

Reviewer 1

In this manuscript, the authors assess the performance of the long-term Antarctic sea ice motion product derived from passive microwave (PMW) observations at NSIDC using buoy observations and high-resolution SAR-derived sea ice drift data. The authors show that the PMW-derived Antarctic sea ice drift generally agrees well with both SAR and buoy observations. However, they also identify a systematic underestimation of sea ice drift speed in the PMW product, particularly in regions where sea ice concentration (SIC) is lower than 50%. The authors further suggest that the optimal interpolation procedure is likely responsible for this behavior.

Overall, I found the objectives and conclusions of this manuscript clear and easy to follow. The analyses are generally solid, and the manuscript is well organized. I enjoyed reading this paper. I recommend minor revisions before the manuscript can be accepted for publication.

- Thank you for your positive feedback. Please see our responses to your comments below. All line numbers are from the track-change version.

Major comment:

- After carefully reading the manuscript, I feel that the paper focuses more on the evaluation/validation of the NSIDC Antarctic sea ice drift product rather than a comprehensive uncertainty assessment. Therefore, I suggest revising the title so that it better reflects the actual content of the manuscript.
 - Thank you for your valuable feedback. We revise the title to “Pan-Antarctic evaluation of National Snow and Ice Data Center (NSIDC) sea ice drift product using high-resolution SAR and buoy data.”
- Scientists from EUMETSAT Ocean and Sea Ice Satellite Application Facility have also developed a widely used Antarctic sea ice drift product. It would be very helpful if the authors could discuss how the NSIDC sea ice drift product compares with the OSI SAF product, including but not limited to retrieval methodology, spatial/temporal resolution, and more importantly the relative performance against independent observations. Including such discussion would substantially improve the scientific significance and broader relevance of this manuscript.
 - Thank you for your constructive comments about the comparison between NSIDC and OSI SAF sea ice drift products. We agree that this comparison is useful, but it is out of the scope of this study. This study is focused on the pan-Antarctic evaluation of the NSIDC product using high-resolution sea ice drift across the Southern Ocean, which addresses the limited coverage of Antarctic buoys. However, the currently available OSI SAF product has a coarser resolution (62.5 km) than the NSIDC product (25 km), which implies that the OSI SAF product cannot really serve as “validation” data for the NSIDC product. Several

inter-comparison studies have been conducted by others, and this inter-comparison or validation of the OSI SAF product is out of scope for this study, as it may require too much content for another separate paper. Therefore, we would like to focus solely on the pan-Antarctic evaluation of the NSIDC product, using high-resolution SAR images and buoys.

Minor comment:

- P2 Lines 42-44, this statement is somewhat new to me. I wonder whether there are existing studies or references that support this claim.
 - It is widely known that Antarctic sea ice exhibits higher velocities and, consequently, higher deformation rates (Kwok, 2010; Kwok et al., 2017; Heil et al., 2001). These higher displacement and deformation rates have a direct and well-documented impact on PMW-based ice motion retrieval. We add these references in L44. We refer directly to Kwok et al. (2010) for more details: *“However, the quality of the data is somewhat lower than that achievable in the Arctic Ocean: the higher daily displacement and deformation rates in the Antarctic ice cover reduce the spatial coherence of image features (brightness patterns) at a faster rate and this impacts the matching schemes discussed above. It is also difficult to produce ice-drift estimates close to the ice edge where atmosphere/ocean processes modify the ice cover at much shorter timescales than the typical satellite revisit time of 1 day.”*
 - Kwok, R.: Satellite remote sensing of sea-ice thickness and kinematics: a review, *Journal of Glaciology*, 56, 1129–1140, 2010.
 - Kwok, R., Pang, S. S., and Kacimi, S.: Sea ice drift in the Southern Ocean: Regional patterns, variability, and trends, *Elementa: Science of the Anthropocene*, 5, 32, 2017.
 - Heil, P., Fowler, C., Maslanik, J. A., Emery, W. J., and Allison, I.: A comparison of East Antarctic sea-ice motion derived using drifting buoys and remote sensing, *Annals of Glaciology*, 33, 139–144, 2001.
- P12 Lines 231-233, does hypothesis (2) also contribute to the underestimation of sea ice drift speed? Please clarify this point further.
 - Yes. We clarify this further in the manuscript: *“These extensive comparisons between PMW_{raw} and SAR sea ice drift strongly suggest that the PMW-based MCC feature tracking successfully reproduces sea ice velocity without a significant intrinsic speed bias, whereas the optimal interpolation systematically introduces a negative bias (i.e., underestimation of sea ice speed) into the final gridded sea ice motion product. We propose two possible, non-exclusive reasons for the widespread underestimation of sea ice speed caused by the interpolation: (1) Smoothing effect: Optimal interpolation is designed to produce a smooth velocity field, which inherently acts to reduce the magnitude of real ice velocity,*

particularly in highly dynamic, higher-speed regions. (2) Bias at ice edge: Sea ice edges typically exhibit higher speeds than the middle of the ice pack. However, velocity at the ice edge is often estimated through interpolation of lower velocity values from the interior pack ice, leading to a substantial underestimation of the true speed near the ice edge.” (L304-312)

- P15 Lines 253, please check the wording “all seasons”, as it appears inconsistent with the earlier statement that only results from March to November are shown (P8, Lines 193–194).
 - Thank you for pointing this out. Yes, our comparison covers only March to November, so we specify “all months from March to November.” (L263)
- Since the optimal interpolation may degrade the performance of the sea ice drift product, which version of the dataset is publicly distributed and recommended for scientific research: the interpolated product or the raw PMW-derived product?
 - Both products are publicly available (<https://doi.org/10.5067/INAWUWO7QH7B>). We would recommend that users select an appropriate product depending on their purposes: (i) Since the interpolated product covers the entire Southern Ocean, the interpolated product is suitable for investigating the overall, multi-year spatiotemporal variations of sea ice velocity. The interpolated product also provides uncertainties associated with the optimal interpolation, so users must account for these uncertainties in their scientific analysis. (ii) If a user wants to focus on accurate ice velocity values, without an estimation bias, the raw sea ice motion product is recommended. We add the final remark in the conclusion section: “*Since the NSIDC sea ice velocity product provides uncertainty estimates associated with the optimal interpolation, users of this product must account for these uncertainties, particularly the underestimation in interpolated areas, in their scientific analyses.*” (L353-355)
- Figure 2, it may be clearer to show only the buoy locations that were actually used for the validation analysis.
 - We revise Figure 2 to show only buoy locations used for the analysis.

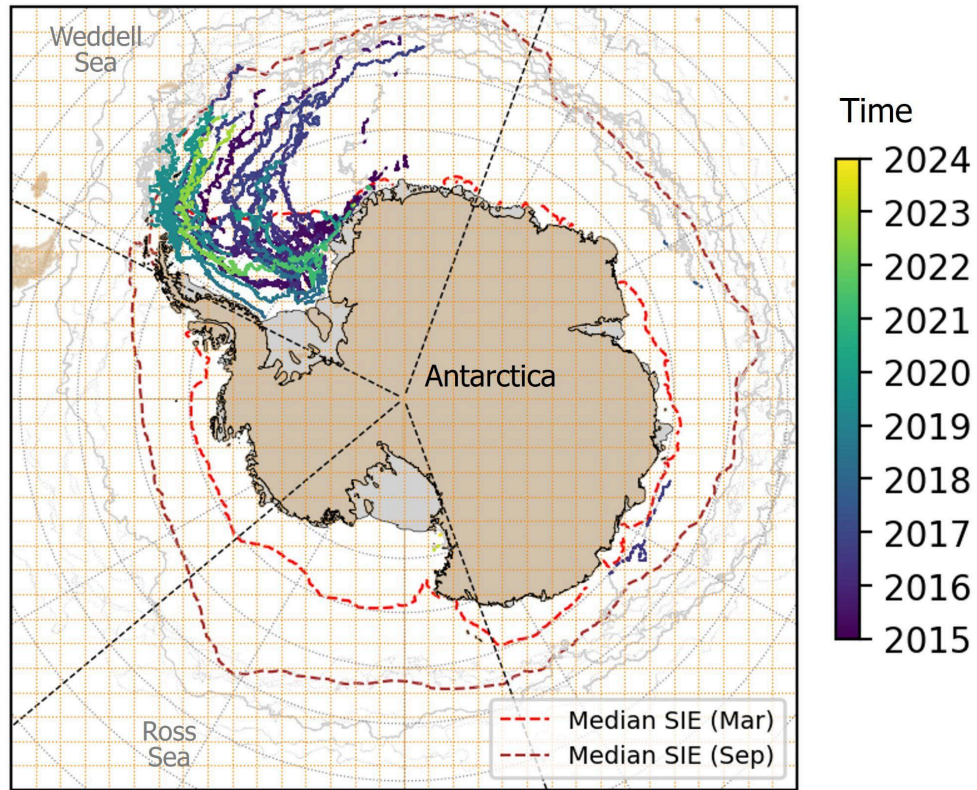


Figure 2. Distribution of Antarctic drifting buoys from 2015 to 2023. The buoys inside sea ice cover (SIC > 15 %) are colorized by the times of the buoy locations, whereas the buoys outside sea ice cover are displayed in gray points. The red dashed line indicates the median March sea ice extent (SIE) in 1981-2010, and the brown dashed line indicates the median September SIE in 1981-2010. While most of the buoys are deployed in the Weddell Sea, these buoys rarely pass through the sea ice area in other regions. Orange dashed lines show the 250 km × 250 km super-grid for Sentinel-1 data collection.

- Figure 9, I noticed that even without interpolation, the PMW_raw sea ice drift still shows an underestimation under low-SIC conditions. Does this imply that factors other than interpolation also contribute to the bias? If so, please discuss the possible mechanisms.
 - Thank you for your valuable comment. We agree that this issue should be discussed in more detail. We add a discussion: *“In low SIC areas, the PMW brightness temperature signal becomes increasingly contaminated by open-water emission, reducing the contrast and spatial coherence and making cross-correlation tracking challenging for coarse-resolution PMW images (Kwok, 2010).”* (L292-294)

Reviewer 2

This paper details a methodology for use of SAR sea-ice drift vectors for validation of PMW sea-ice drift, allowing for full coverage validation of the Antarctic where in-situ data is only available in limited areas, and rigorously analyses the robustness of this methodology. In addition there is an excellent analysis of the sources of error in the NSIDC Polar Pathfinder sea-ice drift product, with recommendations for future improvement. The techniques and analysis in this paper will be a great reference to inform future development for not only the NSIDC product but for other products as well. I recommend publication of this paper with minor changes.

- Thank you for your time and positive feedback. Please see our responses to your comments below. All line numbers are from the track-change version.

Major comments:

- Section 2.4. Once spatially sampled, the PMW and SAR ice drift vectors are representing the average ice drift within sub-regions of radius 25 km, whereas the buoy vectors represent point-like sub-regions. This may be worth a sentence or two of discussion, since the SAR and buoy ground truths represent different spatial scales.
 - Thank you for pointing this out. We add the following sentences, along with some previous studies that mentioned this issue: *“We note that both SAR and PMW ice drift vectors represent the average ice drift within a large area of radius 25 km, whereas the buoy vectors represent point-like ice drift at deployed ice floes. This scale mismatch, alongside spatial and temporal collocation errors, introduces a representativeness error that may partly explain the observed discrepancies between satellite-derived and buoy-measured ice drift (Sumata et al., 2014; Lavergne et al., 2010). Since this representativeness error is difficult to fully separate from intrinsic retrieval errors, the validation statistics reported in this study likely contain contributions from both error sources.”* (L190-195)
 - Sumata, H., Lavergne, T., Girard-Ardhuin, F., Kimura, N., Tschudi, M. A., Kauker, F., Karcher, M., and Gerdes, R.: An intercomparison of Arctic ice drift products to deduce uncertainty estimates, *Journal of Geophysical Research: Oceans*, 119, 4887–4921, 2014.
 - Lavergne, T., Eastwood, S., Teffah, Z., Schyberg, H., and Breivik, L.-A.: Sea ice motion from low-resolution satellite sensors: An alternative method and its validation in the Arctic, *Journal of Geophysical Research: Oceans*, 115, 1–14, 2010.
- Given that most of the larger deviations of the PMW vectors from buoy vectors come from areas of low SIC, and that SAR vectors have only been compared to the buoy vectors in regions of SIC > 85% while the PMW vectors have been taken from regions of

SIC > 15%, I would really appreciate seeing statistics (extra figures might inflate the paper too much) for PMW vectors where SIC > 85%, so there is a more direct comparison between the PMW-buoy and SAR-buoy validations.

- Thank you for your insightful and constructive comment. We agree that it is helpful to show additional statistics for SIC > 85 %. In sections 3.2 and 4.1, we add the statistics of PMW v. buoy comparisons for SIC > 85 % areas.
- “For SIC > 85 %, the negative bias is $\sim 1.97 \text{ km d}^{-1}$.” (L248)
- “For where SIC > 85 %, PMW_{raw} exhibits only $\sim 0.6 \text{ km d}^{-1}$ of speed bias against buoy measurements.” (L283-284)

Minor comments:

- A table summarising the statistical values from the different validations could be very helpful to the reader, rather than needing to find the individual values from within the text to compare.
- Thank you for your comments. We add a table summarizing the results (Table 1).

Table 1. Summary of sea ice velocity comparisons (angle and speed) for different dataset pairs.

Dataset pairs	Effective regions	Bias in angle (degrees)	Bias in speed (km d^{-1})
SAR-buoy	Only in the Weddell Sea	-5.9 ± 38.6	0.1 ± 2.9
PMW-buoy	Mostly in the Weddell Sea	3.9 ± 62.5	-3.2 ± 6.8
PMW-SAR	Pan-Antarctic	4.2 ± 32.6	-1.0 ± 2.4
PMW_{raw} -buoy	Mostly in the Weddell Sea	4.6 ± 58.7	0.0 ± 5.8
PMW_{raw} -SAR	Pan-Antarctic	3.7 ± 35.5	0.1 ± 2.8

- L50-55, Just as a point of interest, SH PMW ice drift has also been validated vs buoys in the OSI SAF validation reports for the near-real time sea-ice drift product (<https://osi-saf.eumetsat.int/products/osi-405-d>, doi:10.15770/EUM_SAF_OSI_NRT_2007) and sea-ice drift climate data record (<https://osi-saf.eumetsat.int/products/osi-455>, doi:10.15770/EUM_SAF_OSI_0012).
- Thank you for your information. We add some explanations about these technical reports: “The PMW sea ice drift products from the Ocean and Sea Ice Satellite Application Facility (OSI SAF) have also been validated against buoy data in the Southern Ocean (Lavergne and Down, 2022, 2024).” (L59-61)
- L137 Please define the FT abbreviation on first use.”
- FT stands for feature tracking. We replace FT with feature tracking. (L141)
- L142. Is it worth explaining/justifying why you omit SAR ice vectors above 40 km d^{-1} - is this dependent on your constraint that SAR data is only used for SIC > 85%?
- We used 40 km/day because it is the upper limit of the search window for SAR sea ice tracking (Muckenhuber et al., 2016; Korosov et al., 2017). We add these references. (L146)

- Muckenhuber, S., Korosov, A. A., and Sandven, S.: Open-source feature-tracking algorithm for sea ice drift retrieval from Sentinel-1 SAR imagery, *The Cryosphere*, 10, 913–925, 2016.
- Korosov, A. A. and Rampal, P.: A Combination of Feature Tracking and Pattern Matching with Optimal Parametrization for Sea Ice Drift Retrieval from SAR Data, *Remote Sensing*, 9, 2017.
- Figure 1 could perhaps have larger individual panels, as some of the magenta arrows do not show up well at the current resolution.
 - We enlarged the individual panels in Figure 1 to clearly show the magenta arrows.

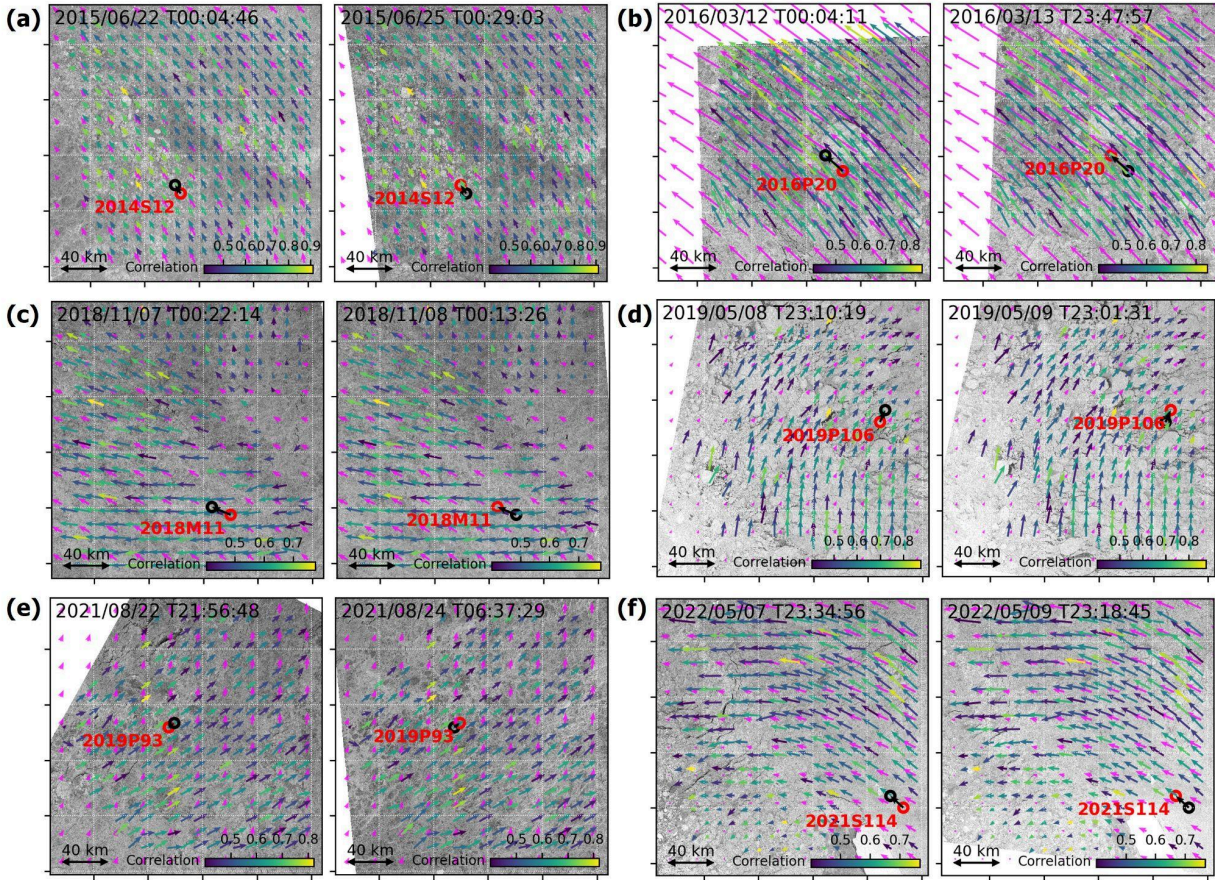


Figure 1. Derivation of sea ice drift from SAR images nearby (a) buoy 2014S12 from 22 June 2015 to 25 June 2015, (b) buoy 2016P20 from 12 March 2016 to 13 March 2016, (c) buoy 2018M11 from 7 November 2018 to 8 November 2018, (d) buoy 2019P106 from 8 May 2019 to 9 May 2019, (e) buoy 2019P93 from 22 August 2021 to 24 August 2021, and (f) buoy 2021S114 from 7 May 2022 to 9 May 2022. Colored arrows indicate SAR-derived sea ice drift, with colors representing the correlation of feature tracking (see bottom-right color bar). Magenta arrows indicate PMW sea ice drift, and black arrows indicate the movements of buoys between the SAR acquisition times; red circles denote the location of the buoy at each image, and buoy IDs are annotated in red. The lengths of the vectors correspond to the actual sea ice displacement.

- Probably too complicated, but it would have been nice to plot figure 9a with the data from figure 5a as a background, to be able to compare easily.
 - Thank you for your suggestion. Plotting Figure 9a with Figure 5a as a background would make the comparison straightforward in a single figure, but we are concerned that this can reduce the legibility of the figure. Hence, we prefer to leave the current figure as is.
- Figure 11b label should probably specify PMW_raw rather than PMW.
 - We specify “PMW_{raw}” in Figure 11, and “PMW” in Figure 7.