Response to Editor

Dear Dr. Xichen Li,

Thank you for giving us the opportunity to revise the manuscript. We are grateful to reviewer 2 for the valuable comments that helped to improve the quality of this work. Please see below for a summary of our revision:

1) **Methodology:** We clarified the rationality of the study area selection, explained the interpolation technique and its potential accumulation of drift error over time, and the reasons for choosing the 25km sea ice motion product instead of high-resolution product.

2) **Results and Discussion:** We condensed Section 3.2, revised the backtracking analysis in Section 4.1, and revised the interpretation of the impact of the atmospheric circulation indices in Section 4.2 to present clearer results.

3) **Additional Analysis:** For validation, we added the SHEBA and DAMOCLES campaign buoy data and quantitative error metrics to assess the reliability of our reconstructed result, and the effects of year, starting position and interpolation method on the duration to test the robustness of the duration results.

Below, we provide point-by-point responses to the comments, line numbers refer to the revised manuscript with track changes.

Thank you again for your time and consideration.

Best regards,
Ruibo Lei, Xiaoping Pang and co-authors

Response to RC2

Thank you for your time and constructive comments on the manuscript "Estimation of duration and its changes in Lagrangian observations relying on ice floes in the Arctic Ocean utilizing sea ice motion product". We have carefully reviewed all comments and addressed the key concerns in our revised manuscript based on these suggestions.

The manuscript presents an analysis of potential durations and changes in Lagrangian observation trajectories in the Arctic Ocean using sea ice motion (SIM) products from 1979 to 2020. The authors propose a reconstruction method to track synthetic buoys and analyze long-term trends in the survivability of sea ice-based platforms. The work is particularly relevant in the context of planning future Arctic field campaigns, where floe lifetime and trajectory uncertainty are critical.

The manuscript includes a substantial amount of data analysis, including validation against real buoys and exploration of relationships between trajectory duration and climate indices. However, many of the core scientific and methodological concerns raised in the first round have not been sufficiently addressed. Below, I detail unresolved issues, expanded requests, and additional suggestions for a more rigorous and impactful revision. I recommend minor revisions.

General Comments:

1. The manuscript continues to define synthetic deployment points within a fixed rectangular AOI in the central Arctic Ocean. This choice is not convincingly justified, especially given that the study emphasizes EEZ constraints and international boundary considerations later in the paper. Why not define initial locations based on EEZ boundaries or current common deployment areas (e.g., MOSAiC, N-ICE2015)? The reader is still left wondering whether the motivation is to assess ideal deployment zones within political constraints, or simply to map climatological drift patterns in a limited domain. These are fundamentally different objectives and should be clearly separated and addressed.

Reply: We fully understand the need for this choice of AOI to be fully justified. The decision to use a rectangular area is based on the following considerations: in the central Arctic Ocean, i.e., the high Arctic that excluded the exclusive economic zones (EEZs), it is computationally intensive and inefficient to carry out trajectory reconstruction for 1979-2023 for all 4289 grid points. To effectively reduce the amount of computation while maintaining representativeness, a rectangular region was selected as the study area. Tests were conducted to demonstrate the representativeness of the rectangular study area. The details are as follows:

Using the 1979-2023 climatology field of sea ice motion, the ice trajectories were reconstructed for the period starting from October 1 to September 30, i.e., one year, using a total of 4289 points over the entire central Arctic Ocean as starting points. With a threshold of the trajectory being in the central Arctic Ocean beyond the EEZs >= 9 months, we found that 91.6% of the defined rectangular area is eligible, while only 36.0% of the peripheral area is eligible. Even during 2013–2023, a period facing more severe challenge due to the thinner and younger ice, the rectangular region contained 25.6% of effective starting points, while the other regions had no such points. So it is extremely difficult to find suitable areas to deploy ice camps or buoys in the central Arctic Ocean outside of our defined rectangular area in order to maintain Lagrangian observations for a long enough period of time.(**lines 119-128**)

This demonstrates that our defined rectangular area, while balancing computational efficiency, effectively represents the sea ice dynamics in the central Arctic Ocean. The primary objective of this study is to assess ideal deployment strategies under constraints

2. The manuscript still does not adequately explain how sea ice motion vectors are interpolated onto buoy positions during Lagrangian tracking. Is the interpolation linear? Bilinear? IDW? Are velocity fields regridded before or during integration? Moreover, the paper should comment on whether the use of a fully Lagrangian approach (i.e., step-by-step advection) could be compared to semi-Lagrangian methods, or if any correction is made to account for accumulated drift bias over long periods.Reliance on low-resolution, outdated SIM data undermines the validity of conclusions.

Reply: Thank you for suggestion. We added description about the interpolation method during Lagrangian tracking and emphasized comparison between the Lagrangian method and semi-Lagrangian method. The details are as follows:

1) In the Lagrangian tracking process, we used the bilinear interpolation to interpolate sea ice motion vectors onto buoy positions. The velocity field is dynamically interpolated at each integration step. This approach preserves instantaneous spatial variability but may smooth small-scale features due to the 25 km grid resolution. We added descriptions in **lines 180-182**;

2) We have added a comparison of the semi-Lagrangian method with the Lagrangian method in Section 4.1 last time and have now revised the text. The comparison results showed that the reconstructed trajectories from the semi-Lagrangian method are highly similar to the results from the Lagrangian method, however using the buoy trajectory as validation data, we found that the results derived from the Lagrangian method have a relatively high accuracy compared to that obtained from the semi-Lagrangian method. (**lines 372-384**).

And 3) We added the explanation that accumulated drift bias over long periods in the reconstruction process is small so no correction was done (**lines 182-187**). For the NSIDC SIM product used in this study, although there are errors in the individual motion estimates, these errors do not accumulate over long term tracking because the motion estimates are largely unbiased (Tschudi et al.,2020).This is further supported by the study of Tschudi et al. (2010), who found a drift error of 27 km over 293 days of tracking(with bilinear interpolation), which suggests that errors can still be kept within limits over long term tracking.

Tschudi, M. A., Fowler, C., Maslanik, J. A., and Stroeve, J.C., 2010. Tracking the movement and changing surface characteristics of Arctic sea ice. IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens., 3, 536–540, https://doi.org/10.1109/JSTARS.2010.2048305.

Tschudi, M.A., Meier, W.N., and Stewart, J.S., 2020. An enhancement to sea ice motion and age products at the National Snow and Ice Data Center (NSIDC). Cryosphere, 14(5), 1519-1536, https://doi.org/10.5194/tc-14-1519-2020.

3. The study relies solely on the NSIDC Polar Pathfinder 25 km product, which is known to underestimate short-term variability and to smooth dynamic features relevant for station-keeping and observational fidelity. No comparison is made to higher-resolution products (e.g., OSI SAF 6.25 km, MEEREIS), nor are any bias assessments provided. Without this, conclusions about changes in survivability or trajectory characteristics over time are difficult to evaluate.

Reply: Thank you for comment. The choice of the NSIDC 25 km sea ice motion product was primarily motivated by its long-term consistency (1979–present) and availability for large-scale trend analysis, which is essential for our climatological analysis. While higher-resolution products (e.g., OSI SAF 6.25 km or MEEREIS) better resolve short-term variability, their limited temporal coverage (typically post-2010) preclude their use for assessing long-term trends.

We acknowledge that the NSIDC product's smoothing of small-scale dynamics may affect trajectory details, and Section 2.3 discussed this limitation, adding that the errors accumulated in trajectory reconstruction from SIM data are relatively small (**lines 180-187**). Future work will integrate higher-resolution products to refine the representation of short-term processes.

4. Trajectory validation continues to rely on a small number of buoys, mostly post-2014. The use of earlier IABP buoys or additional campaign data (e.g., SHEBA, DAMOCLES) could significantly strengthen the credibility of results. Moreover, distance between reconstructed and real trajectories is reported, but no error metrics such as RMSE, angular deviation, or trajectory similarity (e.g., Fréchet distance) are provided. This is especially important since the method is used to infer survivability duration over multi-month periods. Also, backtracking analysis of long-duration (>9 months) trajectories would provide insight into which ice origins produce the most stable paths. This could help refine AOI definitions or identify zones of persistent ice retention. Unfortunately, this suggestion remains unaddressed, despite being a straightforward addition that could substantially improve the paper's utility.

Reply: Thank you for the suggestions. To improve the robustness of our results, we have revised the following three aspects in Section 4.1:

1) We have collected buoy data obtained from 1997 to 2023 and added the SHEBA and DAMOCLES campaign data for validation (**line 150 and Table A1**);

2) We added error metrics such as the RMSE and Fréchet distance between the buoy and reconstructed trajectories to improve the confidence of the validation (**lines 218-222 and Section 4.1**);

And 3) Actually, we added an analysis of backward trajectories last time and have now revised the text to emphasize this backtracking analysis (**lines 385-393**). For trajectories with ST > 9 months, we reconstructed backward trajectories from hotspot region and displayed the endpoints distribution (gray dots) in Fig. 9b. 66.3% of the endpoints of the backward trajectories were able to return to the moderate- and high- recommendation zones (the region surrounded by the blue or red line in Fig. 9b), indicating that the recommended zones, as a source area for sea ice, have stable paths.

5. Section 3.3 remains somewhat abstract and disconnected from the core analysis. The discussion of drift trends and sea ice circulation patterns is mostly descriptive and lacks linkage to either the survivability calculations or campaign implications. Consider condensing or more tightly integrating this section with the trajectory duration results.

Reply: We have deleted Section 3.3 and moved the ice response to wind forcing to Section 3.2, and condensed Section 3.2 (**lines 298-346**).

6. Section 4.1: no sensitivity or uncertainty analysis. The survivability results are presented without any robustness testing. How sensitive are results to the time of year, small changes in starting position, or minor variations in drift vector? Even a basic bootstrapping or ensemble test would help confirm that the observed patterns are not artifacts of the interpolation method or limited starting conditions.

Reply: Thanks for the suggestion. We added some text in Section 4.1, **lines 394-402**. To test the robustness of the survival results, we added the effects of year, starting position and interpolation method on the duration, using the starting points reaching the BG or TPD region over 90% as an example. The statistical results showed that the standard deviation of duration in 1979-2022 amounted to 76.0 days. It is noteworthy that with the significant acceleration of sea ice motion in recent years (Sumata et al., 2023), this standard deviation decreases to 20.7 days for the period 2007-2022, which corresponds to 7.2% of the mean duration. It should be noted that this study focuses on the mean duration characteristics at the climate scale. The difference between the mean duration in case of starting position offset (±10 km) and the results obtained for the starting position accounts for about 1.1%, and the mean duration obtained from the ice trajectories reconstructed with the nearest neighbor interpolation differs from the results obtained with the bilinear interpolation by an average of 7.6%, which proves that small changes in the initial coordinates and the interpolation method barely affect the reliability of the duration.

Sumata, H., de Steur, L., Divine, D.V., Granskog, M.A., and Gerland, S., 2023. Regime shift in Arctic Ocean sea ice thickness. Nature, 615(7952), 443-449, https://doi.org/10.1038/s41586-022-05686-x.

7. Table 1: interpretation of CAI correlations still vague. The correlation analysis between duration and atmospheric circulation indices is repeated from the original version, with no added clarity. For example, why does autumn CAI correlate with longitude in BH but not IPD? What does the correlation in latitude for both suggest about the spatial mode of influence? Without physical interpretation, the correlation analysis is not actionable and feels disconnected from the rest of the study.

Reply: We revised the relevant physical interpretation to add clarity of the correlation analysis in Section 4.2 (**lines 415-420, 421-422 and 429-432**).

Specific Comments:

Eq. (1-3): Clarify the interpolation technique and its potential accumulation of drift error over time. Describe how errors in SIM data are propagated in trajectory reconstructions. Include justification for using 25 km resolution and for excluding any higher-res or recent products.

Reply: We added some text to explain the interpolation technique and the fact that potential accumulation of drift error over time is small (**lines 180-187**), and emphasized the rationale for choosing the 25-km product in the data section (**lines 137-140**).

Table/Figure 3: Add quantitative error metrics. Distance alone is insufficient, what are direction errors, turning biases, etc.? Expand comparison beyond one buoy trajectory (e.g., include MOSAiC or additional IABP floats).

Reply: Thanks, we added RMSE and Fréchet distance as metrics of quantitative error, and we revised the descriptions to emphasize that the actual comparison is over the range of buoy trajectories in Table A1 (**Section 4.1**).

Why limit the results fixed the time span between 1979-2020 instead of 1979-2024?

Reply: Since the sea ice motion data for 2024 are not yet available, our study period is now from 1979–1980 to 2022–2023.