Reply to Referee Comment RC2

(review in black, author response in blue)

Review on "Mapping of sea ice concentration using the NASA NIMBUS 5 ESMR microwave radiometer data 1972-1977" by Kolbe et al. (2023)

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The submitted paper presents a newly developed sea ice concentration algorithm, that makes use of historic Nimbus-5 ESMR satellite data – a single (low) frequency passive microwave sensor that operated between 1972 and 1977. The new re-processed data set is intended to extend previous CDR of passive microwave sea ice observations back in time. Not only due to an often quite low data quality, with prolonged data gaps especially towards the end of the covered time period, a range of modern processing techniques, various filters steps and additional post-processing are applied to ensure a sufficient output data quality with added uncertainty quantifications. While differences to sea ice extent (SIE) estimations from other comparable OSISAF CDR seem to be rather low, i.e., showing similar magnitudes in the 70ies and 80ies, the authors mnote apparent differences (positive offset) when comparing this new data set to the older NASA ESMR SIC processing by Parkinson et al. (2004). While land mask differences seem to play a role in that context, the overall SIE differences cannot be explained to full extent at this stage, but seem to be more related to algorithm and processing issues.

The paper is nicely written and, in most parts, well-structured and easy to follow. Below, I list several parts that could benefit from some rephrasing/clarification under general and specific comments. Figures and Tables are generally good and informative, but could here and there be improved by some small tweaks, additions and potentially merging (see technical comments below).

Overall, I consider the study well worked out, so that some rather minor changes could well be sufficient to grant publication.

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General comments

- I noted several suggestions to make the figures a bit more concise below under "technical comments". While often a stylistic choice, I would consider this to be an area where the paper could easily be improved a bit – also with regard to some descriptions/discussions in sections 4 & 5.
- Please pay attention with your equations - sometimes they miss proper explanations (see specific comments below) and are quite briefly "rushed" over.
- In your "Sea Ice Concentration Product User Guide for ESMR", I noticed a processing flow-chart that didn't make the jump to this paper here. I would consider this to be a nice addition here as well.
- It would have been nice to read a bit more about the core differences between your new approach and the study by Parkinson et al. (2004). For instance, right in the introduction where it is currently just one short sentence. It doesn't need to be overly long, but it might help to get a sense on where algorithm-related differences might originate from, without having to read the full Parkinson et al. study first.

- As already mentioned in RC1, I also got the impression that sub-sections 3.1 to 3.3 do not necessarily relate to a section entitled "The radiative transfer model". Hence, I agree to think about an alternative way of naming / subdividing section 3.

Thank you very much for your useful comments and input. All comments have been accepted (see detailed answers below and the new manuscript). Only the processing flow-chart from the Product User Guide (PUG) has not been added to the paper, instead a reference to the PUG has been added to the manuscript:

L.185/186 " A flow-chart illustrating this processing chain can be found in the ESA CCI ESMR product user guide (PUG) (ESA CCI, 2022)."

Regarding the differences between our approach and (Parkinson et al.,2004): We have clarified in the manuscript, that the following paragraph in the introduction is describing the difference between their study and our methods:

L.46-49 "**Compared to (Parkinson et al., 2004),** this method reduces atmospheric noise regionally over both ice and water surfaces and uses the pre-processed data to develop a SIC algorithm calibration that is effective in removing both instrument drift and offsets. Seasonal sea ice signature variations are removed by using dynamical tie-points. Lastly, the algorithm calculates time and spatially varying uncertainty estimates."

Specific comments/questions

Introduction (Sect.1)
L.26: I'm sure the references are picked on purpose here, but it seems like a rather long list for this single statement? Is it worth to point out the key differences among those studies here?

The references have been chosen to show that this trend of SIE decline can and has been observed from different observations and data products through time. The chosen references describe data sets of various data sources with different algorithms and trend analyses. We have now separated the dataset and trend analysis references, to better highlight differences between them. The beginning of the introduction has been rewritten to:

L.25-29 "Several sea ice concentration (SIC) algorithms have been developed for passive microwave data (PMW), differing in the usage of e.g. frequencies and polarizations of the PMW data (Comiso et al., 1997), or the usage of static or dynamic tie-points (Parkinson et al., 2004; Tonboe et al., 2016; Lavergne et al., 2019). From the resulting data sets, it becomes apparent that the arctic sea ice extent (SIE) in September has been decreasing at a rate of about 12 percent per decade since the launch of modern satellite multi-frequency microwave radiometers in 1978 (Onarheim et al.,2018; Stroeve and Notz, 2018). "

Instrument & Data (Sect.2)

L.56-68: Reference(s) missing for all these platform / sensor specific information.

Thanks for bringing this to our attention, these references have been added.

The technical details have been taken from the Nimbus-5 User Guide (NASA GSFC, 2016) and the ESMR NSIDC Polar Gridded Brightness Temperatures v2 user guide (Parkinson et al., 1999). (https://nsidc.org/sites/default/files/nsidc-0077-v002-userguide.pdf) , for which a new reference has been added. The other information has been acquired from the data itself.

L.58-68: "The NIMBUS 5 ESMR instrument was a cross-track scanner measuring at 78 scan positions perpendicular to the flight track with a maximum incidence angle of about 64 degrees to both sides **(NASA GSFC, 2016)**. No direct observations at nadir have been made, the closest positions being at +/- 0.7 degrees. The near circular orbit height was about 1112 km with an inclination of 81 degrees. The phased array antenna dimensions was 85.5 x 83.3 cm and the spatial resolution about 25 km near nadir increasing to about 160 x 45 km at the edges of the swath **(NASA GSFC, 2016)**. The full swath was about 3100 km with varying incidence angle and spatial resolution giving a very good (unprecedented) daily coverage in polar regions with no gaps, i.e. no pole holes. The ESMR onboard the NIMBUS 5 satellite was a one channel 19.35 GHz horizontally polarised microwave radiometer operating from 11. December 1972 until 16. May 1977 (1617 days) with some interruptions (see list of days with missing files in Appendix A2). Due to a hot-load anomaly, there are major data gaps between March to May and again in August 1973. Another major data gap occurred from 3 June 1975 until 14 September 1975 because the ground segment was used for receiving Nimbus 6 data instead **(Parkinson et al., 1999)**."

L.77: "…and appended to a NetCDF file, …" – it is the same file as the satellite parameters, this could be phrased a bit clearer.

Thanks for pointing this out, it has now been clarified in the manuscript. Yes, the co-located ERA-5 values are added to the raw ESMR NetCDF files, used as input for the SIC processing.

L.78-81 "All variables in the TAP files were read using online NASA software and converted to NetCDF format without changing the original data structure**, creating raw ESMR NetCDF files**. Each data point in the TAP file was matched with European Centre for Medium Range Weather Forecast (ECMWF) ERA5 re-analysis data (**Bell et al., 2020;** Hersbach et al., 2020) in time and space (nearest) and appended to **the raw** ESMR NetCDF file, serving as input to the processing chain."

L.107 (Eq.2): "n" not explained in the following

An explanation has been added:

L.113-114 "n is the maximum across track index of a row, i.e. for a complete row with valid data points for all 78 incident angles n = 78."

L.110 (Eq.3): Was the threshold for Tb outliers (150 K) also experimentally estimated or was it chosen arbitrarily?

L.117-118 "The threshold of 150K was selected manually after identifying erroneous single pixel outliers in the data."

L.111 / Eq.4: There are some explanations for this equation missing (size of the search window & effect of varying it; meaning of ≠ 0)

Thanks, this was also noted by reviewer 1. If Eq.4 is satisfied, i.e. not equal to zero, the data is kept. We revised the filter section and added explanations to the manuscript.

Regarding the size of the search window, the choice of comparing 7 consecutive TBs is based on qualitative experiments, after obviously corrupted data was found by plotting the raw swath data. The search window shall ensure that the filter only finds points where the observations are corrupted, so that the values do not change at all for consecutive points in

the along track direction. All decimal values are taken into account, though the ESMR TBs are only provided with one decimal, so several points are needed to cover a long enough distance to make sure that the constant TB value is not caused by the observed surface. We would expect the TBs to at least vary slightly for points that are a few hundred kilometres apart. Since this filter is used universally for all incidence angles the smallest distance occurs at the incidence angles closest to nadir, where a sufficient number of neighbouring points are needed to make sure that the non-variant TBs are not natural.

L.121-123 "The choice of comparing 7 consecutive TBs is based on qualitative experiments. Since the filter is used universally for all incidence angles, the search window varies but covers a minimum distance of 175 km."

Radiative transfer model (Sect.3)

L.145 (Eq.7): Careful with the second use of "p". Although different from earlier uses as "p_i" as single pixel indicators, it might be confusing for the reader and should, for instance, be augmented by an additional explanation of "p" and "q" in Eq.7.

Thanks for pointing this out, we added a clarification that p & q are abbreviations in equations 6-8:

L.153 "where p and q are abbreviations for:"

L.182: Please provide more details on the ERA5 OSTIA SIC, as they are quite crucial for the selection of tie points (affecting SIC thresholds and presumably also distance to the ice edge). Further, how is the distance to the ice edge defined, and where/how is this criterion depicted in Table 2?

Thank you for bringing this to our attention, this was also noticed by reviewer 1. ERA5s SIC prior to 1979 comes from the Met Office's HadISST2.0.0.0 product. We agree that this is important information, and have included it to the tie-point section of the manuscript:

L.195-199 " The ERA5 SIC prior to 1979 is based on the HadISST2.0.0.0 data set (Bell et al. 2021), which mainly utilizes digitized sea ice charts for this period (Rayner_et_al_2003). The two main data sources are the Walsh data set (Walsh, 1978; Walsh and Johnson, 1979; Walsh and Chapman, 2001) and National Ice Center (NIC) charts (Knight, 1984). The data sets also consist of several data types besides ice charts, e.g. ship observations and satellite data, both infrared and microwave observations, including data from ESMR. "

Sources:

[Bell et al. 2021] https://doi.org/10.1002/qj.4174 Describes the ERA5 preliminary back extension and states that the used ERA5 utilizes SIC from the HadISST2.0, which is similar to HadISST1.1 described in [Rayner et al., 2003].

[Rayner et al., 2003] https://doi.org/10.1029/2002JD002670 describes HadISST1 and its data sources, which mainly consists of the digitalized sea ice charts of the Walsh dataset [Walsh, 1978; Walsh and Johnson, 1979; Walsh and Chapman, 2001] and National Ice Center (NIC) charts [Knight, 1984].

[Knight, 1984] https://doi.org/10.3189/1984AoG5-1-81-84 talks about NIC/JIC data, which also uses satellite data in their analysis, both visible/infrared and microwave data, including the ESMR data.

[Walsh, 1978] Walsh, J. E. 1978. A data set on Northern Hemisphere sea ice extent, 1953-76.World Data Center-A for Glaciology, Boulder, Colorado, Glaciological Data Report GD-2, p. 49-51

[Walsh and Johnson, 1979] https://doi.org/10.1175/1520-0485(1979)009%3C0580:AAOASI%3E2.0.CO;2

[Walsh and Chapman, 2001] https://doi.org/10.3189/172756401781818671

Regarding the distance to the ice edge criteria: This is not imposed as a distance threshold, but as the "mean sea ice concentration (ERA5) of a 5 x 5 grid point box" shown in table 2, which for ice should be >0.8 and for water tie points <0.01 .

We have added a clarification to the manuscript:

L.201-202 "The distance from ice edge criterium is imposed by putting a threshold on the mean SIC of a 5 by 5 grid point box, which for ice tie points should be larger than 80% or less than 1% for open water points. "

Fig.3: Add data source to caption.

We added ERA5 as the data source for the water vapor to the caption:

Fig.3: "Water vapor data from ERA5 (Hersbach et al.,2020)."

L.200: Add data source for T2m data.

ERA5 was added as the data source in the text:

L.225 "where T2m is the 2 m air temperature, which is taken from the ERA5 data."

Results (Sect.4)

L.267: "This is a consequence of the one channel SIC algorithm." – Can you comment more on this effect? Is there any way / idea to correct for this?

Single channel SIC algorithms have an inherent ambiguity between SIC, ice type and temperature variations. While a single frequency can be enough to detect the difference in surface emissions caused by different physical properties of sea ice, it is challenging to accurately distinguish whether these are caused by differences in ice type, temperature or SIC. This results in e.g. the underestimation of the multiyear ice (MYI) SIC.The focus in this first version of the dataset was on the first year ice (FYI) and marginal ice zone, to be able to estimate a sea ice extent. While the SIC of the MYI is underestimated, it is still above the threshold for the sea ice extent. To improve the SIC of the multiyear ice, additional information like the sea ice type are necessary to improve the algorithm, so that e.g. tie-points can be calculated for FYI and MYI individually, to improve the calculated SIC.

L.292-294 " This is a consequence of the one channel SIC algorithm, which has an inherent ambiguity between SIC, ice type and emitting layer temperature variations. "

L.267/268: Uncertainties are also high along the coastal margins, especially at lower latitudes. Might be worth to mention and explain.

This is a good point and has been added to the manuscript. Coastal regions show also higher uncertainties for the same reason as around ice edges, since the land-spill-over correction is first applied to the SIC after the uncertainty estimations.

L.295-297: "Coastal regions also show higher uncertainties for this reason, since the land-spill-over correction is first applied to the SIC after the uncertainty estimations."

L.270-272: As noted under technical comments below - hard to locate for readers that are unfamiliar with the geographical setting of one or the other hemisphere. Simple lat/lon indications could help (when present on the maps), or alternatively, a regional close-up figure (daily level? Could then even feature other parameters from the data set, such as uncorrected/corrected brightness temperatures).

Thanks for pointing this out, we have added lat/lon indications to all map plots and added coordinates to the text, as well as some references to papers describing these areas.

L.298-301 "One such feature is the Odden ice tongue **(Comiso et al., 2001)** extending eastward from the East Greenland Current, visible in figure 6 **(around 73°N, 0°E)**, while another feature is the Maud Rise Polynya **(Jena et al., 2019)**, an open water area encircled by sea ice, in the Southern Hemisphere, which can be seen in figure 7 **(around 65°S, 0°E**)."

L288: "For the Northern Hemisphere the SIE seems to have been slightly lower during the operational period of NIMBUS 5 ESMR 1972 to 1977 than during the operational period of NIMBUS 7 SMMR from 1978 to 1987."
– To me & purely based on Fig.14, max. values in winter seem to be more or less similar, while the two available min. values in summer are seemingly even slightly higher than in the 80ies. Am I wrong?

Thank you very much for bringing this to our attention, the description has been corrected:

L.316-318 "For the Northern Hemisphere the SIE seems to have been similar in magnitude during the operational period of NIMBUS 5 ESMR 1972 to 1977 as during the operational period of NIMBUS 7 SMMR from 1978 to 1987, with the ESMR minimum extents being slightly higher than the SMMR ones."

Discussions (Sect.5)

L.300: Is it possible to illustrate this with an example? I.e., where do the land masks differ the most?

Thanks for bringing this up, as we previously hadn't investigated the different NSIDC land masks further, since no ESMR land mask file is available. We contacted NSIDC, who haven't made a specific comparison between the ESMR and CDR land masks themselves, but they can report that the source data is the same for both of them and there might be some small differences due to the re-gridding process.

A special report has been published last year, focusing on the evolution of NSIDC's land/surface masks: https://nsidc.org/sites/default/files/documents/technical-reference/nsidc-special-report-25.pdf

Consequently, we have taken out the statement about the NSIDC land masks and rewritten the paragraph:

L.321-327 "Comparisons between different sea ice products and the new ESMR data set proved to be more difficult than initially expected, since not only the processing algorithms

differ, but also the land masks**, map projections and data set grids**. We were not able to find two independent SIC data sets for 1978 onwards and 1972-77, which share **exactly** the same land mask.

Thus, it was decided at the beginning of the processing to use the same land mask as the OSI-420 product (1978 onwards) (EUMETSAT, 2020) for our ESMR data set, i.e. a 25 km equal area grid (EASE-2 version 2) land mask, to at least ensure a fair comparison between these two data sets. The NSIDC ESMR data set (green line in figure **9**) used a different land mask with a polar stereographic projection (Parkinson et al., 2004)**, but was still compared to our ESMR data set. **"

L.325: You mention a planned reprocessing of some sort to increase the number of rescued data points. Do you already have concrete ideas on how you intend to do that?

There are two approaches to improve the data selection during the next processing.

One approach is to change the set of filters, which have been used to remove erroneous data. The filters used in this first time processing have been very strict and used universally (e.g. for all incidence angles in the same way). Therefore, an adjustment of the filter thresholds, usage of different filters, or incorporation of incidence angle dependency could improve the data selection.

Another approach is related to the calibration of the data. Systematic erroneous data has been identified, where whole swaths of data could potentially be rescued by a re-calibration with a new look-up table across the swath.

We added the following to the manuscript:

L.352-356 "There are two approaches to improve the data selection during the next processing. One approach consists of changes to the set of filters, i.e. an adjustment of the filter thresholds, testing of different filters and a possible incorporation of an incidence angle dependency to the data selection.

The other approach is to recalibrate some of the erroneous data files, which have shown some systematic offsets, to rescue whole swaths. "

L.330: Can you name some examples for "related snow and ice processes" that are causing the noise over sea ice? How about atmospheric effects over sea ice that also trouble other widely used SIC algorithms?

The measured brightness temperature can be influenced by sea ice deformation, leads or ridges of the ice. Additionally, snow cover can have an impact as well (which varies depending on the snow depth, snow density and grain size) There can also be meltwater within the snow layer, which influences scattering and emission processes inside the layer. Especially during summer melt and refreezing processes can therefore result in noise of TB measurements.

Atmospheric noise caused by e.g. water vapor and cloud liquid water exists also influences the TB over sea ice, but its influence is smaller (around ⅓ of the total noise [Tonboe et al.,2021]) compared to the geophysical noise from the snow and ice properties.

[Tonboe et al., 2021] Tonboe, R., Nandan, V., Mäkynen, M., Pedersen, L., Kern, S., Lavergne, T., Øelund, J., Dybkjær, G., Saldo, R., and Huntemann, M.: Simulated Geophysical Noise in Sea Ice Concentration Estimates of Open Water and Snow-Covered

Sea Ice. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing. PP. 1-1. 10.1109/JSTARS.2021.3134021, 2021.

We added the following to the manuscript:

L.361-365 "Such processes include sea ice deformation, creation of leads or ridges, as well as changes in the snow layer of e.g. snow depth, snow density and, grain size, but also melting and refreezing, which influences scattering and emission processes inside the layer. Atmospheric noise caused by e.g. water vapor and cloud liquid water influences the TB over sea ice, but its influence is smaller, only around one third of the total noise (Tonboe et al., 2021)."

Technical comments

L.82: Brackets around reference missing (NASA CR, 1974)

The brackets around the reference have been added. (now L.85)

L.100: "a value of 10" – unit missing

We would like to add units, but this is referring to the analog signals of the raw ESMR data, for which the ESMR Nimbus-5 User guide does not provide units and only calls them "voltages of engineering interest" (page 83, https://ntrs.nasa.gov/api/citations/19740020209/downloads/19740020209.pdf).

We therefore added the following to the manuscript:

L.101/102 "The **NIMBUS 5 ESMR** user's guide **(Sabatini, 1972)** does not explain very well what the 16 entries really are**, or what unit the voltages are stored in,** but jumps in these analog signals correspond to anomalous TBs. "

Figures 2, 3, 4 & 5: Similar to other line plots, the addition of grid lines could help to make out differences more easily.

Grid lines have been added to these figures.

Figure 4 & 5: Smaller points could help to reduce the large red "cluster-patches". Further, the captions read more like notes, this could be improved by using proper phrases. Lastly, Fig.4 & 5 could be combined into one Figure 4 (a & b), just to spare two almost identical captions next to each other.

Thanks for the suggestions, the figures have been updated accordingly. Due to the smaller points the individual lines corresponding to the different incidence angles (scan positions) have also become visible. Point size and opacity have been tuned, there is still some cluttering, but even smaller sizes would make the less populated areas more difficult to read (this is of course up to personal preference). The cluttering around the zero line remains and is something the plot is intended to show.

Figure 6 & 7: As before - could be combined into one Figure (a & b) to spare two almost identical captions next to each other.

Figure 6 & 7 have been combined into one Figure 5 (a & b).

L.219-225: Steps 1) and 2) could be formatted as bullet points, thereby reducing potential confusions with the numbers just before point (2).

The text has been re-formatted.

L.246-252 "

1) The c_ice is first estimated using uncorrected TB s and tie-points derived from uncorrected data. The c_ice estimate is truncated to the interval between 0 and 1 and an open water filter is applied, forcing all c_ice values less than 0.15 to 0.

2) The c_ice estimate from step (1) is used in the RTM calculation (Eq. 5) together with ERA5 data for the geophysical noise reduction of the TBs and c_ice is then estimated again in a second iteration, this time using corrected TBs and corrected tie-points. The mean values of V, W, L... used in the reference simulation is a weighted average with c_ice of the mean water and ice tie-point values respectively, i.e. c_ice is used as a ratio to mix the two tie-point values to create mean values of the NWP data for any sea ice concentration."

L.254-255: Double use of "also".

The first "also" was deleted. (now L.281/282)

Figures 8-13: Multiple comments/suggestions

- Size of individual panels could be increased
- Geographic references are missing in all panels – e.g., thin lat/lon lines could be added
- Is the wide spatial extent of the maps chosen on purpose or would it make sense to zoom in a bit, sparing some lower latitude regions?
- Monthly mean SIC & uncertainties could be combined in merged Figures (a & b)

Thank you for your suggestions, we adjusted all figures following your advice. Regarding the wide spatial extent, this was chosen on purpose to show the large extent of the dataset and to act as geographic reference for experienced readers. Since we added lat/lon lines now, we have zoomed in slightly, but are still showing most of the dataset.

L.280 & 283: "threshold of 30%" – better write s.th. like "c_ice ≥ 30%"

The threshold is now being referred to in the text as: "a threshold of c_ice > 30%" in L.299 & L.301/302.

Figure 14 & 15: As before - could be combined into one Figure (a & b) to spare two almost identical captions next to each other. Plus: be more specific with the thresholds: "… a 30% sea ice concentration (SIC) threshold…" and further "…, where the 30% SIC-threshold has been applied".

The figures have been combined into one figure, with changes as in L. 308 & L. 301/302 in the caption.

L.308 "...mean SIE are calculated using a threshold of c_ice > 30%"

L. 311-312 "...using the same threshold for all products (c_ice > 30%)."

L.348 / Section 6: reads more like a Summary and is quite short. One could think about merging this part with section 5 as a "Discussions & summary" chapter, but this is certainly personal taste.

Thanks for the suggestion. We changed section 6 in response to referee response #1, and therefore we chose not to merge it with the discussion section in this revision.

Table A1 (Appendix A): Under "ERA5 variables", I think there is an error with u10m / v10m and their latitude / longitude reference.

Thanks for bringing this to our attention, this has now been corrected.

Table A1:

u10 - u component of the wind speed at 10 m (parallel to **latitude**) [ms−1]

v10 - v component of the wind speed at 10 m (parallel to longitude) [ms−1]

Dataset entry on CEDA archive: The document "Algorithm Theoretical Basis Document (ATBD) - ESMR Sea Ice Concentration" is currently not accessible from the ESA website. Has it been moved?

Thank you for pointing this out, this was an error on the homepage and it has been fixed.

The ATBD (and other ESMR documents) are also available through the ESA Sea Ice webpage: https://climate.esa.int/en/projects/sea-ice/Sea-Ice-Key-Documents/