We wish to thank the reviewers for their very helpful comments. In particular, we thank Reviewer #2 who has tirelessly went through the paper in fine detail and offered many good suggestions, both on improvements to the manuscript and for future improvements to the products.

The most significant changes we made are (1) adding validation of the source motion estimates via comparison with the buoy estimates, and (2) adding further details to the CRREL buoy comparison. In the interest of keeping the main manuscript focused and reasonably concise, we have added a supplement that contains this material. We also moved the rest of the CRREL buoy analysis (Section 2.4 in the previous draft) into the supplement. This keeps that material in one place, which we feel will make it easier for readers to follow both the main text and the supplement material.

We have responded to all of the comments noted by the reviewers and have made all the changes that are feasible to address the reviewers' concerns. Our responses to each comment are inline below.

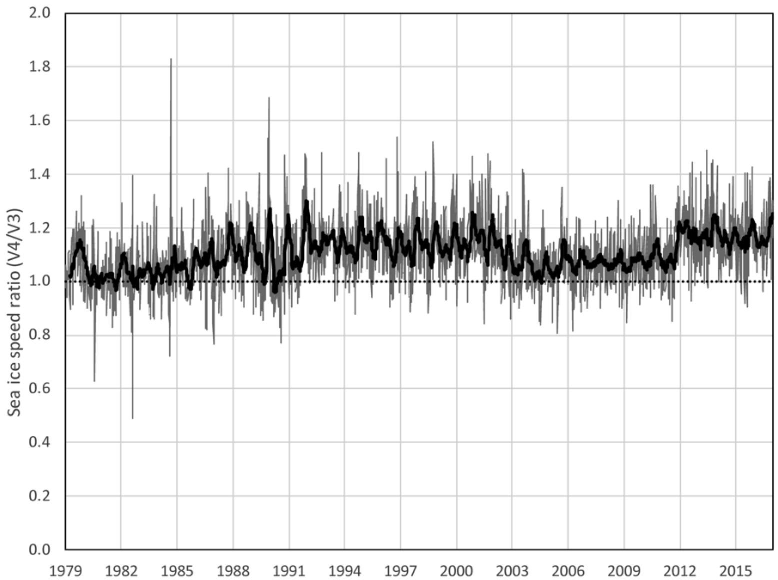
REVIEWER #1

The authors have significantly improved the manuscript, added validation results and evaluation of uncertainties. It would be nice to address only two minor comments.

1. The seasonal variability in the difference between V3 and V4 is attributed to the higher ice drift speeds in summer (on page 19, line 3). Does that mean that the difference between the products is rather multiplicative than additive? Please illustrate that by an extra plot showing relative difference (V4/V3) in addition to the absolute difference (V4 - V3, on Fig. 7). If the factor is nearly constant in various seasons, then it is indeed mostly due to changes in temporal sampling. Otherwise additional explanations are needed.

We plotted V4/V3 (see below) and seasonality is still evident. So, this means that the difference is not strictly multiplicative. However, the effect is likely still related to seasonality. An illustrative example, V3 has winter motions of 1 cm/s and summer motions of 3 cm/s. If it is multiplicative, then if V4 winter motion is 2 cm/s, the summer motion would be 6 cm/s – i.e., the ratio of V4/V3 would be 2 for both summer and winter while the difference would be 1 cm/s in winter and 5 cm/s in summer. But, if instead V4 summer motion was 9 cm/s, then the summer ratio would be 3 instead of two. The difference would be 1 cm/s in winter and 8 cm/s in summer.

Thus, we feel it is still primarily a seasonal effect of higher speeds during summer, but it is not strictly multiplicative. Another factor that we didn't originally include is the fact that there are fewer passive microwave motions during summer because surface melt limits correlation between images. We've added some text to discuss this more, including the lower number of passive microwave vectors during summer.



2. The statement in Conclusions (page 21, line 16) "these artifacts did not substantially affect the weekly sea ice motion or age fields" seem to contradict the statement in Section 4 (on page 19, line 12) "... largest effect of the version change for ice age is ... the amount of multi-year ice in the early part of the record...". Consider rewriting conclusions.

We edited the Conclusion to be consistent with Section 4.

REVIEWER #2

I am referring to my first review of this manuscript for the summary of the paper.

I begin with a reply to a few points from the rebuttal letter to my first review. Obviously, you do not need to comment to these but are of course invited to do so.

General Concerns from 1st review:

GC1: No systematic evaluation of the products has been undertaken - neither for version 3 nor for version 4 of the sea-ice motion product. Also, the associated newest sea-ice age data set is not evaluated. In your case, it is not sufficient to just compare version 3 and version 4 of the product because a systematic, detailed evaluation of version 3 products is missing in the scientific literature. There is hence no benchmark against which this new version 4 can be quantitatively referenced.

Section 2.2 does not provide new results. There is no indication of a true sea-ice motion retrieval uncertainty provided along with the product, like is done for sea-ice concentration and thickness data sets. You do not present results of an evaluation of the newly derived components of the sea-ice motion entering the gridded product as well as the gridded product.

Reply by the authors:

A) There has been significant validation done on the basic algorithm, particularly the MCC

approach (Kwok et al., 1998; Kwok, 2008; Meier et al., 2000), as well as on a previous version of the specific product (Sumata et al., 2014; Sumata et al., 2015).
B) Uncertainty estimates are included in the daily combined motions, based on the optimal interpolation and the relative weights of the source data. We've added mention of this to the text.
C) Sea ice age is difficult to directly validate as there is not validation with sufficient accuracy and coverage. We have added a reference (Lee et al., 2017) to an intercomparison study that shows good overall agreement between the ice age data and other ice type/age products.

My comment to the authors' reply:
To A): I can agree to that. However, this is version 4 and you compare version 4 to version 3. Version 3 has not been assessed even though there have been substantial changes between version 2 and version 3, e.g. in the selection of which passive microwave data are used (see Haumann et al., 2016). Particularly when it comes to the long-term stability and the consistency across different satellite sensor products used - which is a mandatory element of product maturity for such a long-term and important data set as the one you are presenting here, it seems sub-optimal to refer to evaluation activities which only target the basic algorithms. One could have expected a considerable move forward here. I therefore appreciate that you now carried out an evaluation of the combined Arctic product with CRREL ice-mass balance buoy data. This is a good start.

We retitled Section 2.2 to be clear that the discussion is a review of general uncertainties from previous studies.

To B) I am aware of these uncertainty estimates. These are very much based on the merging process of the data. The mentioned relative weights are only valid / can only be computed where there is a buoy for comparison - plus some correlation length scale around these - leaving the majority of the investigated region void of (detailed / accurate) quality information; this applies in particular to the Antarctic, doesn't it?
What about the uncertainties of the individual products, i.e. the AVHRR ice motion vectors or the AMSR-E ice motion vectors?

To reviewer #4, who stated: "Page 8, line 1: The error for each drift product (and used to calculate C) should be included in a Table.", you replied: "These values were calculated early in the development of the original product. There is not a table of errors for each drift product."
"early in the development of the original product" is exactly what I am referring to. It appears there was very limited effort to re-evaluate the newer original data sets input into the merged product. If we'd compare this to the situation in the sea-ice concentration community then this would mean that this community would try to sell a new improved sea-ice concentration data set - referring to the accuracy of the SMMR sea-ice concentration data sets. --> See my general comment GC1 to the revised manuscript.

In response to your suggestion, we have added a supplement to provide a brief analysis of the source data products. We compared the source motion estimates with buoys for selected periods. That is all that is feasible at this time. We do fully agree that a complete reassessment and uncertainty evaluation would be very useful. We hope to do that, pending resources. We hope *that the short evaluation that we've added will suffice for now. Our results agree generally well with other comparisons discussed in Section 2.2*

To C) Certainly I agree that it is challenging to get a reasonable set of evaluation data for this purpose. However, I mean, your group has been THE group to build and maintain this data set for over a decade now and it has received great attention. To my opinion it would have been more than timely to come up with some attempts and advanced ideas to evaluate this data set - at the latest after the publication of Korosov et al. (2018). Therefore, I am inclined to rate the efforts carried out into this direction as not sufficient. While the reference added (Lee et al., 2017) mitigates this impression a bit, it cannot replace a decent evaluation and/or inter-comparison study which underlines the improvement of version 4 over version 3 and underpins the credibility of this data set.

We appreciate the reviewer's assessment that we have been "THE group" to build and maintain this data set. The reviewer's suggestions to improve are greatly appreciated. They are on our list to do for a future version when we have the resources to do so. This paper focused on documenting Version 4 and, to the extent possible, documenting the basic methodology of the previous version. A primary motivation was to address the motion artifact identified by Szanyi and correct other known issues. Version 4 is not meant to be a comprehensive reassessment of the product because there have not been resources to do so.

GC2: The reader and data set user is informed about user statistics, the importance of the two data sets, some selected bits of the history of the retrievals, and a relatively unspecific description of the changes made to the methods. This is, however, potentially not what a reader of this paper and user of this data set would have expected for the following reason: There is no specific paper in which the various retrieval processes, their uncertainties, the caveats of the different spatio-temporal resolution of the input data sets, a detailed description of the merging (optimal interpolation) approach and its uncertainties have been published so that the full package of detailed, high-quality information is visible at a glance. The retrieval, the input data, the pre-processing steps all these are not transparently described. In other words: A benchmark reference paper containing all bits and pieces is missing so far.

Reply by the authors:
Such information is provided is the User Guide for the product, provided by NSIDC. We chose not to include this information in the manuscript in the interest of brevity. We've added reference to the NSIDC User Guide. We agree that a peer-reviewed document on the original development of the product would have been useful. However, the original product developer chose not to submit such a paper. As such, our purpose with this manuscript is not to try to recreate a history of which we do not know all of the details, but to document the changes and improvements the current team has made to the newest product as well as giving an overall summary of the processing that is described in the NSIDC User Guide.

My comment to the authors' reply:
I do understand the challenge behind trying to unwrap the bits and pieces of the original (versions 1 and 2) processing of this data set. I would have hoped that you would be able to undertake this tedious work - because nobody else can do it; you are closest to those people and

institutions which developed the data set. I see that with my review I wasn't able to convince you that for a journal such as "The Cryosphere" it pays back to double efforts to accept this challenge. I assume that this has been a question of funding and therefore need to leave this issue where it is. It is a pity. As I stated in my original review (actually you never received the long version which made me to reject the previous version of your manuscript) it is very tedious for a data user to climb down into all the web pages that are linked from the NSIDC User Guide and it is in addition relatively frustrating that the information one searches for is partly quite limited or simply not available.
Please also see my GC1 to the revised manuscript in this context.

As stated above, we agree with the reviewer that this work should be done and we do hope to do it in the future when/if we procure funding. Under current funding, we were somewhat limited on what we could accomplish. The goal of this paper was to document the changes for V4, address the issue noted by Szanyi et al. (2016), and since the product had never been documented in a peer-reviewed article, we wish to provide at least some more background than what has been previously published.

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Now comes the review of the revised version of the manuscript

Following up with the authors' reply to my general concerns formulated in my review of the first version of this manuscript, and with the comments of the other reviewers, I am convinced that the manuscript will become acceptable after major revisions.

These revisions should cover the general comments GC1 through GC3 (see below).

While the remaining two general comments (GC4 and GC5) are just ideas to think about, I ask you to consider the specific comments. Some of these - to my opinion - require attention for an adequate understanding of your paper and for having it placed in "The Cryosphere". By following the suggestion I formulate in GC1 you might be able to solve some of the specific comments.

Finally, I found a good number of typos and formulations which require attention which I listed separately in the last part of my review; here you will also find suggestions related to the figures.

General comments:
GC1 refers to the insufficient description of production / evaluation of the "old" basic retrieval of the ice motion. I can understand that it might be too time consuming to dig into all the old documents, web pages, reports, folders, whatsoever left behind by the scientist team responsible for the creation of versions 1 through 3 of the ice motion product. I understand that you don't want to do it and that you don't receive funding for it. Still, this information is mandatory for a reader and/or user to fully understand what this product is about, what its limitations are, and where substantial potential for improvement exists. This would be of high value for other scientists to take over and to develop alternative products.

Since you don't want to write a "benchmark paper" as I suggested in my previous review [even though that one would be good for The Cryosphere, while this manuscript here might be more suitable for Earth System Science Data], I suggest that you provide list of the unknowns, open parameters or assumptions, and original evaluation activities in form of a few tables and/or illustrations put into an appendix to this paper.
Example 1: You cannot find out how C and D in Eq. 1 were computed exactly? What the values are? What the correlation lengths are? Mention this explicitly in one of the tables.

We did not think that a table would adequately address the reviewer's concerns. Instead, we have added text where appropriate to provide more details on the original processing and further clarify what the unknowns are.

We have added further information on the C and D values in Equation 1. And we note that the original derivation is not known and that values may not be optimal for the data quality.

Example 2: You cannot find out whether the 4X over-sampling is carried out for all 37 GHz channel data of all three instruments SMMR/SSMI/SSMIS? Mention this explicitly in one of the tables.

The 4X oversampling is done for satellite estimates and is noted in the text.

Example 3: Nobody has yet investigated quantitatively the impact of the switching between 37 GHz and near-90 GHz data for SSMI, AMSR-E, SSMIS data on the obtained ice motion? Fine. Mention this in one of the tables (this is something noted by Haumann et al. 2016 for version 2 of the product, creating a big mess in their search for a credible time series of the ice motion for the Antarctic).

We have added mention of this in a couple of places. First, in Section 2.1 on the gridded satellite motions, we have added a paragraph that emphasizes the differences in the satellite sources and their potential impact on the retrieved motions. We also added to Section 2.3 on the interpolation that the selection of the C values is sub-optimal. And we added a Supplement with a short evaluation of the uncertainty of the source motions where we discuss their differences and how those differences point to the impact of switching between different sources and how the product would be improved with improved weighting.

Example 4: You cannot find out whether the input PMW ice motion vectors have been evaluated after introducing the 4X oversampling? Mention this in one of the tables.

4X is done for all satellite sources, as noted on Page 6, line 20 of the original revision. The 4X resampling has been since the beginning of the product and was not changed for Version 4 (or Versions 2 and 3).

Example 5: The attempts to evaluate ice motions in the Antarctic are unknown / limited to the following (...) studies? Mention this in one of the tables.

We have added a paragraph at the end of Section 2.2 to specifically discuss the limited knowledge of Antarctic motions and the lack of evaluation/validation.

Examples 6: What are the evaluation studies specifically targeting version 3 of the ice motion product? List the references / or NSIDC reports.

The changes from Version 2 to Version 3 were minor, as noted in Table 1. The most significant change was the removal of erroneous buoys estimates and some poor-quality AVHRR motion fields. Correcting these fields was clearly an improvement to the product. The two other changes - using the NSIDC ice mask and the GDAL libraries – improved provenance and conformed to modern standards, but had almost no effect on the output fields. After comparisons between Version 2 and Version 3 showed that the effect of these changes was very small and further documentation of differences was deemed to not be necessary.

I strongly recommend to be as transparent as possible and take over the responsibility to document the status of this unique long-term ice motion product as best as possible.

We agree. This paper is an attempt toward being more transparent. It's not perfect because of the limitations in knowledge of original processing, but we feel it is an improvement in transparency. And as stated earlier, the main focus here is for the first time have a reference that documents to the best of our ability the current state of the product.

GC2 is referring to section 2: When you write about "velocity components" in sections 2.1 and 2.2: do you refer to the meteorological convention, i.e. component u being defined positive from west to east and component v being defined positive from south to north? I am asking because I noted that versions 3, 4 and 4.1 of the ice motion product contain u- and v-velocity components in the direction of the EASE grid used, i.e. a positive u-component at 0degEast is a true west-to-east ice motion while at 180degEast it is an ice motion into the opposite direction. You might want to clarify this at the beginning of your paper.
I note that in section 2.3 you note that the motion is relative to the EASE grid for the gridded product.

Yes, all vectors are retrieved and provided as u and v velocity components based on the EASE grid. We've added a sentence in Section 2.1 to make this clear.

I note further that in section 2.4. it is not clear whether you transferred the CRREL buoy ice motion to the EASE grid notation of u and v. By the same token, users being familiar with the meteorological notion of motion might have difficulties to translate your uncertainties into their understanding of how air, water and ice movement is described, i.e. positive west --> east; positive south --> north.

The CRREL buoys were put on the EASE grid for the comparisons and they were done on the u- and v-components relative to the EASE grid. We've added a sentence in Section 2.4 to clarify this.

GC3: Information about Antarctic sea-ice motion is VERY limited. You could at least have added similar plots like Fig. 5, Fig. 7 and Fig. 8 to illustrate that you also provide ice motion for the Southern Ocean and how this looks like in comparison to the Arctic.

Yes, it will be a challenge to discuss the jumps in the time-series between the different satellite data sources. To my opinion, because your paper is about a bi-polar (or global) data set you have to show these and you have to discuss these and you have to clearly point out the limitations to the users. I rate this a mandatory element which is still missing in the revised version of the manuscript. Alternative: You remove ALL information about the Antarctic.

Since the Antarctic motions are part of the product, we feel it is important to include them in the manuscript. But we agree that in the previous version of the manuscript, we gave them short shrift. We have added Antarctic images for Figures 5, 7, and 8. We have also added a paragraph at the end of Section 2.2 noting that most (all?) motion validation has been done in the Arctic because of the lack of buoys in the Antarctic. We note that the Antarctic motions are of lower confidence level and users should be aware of these caveats when using the product.

GC4: What would you say is a typical uncertainty estimate for the ice age (applies to Figs. 9-11 and their interpretation)? Would it be fair to say that ice-age fractions can be determined as accurate as 50 000 sqkm? ... or rather 100 000 sqkm? I would find such an estimate very useful in the context of the interpretation whether recent changes in ice age fraction are significant or within the noise created by the method.

We agree that this is an interesting question and certainly one worth further consideration. As the reviewer is likely aware, it is difficult to find a quantitative validation source of "truth" for comparison. One can compare the age product with other ice age/type fields, at least for FYI/MYI discrimination. But we feel this is beyond the scope of this paper. It is something we hope to look into in the future.

GC5: This comment applies to Page 20, Lines 13-25. In the context of the various data sources with different resolutions, different spatiotemporal coverage, and different relative weights used for the combined ice-motion product which is subsequently used for the derivation of the ice age: How much, to your opinion, do these differences have an impact on the obtained trends in ice age fractions?

This is an interesting question as well. Our guess is that the effect is likely small. While the daily motion error characteristics of the individual various sources can be quite different, the spatial averaging from the optimal interpolation smooths out these differences. Certainly, different weighting will have some effect, but the number and proximity of observations are also key. Then, using a weekly average motion to derive age ameliorates the different levels of variability seen in daily motions. However, we don't doubt that sources have some effect. One significant change in Version 4 is the weighting scheme for combining the sources (15 highest weighed vs. 15 closest) and the effect on the daily motion fields is quite apparent in terms of the fall-off of the buoy influence (Figure 3). But the effect on the overall trend in ice age is not that large. So, this indicates that the age field and changes over the long-term are relatively insensitive to the specific combination of sources and their weightings. It would be interesting to look at age trends from motion fields derived from a single source (e.g., passive microwave vs. winds) and *see how the resulting age field differs. This is beyond the scope of this paper, but it is something that we would like to look into further. We thank the reviewer this idea.*

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Specific comments:
Page 3, lines 1-6:
- I am wondering whether there isn't knowledge about the relationship between ice age and thickness from earlier studies, i.e. before the NSIDC sea-ice age product era. I am sure there is. What about the book by Untersteiner for instance? Please add a respective reference to the citation of your own work.

Indeed there is! The Maykut chapter in the Untersteiner book shows this, as do papers by Tucker et al., 2001 and Yu et al., 2004. We have added these references.

Just a comment: It might be true that sea-ice age provides additional information - compared to maps of the multiyear ice cover - about when in a certain region sea ice will melt out during summer. But has this been proven yet in the 10+ years the ice age data set has been out? One could imagine that an accurate first-year ice versus multiyear ice discrimination is sufficient here and that it does not really play a role whether the sea ice is 2, 3, 5 or more years old when it comes to melting. Isn't the main interesting information given by the sea-ice age data set that we have a measure of how long sea ice once formed survives as a function of formation location and ice movement?

This is a good point. As MYI ages, the thickness increases less each year, so there is less and less difference. We added some text in this section to note this.

Page 3, paragraph starting in Line 22: This is a good start.
- Please add the work of Sumata et al. (2014, 2015) here because it gives a good overview about existing products and how these compare.

Added.

- Please add the work of Kwok (2008) about summer-time sea-ice motion estimation using near 19 GHz data. It is important for a reader / data user to know that there are alternatives to using NCEP winds based drift estimates during summer.

We added Kwok (2008) to Section 2.2 where we feel it fits better because that is where we specifically discuss summer motion retrievals.

- Please add a few sentences about the various attempts to use SAR data for deriving sea-ice motion. This is important for a reader / data user who is interested in small-scale solutions. It is further important for you yourself as this would underpin how valuable your data set is in terms of spatiotemporal coverage.

We have added couple sentences in the introduction section on SAR along with references.

Page 6, Lines 16-18:
It appears sub-optimal to first state that with 25 km grid resolution one can only estimate the velocity field to the nearest 25 km / day for each motion component (see lines 14-15) and then here state your product obtains useful daily motions by using the described over-sampling. The point I wish to make here is that the native resolution of the 37 GHz channels of SMMR, SSM/I and SSMIS, as given by the footprint sizes, is coarser than the grid resolution used and, in addition, these footprints are only a good approximation of the reality because of the antenna sidelobes. So what you sell to the user here is: brightness temperature observed at 37 GHz, gridded as a daily mean value into a 25 km grid, show features distinct enough that you can move over these 25 km grid cells with increments of 6.25 km. I am wondering how you assessed the improvement in accuracy stated on Page 6, Line 19. Is there a chance to include the respective results in this paper, e.g. as supplementary material / appendix? Possibly the improvement in accuracy is a function of the frequency because the native resolution is much finer for the near-90 GHz channels of SSM/I and SSMIS.

We have added that the effective resolution (i.e., the sensor footprint) is coarser than the gridded resolution. In terms of the effect of oversampling, as noted in the text, during initial development of the product many years ago, 4X was chosen based on improved performance relative to computational expense. Since then 4X has always been used for all satellite-derived estimates. While it would be interesting to compare motions with other oversampling it is beyond the scope of this paper. The 4X oversampling is effectively a part of the basic algorithm and is thus presented as-is.

- Another over-arching question to this oversampling: For brightness temperatures of the near 37 GHz channels of SMMR and SSM/I and SSMIS you apply 4X oversampling. How about for the 12.5 km grid resolution near-90 GHz data of SSM/I and SSMIS? And: How about over-sampling and its application to AMSR-E data at 12.5 km resolution? It appears that the description of the over-sampling procedure is not yet complete; other scientists willing to repeat your steps would not be able to do so because of a lack of information.

As noted in our responses above, the 4X oversampling is applied to all satellite sources, as was noted in the manuscript text.

- How does this over-sampling method compare to the continuous MCC suggested by Lavergne et al. (2010)? It is worth commenting and discussing this issue in this paper because the over-sampling seems to be something introduced relatively recently (?); it deserves to be discussed in the light of alternative choices.

We have added a note about CMCC as an alternative approach presented in Lavergne et al. (2010).

Page 7, Lines 16-23:
- Can you comment on minimum correlation values used by other products? How about the Girard-Ardhuin and Ezraty (2012) products?

We added in the values used by Girard-Ardhuin and Ezraty (2012), Kwok et al. (1998), and Lavergne et al. (2010).

- "Various thresholds ... original development of the product ... qualitatively determined ..." --> This is a relatively vague information and leads to many questions: Was this same threshold applied to all satellite data sets described so far? Has the choice of this threshold been revisited in the meantime? Based on which data set(s) this threshold was selected (when?) by the mentioned qualitative determination? Is there a paper or two to which you can simply refer to which illustrate this determination?

Yes, it was applied to all of the satellite-derived products; we added text to make this clear. No, the threshold has not been revisited. It was determined early in the development of the MCC method and has not been changed in the product. We note that the choice is subjective, but that it is within the range of other MCC and related implementations. We added two early references that discuss the selection of the 0.4 value.

- The description of the neighborhood filter should be precise. Neither is it clear how this is done technically (and at which grid resolution). Nor is quantified what is meant by "similar" ... direction? magnitude? How large a difference can be before the vector is considered to be spurious?

We added more detail here to specify the quantification of the required similarity between vectors.

Page 8: Lines 1-2: "Another change" --> What kind of a change? Please be more specific. If I understood you correctly then this is a version 4 change - so there is no excuse to not detail what apparently has been done recently by you (and not by the other scientists which developed version 1-2 (3)) of the product. Please note: Without referring to figure 4 the information about the apparent improvement by this post-processing step is completely hanging in the air.

We've added details to explain the change in filtering between Versions 3 and 4. We also added some text to Section 2.3 on the effect of this filtering on the combined motion fields, which Figure 4 is relating to.

Page 8, Lines 20/21: "combined motion fields" --> How about the retrieval success of satellite derived ice motion during summer? Aren't during summer these "combined motion fields" only based on buoy motion and NCEP/NCAR winds? Please be more specific in your description. Perhaps you adopted the method of Kwok and use the 19 GHz channels now as well?

This section deals with reanalysis winds, so further discussion of the combined fields does not fit here. Therefore, we have added text to Section 2.2 noting the issues of summer retrievals. We also make clear there that PM motions are derived through the summer even though they have higher errors; there are also much fewer valid vectors during summer. We also reference Kwok's use of the 19 GHz channels from AMSR-E.

Page 12, lines 11-24:

I note that the description of how C and D are found is vague. Nobody could re-do this analysis. It is not clear - after your previous statements about the influence spatial resolution appears to have on precision (or accuracy) - why C is set to a constant value when you are operating with individual ice motion resolutions between ~25 km (using SMMR/SSMI/SSMIS 37 GHz), 12.5 km (same but using near-90 GHz or AMSR-E near-37 GHz), 6.25 km (AMSR-E 89 GHz) or 4 km AVHRR. Please try to be more specific in your description.

We've added details to the descriptions of C and D. We note that a constant C value for all of the satellite-sources is sub-optimal. This is certainly something that can be improved for a future version. But as this paper describes Version 4 where these values were not change

Also, later on you are referring to the improved interpolation used in version 4, pointing out that the buoy weight drops to zero (e.g. Page 20, Line 2) at a certain distance to the buoy. However, it is not clear what this distance is, whether we speak about 50 km, 500 km, 2000 km of these, presumably, correlation lengths. It is not clear how these were calculated and whether and how much these differ between the single products and input data used as input for the merged product.

We have added the value of D. We also edited the text on the buoy weight dropping to zero as that was not correct. The buoy weight doesn't necessarily drop to zero. Either the buoy distance falls outside of the range (D) of a given point (Version 3) or the weight falls below the top 15 weights of observations surrounding a given point (Version 4). In other words, the buoy weight doesn't drop to zero, rather buoy estimate falls outside of the criteria for inclusion at a given point.

Page 13, Lines 5-9:
I strongly recommend to provide more details here. While your Figure 3 illustrates nicely the effect of this amendment from version 3 to version 4 what is missing is information about the distance within which these 15 highest-weighted ice motion vectors are selected. I assume it has something to do with the correlation length scales (please provide examples of these). If not, then one could provocatively say that at any point within the Arctic Ocean the gridded ice motion product is solely determined by buoy motions if at least 15 buoys are reporting - because, as I understand your averaging with C=0.95, these 15 buoys would have the highest weight and would be used no matter how far away they are from the grid cell considered.

We've added text to clarify this in the text. It is possible that 15 buoys may be the 15 highest weighted if the buoys are close enough to the interpolated point. However, as Equation 1 indicates, the weight falls off exponentially with distance. So, buoys that are farther away will be less weighted than nearer wind or satellite estimates and they will fall out of the "top 15". Thus, it is not true that buoys will always be included no matter how far away they are.

Page 14, Lines 18-27:
- Please add information whether you used the daily or the weekly gridded product.

Daily. This is added to the text that has been moved to the supplement.

- Please add the fraction of discarded CRREL buoy motion estimates; I assume it is very small.

We have added this number to the supplement. Yes, it is small.

- Please provide a map of the tracks of these buoys for illustration. In light of the next paragraph you should highlight the track the year 2015 (unless you color code them anyways and unless you decide to use all years instead of just one).

We've added a map all of the buoy tracks for 2015 in the supplement, which is the focus year for the wind-sensitivity study and also the year with the most buoy observations. We feel adding other years would unnecessarily clutter the map.

- Please provide information about the processing steps. The combined gridded ice motion product has u- and v-component of the ice motion aligned with the EASE grid. How about the CRREL buoy data? How did you compute the u- and v-components of the CRREL buoy motion in the EASE grid? This description should also include a notion about how many CRREL buoy position observations of one day form one daily estimate.

We've added these details in the supplement.

- Please describe in detail how you compared the data and hence how you ended up with the numbers shown in Table 3, i.e. did you compare absolute values or the "native" positive and negative values? I assume you did the latter. Did you also compare the direction and the absolute value of the ice motion vectors?

It was the native positive and negative values – this yields the bias values. We compared u-component and v-component (relative to EASE grid), not speed and direction. We've added this information to the supplement text.

- Please provide at least one plot for each ice-motion component which illustrates how the ice-motion values scatter. You could do this as a scatter-plot, a 2-dimensional histogram, regular histograms, ... whatever you like, but please show the reader / user more than just a table.

We have added 2-dimensional histograms into the supplement that we have added. We've chosen to add a supplement to address this suggestion because the main manuscript is already quite long. Table 3 shows that Version 4 is improved vs. Version 3. The supplement provides further details supporting this conclusion.

Page 18, Lines 19-27:
- Just to re-cap: The 4X oversampling is something introduced from version 2 to version 3? Or was this already introduced in version 1?

No. The 4X oversampling was used from the very beginning of the method and thus was in Version 1 of the product.

- Line 25: I don't understand why the different temporal sampling of SMMR explains why the difference in the weekly average drift speed between version 3 and version 4 is near zero.

This was not originally explained well and we have edited the text to be clearer and more complete. The SMMR data were not changed at all between Version 3 and Version 4. The only change in the combined motions during the SMMR era was the changing in the weighting to use the 15 closest vectors. Since there are relatively fewer buoys, and there are not generally a lot of AVHRR estimates, the effect is small. The over-filtering issue affected SSMI and SSMIS, which were reprocessed for V4; so, the change to V4 is bigger for this period. AMSR-E was not affected by the over-filtering and also was not reprocessed for V4; thus, the contribution of AMSR-E motions muted the over-filtering of SSMI-SSMIS and reduced the V4-V3 difference. The difference increased again after AMSR-E dropped off the record and the differences increased again.

Page 19, Lines 1-3: How much of the larger differences between version 3 and 4 during summer can be attributed to the change in weights in combination to a predominant usage of NCEP/NCAR winds based ice motion [assuming that in summer there as substantially fewer valid PMW ice motion vectors]?

Yes, there are fewer PM vectors during summer, so winds are used relatively more. With winds having a lower weight, the buoys will be used over a relatively larger distance compared to PM. The other factor is the change to address the over-filtering in SSMI/SSMIS. The relative effects can be seen in Figure 7 where the seasonality is larger in the SSMI/SSMIS-only period where the over-filtering has an effect vs. the SMMR period where only the weighting is an effect and the AMSR-E period where the over-filtering of SSMI-SSMIS is muted by the presence of AMSR-E motions. We've added text to explain this.

+++

Editoral comments / typos:
Page 4, Line 11:
I'd say Szanyi et al. (2016) referred to the sea-ice motion product as well; therefore I suggest to add "sea-ice motion" here as well. This would also comply better to the "both products" notion in the next line.

Added "motion".

Page 4, Line 21:
"monthly" --> It might make sense to either correct the NSIDC web page or the text. Monthly estimates seem not to be available.

Removed "monthly". Monthly fields are no longer part of the product. We've added this note to Table 1 as well.

Page 5, Line 19/20: "a region around that grid cell" --> Does this mean that the search window is

centered at the center of the grid cell center and hence extends by typically 25 km in x- and y-direction?
"typically 50km" --> this reads as if different search window sizes are used. Is this the case? Please be more specific.

The 50 km is not from the center of the grid cell, but from the edges of the grid cell – i.e., for a 25 km grid cell, it would be two grid cells in each direction. We clarified this in the text.

Page 5, Lines 22-24: "The highest correlation value, i.e., the correlation peak, is determined to be the offset in the position of the grid cell between the earlier and the later image; then, the ice velocity is computed by dividing this offset by the time separation between images."
I don't think that the correlation itself gives the spatial offset, does it? How about "The highest correlation value, i.e., the correlation peak, is assumed to coincide with the most likely offset in the position of the grid cell between the earlier and the later image. This offset in the position yields a displacement vector pointing into the direction of the ice motion while the ice velocity is computed by dividing its magnitude by the time separation between the two images used."

We changed the wording as suggested.

Page 6, Line 11:
"daily": SMMR did not provide daily data. This needs to be corrected in the text.

Corrected.

Page 6, Line 14:
"a gridded a resolution" --> "a gridded resolution"

Corrected.

Page 6, Line 15:
"many similar" --> please be more specific and refer to these, e.g., with a reference. Perhaps "many" could be deleted?

References added and "many" deleted.

Page 6, Line 20:
What about SMMR? Is the oversampling applied here as well?

Yes. We note in the text that the 4X oversampling is applied to all satellite estimates.

Page 6, Line 21: I suggest to add "theoretical" to "motion precision".

Done.

Page 6, Paragraph starting at line 25:
- Why were AMSR-E data not used for the ice motion product of the Southern Hemisphere?

Please either add the reasoning or at least mention that AMSR-E was only used in the Northern Hemisphere.

We added a note to the text that AMSR-E is only used in the Northern Hemisphere.

This was a decision made at the time. In the original product development, the Southern Hemisphere was not a particular focus and the motion fields were developed at a basic level. This is something that we will look into further – adding AVHRR, AMSR-E, and wind motions to the Antarctic fields.

- This part: "AMSR-E had more than double the spatial resolution of the previous sensor, 6.25 km gridded resolution for some channels, so its motion resolution was likewise improved. So, during this period (2002-2011), it was also used as a source for ice motions." should be re-written as it does not read well. It might help to refer to Table 1 by the way. "of the previous sensor" --> better "than SSM/I and SSMIS"

This has been rewritten to read better.

- On Page 6, Lines 7 and 9, you provide references for the SSM/I - SSMIS data product and the SMMR data product. An adequate reference for the AMSR-E data is missing.

AMSR-E references added.

Page 7, Lines 6-14:
- Why were AVHRR data not used for the ice motion product of the Southern Hemisphere? Please either add the reasoning or at least mention that AVHRR data were only used in the Northern Hemisphere.

Similar to AMSR-E above. This was a decision made at the time. In the original product development, the Southern Hemisphere was not a particular focus and the motion fields were developed at a basic level. This is something that we will look into further – adding AVHRR, AMSR-E, and wind motions to the Antarctic fields.

- Your reasoning that AVHRR data were not used after the year 2000 because AMSR-E became available reads a bit strange given the fact that AMSR-E became available in May 2002. I assume that AVHRR data usage was simply confined to version 1 (and version 2) of the NSIDC sea-ice motion product and/or that the AVHRR data set used those days (...) simply terminates at the end of 2000?

The AVHRR product used ended in 2000. We added this note to the text. While other AVHRR products could be used to continue use of AVHRR, particularly for 2001 and 2002 before AMSR-E's launch, it was deemed not worth the effort at the time. In a future version, we plan to look at newer AVHRR products that continue past 2000 and include them in the product.

- AVHRR has visible and infrared channels as you state. But which are used for the "Daily gridded composites"? In other words, are the AVHRR ice motion vectors based on visible or infrared data?

Both visible and infrared are used – visible during summer, infrared in winter.

- "higher resolution = more accurate motion estimates" --> Is this the case? Or is it mainly the precision which improves as resolution refines? In any case, it might be superb to add information about an inter-comparison between buoy, AVHRR and, e.g., SSM/I based ice motion estimates illustrating this statement in the supplementary material.

We changed "accurate" to "precise".

- Line 12: "(6.25 km vs. 4 km)" This reads as if the often strongly weather influenced near-90 GHz channels are the backbone of the ice motion estimates using AMSR-E. Is this the case? If not, then you need to mention the 12.5 km grid resolution for the near-37 GHz data. If yes, then your description about the over-sampling of the 25 km gridded data (near 37 GHz data) is given a bit too much weight because then one would assume that also for SSM/I and SSMIS the backbone data set are the near-90 GHz channels which in fact come at 12.5 km grid resolution. Your writing is hence inconsistent and should become more specific.

Here we make the point that AMSR-E near-90 GHz have a similar resolution as AVHRR, but can see through clouds. So AVHRR largely duplicates the AMSR-E near-90 GHz capabilities in terms of spatial resolution, but with so few vectors that with AMSR-E there is even less contribution from AVHRR. Thus, use of AVHRR was discontinued.

We have edited this paragraph to make this clearer. And we also make it clear that the 36/37 GHz channels of AMSR-E are also used. We also added text in the SSMI-SSMIS discussion above that both the 37 GHz and 85 GHz channels are also used.

- On Page 6, Lines 7 and 9, you provide references for the SSM/I - SSMIS data product and the SMMR data product. An adequate reference for the AVHRR data is missing.

We added this reference for the AVHRR data:

W. Emery, C. Fowler, T. Haran, J. Key, J. Maslanik, T. Scambos 2000. AVHRR Polar Pathfinder Twice-Daily 5 km EASE-Grid Composites, Version 3. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. doi: https://doi.org/10.5067/HRMXN6PE1Q0Q.

Page 10, line 16: I suggest to add "theoretical" in front of "limit of precision"

Added.

Page 10, paragraph starting on Line 16:
- This is a very globally written, non-specific paragraph. Please note clearly which versions of the NSIDC ice-motion products were compared here. It would also be important to know whether these comparisons were done using the single ice-motion vectors or using the daily

gridded product. It would further be important to learn about the amount of data compared here, i.e. are we talking about several years' worth of data or a few months or even only days? Example 1: In Line 21 it only states "the Lagrangian motion product". Example 2: In Line 23 it is not clear whether these "SSMI-derived daily velocity components" are from a gridded product or single motion vectors. The same applies to Line 24, wherein you write about the AMSR-E ice motion. Here, one asks oneself what "error" is meaning in particular. Example 3: In Lines 25/26 it only says "the ice motion data". Neither the time period, nor the gridding or the version number are given. Note: a high correlation is wonderful but how about bias and RMS error for the Sumata et al. studies?

This section is meant to provide an assessment of the general error characteristics of the source motion estimates based on previous studies. We've renamed the section title to be clearer, and made clarifying edits within the section. We removed "Lagrangian" and refer simply to "SSMI-derived", which is what was analyzed in Kwok et al. (1998). We added clarifying text in the AMSR-E sentence. We removed the sentence about the Sumata comparison because that was for the gridded composite product, which isn't relevant for this section.

Page 11, Lines 5/6: Please check this first sentence. It gives not clear meaning.

Edited the first sentence to be clearer.

Page 12: Line 2 "and monthly" --> should be deleted as there appears to be no monthly ice motion field available (anymore). At least they are not accessible via the product's web page.

"and monthly" removed.

Page 12, Lines 11-24:
- You mention three times that C is a assigned a value of 0.95 for buoys. One time might be enough.

The paragraph was rewritten to be less repetitive.

Page 13, Line 14: Please provide a reference for the correlation length scale of ice motion. Is it the same in the Arctic?

Added Meier et al. (2000) as a reference.

Page 13, Line 20: The perfect place to refer back to Figure 2 which nicely illustrates how smooth the "Winds" ice motion is compared to the PMW ice motion.

We added a note here that the winds fill in for PMW in the Arctic, which ameliorates the PMW over-filtering; we also add a reference back to Figure 2.

Page 13, Line 21: "corrects this over-filtering" --> How? This is your recent work and should be detailed more. See my previous comment on this issue.

We've added text to explain this in more detail.

Page 14, Lines 1-15:
- I note that in this paragraph finally you do not mention the monthly product anymore.

Thank you. Old habits are hard to break.☺

- Line 10: "discretization effects" --> Could these also be caused by the fact that your 4X downscaling applied to original 25 km gridded resolution (with even coarser footprint) data often cannot resolve the anticipated smaller-scale variations in ice motion but in contrast enhances noise - particularly in the direction of the motion? I recommend to spend a sentence or two about this issue and also take into account the paper by Lavergne et al. (2010).

The discretization effect we mention here is akin to the quantization noise noted in Lavergne et al. (2010) – i.e., the MCC can only estimate if there is a displacement in one grid increments: a parcel is estimated to move only 0 km, 25 km, 50 km, etc. The 4X oversampling cuts this by a factor of 4 – e.g., the parcel is detected to move 0 km, 6.25 km, 12.5 km, 18.75 km, 25 km, etc.

There may be more noise in the 4X fields because it allows for more variability, some of which may be an artifact of the oversampling. We've added text to provide more detail of the 4X oversampling and we reference Lavergne et al. (2010).

Page 15, Lines 1-13:
- In Line 1 please refer to the respective paragraph or subsection.

Added "in Section 2 (Reanalysis winds)".

- Line 3: Is the ice speed increasing? Then we are talking about a positive trend and not about an "increasing trend". Or is an already existing positive (or negative) trend increasing? Please be more clear in your formulation.

We changed "increasing" to "positive".

- What is your explanation for the 10% difference between versions 3 and 4 in the bias of the v-component compared to the near-1 % bias of the u-component?

This is a good question. The main reason is that while the u-motion tends to be fairly equal in each direction, the v-direction is largely negative (to the bottom of the grid) because the way the grid is oriented, the TDS and the Fram outflow are almost totally in the negative v-direction, with little u-component. Also, the northern half of the Beaufort Gyre is also in the negative v-direction. Only the southern Beaufort Gyre is primarily +v. So, I think because v is so skewed, there is more apparent bias.

- Lines 11-13: Frankly speaking I am very surprised about the small impact of using 2% instead of 1% to derive ice motion from NCEP/NCAR winds, but I am quite confident that this can be explained with your choice of data. Therefore, while I appreciate your future plans with respect to regions and long-term trends I am suggesting at first to carry out the comparison for the entire CRREL buoy motion data set (why 2015?) available (as used in the previous paragraph). Secondly, as you correctly write, the weights used for NCEP/NCAR wind-speed based ice motion are very low - particularly during winter when you have plenty of useful PMW ice-motion estimates. I am sure this changes during summer melt. Therefore it would certainly be much more informative to show the comparison with CRREL buoy ice-motion data alongside with purely NCEP/NCAR based ice motions (i.e. those exemplified in Figure 2 c). If you do this as a time-series you could also account for the fact that during summer NCEP/NCAR winds-based ice-motion estimates potentially play a substantially larger role for the combined gridded ice motion product.

We chose 2015 simply because it was a year with a high number of buoys and the last full year available in the CRREL archive. As we're interested in a change from 1% to 2%, any reasonable number of samples (i.e., large enough to have reasonable statistics) will suffice.

While it seems like doubling the winds might have a bigger effect, it demonstrates that the weighting of the winds is small compared to the passive microwave and particularly the buoy motions.

The rationale of the comparison presented here is to investigate the effect of the wind-ice scaling (1% vs. 2%) on the combined gridded motions. It is not to analyze the relationship of the winds to the buoys; while that is an interesting study, it is tangential to the purpose of this paper.

Page 15, Line 15: "the motion product" --> which one? The combined gridded one? Please write specifically what you use and do.

Yes, the combined gridded one. We have clarified this.

Page 16, Line 7: "1" --> "one"

Changed.

Page 16, Line 12: Is an "increment" by definition positive?

Yes, the parcels get one year older. We changed "incremented" to "increased" to be clear.

Page 18, Line 17: "motion age"?

Fixed.

Page 18, Lines 20-21: "motions are smoothed out"? So they are zero?

No, they are not zero. This refers to the temporal averaging the "smooths out" daily variability. We have rewritten this to be clearer.

Page 19, Line 7: "increasing trend" <--> "positive trend"; see my previous comment.

Changed.

Page 19, Lines 7/8: Isn't it strange to see that for the version 4 product, which is faster than the version 3 product especially for the SSM/I period (see Figure 7) you get a larger positive trend from version 4 than from version 3 data? Perhaps you should mention in the context of Figure 7, that after the AMSR-E period, the difference between versions 3 and 4 is even larger than before the AMSR-E period.

We've added text earlier to more thoroughly describe the characteristics of the V4-V3 differences in Figure 7 and here we note that these differences do impact the trend values.

Page 20, Line 11--: What does, to your opinion, explain the fact that the differences between version 4 and version 3 are near zero for all ice-age classes for winters 2005/06 'til 2012/13? Do we really understand why for these winters (dominated by AMSR-E 89GHz PMW ice motion input at 6.25 km grid resolution) the change in the interpolation method between version 3 and version 4 appears to have no influence?

This is because during these years, AMSR-E dominated so the filtering change to SSMI/SSMIS had minimal effect.

Page 21, Line 8: Please add the information that the winds originate from the NCEP/NCAR atmospheric reanalysis product.

Done.

Page 21, Line 28: I suggest to replace the ESA CPOM 2015 link by the recent paper by Salilla et al. from 2019 in The Cryosphere; this paper gives a comprehensive overview about currently existing CryoSat-2 sea-ice thickness products.

Replaced reference.

Page 22, Line 1: "ice age motion" ?

Corrected.

Page 22, Line 6: Please add "like suggested by Korosov et al. (2018)" behind "... EASE grid cell" to indicate that this is a feasible idea which has been followed up with already by other scientists.

Done.

Figure 1: I note that this figure omits the AVHRR data.

We show this figure as example of the inputs and the interpolated field. We chose a relatively recent year (2016) as being of more interest. Other years could also include AVHRR or AMSR-E, but a 4-panel figure is easier to read and gets the main point across – showing the individual *source motions and the combined, interpolated field side-by-side. We have added a note to the caption mentioning AMSR-E and AVHRR.*

Figure 3:
I note that in panel (a) a lot of the circular features with substantially different ice motion than the surrounding do not contain a red dot for a buoy being present. One example is found in the northern East Siberian Sea and another, more pronounced example is north of the Laptev Sea. How do you explain this?

We double-checked this and all buoys are marked with the red dot. The other regions are SSMI estimates that have noticeable differences than the wind-driven motion estimates. Like the buoys, there is a drop off as the higher-weighted SSMI drop out of the 15 nearest (V3) or highest weighted (V4) ranking.

- Is the grey scale the same between panel (a) and (b)? I am asking because I am surprised to see that the area with high positive values in the northern East Siberian Sea has so much increased (both in extent as well as in magnitude of the values) from panel (a) to panel (b). Please comment on this.

Yes, the scale is the same. The high positive values in the northern East Siberian Sea is because there is one buoy near the ice edge and no other buoy to the east. So, using the highest weighted approach for V4, that buoy's influence extends out much farther to the east and northeast. There isn't a similar change to the west because there is another buoy just to the west that "mutes" the influence of the eastern buoy in the region.

- I recommend to also show the respective uncertainty information for these two maps to illustrate to the user what the effect of this step is on this parameter. This might be an important information for users attempting to assimilate your product.

We've added information on the uncertainty field to the Figure 3 discuss. We have decided to not add a figure with uncertainty because it shows much the same pattern as in Figure 3 and thus in our view does not add information.

Figure 7: Please state in the text and the Figure caption on which grid cells this difference is computed. Did you use all grid cells? This could mean that you are superposing the true difference between version 3 and version 4 ice motions with an influence of the change in the ice drift distribution due to the sea-ice retreat which (the influence) might be different for version 3 than for version 4. Therefore I ask: How would this figure look like if you limit this comparison to the NSIDC region "Arctic Ocean"? Would the differences still be of the same magnitude?

Yes, we used all valid motion values. There is no difference between the sea ice mask in Version 3 and 4. It is true that different regimes will have different motion characteristics and these may vary spatially and temporally. This may be one reason why there is seasonality in the difference – in summer, motions are only in the Arctic Ocean, and there is more free drift. It is an interesting question as to how these motions vary seasonally, but we feel this is beyond the scope of this manuscript. The figure is included to show how the motions from V4 and V3 differ.

Figure 9 and its interpretation:
- What is special in winters 1995/96 and 1996/97 causing version 4 and version 3 4+year old ice extent to be similar even though we are still in the middle of the SSM/I period?

This is indeed an interesting feature. It may be related to the high variation between the 1995 summer minimum (record low to that point) and 1996 (very high). It could also be related to the end of the high AO period around that time. It is something we'd like to look into further, but is beyond the scope of this paper.

- While the previous issue is difficult to understand the one I am refering to now is logical and should be explained in more detail in your text. Apparently, introducing AMSR-E data in summer 2002 did not have an impact on the 4+ years old ice immediately but it took until winter 2004/05 or 2005/06 to see its effect on the difference between both product versions. Likewise, the termination of AMSR-E usage in fall 2011 and hence switch to coarser resolution SSMIS data manifests as late as 2014/2015. This is logical because it takes 3 years for the benefit of first the finer, later the coarser resolution to have an effect on the old ice.

We added a phrase to the discussion noting that age is gradually affected over the years when new data sources come in.

Figure 10:
- Please provide a similar time axis as you used in Figure 9.
Done.

Figure 11:
- Please provide a similar time axis as you used in Figure 9.
Done.

- What is the rationale behind including Kara and Barents Sea into this plot?

This is the region of the NSIDC "Arctic Ocean" mask. The rationale is that it includes all areas in our domain that may have a reasonable amount of MYI that could circulate into the Arctic. Hudson and Baffin have only minimal amounts of MYI and they melt out each summer. There are no data in the Canadian Archipelago. Bering Sea and Okhotsk have only FYI. Greenland Sea has MYI, but it quickly drifts south and melts. Barents and Kara generally have minimal MYI, but what it has can potentially circulate into the main part of the Arctic, so those regions are included. This region has been used in past reporting of age values, notably the Arctic Report Card. We've added a reference to the latest report card here.

- Caption: I have a problem with usage of the word "trend" here. To me a trend is something I compute from a time series of data, e.g. via a functional relation, and it has, in its simplest form an intercept and a slope. What you plot here are, to my opinion, time series of the fractions of the different ice-age classes.
We changed "trend" to "timeseries".

An enhancement to sea ice motion and age products at NSIDC

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Abstract. A new version of sea ice motion and age products includes several significant upgrades in processing, corrects known issues with the previous version, and updates the time series through 2018, with regular updates planned for the future. First, we provide a history of these NASA products distributed at the National Snow and Ice Data Center. Then we discuss the improvements to the algorithms, provide validation results for the new (Version 4) and older versions and intercompare the two. While Version 4 algorithm changes were significant, the impact on the products is relatively minor, particularly for more recent years. The changes in Version 4 reduce motion biases by ~0.01 to 0.02 cm/s and error standard deviations by ~0.3 cm/s. Overall, ice speed increased in Version 4 over Version 3 by 0.5 to 2.0 cm/s over most of the time series. Version 4 shows a higher positive trend for the Arctic of 0.21 cm/s/decade compared to 0.13 cm/s/decade for Version 3. The new version of ice age estimates indicates more older ice than Version 3, especially earlier in the record, but similar trends toward less multi-year ice. Changes in sea ice motion and age derived from the product show a significant shift in the Arctic ice cover, from a pack with a high concentration of older ice, to a sea ice cover dominated by first-year ice, which is more susceptible to summer melt. We also observe an increase in the speed of the ice over the 30+ year time series, which has been shown in other studies and is anticipated with the annual decrease in sea ice extent.

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1 Introduction

Arctic sea ice conditions have undergone significant changes in recent years with dramatic reductions in the overall ice extent, ice age, and ice thickness. The decline in Arctic sea ice extent is one of the better-known and more striking examples of a changing Arctic [e.g. *Meier et al.*, 2014; *Comiso et al.*, 2008;

2012; 2017a; *Stroeve et al.*, 2011; 2014]. Recent estimates indicate that September Arctic sea ice extent has decreased by approximately 13% per decade since 1979, with record or near-record minimum extents occurring several times in the last few years [e.g., *Perovich et al.*, 2019]. In the Antarctic, the trends are smaller and there is higher interannual variability [e.g., *Parkinson and Cavalieri*, 2012]; overall the Antarctic trends are slightly positive, but with strong regional variability [*Comiso et al.*, 2017b].

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Data on sea ice thickness are far less comprehensive and it is more difficult to determine solid quantitative thickness or volume trends. However, there is broad evidence, from observations [e.g., *Kwok*, 2018] and models [e.g., *Stroeve et al.,* 2014] that Arctic sea ice thinning trends are even stronger than the extent decrease. One explanation for the stronger decline in ice thickness is the preferential loss of thicker, old ice in comparison with relatively thin first-year ice. For example, *Johannessen et al.* [1999] and *Comiso et al.* [2008, 2012] noted the decline in multiyear sea-ice was roughly twice that of first-year ice. In a study examining ice age since the early 1980s, *Maslanik et al.* [2011] found continued recent loss of the oldest ice types, which accelerated starting in 2005. This trend has continued through 2019 [*Perovich et al.*, 2019; *Kwok*, 2018].

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A continued decline in the sea-ice cover and the shift from thick multiyear ice (MYI) to more easily navigable first-year ice (FYI) arguably will have one of the biggest impacts on humans and the Arctic environment [e.g., *Pizzolato et al.*, 2016]. In particular, the prospect of new shipping lanes, extraction of oil and gas from previously inaccessible regions, and increased national security concerns associated with easier and more accessible Arctic waters have already been identified as significant economic and cultural changes related to the sea-ice cover [*Huntington et al.*, 2007]. More open water along the coast will also add to the risk of storm surge and coastal erosion [*Vermaire et al.*, 2013; *Francis et al.*, 2006, 2005; *Lynch et al.,* 2004] and there is some evidence that reductions in sea ice may affect locations far from the Arctic [e.g., *Overland*, 2016], manifesting particularly through extreme weather in the mid-latitudes [e.g., *Cohen at al.*, 2014; *Francis and Vavrus*, 2012].

The distribution of the age of Arctic sea ice contributes to the vulnerability of the ice cover during the melt season because older ice is on average thicker than younger ice [*Maykut et al.*, 1986; *Tucker et al.*, 2001; *Yu et al.*, 2004; *Tschudi et al.*, 2016], at least in terms of thermodynamic growth over several years. Younger ice is more susceptible to deformation and melts out more readily during the summer, whereas older ice is more likely to remain through the melt season if it does not advect out of the Arctic Ocean. However, the thickness increase with age diminishes over time so that as sea ice gets older (*Maslanik et al.*, 2011), its resiliency against melt does not continually increase. The pre-melt distribution of ice age may therefore serve as a descriptive predictor of how much sea ice will disappear during the melt season and indicate where summer ice loss is more likely to occur.

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Ice thickness observations are becoming more widely and readily available from satellite altimeters such as NASA's Ice, Cloud, and land Elevation Satellite (ICESat) [*Kwok and Cunningham*, 2008] and ESA's CryoSat-2 [*Laxon et al*., 2013; *Kurtz et al*., 2014]. However, these satellite-derived data cover a limited time span. ICESat collected twice-yearly monthly estimates from 2003 to 2008 and CryoSat-2, launched in 2010, produces complete Arctic-wide fields monthly [*Tilling et al*., 2016]. The laser altimeter on NASA ICESat-2, launched in September 2018 [*Markus et al*., 2017], provides a significant new source of snow+ice freeboard, and potentially thickness. Along with satellite-borne altimeters, NASA's Operation IceBridge has yielded thickness estimates during 2009 through 2019 in selected regions [e.g., *Kurtz et al*., 2013]. Submarine upward-looking sonar has also been used to estimate thickness sporadically since the 1950s over a selected region in the central Arctic. These data have been connected to the satellite altimetry record [*Kwok*, 2018] to create an intermittent long-term timeseries over part of the Arctic. While these direct ice thickness estimates are useful, such products lack the long-term and/or the basin-wide coverage that is available from the multi-decadal sea ice age record.

In contrast, sea ice motion can be used to track parcels in a Lagrangian sense and record their age. Several sea ice motion products have been developed by various groups. Most products use some sort of motion tracking approach to estimate the drift of features or patterns in satellite images. The EUMETSAT Ocean and Sea Ice Satellite Application Facility (OSI SAF) has two products. One is a low-resolution (62.5 km spacing) product that derives 2-day motions based on passive microwave and scatterometer inputs [*Lavergne et al.*, 2010]. A medium resolution OSI SAF product based on visible/infrared sensor inputs provides daily coverage at 20 km spatial resolution [*Dybkjaer*, 2018]. Another product, developed by the French National Institute for Ocean Science (IFREMER), combines passive microwave and scatterometer inputs to produce 3-day motion estimates [*Girard-Arduin and Ezraty*, 2012]. Several of these products were inter-compared in *Sumata et al.* [2014, 2015]. High resolution SAR imagery has also been used to track motion at much finer spatial scales [e.g., Curlander et al., 1985; Kwok et al., 2003; Howell et al., 2018]. While high resolution, SAR has had limited spatial and temporal coverage, the data were large and difficult to work with, and reasonable coverage did not start until the mid-1990s. This has changed in recent years, but long-term climate records from SAR are limited.

In this paper, we specifically discuss the "Polar Pathfinder Daily 25 km EASE-Grid Sea Ice Motion Vectors" product [*Tschudi et al.*, 2019a]. These sea ice motions derived from satellite instruments and buoys are then used to obtain a continuous, complete, long-term record of sea ice age, the "EASE-grid Sea Ice Age" product [*Tschudi et al.*, 2019b]. Because of its length and completeness, this ice age timeseries has been used in several studies [*Maslanik et al.*, 2007, 2011; *Tschudi et al.*, 2016; 2010] and reviews of Arctic change [*Stroeve et al.*, 2011; *Meier et al.*, 2014; *Perovich et al.*, 2019] to assess changes in the ice cover. Over time, enhancements and improvements have been made to the ice motion and ice age products. The latest version of the ice motion and age products addresses issues noted by users [*Szanyi et al.*, 2016] and both products are enhanced through a refined optimal interpolation approach that improves the spatial continuity of the gridded motion and age fields. Our focus in this paper is to highlight the changes in the new version, compare the new version with older versions, and provide an updated assessment of ice age trends. As further background, we also document the algorithms and production of the products. Because the ice age product is produced by utilizing the sea ice motion product, we outline the production of the motion product first.

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2 The Polar Pathfinder Sea Ice Motion Product

The sea ice motion product is archived and distributed by the NASA Snow and Ice Distributed Active Archive Center (DAAC) at the National Snow and Ice Data Center (NSIDC). The ice motion product provides gridded daily estimates and weekly averages of ice motions for both the Arctic and Antarctic regions. In this section, we describe the basic processing methodology and data sources, as well as noting the changes made in the new Version 4 of the product. The version history of the motion product (and the age product discussed in Section 3) is summarized in Table 1, including the release date and enhancements for each version.

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2.1 Sea ice motion data sources and derivation techniques

Here we provide an overview of the source data and the basic derivation approach. Further details are provided in the product User Guide, available at NSIDC (https://nsidc.org/data/nsidc-0116). There are three primary types of sources for the sea ice motion product: (1) gridded satellite imagery – from several sources, (2) winds from reanalysis fields, and (3) buoy position data. Motions are independently derived from each of these sources. A list of the sources, temporal coverage, and spatial resolution is provided in Table 2. A complete daily gridded product is then produced by combining all sources via an optimal interpolation scheme (Figure 1), which is described further below.

Gridded satellite imagery

The approach used for deriving ice motion from satellite imagery is a pattern-matching method that uses cross correlations between patterns in coincident images separated by a given time interval. Such an approach is commonly called "feature-tracking", but at the spatial scales for these images, it is a spatial pattern of many features that are being tracked. Specifically, for our product, motion vectors are computed using a maximum cross-correlation (MCC) pattern-matching method [*Emery et al.*, 1991, 1995]. Two geolocated, spatially-coincident, temporally-consecutive satellite images are selected. Typical time separation between images is 1 to 3 days. For each valid sea ice grid cell, a "search window" is defined for a region around that grid cell, sized so that it will encompass the range of potential motion during the prescribed time interval (typically ~50 km beyond the grid cell in all directions). The later image is translated relative to the earlier image within this search window, and the correlation between the two images is calculated for each translation. The highest correlation value, i.e., the correlation peak, is assumed to coincide with the most likely offset in the position of the grid cell between the earlier and the later image. This offset in the position yields a displacement vector pointing into the direction of the ice motion; the ice velocity is computed by dividing its magnitude by the time separation between the two images used. All satellite motions are calculated as u and v vector components relative to the EASE grid employed for the product.

The imagery sources have changed over time, depending on which inputs have been available. The primary source has been passive microwave imagery from a series of sensors. Horizontal and vertical polarization fields of 37 GHz and 85/91 GHz channels are used when available. These began in late 1978 with the Scanning Multichannel Microwave Radiometer (SMMR) on the NASA Nimbus-7 platform, which operated until August 1987 (SMMR did not include the 85 GHz channels). After SMMR, a series of Special Sensor Microwave Imagers (SSMI) on U.S. Defense Meteorological Satellite Program (DMSP) platforms carried on the time series. These were used for the motion product through 2006. Starting in 2007, the motion product transition to the DMSP successor instrument, the Special Sensor Microwave Imager and Sounder (SSMIS), of which three still continue to operate (as of March 2020). The SSMI and SSMIS imagery are derived from the DMSP SSM/I-SSMIS Daily Polar Gridded Brightness Temperatures, Version 4 product [*Maslanik and Stroeve*, 2004] and the SMMR imagery are from the Nimbus-7 SMMR Polar Gridded Radiances and Sea Ice Concentrations, Version 1 product [*Gloersen*, 2006]. Motions were derived from both the 37 GHz and 85/91 GHz channels from SSMI and SSMIS.

These SMMR-SSMI-SSMIS sources are useful because they provide complete daily (every other day for SMMR) coverage in all-sky conditions (i.e., including night and through clouds). However, their low spatial resolution limits the resolution of motion estimates that can be retrieved. For SMMR, SSMI, and SSMIS the 37 GHz fields are gridded at 25 km resolution, while 85/91 GHz fields are gridded at 12.5 km

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resolution. However, the actual resolution, i.e., the sensor footprint, is even coarser; so the effective resolution of the imagery is lower than the gridded resolution. For the SSMI-SSMIS fields, with a gridded resolution of 25 km, daily velocity can only be estimated to the nearest 25 km/day for each velocity component (and actually less in terms of the sensor footprint resolution). This result in a coarse and noisy motion field. For this reason, similar motion-tracking methods reduce the effect of the coarseness though interpolating the cross-correlation function [e.g., *Kwok et al.*, 1998] or through continuous optimization methods [*Lavergne et al.*, 2010]; often other methods also use a two or three day time separation to reduce noise. Our product obtains useful daily motions by applying an oversampling procedure – effectively moving the correlation window fractions of grid cells – to obtain sub-pixel resolution. During initial development of the motion algorithm, various oversampling intervals were evaluated for improvement in accuracy versus computational expense. Based on these empirical analyses, an oversampling of 4X was chosen. This oversampling is applied to all satellite estimates. This improves the SSMI-SSMIS effective sampling interval to 6.25 km/day, which corresponds to a theoretical motion precision of 7.23 cm/s. The optimal interpolation method described below smooths this “discretized” motion, allowing estimation of much slower motions.

In 2002, a more advanced passive microwave sensor, the NASA/JAXA Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E), was launched on the NASA Aqua satellite and operated until October 2011. AMSR-E has more than double the spatial resolution of SSMI/SSMIS. AMSR-E 89 GHz data are gridded at 6.25 km resolution, compared to 12.5 km for 85/91 GHz SSMI/SSMIS; likewise, AMSR-E 36 GHz data are gridded to 12.5 km compared to 25 km for 37 GHz SSMI/SSMIS. With the higher resolution of the source data, AMSR-E’s motion resolution is likewise improved. So, during this period (2002-2011), brightness temperatures from AMSR-E (Cavalieri et al., 2014a,b) were also used as a source for ice motions in the Northern Hemisphere. In 2012, JAXA launched AMSR2 on their Global Change Observation Mission – Water (GCOM-W) satellite, which continues to operate (as of March 2020). AMSR2 has not yet been added as a source, but this is planned for a future release of the motion product.

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For the period, 1981-2000, vectors were produced from the Advanced Very High Resolution Radiometer (AVHRR) for the Northern Hemisphere. AVHRR is a visible/infrared sensor that provides higher spatial resolution than the passive microwave sources. Daily gridded composites at 4 km resolution were used as input to the maximum cross-correlation algorithm [*Emery et al.*, 2000]. The higher resolution of the sensor provided more precise motion estimates than the SMMR-SSMI source. However, motions could only be derived when there were cloud-free conditions on consecutive days. This yielded relatively few vectors, and the impact of AVHRR on the gridded composite fields was relatively small. The AMSR-E 89 GHz channel nearly matches the AVHRR gridded resolution. While the 89 GHz channels are affected by atmospheric emission, retrievals through many cloud conditions are possible, which allows AMSR-E to obtain many more valid motion estimates than AVHRR, at a comparable spatial scale. In addition, the 37 GHz channels have less atmospheric emission and while lower resolution still mark a substantial improvement over SSMI and SSMIS. Thus, inclusion of AVHRR as a motion source was discontinued after 2000 (when the source AVHRR product ended).

To further reduce errors, post-processing filtering techniques are applied to the cross-correlation scheme. First, a minimum correlation threshold of 0.4 is applied to the motion estimates from all of the satellite-derived MCC estimates. This removes 'weak' matches that are more likely to be incorrect. Various thresholds were investigated during the original development of the method [*Emery et al.*, 1991] and 0.4 was determined to be reasonable in terms of balancing the allowance of too many erroneous matches versus incorrectly removing many "good" matches [*Emery et al.*, 1986]. Our value of 0.4 is a subjective choice, but is within the range of thresholds chosen by other methods, e.g.: 0.6 [*Girard-Ardhuin and Ezraty*, 2012] or 0.3 [*Kwok et al.*, 1998; Lavergne et al., 2010].

Second, a neighborhood filter is applied to each individual motion source. At the low-resolution of the satellite data, motion is spatially well-correlated across several grid cells. For each vector retrieved, it is compared with two neighboring vectors. To pass the filter, the motion displacement must be consistent within two grid cells of the displacements of the two neighboring vectors. If the displacements are not consistent within the 2-grid cell limit, the vector is considered to be spurious and is rejected. Essentially,

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this means there must be at least three consistent motion estimates adjacent to each other. These spurious vectors occur most frequently near the ice edge.

These satellite-derived motion sources have different characteristics, which influence the precision and quality of the retrieved ice motions. The different microwave frequencies and polarizations are sensitive to different aspects of the surface that may affect the cross-correlation; different frequencies also have different spatial resolutions that affect the theoretical precision (e.g., 85/91 GHz have a higher gridded resolution). AMSR-E provides substantially higher resolution that yields more precise motion estimates. AVHRR is sensitive to visible or infrared characteristics of the ice that yield a different correlation basis for feature matching. All of these differences make merging these disparate sources into a combined field inherently complex.

Version 4 changes. There have been two significant changes made to the satellite imagery processing for Version 4. First, the final quality-controlled and calibrated gridded SSMI and SSMIS brightness temperatures [*Maslanik and Stroeve*, 2004] have been used throughout the record. In previous versions, near-real-time gridded brightness temperatures [*Maslanik and Stroeve,* 1999] were used to augment the time series and there was no provenance on when the near-real-time or final source was used. Another change corrected over-filtering of SSMI and SSMIS vectors that removed valid motion estimates in Version 3 of the product. Motion estimates are computed using the MCC individually from SSMI and SSMIS 37 GHz and 85/91 GHz fields. In Version 3, SSMI and SSMIS vectors were only included if a similar SSMI/SSMIS vector was found in three adjacent grid cells instead of two. In Version 4, SSMI/SSMIS vectors were included if (a) there are at least two SSMI/SSMIS estimates at adjacent grid cells with similar velocities in each frequency-derived field, and (b) there are at least four similar velocities at adjacent grid cells among the combined four SSMI/SSMIS frequency-derived fields. The net effect of this change was to reduce over-filtering of valid SSMI/SSMIS-derived ice motions. This had a relatively small effect in the Arctic because the multiple motion sources provided nearby motion estimates to compensate for the lack of microwave estimates; however, in the Antarctic, where the SSMI and

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SSMIS estimates provide the primary (and after 2000, the only) motion information, the sparser motion estimates often resulted in unrealistic circulation patterns; this is discussed further below in Section 2.3.

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Reanalysis winds

The satellite imagery sources are augmented in the Arctic with motions derived from wind forcing using the NCEP/NCAR Reanalysis [*Kalnay et al*., 2016] on a roughly 2° x 2° latitude-longitude grid, which are interpolated to a 50 km EASE-Grid (see Table 2). Wind-derived motions are not currently used in the Antarctic. The ice motions estimates are derived based on a simple relationship between winds and ice motion. The sea ice is assumed to move in the geostrophic wind direction, as provided by the reanalysis fields, with a magnitude of 1% of the wind speed. This was implemented based on the estimate from *Thorndike and Colony* [1982]. Other studies have shown a higher percent (e.g., 2%) for the ice vs. wind speed relationship. Recent studies indicate that the ice is becoming more responsive to winds [e.g., *Spreen et al*., 2011]. So, the 1% value used here likely underestimates the wind-driven ice speed. However, no changes were made to the wind-derived motions for Version 4. In the supplementary material, we show that the combined motion fields are largely insensitive to the magnitude of the wind contribution because it has a relatively small weight compared to the other sources. In a future version, we plan to revisit this relationship in the Arctic and investigate adding wind-driven motions for the Antarctic.

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Buoy positions

Ice motion vectors are also computed by incorporating position data from the network of drifting buoys deployed as part of the International Arctic Buoy Program [*IABP*, 2008]. These buoys monitor meteorological and oceanographic conditions for real-time operational requirements and research purposes, and provide ice motion by transmitting updated locations. This product uses the twice daily (midnight and noon) locations of the IABP "C" buoy product. Two motion estimates are computed from these locations: one from noon of one day to noon of the following day, and one from midnight of a day to midnight the following day. No buoys are included in the Antarctic motion fields because there have been few buoy deployments on ice in the Southern Ocean.

Version 4 changes. The principal change for the buoys is how the twice-daily observations are integrated into a daily product. Previous versions of this product considered these motions independently of each other and effectively used the most recent observation for a day. In Version 4 the two estimates are averaged to provide one daily motion estimate for each buoy. Thus, each day's buoy motion is an average of midnight to midnight (UTC) of the current day and noon the previous day to noon the current day. Also, the IABP source product recently started including floatable buoys, resulting in motion estimates from off the ice. These were not screened out in earlier versions. The effect was relatively small and primarily influenced motions near the ice-edge because of the distance-weighting interpolation. Version 4 now applies an ice mask to the buoys, making the buoy motion domain consistent with the other sources.

Masks for valid motions

Two masks are applied to limit motion retrievals to only regions where sea ice exists. First, a modified land mask is applied. The standard land mask is "dilated" so that cells near land are also excluded because motion retrievals near the coast are unreliable due to the effects of mixed land and ice/ocean grid cells. Because of its narrow channels, the Canadian Archipelago region is also masked out.

Second, a sea ice mask is also applied to limit motion retrievals to only ocean regions that are ice-covered on the days under consideration. The mask is based on the "Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data, Version 1" at NSIDC [*Cavalieri et al.*, 1996]. The mask defines all areas with concentrations greater than 15% as ice-covered so that valid ice motions can be computed.

Version 4 changes. Previously, the sea ice mask from only the first day was used to define the valid motion region. This was changed in Version 4 to allow motions only where ice is present on both days used to retrieve motions. This results in very small changes near the ice edge. As noted above, the mask is now applied to buoys as well as the other sources.

2.2 Review of uncertainty characteristics of motion estimates from previous studies

In this section we provide an overview of general uncertainty characteristics of the source motion estimates found in previous studies, focusing particularly on passive-microwave error estimates. Errors in the ice motion and ice age products are dependent on the resolution of the satellite sensor, as well as geolocation and binning errors for each image pixel [*Meier et al.*, 2000]. The distance precision of motion detection is limited by the grid cell resolution – a pattern can nominally be "observed" to move only an integer number of grid cells. Particularly for the low-resolution inputs, this yields high uncertainty for each individual estimate and an overall noisy motion field.

As noted above, for a 25 km gridded passive microwave input with 4X oversampling, the theoretical limit of precision of the motion is 7.23 cm/s (6.25 km/day). Atmospheric effects and temporal variability of the surface are additional sources of error, especially in the summer. However, several evaluation studies have found that in practice errors are often lower because the different sources of error offset each other. *Kwok et al*. [1998] compared ice motion estimated from the European Space Agency (ESA) Remote Sensing Satellite (ERS-1) synthetic aperture radar (SAR) along with drifting buoy motion to SSMI-derived motions and found an error of 5-12 km/day (~6-14 cm/s). Meier et al. [2000], comparing with buoys, found RMS errors of SSMI-derived daily velocity components to vary between ~5-7 cm/s, depending on conditions, with near-zero bias. AMSR-E, with higher spatial resolution, yields motion estimates with velocity component errors of 4-5 cm/s [*Meier and Dai*, 2006; *Kwok*, 2008].

Summertime drift error is higher due in part to surface melt, which affects the passive microwave identification of ice parcels. Our product incorporates summer drift estimates from passive microwave, but the errors are substantially higher and the number of valid motions is lower (see supplementary material). *Kwok* [2008] showed that AMSR-E 19 GHz channels can provide improved summer estimates

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compared to other frequencies. However, the large sensor footprint of 19 GHz makes such retrievals impractical except from the higher resolution AMSR-E sensor. 19 GHz was not used as an input to our product. The largest drift error was found to occur in the fall, likely due to formation of new ice [*Meier et al.*, 2000]. Optimal interpolation (discussed below) reduces errors through its error and distance-based weighting, particularly when buoys are incorporated. Temporal averaging further reduces errors in the weekly estimates.

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In addition, the errors are not generally cumulative, because the motions were found to be largely unbiased evaluations done during the development of the original product; this allows for accurate tracking of parcels (e.g., ice age) over time. These evaluations, described in the product documentation at NSIDC (https://nsidc.org/data/nsidc-0116), show *u* velocity component biases of ~±0.05 cm/s and *v*-component biases of 0.4-0.7 cm/s. Other published studies (such as the references above) show similar results. The low bias in the estimates means that errors in long-term (weeks to months) displacement are relatively small. *Tschudi et al*. [2010] compared drift tracks composed from the sea ice motion product to the drift of the Surface Heat Budget of the Arctic Ocean (SHEBA) ice camp [*Uttal et al.*, 2002] and found a drift error of 27 km over 293 days. There is some effect from the different passive microwave sources due to temporal sampling between SMMR (every other day) and SSMI/SSMIS (daily); the higher sampling rate from SSMI/SSMIS changes the discretization of the retrieved motions. Also, the higher spatial resolution of AMSR-E affects the discretization of the motions as well. This is discussed further in the supplementary material.

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Deleted: Ice motion estimates in the Antarctic are not easily validated due to the lack of buoys for comparison. Generally, Antarctic motions are considered to be less accurate due to the lack of buoys, the more dynamic nature of the Antarctic sea ice, and the larger variability in microwave emission (e.g., flooding and snow-ice formation), limiting the effectiveness of the cross-correlation scheme.

We note here that evaluation of sea ice motions has come nearly exclusively from the Arctic region. The primary reason for this is the existence of the IABP buoys that offers a reliable “truth” for evaluation of satellite-derived motions and other methods. The Antarctic has had few or no buoys. Thus, our knowledge of the error characteristics of Antarctic motions have not been quantified. While the cross-correlation approach for the satellite-derived motions is the same in the Antarctic and the theoretical precision is thus the same, the Antarctic sea ice surface is different (e.g., thinner ice, deeper snow, snow-ice formation). Other factors, such as a more dynamic sea ice cover and different atmospheric influence also have an effect. As such, there is lower confidence in Antarctic motions and the error characteristics are more uncertain. The Antarctic motions are included with the product for completeness, but users should note these caveats.

2.3 Combined gridded sea ice motion fields

Daily motion fields are provided from each of the sources during their period of availability. However, for many users, the most useful parameter is the combined gridded product. This combines via an optimal interpolation scheme all available sources for a given day onto a version of the 25 km EASE-Grid [*Brodzik et al.*, 2002]. For further information on the grid, see NSIDC's documentation for this data product [*Tschudi et* al., 2019a]. For each 25-km ice EASE-grid cell, the speeds (cm/s) in the EASE-grid x-direction (*u* velocity component) and y-direction (*v* velocity component) are stored. The daily motions fields are also averaged into weekly fields.

Optimal interpolation (also called "kriging") is not simply a spatial average, but considers the accuracy of different sources and the spatial distribution of the source estimates. The motion estimates vary in expected quality, with buoys considered most accurate, followed by passive-microwave and/or AVHRR-based estimates and finally by the wind field. This weighting is of the form:

$$w = Ce^{(-d/D)} \quad (1)$$

where w is the weight, C is a source-based coefficient (0.45 for wind, 0.95 for buoy, 0.8 for other sources), d is the Euclidean distance between the pixel in question and the motion estimate on the EASE grid, and D is the length-scale (constant) over which the estimates are correlated. The values of C are constant for each source and are based on early comparisons between each source and buoy estimates. Buoys, being the most accurate, were assigned the 0.95 value. The buoys were used as the baseline for estimating the other weights. The values of C for the other sources were estimated *a priori* based on comparisons between the source motions and buoy estimates. The original derivation of the C values was not retained it is likely that the values are not optimal in all cases. For example, the quality of the satellite estimates

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varies depending on source and spatial resolution, so using 0.8 for all of them is sub-optimal (see supplementary material). Another example is that wind-derived estimates appear to be comparable to many of the satellite estimates (see supplement), suggesting that winds should be weighted relatively higher. However, these were not changed for Version 4 and here we simply provide the values used in the product.

Estimates that are closer (low *d*) and higher quality (sources with higher *C,* e.g. buoys), are weighted higher. The correlation length-scale, *D*, was given a value of 417 km, also determined empirically, based on cross-correlations of estimates separated by varying distances. This distance is lower than the full correlation length scale. However, the method limits the number of interpolated source observations to a maximum of 15 and this distance is large enough to encompass that limit. Other studies (e.g., Meier et al., 2000) found that using longer length scales did not appreciably affect the interpolation values. The method loops through all grid cells in the domain that are flagged as sea ice-covered. Figure 2 shows an example of the individual motion sources and the resulting combined motion field. The optimal interpolation converts the sparse and/or noisy individual motion fields into a complete and smoothly varying combined motion grid.

Version 4 changes. The most notable change in the motion product for Version 4 involves the optimal interpolation approach. In previous versions, the combined estimate at each valid grid cell was estimated by optimally interpolating (kriging) the surrounding 15 closest vectors. While this generally gives a good spatial distribution around grid cells, it does not necessarily include all estimates that fall within correlation length-scale and that theoretically could influence the interpolated estimate. This means that discontinuities can potentially occur, particularly as highly-weighted estimates (i.e., buoys) fall off the list of closest estimates. When the buoy motion estimates differ significantly from other sources, artificially large spatial gradients in velocity magnitude can arise [*Szyani et al*., 2016]. In Version 4 of the product, the methodology has been revised to use the 15 highest-weighted ice motion vectors at each grid cell, regardless of source. So, a source with a high value of *C* (i.e., buoys) will have a weight, *w*, higher than *w* for a source with a lower *C* value (e.g., winds) over a longer spatial distance. This means that

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higher weighted observations have influence over a longer distance and their influence drops off more gradually. This approach significantly reduces and often removes the discontinuity artifact in the daily combined product (Figure 3). It is also reflected in the interpolation error estimates included with the daily product (not shown), where the low error in the neighborhood of the buoys has a smoother gradient.

As noted above, the Version 4 algorithm also eliminates an over-filtering of SSMI and SSMIS passive microwave vectors that occurred in Version 3. Since these vectors are the primary source in the Antarctic (other than SMMR during 1978-1987 and AVHRR during 1981-2000), they are the main input to the optimal interpolation, and the over-filtering of the vectors resulted in a sparse raw motion field. With the length scale value, *D*, of 417 km, given the coarse spatial resolution and high noise in the daily passive microwave derived motion vectors, such few vectors often did not provide a spatially representative sample of the large-scale motion circulation. In other words, the interpolated motion field of the Antarctic ice motion field was often being driven by very few underlying motion estimates, which led to unrealistic circulation patterns in the Antarctic because there were too few vectors to create a representative field. The over-filtering also occurred in the Arctic but was much more limited because other sources exist to augment the passive microwave estimates; in particular, use of spatially complete and smoothly varying wind-driven motions in the Arctic "filled in" any place where passive microwave vectors were sparse (see Figure 2). Version 4 corrects this over-filtering, yielding more passive microwave motion estimates over a broader area; this is particularly noticeable in the Antarctic. An example of this is shown in Figure 4 where the Version 3 product has very few vectors. In the eastern Weddell Sea, this results in southward onshore ice motion. This would be very unusual for the region and comparisons with winds (not shown) indicate that this motion is not realistic. Version 4 yields more source vectors that better represents the spatial variation in the region. The result is a general eastward circulation, which is more typical for the region and is consistent with the wind field.

A final change in the motion product for Version 4 is that the data are now provided in NetCDF format, with daily files for each underlying motion field, e.g. SSMI, buoy and wind-driven motions – as well as files containing the daily combined (optimally interpolated) estimate and a weekly average sea ice motion.

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The self-describing file format provides improved metadata (including georeference information) and easier access for many users. In the daily combined field, an error estimate is included that gives the error from the optimal interpolation, which is a function of the number, spatial distribution, and quality of all input vectors interpolated at a given grid point. Flag values are used to denote potential low-quality interpolation due to lack of nearby vectors and/or vectors near the coast (where retrievals have higher errors). Because the passive microwave daily ice motions are at a coarse resolution, they tend to exhibit discretization effects at daily timescales (e.g., Lavergne et al., 2010), even when applying the 4X oversampling. These effects are diminished in the weekly fields as day-to-day "noise" in the observations are averaged out over the seven days. Thus, the weekly sea ice motion fields are the recommended product for most applications; users of the daily product should recognize its limitations and use caution in interpreting features and changes in the daily fields. The NSIDC archive also provides browse imagery of the weekly sea ice motions (Figure 5), which has also been updated to improve visual appearance.

2.4 Validation of combined motion fields

The combined daily motions are validated in the Arctic through comparison with independent buoys from the CRREL Ice Mass Balance Buoy program [*Perovich et al.*, 2020]. We compared estimates to 101 CRREL buoys from 2000-2016. All of the CRREL buoy positions were converted to EASE grid coordinates and the u-component and v-component of velocity (relative to the EASE grid) was derived from the change in position over a 24-hour period. The combined estimate closest to each CRREL buoy was selected for comparison; thus, each comparison was made generally within ~25 km. A small number (<0.1%) of CRREL observations with erroneous velocities that were obviously too large were removed from the comparisons. This resulted in a total of nearly 26,000 pairs of observations from buoys and the combined motion field. The results (Table S2) show that biases are around -0.1 cm/s for the u-component and around -0.66 to -0.69 cm/s for the v-component. Most notably, the biases were slightly reduced in Version 4, indicating that the improvements in processing do result in improved accuracy of the motions. Similarly, the error standard deviations are around 4 cm/s for both velocity components and Version 4 reduces this error by ~0.3 cm/s over Version 3.

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As noted above in Section 2 (Reanalysis winds), for the wind forcing, we used a 1% scale factor for the ice speed relative to wind speed. Other assessments have shown that 2% may be more legitimate, especially in recent years with the observed positive trend in ice speed. To investigate the potential effect of underestimating ice speed from winds in our product, we compared the combined motion fields with both 1% and 2% scale factors to the 2015 CRREL buoy observations. The results indicate little effect due to wind speed (Table S3), which is expected since the weighting of the wind-driven motion is lower than other sources. The comparison indicates that the magnitude of the bias changes little for the u-component, but actually increases for the v-component. The error standard deviations decrease, generally by ~0.5 cm/s. This suggests that 2% may indeed be an improvement, but the impact on the combined gridded is relatively small. Of course, the relationship between wind speed and ice motion is complicated and can be quite variable. It depends on the compactness of the ice cover, thickness, and wind direction relative to nearby coasts. We plan to investigate the relationship further in the future, both regionally (for different sea ice conditions) and temporally (to investigate the effect of the long-term trend toward increasing speeds).

3 The EASE-Grid Sea Ice Age Product

The EASE-Grid Sea Ice Age product [*Tschudi et* al., 2019b] builds upon the combined motion product and is also a popular dataset with over 650 unique users having accessed the data as of this writing [*NSIDC*, personal comm.]. Version 2 of the sea ice age data is also part of NASA's Making Earth System Data Records for Use in Research (MEaSUREs) dataset at NSIDC [*Anderson et al*., 2014]; however, the MEaSUREs product is not regularly updated and does not include the newest enhancements described here. Animations of motion and age have been posted on NOAA's ClimateWatch online magazine [2016] (http://www.climate.gov/news-features/videos/old-ice-arctic-vanishingly-rare), as well as the NASA Scientific Visualization Studio (https://svs.gsfc.nasa.gov/4750). Sea ice age distributions and trends are described annually in the Arctic Report Card [*Perovich et al.*, 2019] and have been analyzed by *Maslanik et al.* [2007; 2011].

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The Sea Ice Age product was introduced by *Fowler et al.* [2004] and described further by *Maslanik et al.* [2007; 2011], *Tschudi et al.* [2010], and *Stroeve et al.* [2011]. The ice age product algorithm estimates the age (in years) of Arctic sea ice using input from the previously described sea ice motion product. Weekly averaged motions are used to reduce computational complexity and to temporally average discretization artifacts in the daily motion data. Also, the 25 km resolution motions are bilinearly interpolated to a 12.5 km resolution grid in order to provide finer granularity in the ice age fields.

At the beginning of the ice motion record, all parcels in the 12.5 km ice age grid are initialized with an age-class of "first-year ice", meaning ice that is less than one year old. These parcels are then treated as Lagrangian particles and are advected at weekly time steps with the motion product estimates. When two or more parcels merge into a grid cell, the age of that grid cell is represented as the age of the oldest parcel. Rarely, ice motion results in all parcels being advected out of a grid cell; when this occurs, a new parcel of "first-year ice" is initialized in that grid cell. During the week of the Arctic sea ice extent minimum, the age of all parcels is increased by one year. At each time step, all parcels found within a grid cell that have an ice concentration of less than 15% are considered to have melted and are no longer considered in determining the ice age. Parcels are tracked for up to 16 years, after which they are no longer considered (such parcels are simply removed).

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This approach does not consider new ice that may form within a grid cell because it retains only the oldest ice in its accounting. Thus, the product is effectively an estimate of the oldest ice in a given grid cell. Tracking of partial concentration of age categories can provide a more detailed picture of the ice cover [*Korosov et al.*, 2018] and is something we may consider for future versions.

The source motion data for the age product begin in 1978, with the age of all parcels initialized as first-year (0-1 years old) ice. Because the method tracks age over time, several years are needed to build up older ice categories. For this reason, the ice age product begins in 1984. The youngest ice age category is first-year ice (FYI), which is ice that is less than a year old. Similarly, second-year ice is one to two years old, and so on for older ice age categories. Ice older than 4 years (5th-year and older ice) makes up a very small percentage of the ice cover, so depicting ice older than this category as a separate field in browse imagery is not undertaken. Therefore, the ice age is frequently categorized as being of ages: 0-1 (i.e., FYI), 1-2, 2-3, 3-4, and more than 4 years old (i.e., 5th-year and older ice).

Version 4 changes. The primary changes in Version 4 of the ice age product result from the changes in the source ice motion products described above. The most substantial change addressed anomalous behavior in the motion and age fields documented by *Szanyi et al.* [2016]. They showed that discontinuities in the interpolated motion field, caused by sub-optimal interpolation of buoys with the other data sources, created artificial ice divergence and new ice formation in the Version 3 product. This potentially results in an underestimation of multi-year and an overestimation of first-year ice. The change in the interpolation weighting, described above, reduced this effect as seen in Figure 3; the Version 3 field has the circular features surrounding the buoys where the buoy contribution suddenly drops out, resulting in a discontinuity where false divergence can occur. The new weighting scheme smooths that discontinuity and eliminates much of the false divergence. The effect of this change can be seen qualitatively in the age fields as less "speckling" of first-year ice interspersed within the multi-year ice pack; the age fields show a more realistic consolidated multi-year ice pack. Qualitatively, the net effect is less first-year ice (the "speckling" that results from the false divergence) and an increased amount of multi-year in Version 4 compared to Version 3 (Figure 6). This effect becomes much less noticeable during the latter part of the record. There are three reasons for this. First, there is less passive microwave coverage during the early SMMR period, so a sparser number of vectors, which will accentuate interpolation-induced artifacts in the data. Similarly, in the early part of the record, there were far fewer buoys, so the buoy interpolation discontinuities are more noticeable. In recent years, there are enough buoys such that the interpolation distances of neighboring buoys often overlap, so discontinuities with the passive microwave and wind fields are less common. Finally, there is simply much less multi-year ice in recent years, so the discontinuity effects are less pronounced. A quantitative assessment of the version changes in the ice age product are discussed further in Section 4 below.

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Two other minor changes to the ice age product have been introduced in Version 4. First, the week-numbering convention was slightly modified to be consistent with the motion weeks. Second, browse imagery (Figure 6) was improved to explicitly show ice-covered ocean areas that are outside of the age and motion domain (e.g., the Canadian Archipelago).

Validation of sea ice age is difficult because there is no known suitable validation data set that can be used for a comparison. Here we primarily rely on the fact that the ice age product is directly derived from the ice motion product. Thus, the demonstrated improvement in the motion fields indicates that the age fields are also improved. This is particularly noticeable in the reduction of the circular features in the motion field, which reduces the "speckling" in the Version 4 age fields. While this is qualitative, we feel this does demonstrate an improvement in the age fields. A recent study [*Lee et al*., 2017] included the NSIDC ice age fields in a comparison with passive microwave ice age retrieval methods, including multiyear fraction from the NASA Team algorithm, the OSI-SAF ice type product [*Aaboe et al*., 2017], and a microwave emissivity approach. The spatial patterns of first-year and multi-year ice in the NSIDC age product matched well with the comparison products, showing that our age product is at least consistent with other approaches.

4 Trends and variability in Version 4 ice motion and age and comparison to Version 3

Here we evaluate how the changes from Version 3 to Version 4 of the products affect the long-term trends and variability in the sea ice age fields. We also provide updated motion and age trends through 2017.

As seen in Figure 3, the change to Version 4 does noticeably affect parts of the daily fields in regions around buoys. Over a weekly period, the changes are less significant because the temporal averaging smooths out the variability in the motions. The weekly average speed is generally faster in Version 4 than in Version 3 (Figure 7). (The differences in the *u* and *v* motion components (not shown) have similar characteristics over the time series.) This change in speed between Version 3 and Version 4 reflects the two major changes made for Version 4: (1) the use of the 15 highest weighted observations for the interpolated combined fields, and (2) the correction of the over-filtering of the SSMI and SSMIS vectors.

During the SMMR part of the record, the differences are generally near-zero. This is because only the change in weighting had an effect on this period. In the Arctic this primarily changed the influence of the buoys and there were fewer buoys during the SMMR period. In the Antarctic (Figure 7b), the change is even smaller because there are no buoys and thus less impact of the adjusted weighting scheme. For the SSMI and SSMIS period, the Version 4 motions are ~0.5 – 1.0 cm/s faster than Version 3 in the Arctic and ~0 – 2 cm/s faster in the Antarctic. In this period, both the change in weighting and the over-filtering correction affected the motions. The over-filtering effect on the number of valid SSMI and SSMIS has larger effect, especially in the Antarctic where there are no buoys or wind-derived fields. During 2002-2011 when AMSR-E is included, the Arctic speed difference is reduced with Version 4 speeds ~0.25 – 0.5 cm/s faster. AMSR-E motions did not change between Version 3 and 4; SSMI and SSMIS were also used in this period, but with higher resolution, more AMSR-E motions were used. Thus, the over-filtering issue in the SSMI-SSMIS estimates was muted in the AMSR-E period. After the end of AMSR-E the differences increase again. In the Antarctic, there is no notable change because AMSR-E is not used

There is seasonal variation with larger differences during the Arctic summer. The main factor is likely overall speeds, as seen in the Version 4 weekly average speed timeseries (Figure 8) that show strong seasonal variability in Arctic motions with speeds peaking during summer. In the Antarctic, the version differences are actually largest in winter and smaller in the summer; this may reflect fewer vectors with minimal summer ice cover. Also, in the Antarctic winter, the ice extends far northward and the pack is quite dynamic in response to winds and currents. Other factors also play a role, including the number of vectors from different sources at different times of year (e.g., fewer passive microwave vectors during summer) and, in the Arctic, the revised weighting scheme that effectively yields more influence of buoys during the summer (when there are fewer passive microwave motions).

There is also interannual variability (Figure 8), some of which is related to the SMMR every-other-day sampling, resulting in slower speeds and less variability for the 1979 to 1987 period (more noticeable in the Antarctic because of the lack of wind-derived and buoy motions). Beyond that, there is an overall positive trend in Arctic sea ice speed of 0.21 cm/s/decade in Version 4 versus 0.13 cm/s/decade in Version

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3. The increasing speed is in general agreement with previous studies that noted a trend toward faster moving ice [e.g., *Spreen et al.*, 2011] and linked the trend to greater response to wind-forcing by a thinner ice cover. In the Antarctic, there is also an increasing trend of 0.61 cm/s/decade in Version 4 versus 0.41 cm/s/decade in Version 3. But as noted above, the differences in the trend values from Version 4 and Version 3 at least partially reflect the effects of the changes in the motion sources and their relative impacts over the time series.

The largest effect of the version change for ice age is, as noted above, the amount of multi-year ice in the early part of the record, particularly in the oldest ice categories. This is illustrated in the timeseries of ice age (Figure 9). Both versions show a strong decline in 4+ year old ice over the record, with a steep loss of old ice in the late 1980s through the mid-1990s, which is associated with a persistent positive mode of the Arctic Oscillation (AO) [*Rigor et al.*, 2002]. A positive AO results in increased drift from the Siberian coast and greater advection of ice out of the Arctic through Fram Strait, which serves to "drain" older ice out of the Arctic [*Rigor and Wallace*, 2004].

The change to Version 4 results in higher extent of the old ice over most of the early part of the record, with the exception of 1995-1996 (perhaps related to the end of the positive AO period and/or large changes in minimum extent between the two summers). Version 4 extent of 5+ year old ice is on average 367,000 km^2 higher than Version 3 for the first five years (1984-1988) of the record. This is an effect of the improved interpolation weighting scheme and is a quantitative indication of the reduced "speckling" discussed earlier. However, the impact dissipates over time; during the last five full years of the record (2012-2016), the difference between Version 4 and Version 3 is only 42,000 km^2. The amelioration of the difference is likely due to two factors: (1) the transition from SMMR to SSMI-SSMIS and the resulting improved coverage; and (2) the increasing number of buoys over time. As noted above, the two-day SMMR separation does change the motion discretization and the spatial coverage. So, the relative effect of the buoys is greater during the SMMR era. And as buoy coverage increases over the years, there is more overlap in buoy influence, so the change in weighting that increases the distance of buoy influence has a relatively smaller effect. With daily data and better spatial coverage in SSMI, the differences

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Both versions of the ice age field show a transition from one dominated by older ice to one dominated by younger ice (Figure 11). Interannual variability is evident in all ice age classes, particularly first-year ice, which is not surprising given the variability of the summer ice cover. Less variability is seen in older ice. Nonetheless, the decline in older ice is apparent during the late-1980s through the mid-1990s persistent positive mode of the Arctic Oscillation [*Rigor et al.*, 2002]. After 1994, there was some recovery in multi-year ice before beginning a significant decline after 2004. Linear trends are estimated for the Arctic Ocean region. This is a region bounded by the northern coasts of the continents, the Bering Strait, Fram Strait, and the ~20 E meridian between Svalbard and the Fennoscandian Peninsula. The total area of the region is ~7.8×10^6 km^2. Using this region excises areas where only first-year ice exists, so it focuses on the areas where there is variability in the ice age. There is a strong increasing trend in ice less than 1 year old (Table 3) and a similar decreasing trend in 4+ year old ice. Trends in the intermediate ages (1-4 years old) are smaller. This is partly due to smaller extents of these ages as well as the fact that ice transitions through these categories between the larger extents of the oldest and youngest ice.

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5 Conclusions

New versions (4.0) of the sea ice motion [*Tschudi et al.,* 2019a] and sea ice age [*Tschudi et al.,* 2019b] datasets have been produced and are now available at NSIDC. Routine updates will regularly occur when the underlying data – buoy positions, brightness temperature fields and sea ice concentration fields – become available. This is expected to occur every few months.

Arctic sea ice motion vectors are currently constructed by merging motion vectors estimated using three sources: buoys, passive microwave satellite imagery, and winds from NCEP/NCAR. In the Antarctic, only the satellite imagery vectors are used. Sea ice age is produced for the Arctic using the weekly sea ice motion product as input, tracking ice parcels and aging them each year if they neither melt nor advect out of the ice pack.

The most recent sea ice motion algorithm revision incorporates improvements such as an improved vector weighting scheme, corrections to passive microwave vectors, new browse imagery, and the underlying code base through the use of Python. Furthermore, the Version 4.0 upgrade addresses artifacts in the ice motion resulting from the interpolation. These artifacts did have a noticeable effect on the weekly motion and age fields early in the record, but in more recent years, the effect of these artifacts is diminished due in large part to many more buoys in the Arctic, which results in overlapping influence of buoys and thus fewer artifacts..

We note the decrease in older sea ice over the ice age record, from the 1980's, when older ice constituted ~30% of the ice pack, to recent years, when older ice occupies less than 5% of the pack. *Tschudi et al.* [2016] compared ice age to ice thickness derived from ICESat [*Kwok et* al., 2009; *Kwok and Cunningham*, 2008] and NASA's IceBridge campaign [*Kurtz et al*., 2012, 2013]. They found that the thickness/age relationship has an approximate linear fit for the ICESat dataset, but that the relationship was much more variable for IceBridge, due to the Arctic basin-wide coverage of ICESat thickness data and the more limited areal coverage for IceBridge aircraft-acquired data. The relationship found between ice age and thickness for the basin-wide ICESat dataset suggests that the ice age product may be used as a general indication of the sea ice thickness distribution, and could be compared to other Arctic basin-wide sea ice thickness estimations, such as those from CryoSat-2 [*Salilla et al.*, 2019].

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The ice motion and age products are continuously being improved. We plan to utilize passive microwave imagery from the AMSR2 instrument aboard the GCOM-1 satellite in a future release of the motion product, which may reduce the error in motion, due to the improved higher spatial resolution of AMSR2 over SSMIS. We also plan to further improve the age product by categorizing the age distribution in each EASE grid cell (as suggested by *Korosov et al.*, [2018]), instead of retaining only the oldest ice age. Other improvements in the sea ice motion and age products are under consideration.

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Table 1. Version histories of the sea ice motion and age products.

Version	NSIDC Release Date	Motion	Age
1	Not distributed by NSIDC	Original version based on SMMR, SSMI, and AVHRR imagery, and buoy motions	Original research product
2	Sep 2013 (motion) Dec 2014 (age)	• Added AMSR-E sources • Added NCEP/NCAR wind-derived motions for Arctic	• First version distributed at NSIDC (as Version 2) • Used Version 2 ice motion product as input
3	Feb 2016	• Removed erroneous buoy and AVHRR-derived motions • Updated buoys motions through most recent date • Derived sea ice mask from NSIDC* product instead of internally derived concentration estimates • Used GDAL** library to interpolate SSMI fields from polar stereographic to EASE grid • Improved browse images	• Used Version 3 ice motion as input • Improved browse images
4	Nov 2018	• Used highest-weighted vectors for interpolated gridded fields instead of nearest vectors • Daily buoy motions averaged instead of using latest observation • Open water buoys removed • Final quality-controlled SSMI and SSMIS brightness temperatures used throughout record • Corrected over-filtering of SSMI and SSMIS vectors that had removed valid motion • Improved browse images • Removed monthly average fields from the product.	• Used Version 4 ice motion input • Updated week-numbering convention to be consistent with motions • Improved browse images

*Cavalieri et al., 1996; **Geospatial Data Abstraction Library (https://gdal.org).

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Table 2. Temporal coverage of input source data, as of Nov. 2019. The products will be updated approximately yearly. Buoy motions are from GPS location data. *NCEP-NCAR winds are on T62 Gaussian grid, which ~100 km in the latitudinal direction, with variable longitudinal spacing.

Data	Source	Temporal Range	Source Resolution (km)	Gridded Motion Resolution (km)
Daily Sea Ice Motions	Interpolated from input data	01 Nov1978 – 31 Dec 2018		25
Weekly Sea Ice Motions	Averaged from Daily Sea Ice Motions	05 Nov1978 – 31 Dec 2018		25
Input Data	AMSR-E	19 Jun 2002 – 08 Aug 2011	6.25, 12.5	37.5
	AVHRR	24 Jul 1981 – 31 Dec 2000	5	50
	IABP Buoys	18 Jan 1979 – 31 Dec 2018	NA	NA
	NCEP/NCAR U-wind and V-wind	25 Oct 1978 – 31 Dec 2018	~100*	50
	SMMR	25 Oct 1978 – 08 Jul 1987	25	75
	SSM/I	09 Jul 1987 – 31 Dec 2006	12.5, 25	75
	SSMIS	01 Jan 2007 – 31 Dec 2018	12.5, 25	75

Table S2. Validation statistics from comparison with CRREL buoys.

	u-component (cm/s)	v-component (cm/s)
Bias		
Version 3	-0.115	-0.687
Version 4	-0.111	-0.660
Error St. Dev.		
Version 3	4.20	4.32
Version 4	3.90	4.03

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Table S3. Comparison with CRREL buoys of combined motions using different wind-speed scaling.

	u-component (cm/s)	v-component (cm/s)
Bias		
1% of wind speed	-0.267	-0.190
2% of wind speed	-0.263	-0.220
Error St. Dev.		
1% of wind speed	4.95	4.43
2% of wind speed	4.47	3.99

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Table 3. Linear trends for ice ages over three periods. The main values are for Version 4, with Version 3 values in italics on the line below. These values are for the Arctic Ocean region.

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Sea ice age	1984-2017 Trend [km²/year]	1984-1996 Trend [km²/year]	1997-2017 Trend [km²/year]
0-1	**69,200** ***(67,700)***	**96,200** ***(94,000)***	**92,500** ***(95,600)***
1-2	**10,500** ***(4,900)***	**22,100** ***(18,000)***	**4,500** ***(-3,500)***
2-3	**-4,900** ***(-7,300)***	**10,000** ***(2,000)***	**-12,500** ***(-11,900)***
3-4	**-10,100** ***(-11,200)***	**-11,400** ***(-9,000)***	**-16,100** ***(-16,700)***
4+	**-75,500** ***(-64,800)***	**-104,100** ***(-91,000)***	**-93,300** ***(-88,000)***

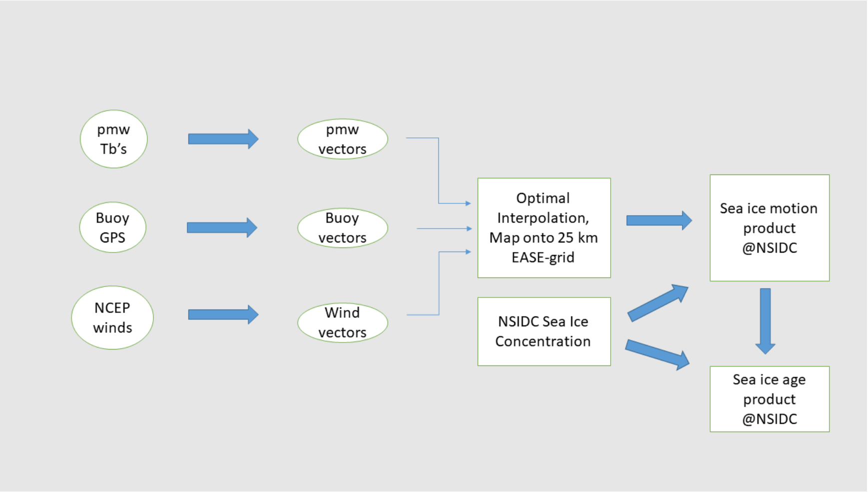


Figure 1. Flow chart for the production of the sea ice motion and age products.

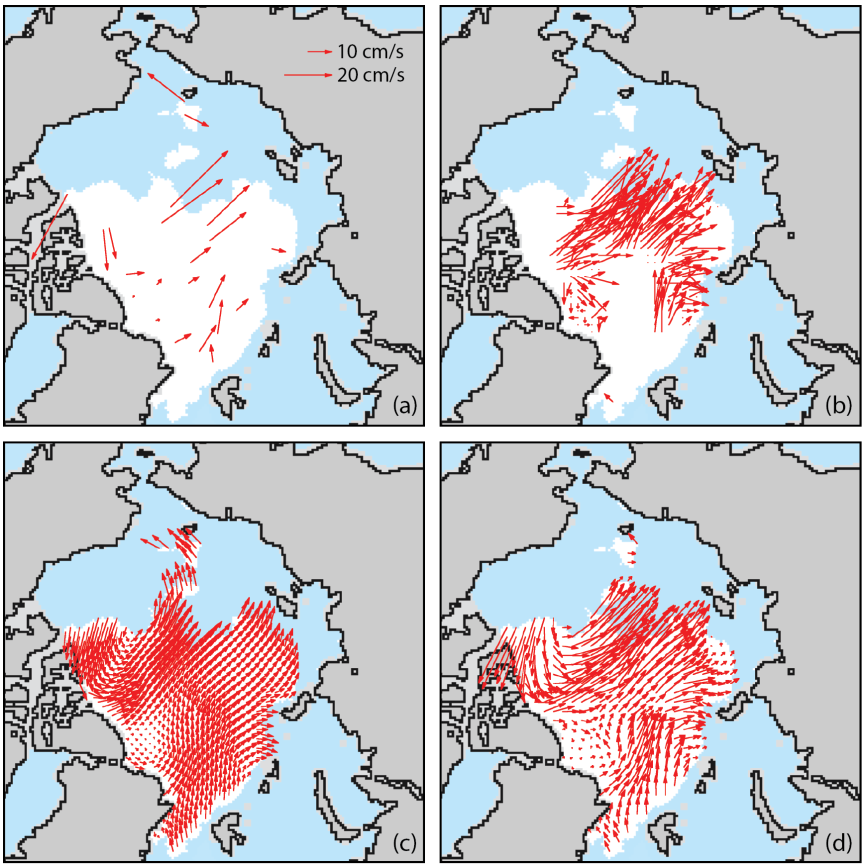


Figure 2. September 16, 2016 daily motion vectors from (a) buoys, (b) passive microwave, and (c) winds. The three sources are then merged to form (d) the daily interpolated sea ice motion field. Sea ice (white), ice-free ocean (blue), land (gray) and coast (black) are also shown. All buoys are shown, but other fields show only every 4th vector for legibility. In some years, AMSR-E or AVHRR also contribute vectors.

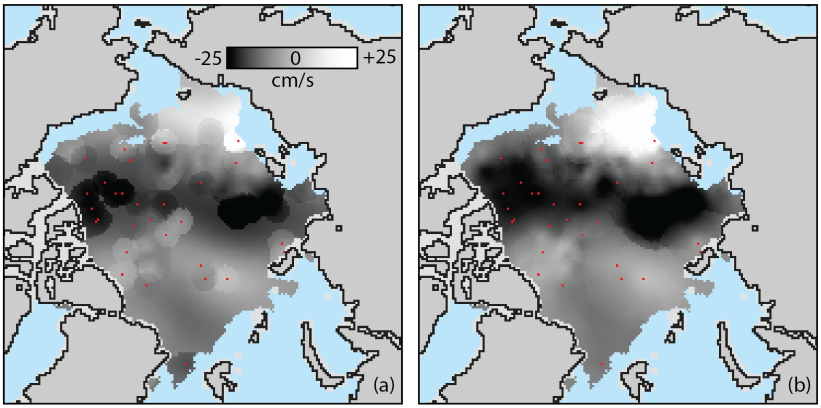


Figure 3. U-component of the daily interpolated vector field for September 17, 2001 from (a) Version 3 and (b) Version 4. The Version 3 fields show sharp gradients in the velocity when highly-weighted buoy estimates – buoy locations shown with red dots – no longer contribute to the motion field. Version 4 removes these sharp gradients by considering the highest weighted - rather than closest - underlying estimates.

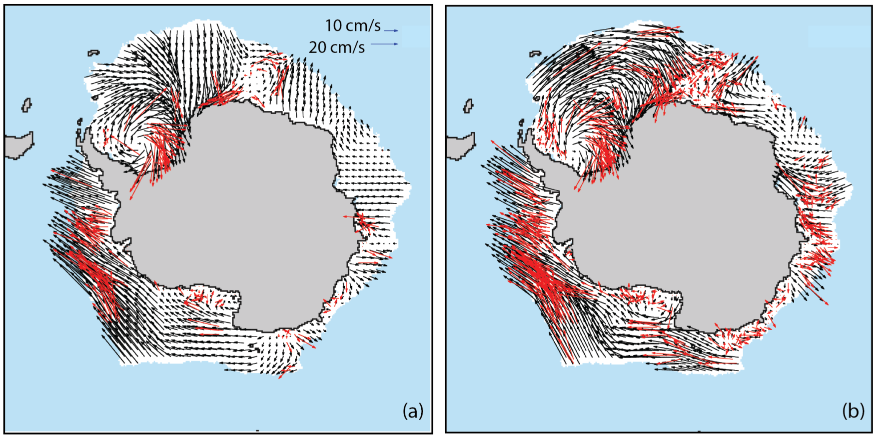


Figure 4. Version 3 (a) and Version 4 (b) Antarctic SSMI vectors (red) and resulting interpolated vectors (black) for August 22, 2001. Version 3 over-filtered the number of underlying SSMI vectors, often resulting in an ice field constructed from very sparse underlying data. Version 4 corrected this and includes more SSMI vectors. Every 4th vector is plotted for easier legibility.

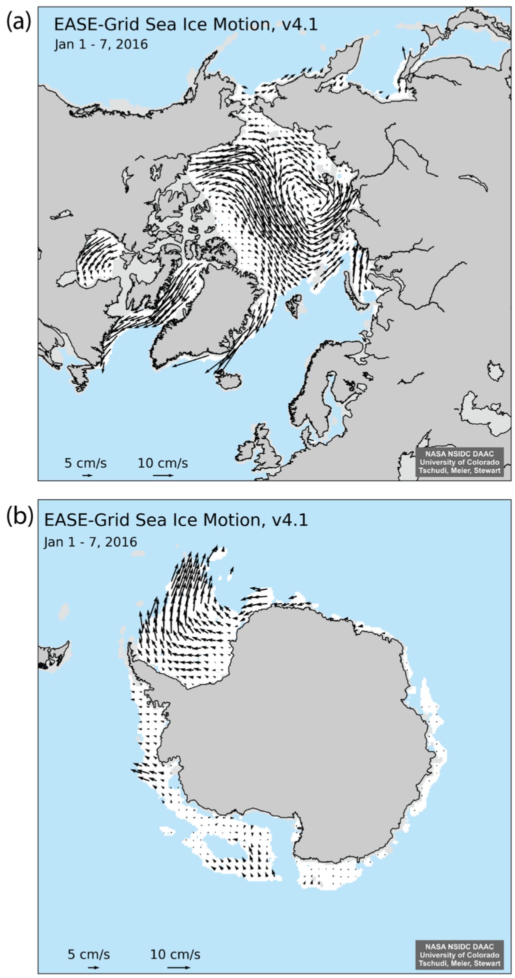
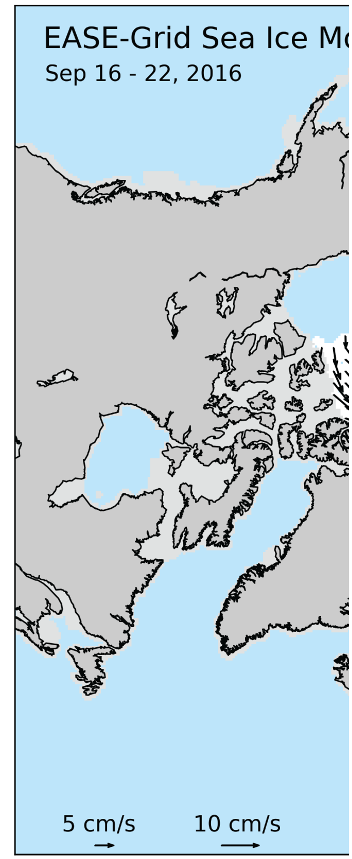


Figure 5. Example EASE-Grid sea ice motion for the Arctic region, the week of January 1-7, 2016 for (a) Arctic, and (b) Antarctic. White indicates the sea ice mask region (>15% concentration). Note that motions are not retrieved in the Canadian Archipelago region or near coasts in the Arctic. Every 4th vector is plotted for easier legibility.



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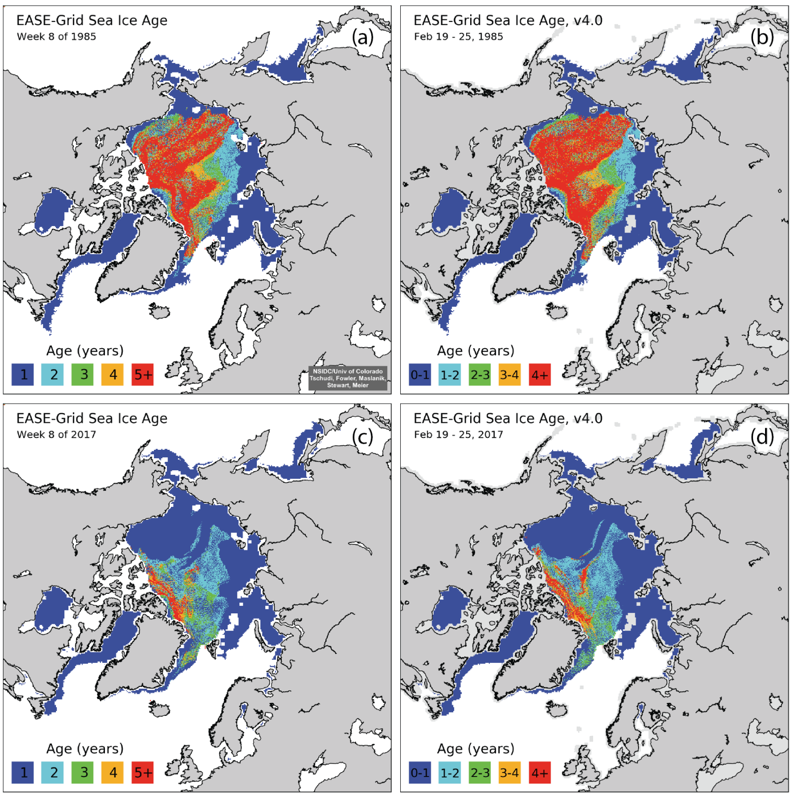

Figure 6. Comparison of Week 8 (Feb 19-25) ice ages for 1985 (a) Version 3 and (b) Version 4, and for 2017 (c) Version 3 and (d) Version 4.

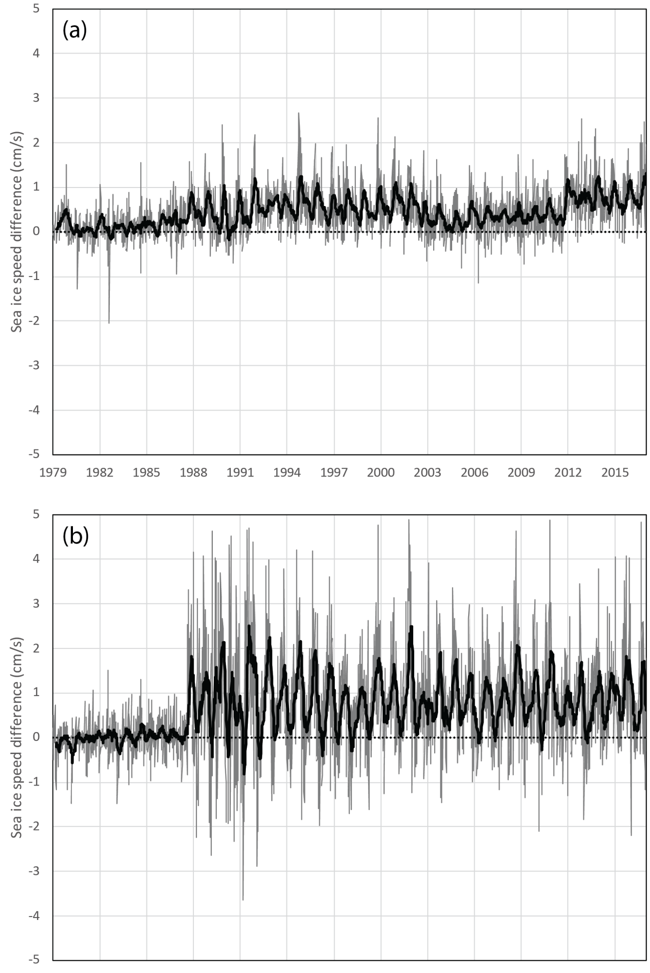

Figure 7. Arctic weekly average sea ice drift speed difference between Version 4 and Version 3 (V4-V3), 1979-2017. A 13-week running average is overlaid on the weekly values to highlight seasonal variability. The weekly average value is derived by averaging all vectors in the weekly motion field.

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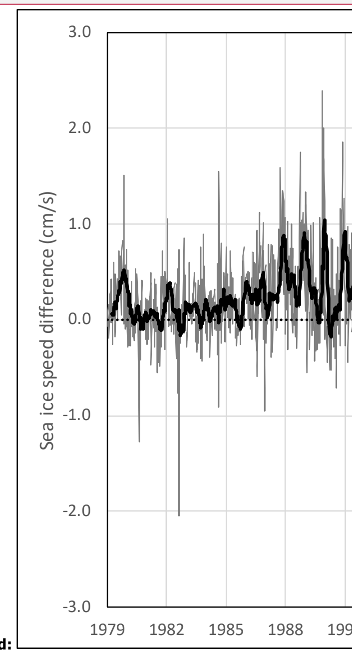

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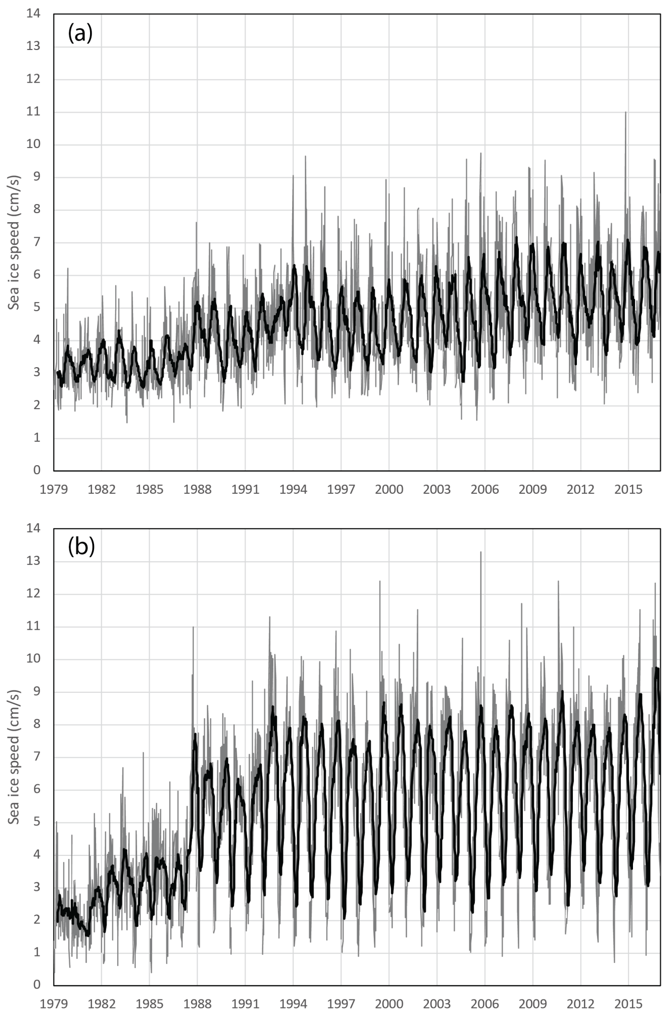

Figure 8. Arctic weekly average sea ice drift speed for Version 4, 1979-2017. A 13-week running average is overlaid on the weekly values to highlight seasonal variability.

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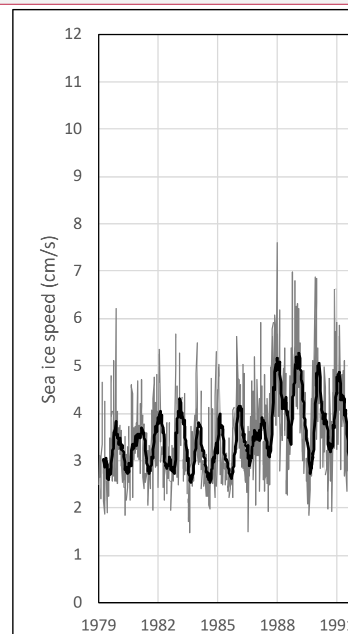

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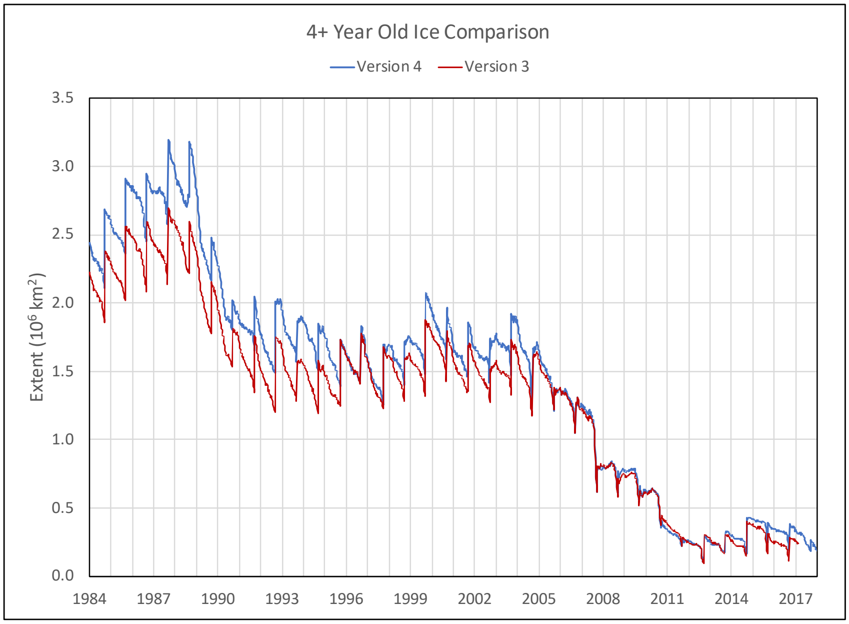

Figure 9. Comparison of 4+ year old ice from Version 3 (red) and Version 4 (blue) for 1984-2017.

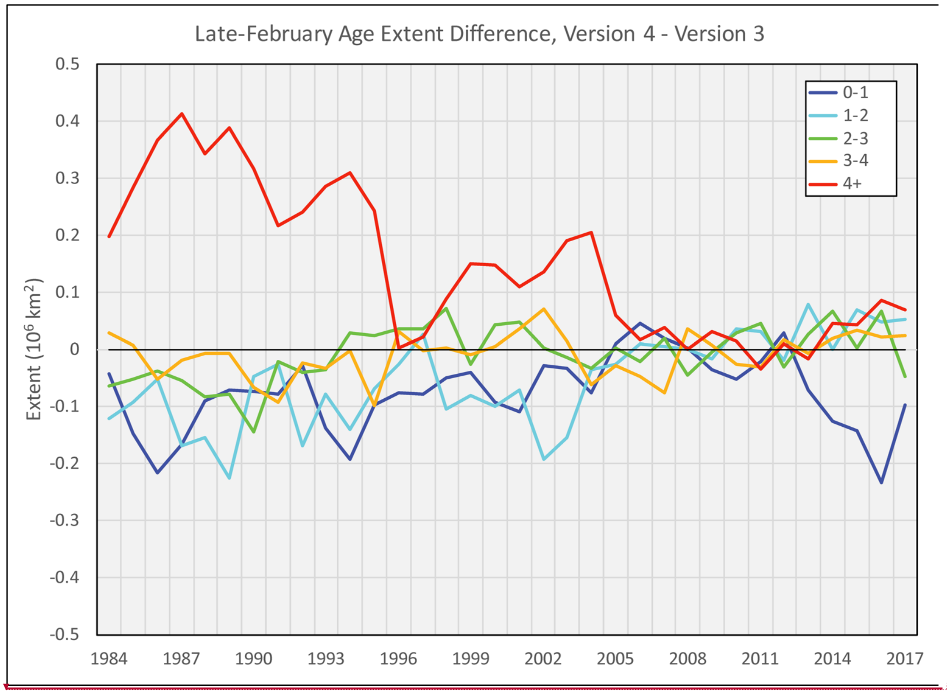

Figure 10. Extent difference between Version 4 and Version 3 sea ice age categories for the week of February 19-25 from 1984 to 2017.

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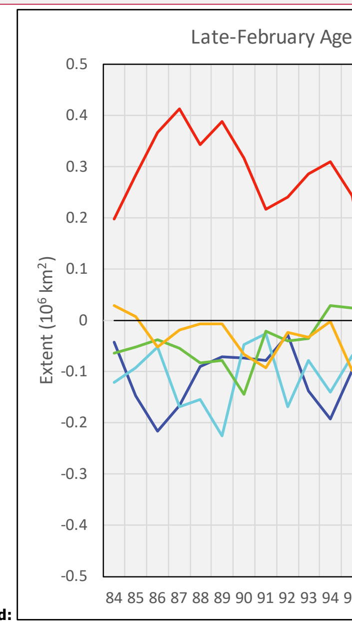

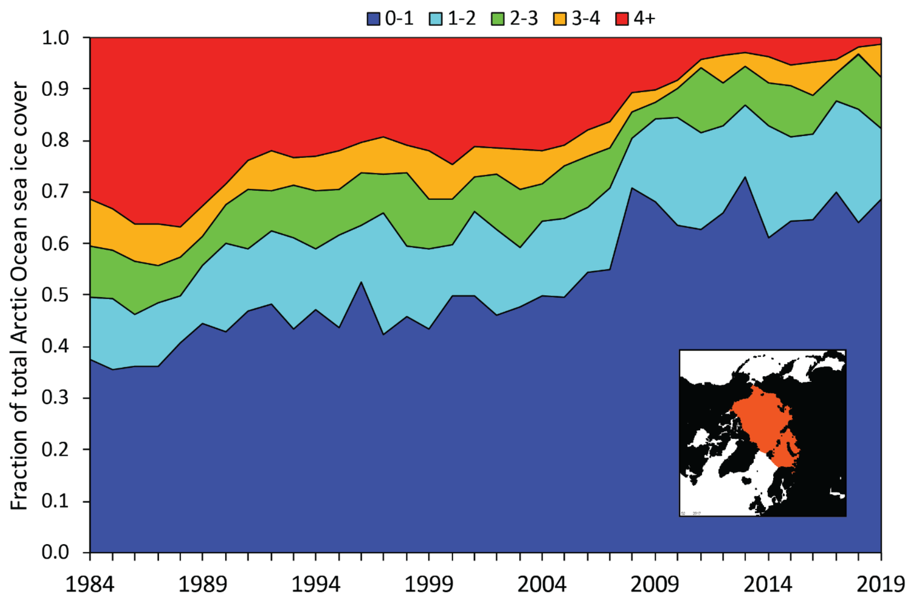

Figure 11. Timeseries of fraction of total sea ice coverage by sea ice age category for the week of February 19-25, 1984-2019. These timeseries are for the Arctic Ocean region, which is the region shaded in orange in the lower right inset image (Perovich et al., 2019), used to include only regions were MYI may exist at a non-negligible level.

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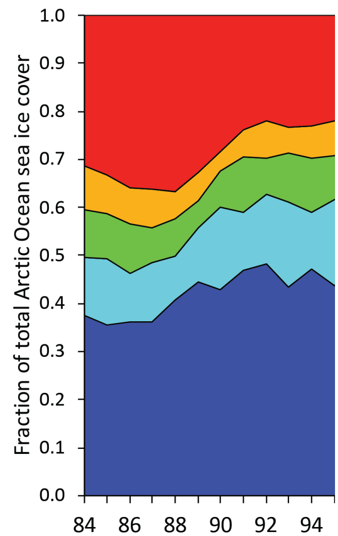

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