1 Reviewer 1

Relevance of warm air intrusions for Arctic satellite sea ice climatologies

Rostosky and Spreen

This paper investigates the impact of Arctic warm air intrusions (WAIs) on four passive microwave sea ice concentration products. To complete this analysis, the authors developed a methodology to detect WAI events from ERA-5 reanalysis temperatures and classify their intensity into three categories. Results show that the most extreme warm air intrusions reduce sea ice concentrations in most data products leading to an underestimation of sea ice area within the affected area of 2-4%. Further, the authors demonstrate a non-significant (due to high interannual variability) increase in the frequency of WAI events with a peak occurrence of the most severe events in April.

I think this paper makes a good contribution to the literature and makes the case that these WAI events have a significant impact on passive microwave sea ice concentration retrievals, the effects of which are expected to increase due to climate change. The analysis is thorough and appropriate for publication in The Cryosphere. I do think the paper would be improved with minor revisions to clarify some points of the methodology as I describe in my comments below.

We thank the reviewer for their positive and helpful comments. We believe that, thanks to these reviews, the manuscript has improved a lot. Please find below our responses to the individual comments. Note that Reviewer 2 pointed out that an updated version of the OSI-SAF CDR (OSI-450-a, version 3) is available. In the revised version of the manuscript, we updated our analysis using the OSI-450-a. While some numbers slightly changed, the outcome of this study remains the same.

General Comments

"... climate data records (CDR) and provide a stable time series of more than 40 years." (L68): Other SIC data sets that are not CDRs also provide stable, long time series. The big thing that differentiates the NSIDC CDR from, for example, NASA-generated SIC products is that as a CDR, the NSIDC product does not involve any manual corrections that cannot be reproduced exactly by the code. This is the important distinction that defines how a CDR is different from any other long data time series. For this study, I don't think that the distinction between CDRs and other time series of SIC is as important as the text would indicate.

We thank the reviewer for this valid point. We will reformulate the description of the CDRs and clarified their relative importance for this study. We e.g., will add
"CDRs are designed to provide consistent, reproducible long-term timeseries of climate variables. Long term sea ice concentration is also provided by e.g., the NASA-Team algorithm which is frequently used and is part of the NSIDC CDR."

"... the NSIDC CDR benefits from including the Bootstrap algorithm..." (L324-325): I was waiting for this point to be stated throughout reading the whole paper, but it does not appear until the very last paragraph and is only one sentence. I think a slightly longer explanation for the reason why the NSIDC product is performing better than the other is necessary for the readers especially since the NASA Team algorithm (from within the NSIDC CDR) performs very differently than the NSIDC CDR throughout your analysis. Specifically explain (1) that the NSIDC CDR SICs are primarily sourced from the Bootstrap algorithm during the WAIs and (2) some details on how the Bootstrap algorithm avoids the extreme sensitivity to the WAI events seen in the other algorithms (e.g., daily dynamic tie points, etc.). Point 2 would explain the "why" for point 1. This discussion should be moved to Section 5, and not be introduced in the conclusions.

We will introduce the Bootstrap algorithm in the data section and will add a paragraph about the performance of the NSIDC CDR in the discussion section
"Since the NSIDC CDR is less influenced by warm air intrusions, it is worth discussing the reason for its performance. The

NSIDC CDR is computed from the NASA-Team and Bootstrap algorithms. The CDR sea ice concentration is based on the sub algorithm with the higher sea ice concentration, which, in case of strong warm air intrusions, is the bootstrap algorithm (since the NASA-Team shows a strong underestimation of sea ice concentration during warm air intrusions). In the NSIDC CDR, an updated bootstrap algorithm with dynamic (daily adapted) tie points for open ocean and full sea ice cover is used (Comiso et al., 2017). By using dynamic tie points the impact of changing snow and surface conditions are mitigated and thus the impact of warm air intrusions on the derived sea ice concentration is reduced."

I suggest that the authors consider moving the algorithm details from appendix A1 and A2 to the methodology (section 3). As it is now, neither section 3 nor the appendices are complete descriptions of the method, and some information is repeated in both places.

We agree with the reviewer and will merge the appendix A1 and A2 with section 3. In addition, we will restructure parts of section 3 to improve its readability

Specific Comments

L99: Here you state that you use the daily maximum 2m air temperature, however, throughout the rest of the paper you only refer to 2m air temperatures. These are not the same. I suggest changing your wording when mentioning 2m air temperatures to clarify that it is the daily max 2m air temperatures instead.

We will now always refer to the daily max. 2 m air temperature

Figure 2 and L147-157: There is 10 days difference between the max loss days between the NSIDC and other three algorithms. Why is this the case when the peak temperature is 19 April? The max loss dates from case 1 (Figure 1) are much closer (only 1 day difference). Can you add some commentary to this paragraph explaining why case 2 has a much longer time difference in max loss days?

Figure 2 highlights the case that the maximum of sea ice underestimation does not necessarily occur on the the same day as the maximum of the warming. A unique feature of this particular warming event was the formation of large scale surface glazing happening after the warming event (refreezing). Details are described in Rückert et al 2023 (submitted), the study is available here: https://doi.org/10.31223/X5VW85. Note that the NSIDC CDR is almost not affected by this WAI (at category 2) and thus the date of maximum sea ice reduction is not meaningful for this algorithm. Also for Figure 1, the day of maximum loss is not that meaningful for the NSIDC retrieval since the loss is overall very low. We therefore mainly focus on the day of the three other algorithms. We will add
"In both examples, the day of minimum sea ice concentration is consistent within the products except for the NSIDC algorithm. However, the overall sea ice concentration reduction for the NSIDC CDR is very low and thus the result are less meaningful for the NSIDC retrieval."

Comments on Appendix A1: (L347) How many days are between the “new and previous warm air intrusions”? If I understand the procedure correctly (L346-349), there can only be one WAI event detected in any 5-day period? Is that correct? If that is not the case, I need more clarification as the schematic in Figure A1 is not very detailed. Why is a 65% SIC threshold (L343) chosen for the ice edge mask. Is it arbitrary or based on some other knowledge? How often does the SIC need to drop below 50% to be masked as a polynya (or how many times is “frequently”? L344)?

The algorithm detects any number of warm air intrusions within the 30-day window. The 5-day period is referring to the time difference between the "new and previous" WAI. Note that the similarity check compares each newly detected WAI with each previously detected WAI. We reformulated the paragraph and hope that it is more clear in the revised version. For example, we will add
"The algorithm can detected several not-connected warm air intrusions. If their borders are separated by 2 pixels (= 50 km)

or less, the intrusions will be merged.".
In L352 to L355 (original manuscript) we describe how the 5-day window method is applied
"In this study, the algorithm is applied for the winter season November – April. With a 5 day time step, in each iteration, 30 days of T2m and SIC are analyzed"
Using 65% as the ice edge detection is somewhat arbitrary. We noticed that analyzing all WAIs, the OSI-SAF SIC never drops below 65% in the affected areas in the central Arctic. Thus this number seemed to be a fair compromise excluding the ice edge where the SIC is generally low and including most of the WAI events. We will add
"By analyzing all warming events, we found that the sea ice concentration in the Central Arctic from the OSI-SAF algorithm never drops below 65% in the areas affected by an WAI. Thus, this number is a good compromise in order to include as many warm air intrusions as possible while reducing the effect of a moving ice edge on the results." to the manuscript.
For the polynia mask, we analyzed 40 years of winter (January - February) SIC and then masked the areas where the SIC was 15% of the times below the threshold of 50%. We only applied this analysis close to the land areas. We will add
"or the polynya mask, we analyzed 41 years of winter (January and February) OSI-SAF sea ice concentration and masked out areas where the SIC frequently ($>$ 15% of the days) dropped below 50% while the ice edge was far away."

Comments on Appendix A2: (L364) I assume you are accumulating the area representative of the daily SIC difference from the background SIC over the duration of the WAI event, but you don't specifically state how you compute the effective area loss shown here. Please state specifically how you compute effective area loss. (L369) Is there an average length of WAI events? How was 10 days after the peak warming day chosen? I think revising such that the appendices and the methods are in one section can help with clarifying the above questions.

L364: Yes, the effective area loss is the sum over the all influenced days (red line in Figure A3). We will add a more detailed description to the manuscript
"The maximum affected area by this warm air intrusion was around $2 \cdot 10^6$ km^2. The average sea ice concentration is above 99% before and after the event and drops to 95% during the warm air intrusion (red). The resulting effective area loss, i.e., the sum of the differences between SIC reduced and the average reference SIC, is $6 \cdot 10^5$ km^2 over the whole red period (16 days) or $\approx$2%/day."
L369: This sentence was not clear enough formulated. The 10 days is referring to the day of maximum SIC reduction and not the temperature peak. We reformulated it to:
"If the latter does not apply, the end of the affected period is set to 10 days after the maximum of the SIC reduction. 10 days was chosen by manual analyzing several detected warm air intrusions. We found that most of the times, after 10 days, the effect of warm air intrusions on the sea ice concentration is negligible."

Figure A3: What determines the black portions of the SIC curve where the SIC is below the background value but not included in the WAI event? How is that defined? It's not explained in text. Also, convert the temperature scale to °C to be consistent with the text and other figures.

We will convert the temperature scale to °C and improve the description of the effective area loss calculation given in lines 368 – 373 (original manuscript) to
"Defining the time period during which the sea ice concentration is affected by the warm air intrusion is not straight forward. In this study, the following procedure was chosen: The start of the affected period (SIC reduced) is based on the day, when the 2 m air temperature first crossed the $> -10°C$ mark. The end of the period is reached when the sea ice concentration is close (within 1%) of the reference sea ice concentration. If the latter does not apply, the end of the affected period is set to 10 days after the maximum of the SIC reduction. 10 days was chosen by manual analyzing several detected warm air intrusions . We found that most of the times, after 10 days, the effect of warm air intrusions on the sea ice concentration is negligible. The reference SIC (blue lines) is the average of the sea ice concentration before and after the warming events. In this example, the drop in SIC around day 10 is related to a different WAI and thus excluded in the analysis."

Technical Corrections

L20: expand the ASI acronym

Changed

L33: Warm air intrusions enter the Arctic region, not the Arctic Ocean.

Changed

L54: typo – snow/ice

Corrected

L58: typo – influences

Corrected

L60: The punctuation around the references to papers and figures here is confusing. Please revise.

We believe that the reviewer refers to " Figure 4 in (Rückert et al., 2023) (see also Figure A7) " and changed it to "Figure B1 (figure 4 from Rückert et al., 2023)"

L85: typo – daily gridding

Corrected

L105-107: This sentence is important, but confusing as written. Please revise to clarify.

We will rewrite the sentences
"An initial temperature threshold is set at $-10°C$. In addition, the duration of the wave during which the temperature threshold must be at least two days in order avoid short-term fluctuation around the threshold close in the marginal ice zone."
to "... a temperature threshold for an initial detection of a potential warm air intrusion is set at $-10°C$. Especially in the marginal ice zone, the 2 m max air temperature can sometimes fluctuate from day-to-day around this threshold even if no WAI is present. In order for the WAI to be further considered, the duration during which this temperature threshold is crossed must be at least two consecutive days."

L264: extent should be extend

Corrected

L289: typo – Another

Corrected

L309: revise, "…Arctic amplification have these warm air intrusions increased…"

We will change the sentence to
"II) Did the recent amplified temperature increase in the Arctic led to an increase in frequency and extent of winter warm air

intrusions? Has the impact of warm air intrusions on satellite sea ice concentration algorithms increased in recent years?"

Figure 3: Can you make the area notation consistent with the rest of the paper (e.g., 104 km2, etc.)

Changed