REVIEWER'S COMMENTS and ANSWERS

Reviewer #1

General comments

Q1: While the freshening event and the observational dataset are of clear interest, I find that the current analysis remains somewhat limited in depth, and that several conclusions appear stronger than what is fully supported by the presented evidence at this stage. In addition, some arguments would benefit from clarification or revision, as certain interpretations appear inconsistent or insufficiently justified.

A: We hope that our revisions have addressed the reviewer's concerns and improved the manuscript.

Q2: The overall quality of the figures is also a significant concern. Several figures lack axis labels, have readability issues, or are difficult to interpret in their current form. Substantial effort is needed to improve figure clarity and consistency before the manuscript can be considered publication-ready. In addition, some figures appear redundant and do not always add new information. For instance, Figures 2–7 show overlapping aspects of the same signal, Figure 8 is extremely difficult to read, Figure 12 adds limited insight, and Figure 15 duplicates information already shown in Figure 14. Some of these figures could likely be removed or moved to the Supplementary Materials.

A: We followed the specific advice regarding figures and addressed most comments. We also provide justification where suggested changes were not implemented. In particular, we (using the original figure numbering) (1) moved Figures 5 and 15 to the Supplementary Material, (2) added axis labels to Figures 7, 8, and 10, and (3) revised Figures 8, 10, 11, 12, and 14.

Q3: From a scientific perspective, the proposed link between river discharge and the observed freshening is likely, but several aspects of the observed signal remain unexplained and would benefit from discussion. In particular:

● What is happening in the surface layer, and is it possible that the anomaly was already present there in summer 2015?

A: We hope that we have presented a compelling argument that our records capture the major freshening signal.

● Why does the freshwater anomaly appear to arrive abruptly down to ~100 m at some moorings, while the meteoric water fraction increase is confined to the upper ~25 m (Fig. 8)?

A: We often observe signals arriving at mooring locations abruptly over an extended depth range. This likely reflects two factors: 1) the signal is often barotropic and 2) vertical mixing is enhanced along the continental slope.

The apparent discrepancy arises because salinity is a directly measured bulk property, whereas meteoric water (MW) fraction is a derived quantity based on end-member analysis (e.g., salinity, AW/PW contributions, and $\delta^{18}O$). As a result, MW estimates carry substantially larger uncertainties, typically on the order of ±0.01–0.02 in fractional units. While the freshwater anomaly remains detectable in salinity down to greater depths, the corresponding MW fraction becomes small relative to its uncertainty and is therefore not well resolved. In addition, vertical mixing and dilution reduce the distinct meteoric water signature with depth, even when the total freshwater anomaly persists. Consequently, MW increases appear confined to the upper ~25 m, where the signal-to-noise ratio is highest. The positive MW anomalies nevertheless indicate an enhanced riverine contribution to Arctic surface waters, concentrated primarily within the upper ~25 m. We now emphasize this uncertainty more clearly in the text.

● Why does the anomaly appear weaker in summer 2016 compared to the preceding and following winters?

A: We believe that this is due to the seasonal signal. Although we de-seasoned our records, a residual seasonal signal likely remains. This is because the seasonal cycle varies from year to year, and subtracting a mean seasonal climatology does not fully remove it. In addition, seasonality is expressed not only in the mean but also in the variance (e.g., Arctic air temperature exhibits much stronger variability in winter than in summer). This component is not removed by traditional de-seasoning methods. We have added these arguments to the Methods section.

● Why is the freshwater anomaly associated with different (and sometimes opposing) temperature signals at different moorings?

A: We addressed this reviewer's question in our responses to their specific comments. Briefly, this arises from the contrasting thermal regimes of the shallow and deeper parts of the continental slope, which are separated by a hydrographic front.

While definitive answers to all of these questions may not be possible, acknowledging and discussing these features would improve the physical interpretation of the results.

A: We hope that the reviewer finds our responses satisfactory.

Q4: The discussion of the impacts of the freshening event would also benefit from clarification. In particular, the link between freshening and changes in surface currents is not entirely clear, and it is difficult to assess whether the freshening alone can explain the increased sea-ice cover observed in summers 2016 and 2017, given the potential influence of other factors.

A: We added a clarification to the text regarding the connection between stratification and current speed (see also our response to specific comments). Regarding the relationship between stratification and sea-ice state, the conclusions of this study are highly consistent with those of Polyakov et al. (2025). We have therefore added this reference to the manuscript.

Q5: Finally, some aspects of the analysis are unclear. For example, the calculation of $\bar{V}.\Delta S$ does not seem to provide information about a potential cross-slope shift of the Atlantic Water core, as it compares a mean-state salt flux with a temporal salinity anomaly. This interpretation likely needs to be reconsidered.

A: We have revised the text and hope it is now clearer. Please see our responses to the specific questions below.

Specific comments:

l. 32–34: "*exemplifying the phenomenon of Arctic amplification*"

The logical connection in this sentence is unclear. The numbers in the paragraph show that

the Arctic is warming, but they do not illustrate Arctic amplification.
A: We edited the sentence removing the part related to amplification.

l. 47–53: Consider moving this to l. 38, where you introduce the presence of freshwater in the Arctic.
A: We prefer to keep this paragraph as is. The preceding discussion addresses freshwater changes across the Arctic, whereas this paragraph focuses on the Siberian Arctic.

l. 90–93: "*indicating that interpolation of SBE data introduces negligible error*."
You have not yet mentioned that the data are interpolated. I suggest moving this sentence to the end of the subsection.
A: We revised the sentence to remove referencing to interpolation.

l. 149: Is this wavelet-based method more accurate than simply analyzing anomalies relative to the seasonal cycle?
A: To calculate anomalies, it is necessary to define transition points between positive and negative phases. In the presence of noise, this is not straightforward; wavelet analysis provides a more objective way to identify these transitions.

l. 159–170: I would shorten this paragraph: simply define zl and z2 , and state that using the depth at which the anomaly becomes statistically indistinguishable from zero would yield similar results.
A: We have shortened this paragraph.

Definitions of freshwater content, Q, and APE: Is z1 the surface or the depth of the shallowest reliable salinity record zl defined earlier? You state that it is the surface for APE, but this is not clear for freshwater content and Q.
A: z_1 is the shallowest depth with available data (or as otherwise specified) and is adjusted to be consistent with the definition of APE.

Analysis of Figure 2: The abrupt arrival of the fresh anomaly at moorings M14 and M3 in January 2016 is intriguing. The anomaly then weakens during the following summer before strengthening again in winter 2016–2017. This variability is also visible in Figures 4, 5 and 6. Why do the anomalies appear stronger during the two winters? Is it because part of the freshwater anomaly resides closer to the surface in summer (in a layer not resolved by the moorings) and is transferred to deeper layers by winter mixing? Or is there another explanation?
A: This signature is seen in all records (see Fig. 5). It is a fingerprint of the seasonal cycle. Freshening is due to mixing which makes water saltier in the SML and fresher in the halocline. This is a very well-known feature. It is discussed in the text.

l. 286: "*For instance, the freshwater content averaged over four deeper moorings increased* *by 0.67 m*."

The statement that freshwater content increased by 0.67 m when averaged over four deeper moorings is difficult to interpret meaningfully, given surface-layer limitations (see also l. 330–332).

A: In winter, the absence of data in the upper 30–50 m is not critical because the layer is well mixed. In summer, however, missing near-surface data may be more important. To assess this effect, we use Ice-Tethered Profiler (ITP) data extending to 10 m and simulate the removal of data from the upper 30 m and 50 m layers. The impact on freshwater content (FWC) estimates is limited (Fig. S2 using new numbering). For example, removing data above 30 m—available at three of the six moorings during the freshening event—changes the annual mean FWC (10–175 m) by only 2.9%, increasing to ~10% when the upper 50 m is excluded.

Figures 3 and 4: There is some redundancy between these figures; choosing one would likely be sufficient. The qualitative results (lower salinity corresponding to larger freshwater content and higher APE) are obvious, and quantitative estimates are not possible because the moorings do not cover the surface layer.

A: We consider both Figures 3 and 4 essential, as they depict different water properties and together help build the overall narrative. We therefore prefer to retain both. It is possible that the reviewer was instead referring to redundancy between Figures 4 and 5; in that case, we agree and have moved Figure 5 (APE time series) to the Supplement.

We disagree with the reviewer's statement that quantitative estimates are not possible using the available data. First, for vertically integrated quantities such as FWC, we provide quantitative estimates for specified depth ranges. Although these do not cover the upper ocean to the very surface, they still represent robust measures of freshening. Second, as shown in our response to the previous comment, these estimates are not substantially different from those obtained when data extend to 10 m depth. Third, the strong consistency of FWC anomalies across different mooring records—including those with observations extending to 30–40 m and shallower—demonstrates that even records lacking near-surface data provide meaningful estimates of freshwater anomalies during 2015–2017.

l. 281–288: The contrasting tendencies in temperature and OHC between the moorings are difficult to interpret. At mooring M11, for instance, the average anomalies have opposite signs (positive temperature anomaly and negative salinity anomaly), yet temperature (or OHC) and salinity (or −FWC) appear correlated during 2015–2017. Do you have an explanation for this?

You also state that "*The potential underlying mechanisms for these contrasting signals are discussed in Section 6*," but there is no Section 6 in the manuscript. Such a discussion would improve the interpretation of the results.

A: We revised the text to clarify that these contrasting regional differences should be considered in the context of the hydrographic front, located near the ~750 m isobath, which separates the shallow $M1_1$ and $M1_2$ moorings from the deeper ones. The shallower and deeper domains exhibit markedly different thermal regimes (e.g., Baumann et al., 2018).

Figure 7: The figure is difficult to read and would benefit from improved resolution.

A: The original figure is very clear and readable, and we expect it will remain clear upon publication.

l. 297–310: This analysis is unclear to me. As I understand it, $\nabla.\Delta S$ is calculated from time-averaged velocity and salinity at each mooring location, representing one component of the mean salt balance. You then compare it with salinity anomalies during the freshening event, which represent temporal changes. I therefore do not see why these two quantities should be related. One possible alternative might be to examine changes in $\nabla.\Delta S$ between the pre-2015 period and the freshening event.

A: In the "normal" state (with no freshening), the cross-slope salinity distribution exhibits a maximum at mooring $M1_3$. Displacement of this maximum in either direction (closer to the shore or toward the deeper ocean), following the meridional shift of the AW jet, would produce salinification at some mooring locations, which contradicts our observations in 2015–2017. To illustrate this more formally, we assumed that near-slope salinity changes due to the cross-slope (meridional) migration of the AW jet can be described by a reduced salinity conservation equation, in which we retain only two terms: the temporal change of S and the meridional advection of salt. Under this framework, freshening (negative $\partial S/\partial t$) should be balanced by meridional advection of the corresponding sign. If this balance is violated—as indicated by our estimates—the observed freshening cannot be explained by a cross-slope shift of the salty AW core.

To make our analysis clearer, we edited this section.

Table S2: Please add units to the column headers, or remove the table if you agree with my previous comment on this calculation.

A: The original table caption included units, but the unit for the advective term was inadvertently omitted and has now been added. These estimates help clarify the potential role of cross-slope meandering in shaping the observed freshening event.

Figure 8: This figure is difficult to read. It would benefit from improved resolution, enlarged caption, and axis titles and units. Also, it would be good to specify the months over which these profiles were computed. This may be important for your analysis if the increase in meteoric water fraction was already present in summer 2015.

From what I can see, the main changes in meteoric water occur in the upper 25 m, which are not covered by the moorings. It would be useful to propose an explanation. Could this initially be a surface anomaly starting in summer 2015 that is not detected by the moorings and is later transferred to deeper layers by winter mixing?

A: We edited this figure and its caption.

Yes, this is our interpretation: the anomaly, originating from anomalous riverine discharge, forms initially as a thin surface layer near river mouths. It is then advected toward the mooring locations as a shallow fresh layer, where it is subsequently mixed into the ocean interior. Because five of the six mooring records used in this study begin within the upper 50–55 m during the freshening event (49 m at $M1_1$, 31 m at $M1_2$, 65 m at $M1_3$, 38 m at $M1_4$, 41 m at $M1_5$, and 30 m at M3), they capture most of the freshening signal, as shown in the new Figure S2, using new numbering.

l. 326: It is not clear from the figure itself that Yenisey discharge was lower in 2013 than in subsequent years, the calculations provided at l. 327-329 are necessary to say that.

A: We edited this paragraph stating that although the Yenisey exhibits a higher *instantaneous* peak in 2013, this peak is short-lived. In contrast, the 2014–2015 discharge is sustained over a longer period, resulting in a larger *integrated* runoff.

l. 327–330: Are these anomalies calculated relative to 2013 only? Why not use the 2013–2018 average as a baseline instead? Also, it is not clear at this stage of the article why the Lena River is not discussed, while it is also shown in Figure 9.

A: We aimed to illustrate the anomalous state of the system during the freshening event relative to its undisturbed state, with 2013 representing the baseline year before the freshening occurred. We also added a discussion of Lena River discharge to this paragraph.

l. 330–332: The estimate of 0.60 m of additional freshwater content is difficult to interpret, given both spatial variability among moorings and incomplete vertical coverage. Besides, summing the anomalous discharges from 2013 and 2014 implicitly assumes that freshwater from both years arrives at the mooring line simultaneously, which may not be the case.

A: The reviewer is correct, and we have revised the sentence accordingly.

l. 342: "*The downstream impact of this anomalous freshwater input is evident…*"
The downstream propagation of a single freshwater anomaly is not obvious from the presented maps, which show a mix of local and basin-scale patterns, including local freshening near river discharge regions and broader large-scale anomalies extending into the Eurasian Basin. I would suggest either showing only one or two maps illustrating the spatial extent of the anomaly, or presenting a lagged regression map of surface salinity anomalies onto Yenisey and Ob discharge anomalies.

A: We have retained a single map to illustrate the spatial pattern of the freshening event and have revised the text accordingly.

Figure 11: This figure is useful for illustrating the link between river discharge and the freshening anomaly. You state that all correlations are significant at $p<0.001$. What statistical test was used, and how were the degrees of freedom estimated? I would expect the correlation with M11 ($R = 0.39$) to be significant at $p<0.05$, but probably not much more.

A: The t-statistic from the Student's t-distribution is used for these estimates. For the 5yr record, the *p*-value just slightly above 0.001. We corrected the p value from "<0.001" to "<0.05" in this panel. Thank you for catching this.

Figure 12: Captions and titles are cropped, and overall presentation needs improvement.

A: We have replaced this figure with a new version.

l. 365–372: This explanation is unclear. Winds during the event appear to drive Ekman transport that is along-slope or even toward the coast, whereas the moorings are located in the basin interior. Such winds would be expected to limit freshwater transport toward the moorings. While it is likely that winds influenced shelf–basin freshwater exchange, it might be more appropriate to focus on wind patterns during the months surrounding the onset of the event (summer–fall 2015) rather than over 2015–2017 as a whole.

A: As advised, we have replaced the original figure with a revised version and updated the text accordingly. The new figure illustrates the wind pattern during the onset of the freshening event, which is conducive to the eastward transport of freshwater from the Kara Sea into the Laptev Sea.

l. 381–382: "*the resulting trajectories reveal that upper eastern Eurasian Basin freshening originates in the Kara Sea*." This argument should appear much earlier. All analyses from Figure 9 onward rely on the assumption that the anomaly originates in the Kara Sea.

A: We added an introductory statement at the beginning of Section 3.2.2 to clearly state that the subsequent analyses (from Figure 9 onward) are based on the premise that the freshening originates in the Kara Sea.

Figure 14: The font, style, and overall appearance differ from the other figures. Please ensure a consistent visual style. The time-axis ticks in panel (a) are not visible.

A: We appreciate the reviewer's comment. The figure was produced using standard, widely accepted software, and we note that the choice of software does not influence the scientific content or conclusions. As such, we have not modified the figure. However, we added external ticks to time axes.

l. 395–397: Are you suggesting that the freshening caused the decrease in surface currents? If so, what physical mechanism would explain this?

A: These results do not represent a suggestion of current decrease on our part; rather, they are based on mooring observations showing a reduction in measured surface currents. We interpret this as being associated with a strengthening of upper-ocean stratification, which likely inhibited the downward propagation of wind energy into the ocean interior, confining the response to a very thin (<10m) near-surface layer. Unfortunately, due to surface reflection and associated contamination, ADCP-based measurements are not reliable within this thin surface layer. We added a clarification to the text.

l. 403–405: "*the divergent heat flux across the halocline decreased from 20 W/m² to 3 W/m².*"

Where do these values come from? Are they taken from Polyakov et al. (2020b)? Do they apply to a specific mooring or represent an average?

A: These values are taken from Polyakov et al. (2020b) and are based on the M3, $M1_2$, $M1_3$, and $M1_4$ mooring records, representing a multi-mooring estimate of the divergent heat flux across the halocline. We have revised the text accordingly.

l. 408–414: You argue that the freshening led to increased sea-ice cover in summers 2016 and 2017, but Figures 2, 4, 5, and 7 suggest that the freshening event ended in spring 2017.

It is therefore not obvious how it would affect sea ice during the following summer. Is this due to delayed effects of reduced winter mixing in 2016–2017? In any case, I would moderate the strength of the claimed link.

A: The reviewer is correct that there is a delayed sea-ice response to changes in stratification, mixing, and winter sea-ice formation, with impacts becoming evident as reduced sea-ice extent in the Siberian Arctic the following fall. This is consistent with a positive ocean heat–ice albedo feedback (e.g., Polyakov et al., *2025*). We have moderated the statement accordingly.

Figure 15: This figure does not add new information (the SIC time series at M1 already appears in Figure 14). I suggest removing it.

A: This figure shows that this process occurred not only at a single mooring site but across the broader region, as indicated by sea-ice records from all mooring locations. We have moved this figure to the Supplement.

l. 435: Why describe this event as “extreme”? It is clearly significant, but no evidence is provided that such events are rare.

A: We removed this word from the sentence.

l. 440–441: “*the observed freshening cannot be explained by cross-slope shifts of the AW salty and warm core*.”

The demonstration of this point is unclear to me.

A: We hope that our clarifications have made this point clear. We reiterate that when a salinity maximum is located over the middle part of the slope, uniformly northward currents cannot produce spatially uniform freshening, as a shift of the Atlantic Water core would instead lead to salinification elsewhere.

l. 443: “*exceptional increase*.”

The data show an increase, but the time series are too short to justify the term “exceptional.”

A: We moderated the tone of this statement.

l. 446–448: The timing is not fully consistent: if Kara Sea anomalies in spring 2015 take nearly two years to reach offshore moorings, they would arrive in spring 2017, which you identify as the end of the event.

A: The timing estimates based on lagged correlations (Fig. 11 in the original notation) are not sufficiently precise to accurately determine the arrival of the fresh anomaly from the Kara Sea to the Laptev Sea, as evidenced by the broad correlation peaks. We have added a statement to this effect in Section 3.2.2 and revised the Discussion accordingly. Moreover, the lag corresponding to the maximum correlation does not indicate the onset of the process; rather, it represents the time at which the freshening signal from the Kara Sea reaches its peak expression in the Laptev Sea.

l. 452–453: “… which aligns with the varying start dates of freshening observed at the moorings (Fig. 3).” I would nuance this statement. Differences in the onset of the freshening event among moorings are on the order of 3–4 months, not more than a year.

A: We edited this text.

l. 456–457: “Indeed, Polyakov et al., (2020b) showed that the divergent heat flux…” This was already mentioned and is a result from another paper. I suggest removing it.
A: We removed this sentence.

l. 485–487: “Consequently, the maximum freshening that often resides in the very top layer cannot be monitored, and the overall magnitude of freshening may be underestimated by the available mooring records.”
This is an important limitation. Given it, I would place less emphasis on quantitative estimates of freshwater content and APE. An alternative approach could be to analyze the freshening in the ORAS5 reanalysis to estimate the fraction of the anomaly captured by the moorings versus that residing near the surface.

A: We hope that our additional analysis in Methods clarified the impact of this limitation. We modified this part of discussion.

Technical corrections:

l. 206: Remove one parenthesis.
A: Done. Thank you.

Figure 2: The caption does not fully correspond to the figure. In particular, there is a confusion between solid and dashed red lines and between red and black lines delimiting the event and the preceding and following periods. The black dashed lines separating the different years could also be mentioned.
A: The caption was edited.

l. 403: Remove parentheses around the reference.
A: Done, thank you.