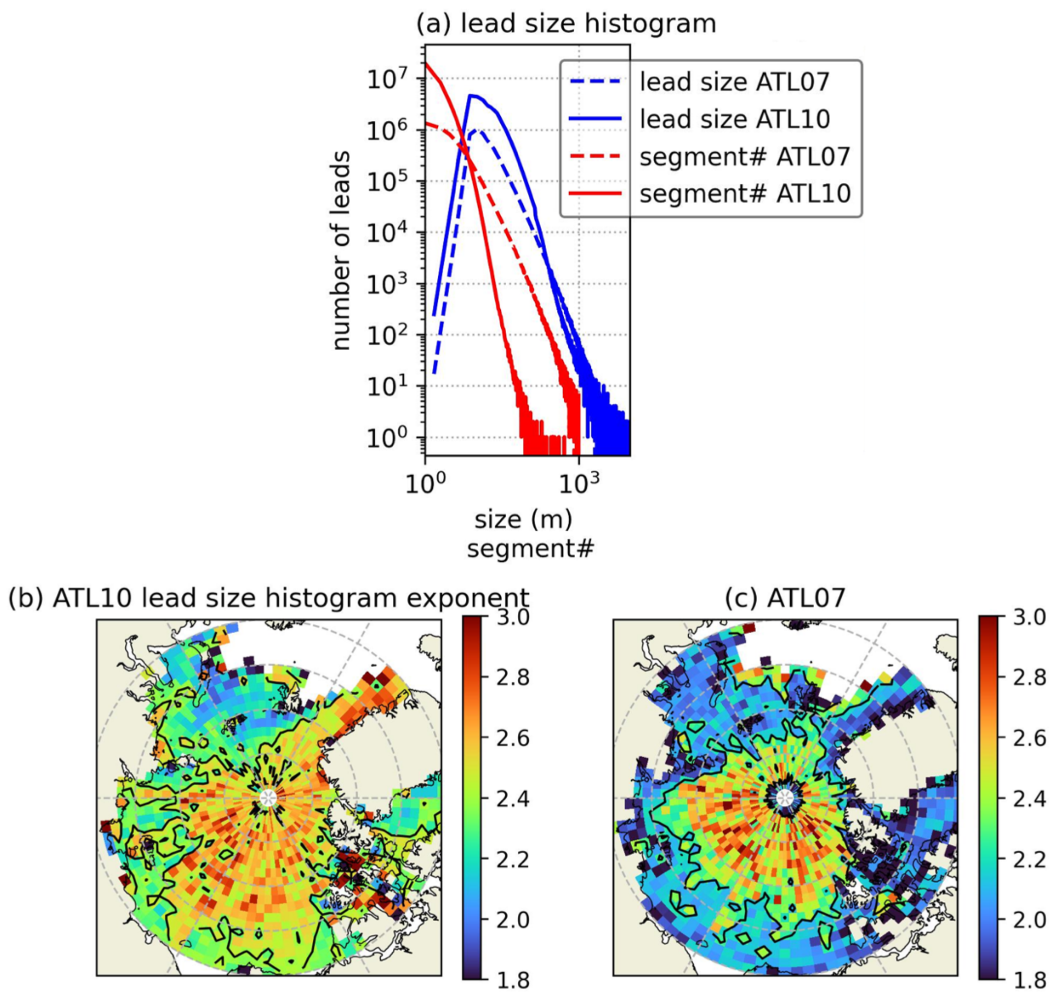
(These are floe-size focused, but may help frame interpretation of scaling regimes and physical processes.)

We thank the referee for providing us with useful reference papers. The power-law distribution in both lead and ice floe size is noteworthy and should be discussed together to better characterize sea ice. We have rewritten the second paragraph of section 5.1 adding the suggested papers, addressing this comment and comment 7.

5. Figure 3a (readability):

Figure 3a is difficult to read at its current size. Consider splitting into two panels/figures (one for lead-size distribution, one for segment-number distribution) or enlarging/adjusting layout so axes and legends are legible.

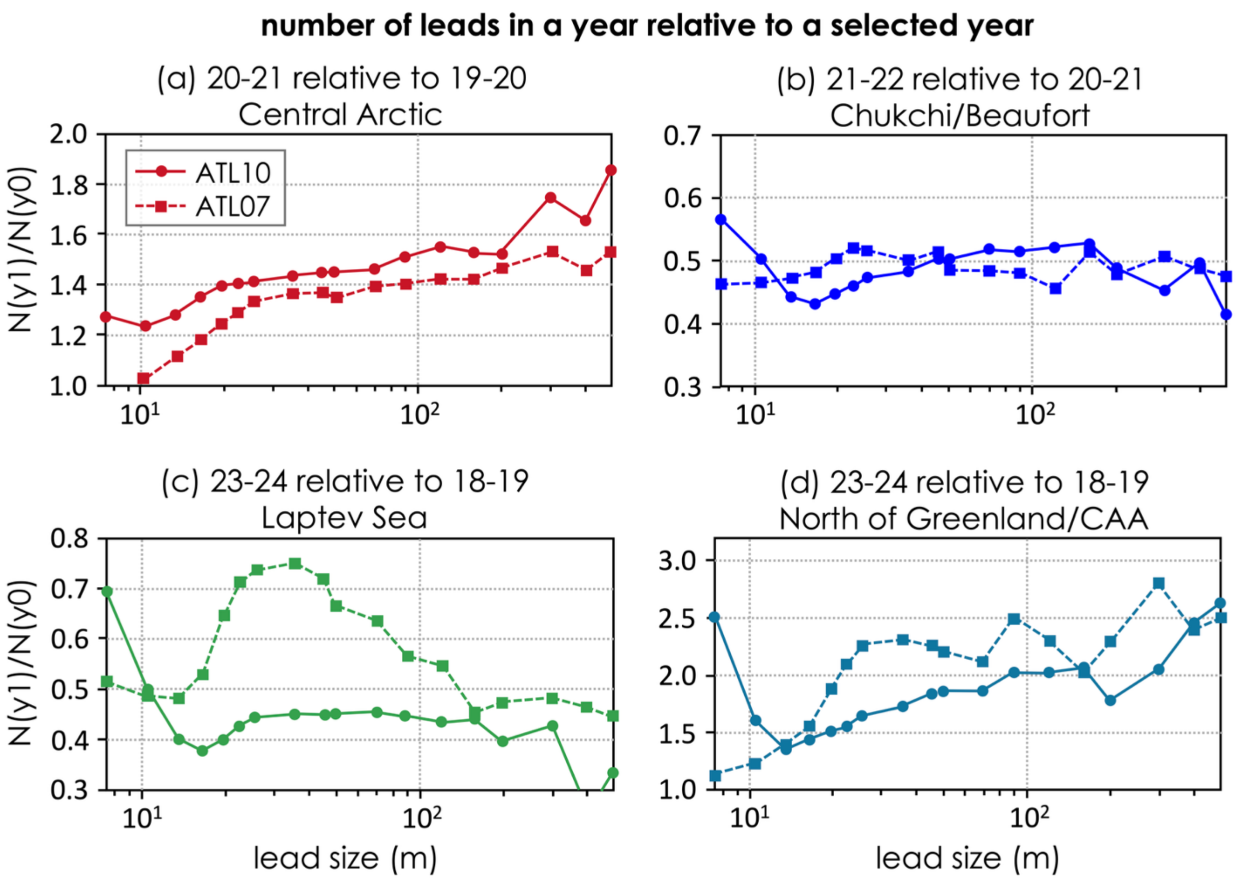
Figure 3 in the comment is Figure 4 now in the highlighted manuscript (following a comment from referee #1 to add a flowchart). We have adjusted the layout and enlarged panel (a) for better readability. The updated figures are also shown below.



6. Figure 6 (visual consistency):

The mix of lines (ATL10) and bars (ATL07) is visually confusing. I recommend using a consistent representation (e.g., lines for both products, or separate panels). Also please adjust titles/labels to avoid overlapping plotted data.

Figure 6 in the comment is Figure 7 now in the highlighted manuscript. We have updated the figure and the captions as suggested.



7. Sect. 5 (interpretation of apparent scaling changes):

The apparent change in power-law scaling is an important result. It would benefit from a deeper discussion of plausible mechanisms and why they might differ by region and year (e.g., fracture/strain regimes, wind forcing, consolidation/thermodynamic growth, lead refreezing).

We have restructured and extended the second paragraph of section 5.1 where the power-law distribution and the nonuniform exponents are discussed. The discussion is now contextualized with ice floes, as suggested in comment 4. The paragraph now reads "The power-law distribution of the sea ice leads reflects the fractal nature and nonlinearity in sea ice fracturing, which exhibit self-similar behavior that is often generated by repeated physical growth process \citep{Vicsek1992}. Many other variables exhibit the same fractal nature that follows a power-law distribution of their sizes, including the complementary solid component of the ice cover -- sea ice floes \citep[e.g.,][]{Toyota2006,Stern2018a,Stern2018b,Christensen2021}. Here, we find evidence that the power-law exponent increases with lead size and varies across regions and time, likely reflecting differences in winds \citep[e.g.,][]{Wangqiang2016,Wang2016} and ocean forcing like waves \citep[e.g.,][]{Wang2016,Voermans2020} acting on varying sea ice conditions that modulate its resistance to deformation \citep[][]{Herman2017,Heorton2018}. Lead refreezing rate under different thermodynamic and dynamic processes may also contribute to the scale-dependent power-law exponent.

An increasing power-law exponent has been theorized \citep{Rothrock1984} and observed \citep{Toyota2006} for sea ice floes. Regional and temporal variability in floe size exponents has likewise been linked to the growth–melt cycle and ice precondition \citep[e.g.,][]{Steer2008,Toyota2011,Stern2018a,Stern2018b}. Collectively, our results, and those for sea ice floes, suggests that assumptions of a (constant) power-law distribution could potentially give rise to the misrepresentation of sea ice simulations \citep[see][]{Horvat2017}. In the future, taking into consideration the size-, region-, and time-varying exponent could be useful for the parameterization of lead effects in models.”