

Answers to Anonymous Referee 1

We sincerely thank you for again taking your time to review our paper. Your comments greatly helped to improve structure and clarity of our manuscript. Please find our detailed response to your comments below. Your comments are marked by an **R**, our answers are marked by an **A**.

R: Page 2, line 22: The MODIS Terra product archive starts on 24 February 2000, not on the launch date in 1999. S-NPP VIIRS was launched 28 October 2011. But the first date of release of science data products is 19 January 2012. In this context the date of the first available products should be given, instead of the launch date. Also need to correct those dates in Sect. 2.1.2.

A: Thanks for this hint, we have adjusted the dates accordingly.

R: Check that paragraph indents are consistent. Page 3 has inconsistent paragraph indents.

A: We have made sure that the paragraph indents are consistent throughout the paper.

R: Page 5 line 5: Since the MODIS Aqua product was used it should be referred to as MYD29 throughout the manuscript to clearly identify it as the Aqua product.

A: We now refer explicitly to MYD29.

R: Page 5 line 10: I think I would be more clear to write "... and the data (Sect. 2.2) we used to investigate reasons..." rather than having (Sect. 2.2) at the end of the sentence.

A: Thanks, we have reshaped the sentence according to your suggestion.

R: Page 12 line 3: Perhaps restructure the sentence so it does not start with "Figure 2 shows". Awkward style to start a sentence with "Figure".

A: The sentence has been restructured and now reads "The AMSR2 SIC, MODIS SIC, merged SIC and SAR SIC are compared in Fig. 2a)–d)"

R: In the Outlook section, second sentence: "The benefit towards single-sensor SIC is demonstrated." Is that what you intended to say? Or, should "towards" be "over". Your merged SIC product is good and has advantages over single-sensor as stated in conclusions section, but this sentence does not support that.

A: Thanks for pointing this out, we have replaced "towards" by "over".

We hope that we have addressed your comments in a satisfying manner and thank you again for your assessment of our paper.

Answers to Thomas Lavergne (Reviewer 2)

Please have our sincere thanks for taking your time to assess our paper a second time and recommending publication in The Cryosphere. Your constructive and encouraging feedback is greatly appreciated. Please find our detailed response to your comments below. Your comments are marked by an **R**, our answers are marked by an **A**.

R: The first suggestion is to move from using OSI-401 (the operational SIC product of OSI SAF) to using OSI-430-b (the newly released Interim Climate Data Record – ICDR). OSI-430-b is built with a main objective to be consistent with OSI-450 from January 2016 onwards. Since OSI-430-b has a 16 days latency, it fully covers your time period. You can find OSI-430-b information and data from http://osisaf.met.no/p/ice/ice_conc_cdr_v2.html. It should not be much additional work, and would save you from commenting the consistency between OSI-450 and OSI-401 in section 2.2.1 and 4.1. On that topic, the sentence “The time series of both products is consistent at the transition (Lavergne et al. 2019)” (p. 6 lines 12-13) is very far fetched, since Lavergne et al. 2019 does not deal with neither OSI-401, nor OSI-430-b. The consistency of OSI-450 and OSI-430-b at the transition is -at time of writing- only documented in the Validation Report for the OSI-450 and OSI-430-b products (<https://osisaf.met.no/docs>).

A: Thanks for this suggestion. We now use OSI-430-b instead of OSI-401. Sections 2.2.1 and 4.1 have been adjusted accordingly. Regarding the sentence "The time series of both products is consistent at the transition", we now refer to the product user manual at http://osisaf.met.no/docs/osisaf_cdop3_ss2_pum_sea-ice-conc-climate-data-record_v2p0.pdf instead of Lavergne et al. (2019).

R: The second suggestion for Figure 1 starts as a question: is the 1979-2017 average computed from the “ice_conc” variables in OSI-450 data files, or does it also use “raw_ice_conc_values”? Variable “ice_conc” only contains SICs up to 100%, while “raw_ice_conc_values” gives access to the full error distribution of retrieved SICs, that is including values retrieved above 100%. A suggestion is thus to combine variables “ice_conc” and “raw_ice_conc_values” to prepare a non-thresholded SIC field before averaging. Using the non-thresholded is the correct way to prepare Figure 1, as otherwise the average curve can only be below 100%. The impact on the curve is not known, but it might raise the mean level to something closer to 100% (as expected). If you implement this change, please add a sentence to describe that you did combine the two variables before averaging. If you do not implement this change, please add a sentence stating that your average did use the thresholded SICs, and thus must result in lower SICs than could have been the case.

A: We have used the "ice_conc" variable. Thanks for pointing out that this must result in SIC beneath 100%. We have decided to keep the time series as it is now and added the sentence "The OSI-SAF SIC are capped at 100%, thus the SIC average can only be

beneath 100% and must result in lower SIC than might have been the case. " in Section 4.1.

R: Finally, I would invite you to include in your discussion a dedicated paragraph on the difference between lead fraction products, and SIC products. You have elements of this in your text, but it would be an added value of this paper if you could wrap this in a "discussion" paragraph. In effect, you consider your merged SIC product is better because it shows more leads (at the beginning of the event). However, as you note, these leads might well be already refrozen when observed by MODIS (and AMSR2). In that case, a perfect SIC product should not show them at all. I understand the thrust towards showing high-resolution features such as leads in coarser resolution products, but should they all really be shown as reduced sea-ice concentration? Are there other ways the lead information could be shipped to users? Please discuss shortly.

A: If a lead is covered by sea ice thinner than approximately 10 cm, it will likely show up as reduced sea-ice concentration, even in the AMSR2 SIC. Leads covered by more than approximately 10 cm of sea ice can be retrieved by our merged product because of the larger sensitivity of the MODIS SIC to sea-ice thickness. For this study, we have decided for including these reduced SIC to indicate the presence of leads. In future, we could include a flag in our product which shows whether the AMSR2 SIC at the corresponding SIC is 100%. The user could then decide her/himself whether she/he would like to have the lead shown as reduced SIC or whether she/he prefers to consider the lead as 100% sea-ice covered. In that case, the flag could be used to set the corresponding SIC to 100%. A paragraph discussing this has been included in the Discussion section.

R: Throughout the text. It is a widely accepted convention to use "sea ice" as a noun ("sea ice froze rapidly"), but "sea-ice" when qualifying one of its characteristics ("the sea-ice concentration dropped", "sea-ice edge moved ..."). Consider fixing throughout the text.

A: Thanks for this hint, we have implemented it throughout the manuscript.

R: All the maps: you consistently have your Greenland filled with green (!). However many of your colormaps contain the color green (e.g. Figure 5, Figure 9). Consider finding a better color for filling Greenland.

A: Greenland is now filled with a light brown, a color which is not contained in the colormaps.

R: P. 1, line 14 : "Two estimates of thermodynamic ... of 60 and 65 cm at the end of March in the area opened by the polynya".

A: This has been done.

R: P2. line 3: "the fraction of a given ocean area which..."

A: The word "ocean" has been added.

R: P2. line 16: “from 40-50 km from 19 and 37 GHz channels...”

A: The word "from" has been added.

R: P2. line 19: “prevents accurate monitoring of the sea ice edge” (or any better word that does not repeat resolution/resolve).

A: We adapted the word "monitoring".

R: P2. line 21: replace “which are typically” by “and are typically”.

A: Done.

R: P3. line 11: “The benefit of merged SIC with respect to single-sensor...” (or compared to).

A: We adapted the formulation "with respect to".

R: P3. line 12: “during the formation of a polynya...”

A: Adapted.

R: P3. line 24: “Single latent heat”... what does “single” means here. Remove or clarify.

A: We removed the word "single". The sentence has been rewritten to be clearer. It now reads "The ten major Arctic coastal polynyas produce roughly 130–840 km^3 of sea ice per year (Tamura and Ohshima, 2011).".

R: P5. line 5: “Sect. 9 lists...” or “provides”...

A: We have adapted the formulation "Sect. 9 lists...".

R: P5. line 15: Find a more explicit heading. Maybe “Input SIC data to merged product”?

A: Thanks for the suggestion, we now use the heading "Input data to merged product" since here we describe the MODIS ice surface temperature and not yet the MODIS SIC.

R: P5. line 17: “It’s orbit has an inclination...”

A: Implemented.

R: P6. section 2.2.1: specify that the OSI SAF SIC OSI-450 and OSI-430-b uses “coarse” resolution instruments (SMMR, SSM/I, SSMIS).

A: We added the sentence "It uses the coarse-resolution instruments SMMR (Scanning Multi-channel Microwave Radiometer), SSM/I (Special Sensor Microwave/Imager) and SSMIS (Special Sensor Microwave Imager Sounder)."

R: P7. eq for FDD: please use index “n” inside the sum (T^{air}_n).

A: The equation now reads

$$FDD = \sum_{n=1}^{n=n_{days}} [-1 * T_n^{air}], \quad (1)$$

where n is the index of the respective day, n_{days} is the total number of days and T_n^{air} is the daily mean air temperature in ° C of the respective day.

R: P8. line 9: what “passive microwave sea-ice concentration” must be beneath 50%? ASI? Please clarify.

A: Yes, ASI. This is specified now in the text.

R: P8. section on the NOASIM model. This section is much more detailed than the other. It can be justified because it is the only model, but please consider if this section can be shortened and the interested reader referred to publications about NAOSIM (e.g. the initialization of the model since 1980)?

A: We have shortened the section and included literature references for the interested reader where we left out details.

R: P8 section on the NOASIM model: are the runs free runs or runs with data assimilation? Clarify, and shortly describe the assimilation (methodology, variables assimilated) if the model is not in free run.

A: There has been no data assimilation. We now state this in the text.

R: P10, line 21: “80% of the picels were covered at least once”. What does “covered” mean here? Cloud-covered? Covered by the product (hence cloud-free)? Clarify.

A: We mean cloud-free. We have replaced "covered" by "cloud-free".

R: P10, line 25-26: move the discussion about the A-train and the Aqua/Terra platform to section 2.1.2.

A: We have moved the corresponding sentences as suggested.

R: P11, line 29: “visual observations showed”... where do these come from? During the flights? In-situ on sea-ice? Visual interpretation of satellite/aerial images? Please clarify.

A:The visual observations were made during the flights, this is stated now.

R:P13, line 24: “The reason is again that they are more sensitive to newly formed sea ice”?

A:We have included "newly formed".

R: P13, line 28: define “open water extent”. Does it use a 15% threshold?

A: Yes, it does use a 15 % threshold. This is now described here in an extra sentence. Section 3.3 gives more details about the open water extent.

R: P15, Figure 3: consider choosing another color scheme (blue and green and red can easily be mixed-up by color-blind persons).

A: Thanks for this hint. We have partly chosen different colors and used a color-blindness simulator to make sure that the color scheme is distinguishable for color-blind people. Other Figures which might cause problems for color-blind readers were also adapted.

R: P16, Figure 4: it is not obvious what the two lower panels bring. Would one of them (the difference) be enough? Or a third one: (Merged-AMSR2)/AMSR2?

A: In our opinion, the middle panel shows the difference more clearly than the upper panel alone. For the lower panel, we follow your suggestion and use the normalised difference (Merged-AMSR2)/AMSR2 of the quotient Merged/AMSR2. This supports our finding that the benefit of the merged SIC is more pronounced during the early break-up phase of the polynya.

R: P18, Figure 5 (right column). What is the unit? Could the colorscale be changed to show more contrast?

A: The unit is greyscale values. This is now stated in the caption. We have made the range of the colorbar smaller to show more contrast.

R: P21 replace “This year” with “During the polynya event,..”

A: Done.

R: P23: it is not clear if, e.g. +90, is westward or eastward drift.

A: +90 means westward drift. We have added this in the text.

R:P27, line 5-6 “Our statement is even stronger...” consider another formulation, e.g. “We confirm and further strengthen the findings of ...”

A: We have adopted the formulation as suggested by you.

R: P28, line 14-15 “Also, refrozen leads with are covered by snow ...” Exactly the type of argumentation that could enter a discussion paragraph about high-resolution features (refrozen leads) into sea-ice concentration products (as suggested in my comments earlier).

A: A paragraph discussing the incorporation of high-resolution features into SIC products has been added (see also our answer to your previous comment).

R: P29, line 29: remove the last sentence (or merged with that line 25).

A: We have removed the last sentence.

R: P31, line 10: “SIC shows closed”

A: Thanks for pointing out this typo, we have corrected it.

R: P31, line 27: “showed more SIC values between ”

A: We have included the word "values".

R: P32, line 6: “Events like this have occurred before ...” add “but not with the same magnitude” ?

A: We have added "but not with the same magnitude".

We hope that we have addressed your comments in a satisfying manner and thank you again for the time you took to assess our manuscript.

References

Lavergne, T., Sørensen, A. M., Kern, S., Tonboe, R., Notz, D., Aaboe, S., Bell, L., Dybkjær, G., Eastwood, S., Gabarro, C., Heygster, G., Killie, M. A., Brandt Kreiner, M., Lavelle, J., Saldo, R., Sandven, S., and Pedersen, L. T.: Version 2 of the EUMETSAT OSI SAF and ESA CCI sea-ice concentration climate data records, *The Cryosphere*, 13, 49–78, <https://doi.org/10.5194/tc-13-49-2019>, URL <https://www.the-cryosphere.net/13/49/2019/>, 2019.

Tamura, T. and Ohshima, K. I.: Mapping of sea ice production in the Arctic coastal polynyas, *Journal of Geophysical Research: Oceans*, 116, <https://doi.org/10.1029/2010JC006586>, URL <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2010JC006586>, 2011.

List of major changes

- ▷ The OSI-SAF Interim Climate Data Record (OSI-430-b) is used for the years after 2015 in the climatology in Fig. 1.
- ▷ A paragraph discussing the incorporation of high-resolution features into SIC products has been added in the Discussions Section.
- ▷ Section 2.2.7 (NAOSIM model) has been shortened.
- ▷ In Figure 4, the quotient Merged SIC/AMSR2 SIC has been replaced by the normalised difference (Merged SIC - AMSR2 SIC)/AMSR2 SIC.
- ▷ All remaining comments concerning style and/or formulations have been followed.

The 2018 North Greenland polynya observed by a newly introduced merged optical and passive microwave sea ice concentration dataset

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Abstract. Observations of [sea-ice-sea-ice](#) concentration are available from satellites year-round and almost weather-independently using passive microwave radiometers at resolutions down to 5 km. Thermal infrared radiometers provide data with a resolution of 1 km, but only under cloud-free conditions. We use the best of the two satellite measurements and merge thermal infrared and passive microwave [sea-ice-sea-ice](#) concentrations. This yields a merged [sea-ice-sea-ice](#) concentration product combining

5 the gap-free spatial coverage of the passive microwave [sea-ice-sea-ice](#) concentrations and the 1 km resolution of the thermal infrared [sea-ice-sea-ice](#) concentrations. The benefit of the merged product is demonstrated by observations of a polynya which opened north of Greenland in February 2018. We find that the merged [sea-ice-sea-ice](#) concentration product resolves leads at [sea-ice-sea-ice](#) concentrations between 60 % and 90 %. They are not resolved by the coarser passive microwave [sea-ice-sea-ice](#) concentration product. The ~~merged product shows up to 60 more open water than the passive microwave product~~ [benefit of](#)

10 [the merged product is most pronounced](#) during the formation of the polynya. Next, the environmental conditions during the polynya event are analysed. The polynya was caused by unusual southerly winds during which the [sea-ice-sea-ice](#) drifted northward instead of southward as usual. The daily displacement was 50 % stronger than normal. The polynya was associated with a warm-air intrusion caused by a high-pressure system over the Eurasian Arctic. Surface air temperatures were slightly beneath 0°_C and thus more than 20°_C higher than normal. Two estimates of thermodynamic [sea-ice-growth-yield-sea-ice-sea-ice](#)

15 [growth yield sea-ice](#) thicknesses of 60 and 65 cm at the end of March [in the area opened by the polynya](#). This differed from airborne [sea-ice-sea-ice](#) thickness measurements, indicating that [ice-sea-ice](#) growth processes in the polynya are complicated by rafting and ridging. 33 km³ of sea ice were produced thermodynamically.

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1 Introduction

Arctic sea ice influences the climate system by radiating incident heat back into space and by regulating the ocean/atmosphere exchange of heat, humidity and momentum. The fraction of a given ocean area which is covered by sea ice is called sea-ice sea-ice concentration (SIC). SIC is of high relevance for physics, biology and the safety of shipping routes. The summer sea-ice sea-ice retreat observed since 2007 is a major driver of the Arctic Amplification, the enhanced warming of the Arctic compared to the mid-latitudes (Dai et al., 2019). While the scientific community largely agrees that Arctic Amplification changes the mid-latitude weather patterns, the exact mechanisms and pathways are subject to debate. A comprehensive literature synthesis is given in Vavrus (2018).

Arctic-wide SIC observations are available every second day by spaceborne passive microwave radiometers since 1979 and daily since 1987 (Tonboe et al., 2016). Passive microwave measurements do not require daylight and are only slightly affected by clouds. Therefore, they can provide data all year and under all weather conditions. The Advanced Microwave Scanning Radiometer (AMSR2) has frequency channels between 6.9 and 89 GHz. The 89 GHz channels are used in this study. The algorithm which we use is the ARTIST (Arctic Radiation and Turbulence Interaction Study) Sea Ice algorithm (ASI) (Kaleschke et al., 2001; Spreen et al., 2008). The resolution of the 89 GHz channels of AMSR2 goes down to 3 by 5 km in the instantaneous field of view. Thus, it is possible to retrieve SIC at 3.125 km grid spacing (Beitsch et al., 2014). The resolution of passive microwave sensors ranges from 40–50 km ~~for~~ from the 19 and 37 GHz channels available since 1979 (Ivanova et al., 2014; Comiso, 1995; Markus and Cavalieri, 2000) to 5 km ~~for~~ from the 89 GHz channels available since 2001 (Kaleschke et al., 2001; Spreen et al., 2008). The spatial and temporal coverage of passive microwave SIC and their year-round availability makes them valuable for climate research. However, the coarse resolution prevents accurate resolution of the sea-ice monitoring of the sea-ice edge, newly formed polynyas and leads. Polynyas are non-linearly shaped openings in the sea ice (WMO, 1970), leads are linear openings in the sea ice (Marcq and Weiss, 2012; Wernecke and Kaleschke, 2015) which and are typically smaller than polynyas.

Thermal infrared data as acquired by the Advanced Very High Resolution Radiometer (AVHRR, since 1979), the Visible Infrared Imaging Radiometer Suite (VIIRS, since ~~2011~~ 2012) and the Moderate Resolution Imaging Spectroradiometer (MODIS, since ~~1999~~ 2000/2002) offer resolutions of 750 m (VIIRS) and 1 km (MODIS, AVHRR). An algorithm to derive SIC at 1 km resolution from MODIS thermal infrared measurements has been presented and evaluated by Drüe and Heinemann (2004, 2005). Compared to a typical AMSR2 5 by 5 km grid cell, this allows 25 subpixel measurements and thus an enhanced potential to resolve leads.

Leads are not expected to show up as completely open water areas in the thermal infrared data since they refreeze rapidly, especially in winter. However, they still show up as reduced SIC while the sea ice is thin. They are responsible for more than 70 % of the upward ocean-atmosphere heat flux in the central Arctic during winter (Marcq and Weiss, 2012). According to Marcq and Weiss (2012), 1 % of lead area fraction can change the surface air temperature by 3.5° C, hence the thermal infrared SIC is quite sensitive to the presence of leads. In contrast, passive microwave measurements do not resolve narrow leads because of their coarse resolution. Also, 89 GHz channels measurements are insensitive ~~towards the sea-ice~~ to the sea-ice

thickness for thicknesses above 10 cm (Heygster et al., 2014; Ivanova et al., 2015). While the high spatial resolution of thermal infrared measurements is a valuable benefit, they are only available in cloud-free locations and thus not suitable if one wants complete spatial coverage as it is needed for long-term climate monitoring.

5 Synthetic Aperture Radar (SAR) data (Karvonen, 2014; Murashkin et al., 2018) have even higher spatial resolution, e.g. Sentinel-1 A/B with about 90 by 90 m in the Extra Wide swath mode used over the Arctic Ocean. Further, they penetrate clouds. If cloud cover is taken into account, there are more SAR data than thermal infrared. However, automated SIC retrieval from SAR measurements is difficult, although attempts have been undertaken, e.g. in ~~Karvonen (2014)~~ Karvonen (2014). Further, the availability and coverage are still limited by the duty cycle and the swath width, so that complete daily Arctic-wide coverage is not guaranteed.

10 This paper for the first time presents a merged product from AMSR2 passive microwave SIC and MODIS thermal infrared SIC at a spatial resolution of 1 km. This merged product benefits from both the high resolution of the MODIS thermal infrared data and the spatial coverage of the AMSR2 SIC. A Sentinel-1 SAR-based lead area fraction product (Murashkin et al., 2018), is used for comparison. The benefit of ~~merged-SIC towards~~ the merged SIC with respect to single-sensor passive microwave or thermal infrared SIC is demonstrated during the formation ~~period-of-the-of a~~ polynya which was observed between February 15 14th and March 8th 2018 north of Greenland (Fig. 1).

Polynyas typically last days to weeks and most of them occur regularly (Morales-Maqueda et al., 2004). It can be argued whether a refrozen polynya which is covered by thin sea ice should be considered as polynya. An argument for referring to it as a polynya is that the heat flux is considerably higher for thin sea ice than for thick sea ice. Also, a refrozen polynya is often visible in SAR images because the sea ice grown thermodynamically under calm weather conditions has a smooth surface. On 20 the other hand, passive microwave measurements retrieve it as fully ~~sea-ice-covered~~ sea-ice-covered as soon as the sea ice is thicker than about 10 cm or covered by frost flowers or snow (Heygster et al., 2014). In this paper, we refer to the polynya as opened as long as the merged SIC are beneath 100%.

There are two types of polynyas: sensible and latent heat polynyas. Morales-Maqueda et al. (2004) describe both types of polynyas in detail. We continue with the description of latent heat polynyas since the one we investigate pertains to this type. 25 Latent heat polynyas normally develop close to the coast due to off-shore winds and/or ocean currents which cause divergent ~~sea-ice~~ sea-ice motion. Sea ice is pushed away from the coast and new frazil/grease ice forms. ~~Single latent heat polynyas produce up to 800~~ The ten major Arctic coastal polynyas produce roughly 130–840 km³ ~~per year~~ of sea ice per year (Tamura and Ohshima, 2011). Heat fluxes are typically between 300 Wm⁻² and 500 Wm⁻² (Haid and Timmermann, 2013; Martin et al., 2004).

30 Polynyas form the basis for food webs by enabling photosynthesis and provide food for mammals, birds and humans alike (Smith et al., 1990; Morales-Maqueda et al., 2004; Schledermann, 1980). Preußer et al. (2016) report that polynyas between January and March have sizes between 400 and 43,600 km². Many polynyas recur annually in the same places (Morales-Maqueda et al., 2004; Preußer et al., 2016), but the one we investigate does not appear frequently (Fig. 1).

The sea ice north of Greenland is one of the oldest and thickest in the entire Arctic (Vaughan et al., 2013). This sea ice was 35 blown off-shore in the course of days in February 2018, forming a coastal polynya which lasted from February 14th to March

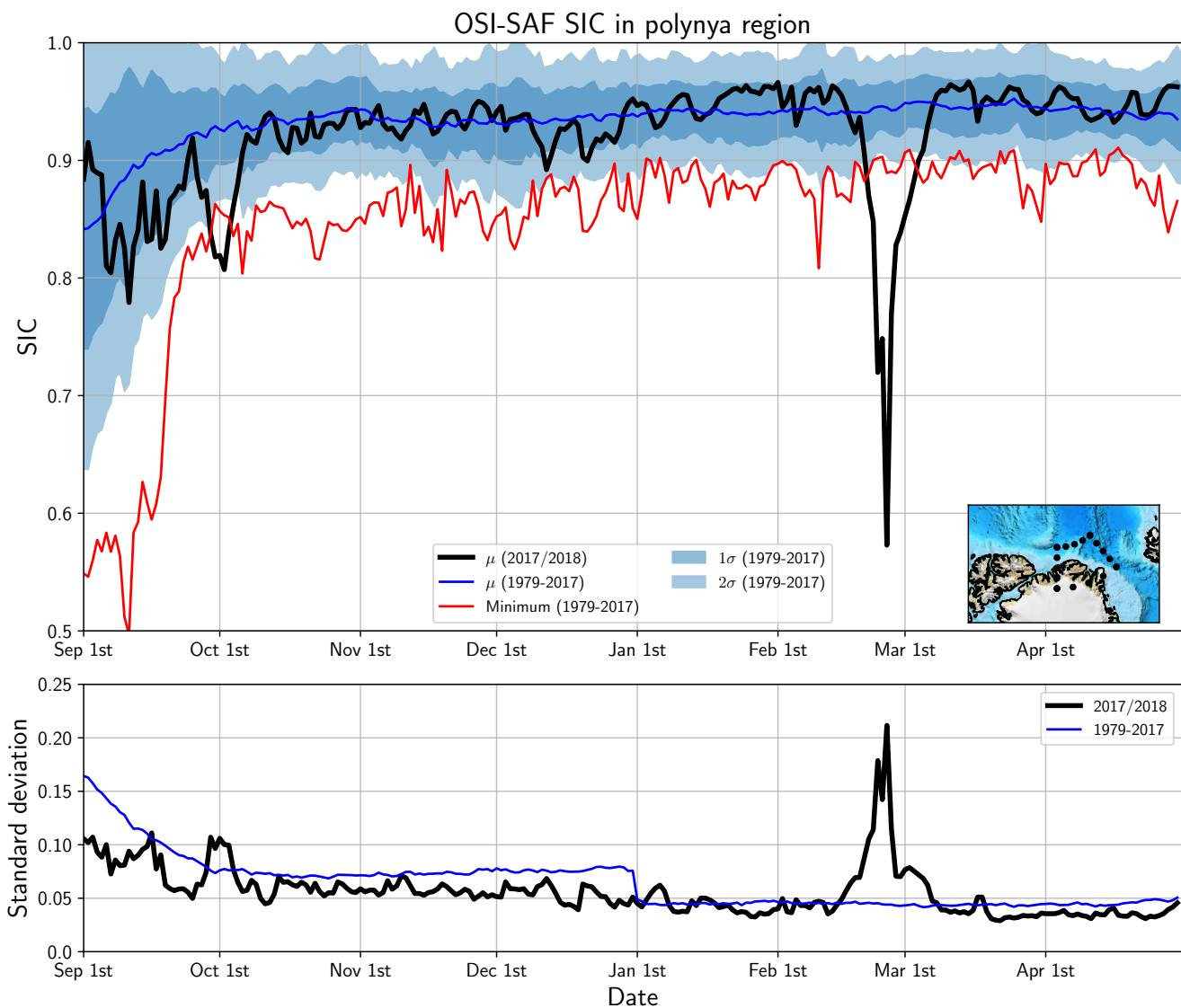


Figure 1. Upper panel: Mean OSI-SAF SIC (Lavergne et al., 2019) in the polynya region (indicated by the dashed box on the map in the lower right corner). The black line shows the mean SIC in 2018. The blue line shows the mean SIC between 1979 and 2017. The dark/light shades indicate the $\pm 1\sigma/\pm 2\sigma$ interval, respectively. The red line shows the minimal mean SIC between 1979 and 2017 for each day. Lower panel: Time series of the standard deviation in the polynya region for 2018 (black). The blue line shows the mean of the standard deviations in the polynya region between 1979 and 2017.

8th and spanned more than 60,000 km² at its maximal extent. A ~~very~~ recent study (Moore et al., 2018) uses the ASI-AMSR2 SIC mentioned above to show the polynya. We demonstrate the benefit of our higher-resolution merged SIC product when describing the formation of the polynya. Moore et al. (2018) identify a sudden stratospheric warming as trigger of the polynya.

We add to their work by investigating ~~sea-ice~~sea-ice drift data. We conclude by estimating the amount of sea ice which grew in the polynya and the amount of heat released to the atmosphere.

This paper is structured as follows: Sect. 2 describes the data used. Sect. 3 describes the merging procedure and the calculation of the thermal infrared MODIS SIC. Sect. 4 compares the SIC datasets and provides basic information about the polynya itself. Sect. 5 describes the local and large-scale 2 m air temperature, the surface air pressure and the ~~sea-ice~~sea-ice drift during the opening and refreezing of the polynya. Sect. 6 gives an estimate of the ~~sea-ice~~sea-ice growth and the heat release in the polynya. Sect. 7 discusses the results. Sect. 8 summarises the results and presents the conclusions. Sect. 9 ~~names~~lists directions for future research.

The following questions will be addressed and answered in this paper:

1. Does merging MODIS thermal infrared and AMSR2 passive microwave SIC allow additional insights about the formation of the polynya?
2. Was the polynya opened thermodynamically or dynamically and how unusual were the environmental conditions?
3. How much sea ice grew in the polynya and how much heat was released to the atmosphere?

2 Data

This section describes the input data for the merged product (Sect. ~~3:22.1~~3:22.1) and the data (Sect. 2.2) used to investigate reasons and consequences of the polynya formation(~~Sect. 2.2~~Sect. 2.2).

2.1 ~~Merging~~Input data to merged product

2.1.1 AMSR2 ~~sea-ice~~sea-ice concentration

The Global Change Observation Mission-Water Satellite 1 (GCOM-W1) carries the Advanced Microwave Scanning Radiometer 2 (AMSR2, https://suzaku.eorc.jaxa.jp/GCOM_W/w_amr2/whats_amr2.html). ~~It~~Its orbit has an inclination of 98° and crosses the equator at 1:30 am/pm on its descending/ascending orbit. AMSR2 measures brightness temperatures at six microwave frequencies between 6.9 and 89 GHz. The 89 GHz brightness temperatures have the highest spatial resolution. It is 5 by 5 km in the effective field of view. The ASI algorithm (Kaleschke et al., 2001; Spreen et al., 2008) derives SIC from these brightness temperatures. To get the smallest possible time lag to the MODIS data, we use swath data. Additionally, the swath data have a spatial resolution of 5 by 5 km while the grid spacing of the daily product is 6.25 by 6.25 km. The daily product is publicly available at www.seaice.uni-bremen.de, the swath data have been processed internally.

2.1.2 MODIS ~~data~~ice surface temperature

The Moderate Resolution Imaging Spectroradiometer (MODIS, <https://modis.gsfc.nasa.gov/>) aboard NASA's Terra/Aqua satellites provides data in the optical and thermal infrared spectrum since ~~1999-2000~~1999-2000 (Terra) respectively 2002 (Aqua). The Aqua

satellite's orbit characteristics are similar to those of GCOM-W1. It has the same inclination and flies 4 minutes behind GCOM-W1. The Terra satellite's equator crossing time is shifted by 45 minutes relative to Aqua. We therefore exclusively use [the MYD29 ice surface temperature of MODIS Aqua](#) and omit MODIS Terra data. The [MOD29-time lag between MODIS Aqua and AMSR2 is normally between three and eight minutes since both satellites, Aqua and GCOM-W1, fly in the A-Train satellite constellation. The A-Train is a suite of satellites which follow each other closely on the same orbit. It was designed to obtain near-simultaneous Earth observation data from different measurements.](#) The MYD29 ice surface temperature dataset was developed by NASA's Goddard Space Flight Center (Hall and Riggs., 2018) and is distributed by the National Snow and Ice Data Center (NSIDC) at <https://nsidc.org/data/MYD29/versions/6>. It has a spatial resolution of 1 km. The data are distributed as granules of five minutes length. For cloud screening, we use the [MOD35MYD35_L2 cloud mask](#) (Ackerman et al., 2017).
A pixel is discarded if it is not labeled as "confident clear" or is over land or is at the coast or is labeled as "cirrus cloud" or "shadow".

2.2 Additional data

2.2.1 OSI-SAF ~~sea-ice~~ [sea-ice](#) concentration

For climatological reference, we use the OSI-450 SIC Climate Data Record product of the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) Ocean and Sea Ice Application Facility (OSI-SAF) which is available from 1979 to 2015 at <http://osisaf.met.no/p/ice/> (Lavergne et al., 2019). [It uses the coarse-resolution instruments SMMR \(Scanning Multi-channel Microwave Radiometer\), SSM/I \(Special Sensor Microwave/Imager\) and SSMIS \(Special Sensor Microwave Imager Sounder\).](#) The data are provided daily since 1987 and every two days before. They are gridded to a Lambert Azimuthal equal area grid, also known as EASE grid 2.0, with a grid spacing of 25 km. For the years ~~2015–2018, the OSI-401 SIC product~~ [2016–2018, the OSI-430-b SIC product](#) (http://osisaf.met.no/p/ice/ice_conc_cdr_v2.html) is used. The time series of both products is consistent at the transition (~~Lavergne et al., 2019~~) (http://osisaf.met.no/docs/osisaf_cdop3_ss2_pum_sea-ice-conc-climate-data-record_v2p0.pdf). For calculating the polynya area time series, we project all data to a north polar stereographic grid with the true latitude at 70° N ("NSIDC grid", https://nsidc.org/data/polar-stereo/ps_grids.html) with 12.5 km grid spacing. The average of all OSI-SAF SIC between 45° W/81° N and 5° W/85° N in geographic coordinates is used for the polynya area time series in Fig. 1. The polynya region is shown in the inset of Fig. 1. The climatology comprises the years from 1979 to 2017.

2.2.2 SAR ~~sea-ice~~ [sea-ice](#) concentration

In addition to SIC, ~~sea-ice drift, air temperature, and air pressure~~, lead area fraction is analysed. It is calculated as a fraction of leads in the area. Binary lead maps are produced by an automatic classification algorithm from Sentinel-1 C-band SAR data at 5.4 GHz (Murashkin et al., 2018). The lead classification algorithm analyses backscatter values and image texture of the surrounding area. Here leads are assumed to be areas of open water of an arbitrary shape. Therefore the polynya is expected to have a high lead area fraction. Sentinel-1 scenes taken in the Extra Wide Swath mode with 40 m pixel size are used. Images

taken within every one day are combined in lead maps of the Arctic with 80 m resolution. Then the lead area fraction is calculated from these binary maps on a 800 m grid. Finally, the data are resampled to the NSIDC grid with 1 km grid spacing for comparison with the other SIC datasets. ~~Sea-ice~~Sea-ice concentration is derived by inverting the lead area fraction:

$$SIC_{LAF} = 1 - LAF, \quad (1)$$

5 where LAF is the lead area fraction. The product is called SAR SIC.

2.2.3 Sentinel mosaics

Since fall 2014, the Technical University of Denmark has produced Near Real Time mosaics of Sentinel-1 SAR data as they become available to the Copernicus Marine Environment Monitoring Service (CMEMS). The mosaics cover most of the potentially ~~sea-ice~~sea-ice covered areas of the Northern and Southern hemispheres respectively. They consist of geometrically and radiometrically corrected data from Extra Wide Swath and Interferometric Wide Swath modes of both Sentinel-1A and Sentinel-1B. The radiometric correction includes a correction for the average incidence angle dependence of the ~~sea-ice~~sea-ice backscatter. The full mosaics are available at <http://www.seaice.dk>.

2.2.4 ~~Sea-ice~~Sea-ice drift, air temperature and air pressure

The OSI-405 low resolution ~~sea-ice~~sea-ice drift product by EUMETSAT OSI-SAF (Lavergne et al., 2010) is used in this study. It has a grid spacing of 62.5 km, a temporal resolution of two days and is projected to the NSIDC grid. ~~Sea-ice~~Sea-ice motion is first derived separately from ASCAT (Advanced Scatterometer) C-band backscatter, AMSR-E/AMSR2 37 GHz, SSM/I 85 GHz and SSMI/S 91 GHz brightness temperatures. Then, the single-sensor ~~sea-ice~~sea-ice drift vectors are merged by an optimal interpolation scheme. A comparison to other ~~sea-ice~~sea-ice drift datasets is given in Sumata et al. (2014).

20 We use ~~station-2~~ m temperature data from the weather station at Cape Morris Jesup operated by the Danish Meteorological Institute. They are sampled in three-hour intervals until 2015 and hourly since 2016. We average the values daily. Additionally, we use surface air pressure and 2 m air temperature at a spatial/temporal resolution of 0.25 degrees/one day. ~~They are obtained~~ from the ERA5 reanalysis (<https://confluence.ecmwf.int/display/CKB/ERA5+data+documentation>, Copernicus Climate Change Service, 2015). The ERA5 reanalysis is run at the European Centre for Medium-Range Weather Forecasts (ECMWF). It is the fifth generation of reanalyses from ECMWF. Hourly reanalysis data of 2 m air temperature and 10 m wind are available in near-real time at a spatial resolution of 31 km (Hersbach and Dee, 2016).

2.2.5 ~~Sea-ice~~Sea-ice growth from freezing degree days

To estimate thermodynamic ~~sea-ice~~sea-ice growth in the polynya, we employ an empirical equation described by Lebedev (1938):

$$30 \quad SIT[cm] = 1.33 * FDD^{0.58} \quad (2)$$

where SIT is the ~~sea-ice-sea-ice~~ thickness in cm and FDD are freezing degree days. Freezing degree days are the sum of air temperatures above/below freezing over a given time, where air temperatures below/above 0° C count positively/negatively:

$$FDD = \sum_{i=1}^{i=n} [-1 * T_{air}]_{n=1}^{n=n_{days}} [-1 * T_n^{air}], \quad (3)$$

where ~~i is the n~~ ~~is the index of the respective day,~~ ~~n_{days} is the total~~ number of days and ~~T_{air}~~ ~~T_n^{air}~~ is the daily mean air temperature in °C, ~~in our case~~ ~~C of the respective day.~~ We use the ERA5 2 m air temperature. We will compare ~~sea-ice-sea-ice~~ thickness from different sources. For a consistent comparison despite the very different grids, we introduce a grid-independent criterion for the polynya region: We consider only those grid cells where the ~~sea-ice-sea-ice~~ concentration was below 50 % at least once during the polynya event. For the freezing degree days, we use the ERA5 ~~sea-ice-sea-ice~~ concentration. In addition to ~~sea-ice-sea-ice~~ thickness, we calculate the ~~sea-ice-sea-ice~~ volume produced by thermodynamic growth. For this, we multiply the ~~sea-ice-sea-ice~~ thickness with the fixed area of grid cells which were at least once beneath 50 % SIC while the polynya was open.

2.2.6 Passive microwave ~~sea-ice-sea-ice~~ thickness

~~Sea-ice-Sea-ice~~ thickness up to 50 cm can be derived from 1.4 GHz-GHz passive microwave measurements (Huntemann et al., 2014; Pařileá et al., 2019). We use the combined ~~sea-ice-sea-ice~~ thickness product of the Soil Moisture and Ocean Salinity (SMOS) and Soil Moisture Active/Passive (SMAP) radiometers to evaluate the ~~sea-ice-sea-ice~~ growth from the freezing degree days. The product is disseminated by the University of Bremen at <https://seaice.uni-bremen.de>. It comprises both dynamic and thermodynamic growth. We need to ensure that we consider only those grid cells with thermodynamic ~~sea-ice-sea-ice~~ growth. Therefore, we apply the same criterion as described in Sect. 2.2.5. We select only grid cells where the ~~passive-microwave-sea-ice-ASI-AMSR2~~ ~~passive microwave sea-ice~~ concentration was beneath 50 % at least once during the polynya.

2.2.7 NAOSIM model

The North Atlantic Arctic Ocean Sea Ice Model (NAOSIM, Kauker et al., 2003) has been used to calculate the ~~sea-ice-sea-ice~~ growth and the vertical heat fluxes during the polynya event. ~~No data have been assimilated.~~ We want to avoid interpolating from the model grid to the NSIDC grid. For a consistent selection of grid cells with thermodynamic ~~sea-ice-sea-ice~~ growth, we select the model grid cells which had beneath 50 % SIC at least once during the polynya event, as described in Sect. ~~2.2.5~~ ~~2.2.5~~, and perform the calculations on the model grid which is described in the next paragraph.

NAOSIM's ocean model is derived from version 2 of the Modular Ocean Model (MOM-2) of the Geophysical Fluid Dynamics Laboratory (GFDL). The version of NAOSIM used here has a horizontal grid spacing of 0.25° on a rotated spherical grid. The rotation maps the 30° W meridian onto the equator and the North Pole onto 0° E. ~~In the vertical it resolves 30 levels,~~ ~~their spacing increasing with depth.~~ The ocean model is coupled to a ~~sea-ice-sea-ice~~ model with viscous-plastic rheology (Hibler, 1979). The thermodynamics are formulated as a zero-layer model following Semtner (1976). Freezing and melting are calculated by solving the energy budget equation for a single ~~sea-ice-sea-ice~~ layer with a snow layer and an ocean mixed layer according to Parkinson and Washington (1979). In contrast to the original formulation the energy flux through the sea ice is

calculated by a [PDF-probability density function](#) for the distribution of [sea-ice-sea-ice](#) thickness based on airborne electromagnetic measurements (Castro-Morales et al., 2014). The sea ice model's prognostic variables are [sea-ice thickness](#), [sea-ice sea-ice thickness](#), [sea-ice](#) concentration, and snow depth. ~~Sea ice drift is calculated diagnostically from the momentum balance. All quantities are mean quantities over a grid box.~~ When atmospheric temperatures are below the freezing point, precipitation is added to the snow mass. The snow layer is advected jointly with the [sea-ice-sea-ice](#) layer. The surface heat flux is calculated using prescribed atmospheric data and sea surface temperature predicted by the ocean model. The [sea-ice-sea-ice](#) model is formulated on the ocean model grid and uses the same time step. The models are coupled following the procedure devised by Hibler and Bryan (1987). ~~At the open boundary near 50N the barotropic oceanic transport is prescribed from a coarser resolution version of the model that covers the whole Atlantic north of 20S ?.~~

10 In contrast to the version described by Kauker et al. (2003), the present version uses a modified atmospheric forcing data set consisting of ~~10m-wind velocity, 2m-air temperature, 2m-specific~~ [10 m-wind velocity](#), [2 m-air temperature](#), [2 m-specific](#) humidity, total precipitation, and downward solar and thermal radiation. For the period from 1979 to 2010 the forcing is taken from the National Center for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (NCEP-CFSR) (Saha et al., 2010) and for the period from 2011 onwards from the NCEP Climate Forecast System version 2 (CFSv2) (Saha et al.,
15 2014).

The initial state of January 1 1980 is taken from a hindcast from January 1 1948 to December 31 1979. ~~As in ? this hindcast run was forced by the NCEP/NCAR reanalyses (Kalnay et al., 1996) and, in turn, initialized from the Polar Science Center Hydrographic Climatology (Steele et al., 2001) (ocean temperature and salinity), zero snow depth, and a constant sea ice thickness of 2 m with 100 sea ice concentration where the air temperature is below the freezing temperature of the ocean's top layer.~~

[For details about the initialisation, the interested reader is referred to Kauker et al. \(2003\).](#) Recently the model parameters were optimised with the help of a genetic algorithm. ~~One set of optimised parameters out of eleven independent optimisations (set number three) is used for the simulation employed in this study starting in 1980. For details on the optimisation procedure and results of the optimisation, i.e. the quality of the simulation we refer to Sumata et al. (2019a) and for~~ [For](#) a detailed analysis
25 of the ~~independent eleven optimised parameter sets~~ [optimisation](#) we refer to ~~Sumata et al. (2019b)~~ [Sumata et al. \(2019a, b\)](#).

3 Methods

3.1 MODIS ~~sea-ice~~ sea-ice concentration

To calculate the MODIS SIC, we adapt the approach used in Drüe and Heinemann (2004). They interpolate linearly between the ice surface temperature of a fully ~~sea-ice-covered pixel~~ (~~sea-ice~~ sea-ice-covered pixel (sea-ice tiepoint IST_I) and that of a
5 fully water-covered pixel (water tiepoint IST_W):

$$SIC = 1 - \frac{IST_{obs} - IST_I}{IST_W - IST_I}, \quad (4)$$

where IST_{obs} is the observed ice surface temperature. IST_W is set to -1.8°C , the freezing point of sea water. For IST_I , the local variability of the ice surface temperature has to be taken into account. MODIS granules normally have 2030 by 1054 pixels. We crop them so that the dimensions are divisible by 48. Then a box of 48 by 48 pixels, called one cell, is taken. The
10 cell is divided into three by three subcells of 16 by 16 pixels. The 25th percentile of each subcell is selected as preliminary ~~sea-ice~~ sea-ice tiepoint. The choice of the percentile does not have significant impact on the final tiepoint (Lindsay and Rothrock, 1995). The ~~sea-ice~~ sea-ice tiepoint for each pixel is then expressed as linear function with two variables:

$$IST_I(x, y) = ax + by + c, \quad (5)$$

where a , b and c are determined by bilinear regression and x and y are the x/y coordinates of the respective pixel within the cell.
15 Subcells are discarded if more than 70 % of the pixels are masked out by the cloud mask. Cells are discarded if they contain less than five valid subcells. Then, the next 48 by 48 pixel box is processed. So far, we strictly follow the approach by Drüe and Heinemann (2004). Then, in difference to them, we shift the box by only one pixel at a time and repeat the bilinear regression before shifting the box by the next pixel. Thus, there are 48 possible IST_I values per pixel. The mean of those values is selected as IST_I . Subsequently, each granule is projected to the NSIDC grid at 1 km grid spacing to be merged with the next closest
20 AMSR2 swath. Of one MODIS granule, there were on average 36 % cloud-free pixels. When considering all granules of one day, 80 % of the pixels were ~~covered~~ cloud-free at least once.

3.2 Merging

For each MODIS granule, the AMSR2 swath with the closest acquisition time is selected. On average, 8 MODIS/AMSR2 matching overflights are available per day. ~~The time lag between MODIS and AMSR2 is normally between three and eight minutes since both satellites, Aqua and GCOM-W1, fly in the A-Train satellite constellation. The A-Train is a suite of satellites which follow each other closely on the same orbit. It was designed to obtain near-simultaneous Earth observation data from different measurements.~~

AMSR2 SIC are given as half-orbits starting either at the North Pole (descending orbit) or at the South Pole (ascending orbit). For a descending orbit, we take the time of the first measurement as acquisition time. For an ascending orbit, we take the
30 time of the last measurement as acquisition time. For the MODIS SIC, we take the starting time of that granule as acquisition time. We use the so-found MODIS/AMSR2 pair if it has at least 10 % of cloud-free overlap. For the merging, we split the

MODIS data in boxes of 5 by 5 km, which roughly corresponds to one AMSR2 footprint. The MODIS and AMSR2 SIC in this 5 by 5 km box are called $SIC_{MODIS,5km}$ and $SIC_{AMSR2,5km}$, respectively. Now, we calculate the difference between the two datasets, $\Delta_{SIC,5km}$, for each box:

$$\Delta_{SIC,5km} = SIC_{AMSR2,5km} - SIC_{MODIS,5km}. \quad (6)$$

- 5 $\Delta_{SIC,5km}$ is now added to the MODIS SIC as shown in Eq. (7). This way, we preserve the mean of the AMSR2 SIC in this 5 by 5 km box. In a last step, we use the AMSR2 data where no MODIS data are available:

$$SIC_{merged_{i,j}} = \begin{cases} SIC_{MODIS,5km_{i,j}} + \Delta_{SIC,5km}, & \text{if } SIC_{MODIS,5km_{i,j}} \text{ available} \\ SIC_{AMSR2,5km_{i,j}}, & \text{if } SIC_{MODIS,5km_{i,j}} \text{ not available} \end{cases} \quad (7)$$

- 10 where the indices i, j denote the position within the 5 km box. To get a smooth field, the box is then shifted by 1 km and the procedure is repeated, before the box is again shifted by 1 km. This way, each pixel is covered 25 times. The mean for each pixel is selected as merged SIC value. This procedure preserves the AMSR2 mean within the 5 by 5 km box, so that there are no sudden in-/decreases of SIC if no MODIS pixel is available. A similar procedure has been applied by Gao et al. (2010). If the AMSR2 SIC is 100 %, the merged SIC at single pixels can be above 100 %. We tolerate this because we want to preserve the mean SIC from AMSR2. Merged SIC above 100 % are set to 100 % in the end.

3.3 Open water extent

- 15 We want to show the benefits of the higher resolution of the merged SIC compared to the AMSR2 SIC. The mean SIC for both datasets is identical by definition. However, the higher resolution of the merged product results in sharper gradients, e.g. at the edges of leads. To show this effect, we calculate the open water extent for both datasets. It is defined as the area covered by all pixels which ~~has~~have at least 15 % open water. Due to its higher spatial resolution, the merged SIC are expected to have a higher open water extent than the AMSR2 SIC. For meaningful comparison, we consider only those data points where
 20 cloud-free MODIS data are available for the merging. Also, we constrain our analysis to scenes when at least 50 % of the pixels are cloud-free measurements. The open water extent is normalised by dividing it by the number of cloud-free pixels.

3.4 Airborne ~~iee~~sea-ice thickness profiles

- We use data of an airborne electromagnetic (AEM) ~~iee~~sea-ice thickness survey carried out over the southeastern region of the refrozen polynya on March 30 and 31, 2018, i.e. roughly five weeks after the polynya had begun to refreeze. Surveys
 25 were carried out with a DC-3/Basler BT67 aircraft (Haas et al., 2010), and were processed as described by Haas et al. (2009). AEM data have an accuracy of ± 0.1 m over level ice but can underestimate the thickness of pressure ridge keels by up to 50 % due to the large footprint of the AEM measurement of up to 45 m over which an average ~~iee~~sea-ice thickness estimate is retrieved. Accuracy was confirmed by a sufficiently large number of small open leads with ~~iee~~sea-ice thickness of zero meters. AEM measurement obtain the total, ice plus snow thickness. Visual observations during the flights showed that the
 30 snow on the young first-year ice of the polynya was less than 0.05 m thick and can be neglected for the purpose of this study.

All measurements over small patches of multiyear ice embedded in the polynya have been removed from the data set. The results therefore represent the thickness of 5 weeks old first-year ice in those specific environmental conditions.

4 ~~Sea-ice~~ Sea-ice concentration

This section first compares the 2018 SIC in the polynya region to that of the entire satellite period (1979–today) in Sect. 4.1.

5 Afterwards the advantage of the merged SIC ~~towards-over~~ the other, single-sensor products is discussed and demonstrated in Sect. 4.2. Finally, the temporal evolution of the polynya is described in Sect. 4.3.

4.1 Climatological context

Figure 1 puts the polynya into a climatological context by comparing it to the OSI-SAF Climate Data Record (OSI-450) which goes back to 1979 (Lavergne et al., 2019). Since the Climate Data Record is only available until 2015, we use the ~~operational~~ 10 OSI-SAF ~~SIC-product~~ Interim Climate Data Record (OSI-430-b) after 2015. The products are temporally consistent at the transition. We show the 1979–2017 mean SIC in the polynya region (box on the inset map) for each day between September 1st and April 30th. Normally, the mean SIC in the region north of Greenland is around 95 %, with a standard deviation of 3 % after the freeze-up period in September and October. The OSI-SAF SIC are capped at 100 %, thus the SIC average can only be beneath 100 % and must result in lower SIC than might have been the case. The climatological mean and the standard 15 deviation do not change much between the beginning of November and the end of April. Except for a 10 % drop during the early freeze-up at the end of September, the 2017/2018 SIC stayed within one standard deviation of the climatological mean until mid January. There was a two-week period of SIC above the climatological mean in the second half of January. In mid February, the polynya started opening rapidly. The mean SIC was at its minimum at February 26th, when it was close to 70 %. Previously, the lowest mean SIC at any day between October 1st and April 30th was 79 %. The time series of the minimal SIC 20 shows that there were other periods during which the mean SIC was outside of the 2σ interval in particular years, for example once in mid December 1986, once in early January 1984 and once in late March 1983 (single years not shown in Fig. 1). However, none of them reached the low extent of the 2017/2018 winter season. We also investigated the homogeneity of the ~~sea-ice-sea-ice~~ cover by calculating the mean spatial standard deviation in the polynya region (Fig. 1, lower panel). It was above 20 % in 2018 while it is normally close to 5 %. This underlines how strongly the normally homogeneously distributed ~~sea-ice~~ 25 sea-ice cover north of Greenland broke up during this exceptional event.

4.2 ~~Sea-ice~~ Sea-ice concentration comparison

The advantage of high-resolution SIC datasets and the differences between the single-sensor datasets are illustrated in this section. ~~Figure 2 shows the~~ The AMSR2 SIC, MODIS SIC, merged SIC and SAR SIC ~~in-comparison-(are compared in~~ Fig. 2a-d)a-d). West of the polynya, the MODIS SIC are lower than the AMSR2 SIC. The merged SIC preserve the AMSR2 30 mean and are thus higher than the MODIS SIC and spatially continuous if there are no MODIS data available. The benefit of including the MODIS data can be seen when looking at the leads which open west of the polynya: They are much more clearly

resolved in the merged product. This is illustrated in the cumulative frequency distribution in Fig. 2e) in more detail. The SAR SIC are the only product which shows 0 % SIC as they have the finest spatial resolution and are based on a binary product. Additionally, a lead covered by very thin, smooth sea ice would still be classified as "open water". These leads show up as reduced SIC of around 20 % in MODIS SIC. The broader leads are also resolved by AMSR2 and show up as SIC between 70 and 80 %. AMSR2 retrieves only few values in the range between 40 and 60 %. The higher amount of SIC between 60 and 80 % is where the merged SIC resolves leads which are too narrow to be retrieved by AMSR2. Over the polynya region, the MODIS SIC and the SAR SIC are higher than the AMSR2 SIC. While AMSR2 retrieves 0 % SIC at the onshore and 20 % at the offshore side of the polynya, MODIS retrieves 40 % SIC at the onshore and 80 % at the offshore side of the polynya. The gradient occurs because the newly formed sea ice is advected away from the coast and pushed towards the northeastern boundary of the polynya. New sea ice forms and piles up at the offshore side of the polynya. Generally, the impact of thin sea ice on the different products can be described as follows: In the very early growth phase, the SAR SIC are close to 0 % as long as the sea ice is smooth. When the smooth ~~sea-ice-sea-ice~~ cover breaks up, the backscatter starts to increase and the SAR SIC increases. Additionally, the algorithm was trained with small leads which have a flat surface (Murashkin et al., 2018). In the polynya area, which is larger, the water surface can be rougher and would therefore not be classified as lead. The MODIS SIC are low during the early growth phase, but not 0 % because the surface air temperature is slightly below the freezing point as soon as there is a very thin layer of sea ice. Their sensitivity to ~~sea-ice-sea-ice~~ thickness decreases as the ~~sea-ice-sea-ice~~ thickness increases. The AMSR2 SIC are sensitive to ~~sea-ice-sea-ice~~ thicknesses up to 10 cm (Heygster et al., 2014). The merged SIC are less sensitive ~~towards-sea-ice-to-sea-ice~~ thickness than the MODIS SIC because they are tuned to preserve the AMSR2 SIC mean. However, because they also include the MODIS information, they still have some sensitivity ~~towards-sea-ice-to-sea-ice~~ thickness above 10 cm. The different sensitivities ~~towards-sea-ice-to-sea-ice~~ thickness are further illustrated in the time series of the mean SIC in Fig. 3. Note that the mean of the AMSR2 SIC is not shown because it is equal to that of the merged SIC by definition (Section 3.2). The MODIS SIC are lower than the merged SIC while the polynya breaks up and after it has frozen over. This is because they are more sensitive to the ~~sea-ice-sea-ice~~ thickness and thin sea ice is shown as reduced ~~sea-ice-sea-ice~~ concentration. During the peak of the polynya area, they are larger than the merged SIC. Here, they are more sensitive to freshly grown ~~sea-ice-sea-ice~~. Also, they are more sensitive to small ~~sea-ice-sea-ice~~ surface temperature variations because the range between the ~~sea-ice-sea-ice~~ tiepoint and the water tiepoint gets very small. The SAR SIC are also larger than the AMSR2 SIC during the peak of the polynya area. The reason is again that they are more sensitive to ~~freshly-grown-newly-formed~~ sea ice than the merged SIC. While recently formed sea ice is retrieved as low SIC by the merged SIC, it increases the backscatter as soon as it breaks up. Due to the drift within the polynya, it is expected that the ~~sea-ice-sea-ice~~ surface is not smooth, but breaks up quickly. Additionally, as mentioned above, the algorithm was not trained to classify rough surfaces as water. To further demonstrate the benefit of the higher resolution of the merged product compared to the AMSR2 SIC, we show the open water extent in Figure 4. The open water extent is the area covered by all pixels which have at least 15 % open water. Consider a typical AMSR2 grid cell of 5 by 5 km with an AMSR2 open water fraction of 10 %. Our 1 km resolution dataset allows the retrieval of 25 different open water fractions in this grid cell whose mean would still amount to 10 %. However, single cells may have an open water fraction above 15 %, so that the open water extent is expected to be higher

for a dataset with higher resolution. A comparison of the time series shows that the difference between the two datasets is small during most of the time. It is 2-3 % while the polynya is open and close to 1 % after it has been closed. The benefit is more apparent when comparing the datasets relative to each other, as shown in the lower panel of Fig. 4. ~~While the polynya is opened, the open water extent of the merged product is 10-60 higher~~The normalised difference is largest during the very early

5 opening phase and smaller towards the end of the opening phase.

February 18th, 2018

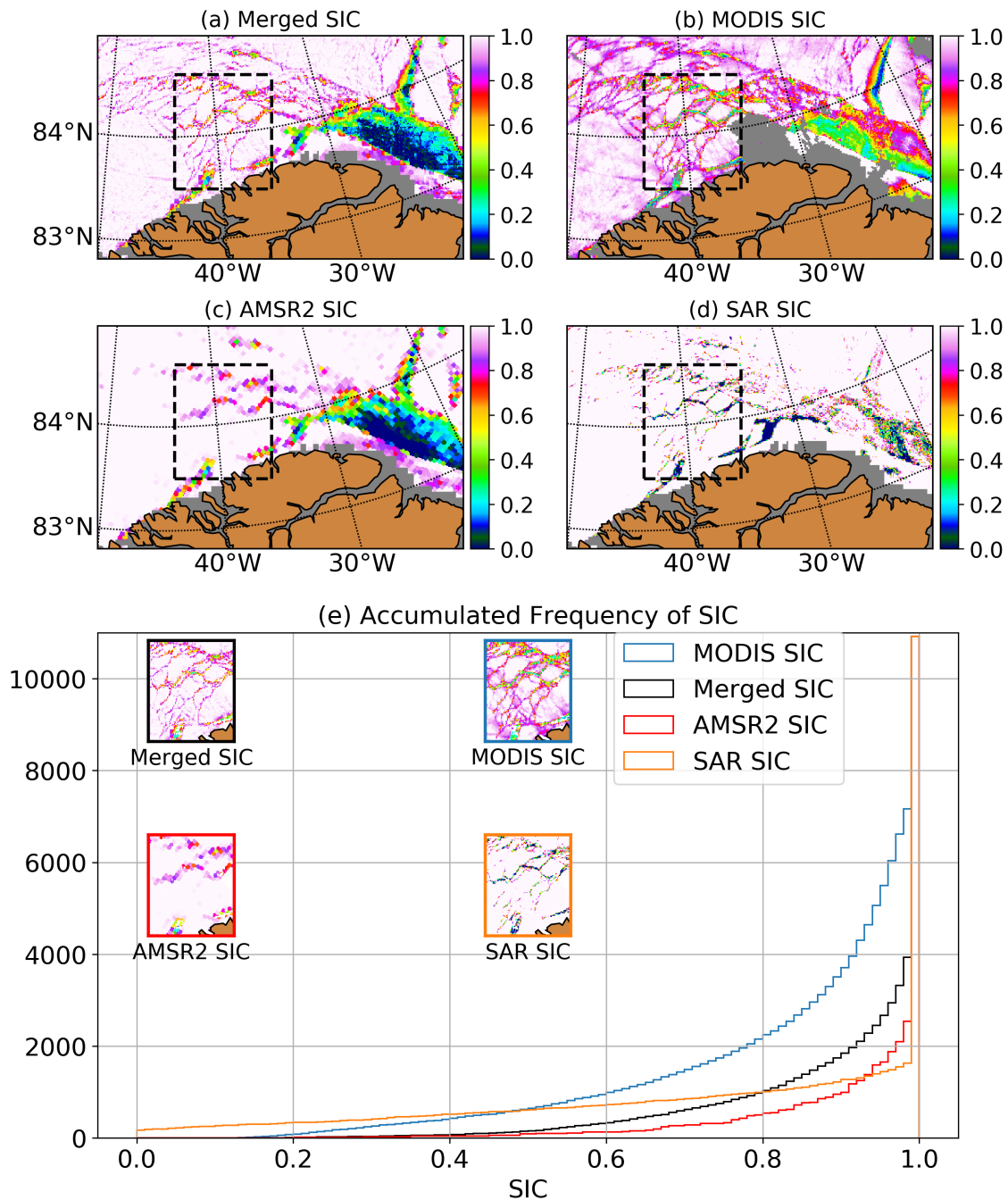


Figure 2. SIC on February 18th, 2018 observed with (a) merged, (b) MODIS, (c) AMSR2 and (d) SAR SIC. The acquisition times for MODIS/AMSR2 were 11:45/11:39 am UTC, respectively. The black dashed box in (a)–(d) marks the region used in Fig. 2e). (e) Cumulative histograms for the four datasets. The insets show the SIC distribution for the single datasets. Data points where one of the products was not available were discarded [for all products](#).

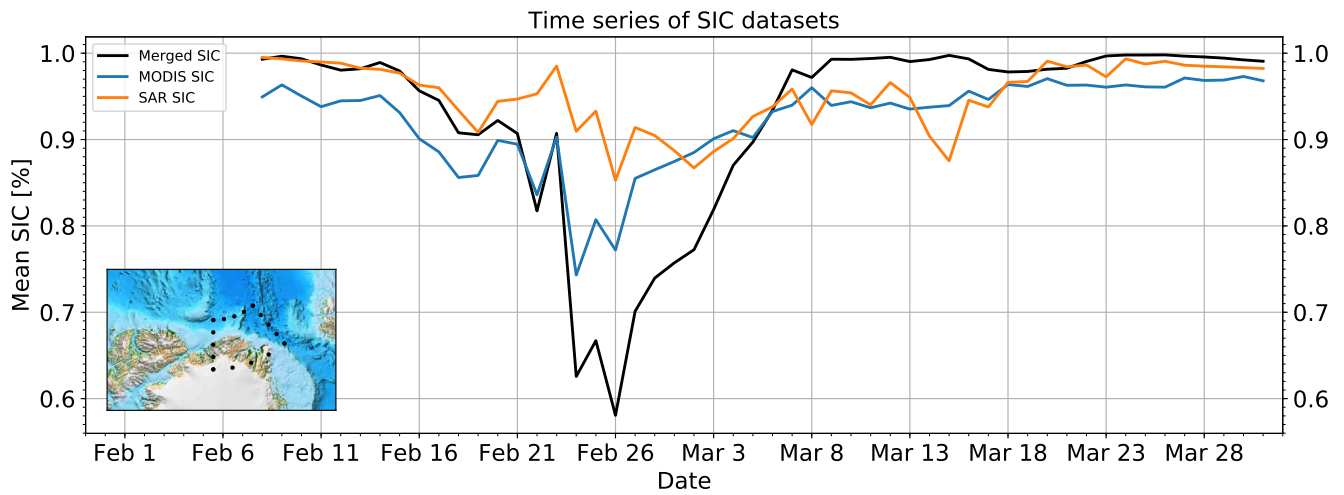


Figure 3. Time series of the mean merged, MODIS and SAR SIC in the polynya region. The AMSR2 SIC are not shown because their mean is equal to the mean of the merged SIC by definition. Only points where all datasets were available have been considered. The map in the lower left shows the region which was considered for the time series as dotted polygon.

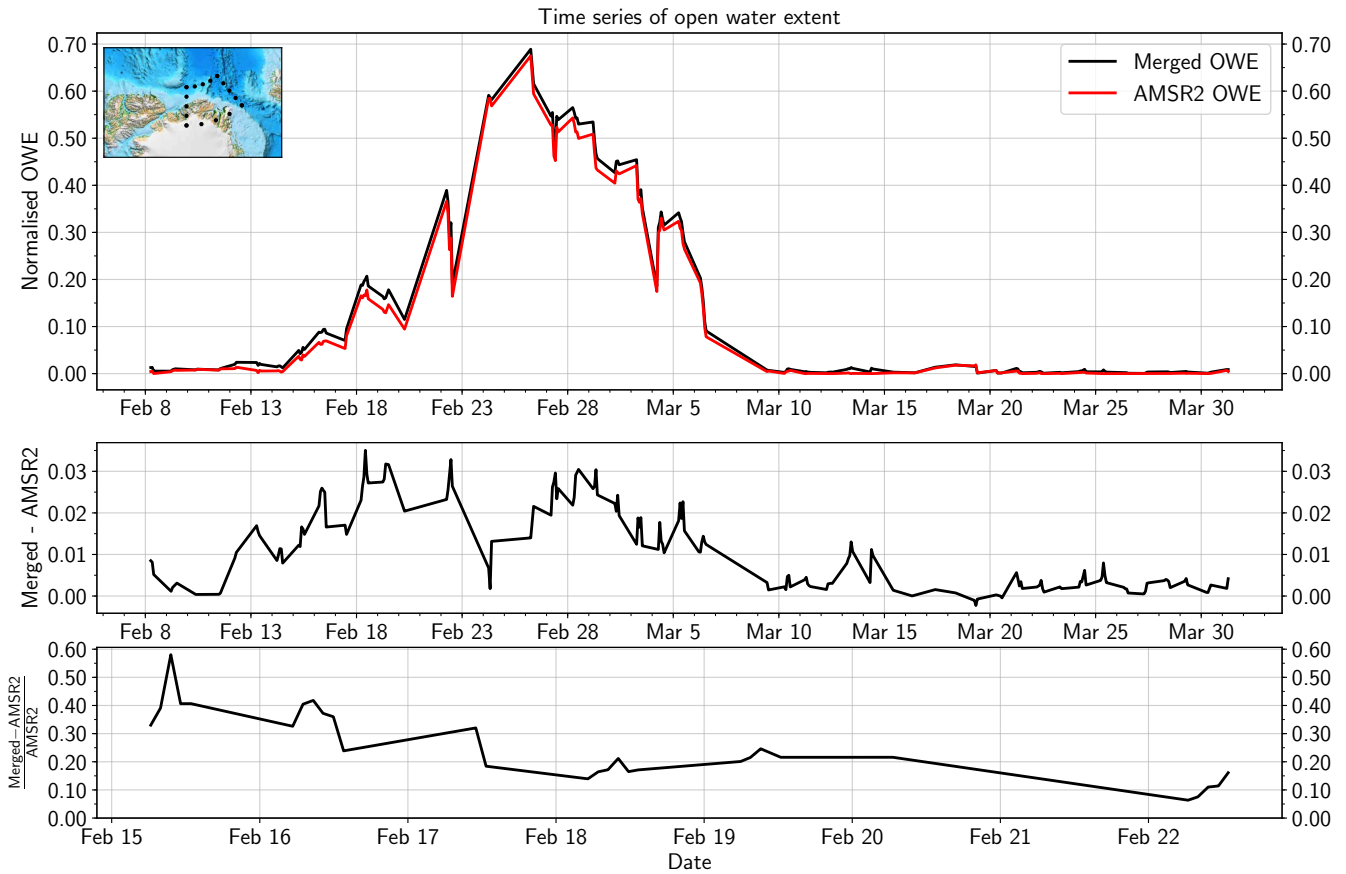


Figure 4. Time series of the merged and AMSR2 open water extent. The upper panel shows the **absolute value of the open water fraction extent** for both datasets. It was normalised to the number of cloud-free pixels. The middle panel shows the difference of the merged and the AMSR2 open water **fraction extent**. The lower panel shows the **quotient-normalised difference** of the two datasets during the opening phase. Mind the different time span of the lower panel. Only points where MODIS data were available were considered for all three panels.

4.3 Polynya development

Having shown that the polynya was unprecedented in magnitude and having demonstrated the benefit of our merged SIC product, we now focus on describing the temporal and spatial development of the polynya during the opening and refreezing. For this, we show maps before, during and after the polynya event in Fig. 5a)–h), as well as a time series of the open water area from the merged product (Fig. 5i). First leads are already visible on February 8th, six days before the polynya actually starts to open. Also, the shear zone parallel to the coast where the polynya will break up later is already visible. This demonstrates the benefit of the merged product ~~towards~~over the AMSR2 SIC, which would be too coarse to resolve these leads, as seen in Fig. 2. Starting on February 14th, the polynya area increases steadily until February 22nd, when it already spans 30,000 km². The polynya area decreases on February 22nd and 24th. Apart from this, the polynya area increases strongly until it reaches its maximum extent on February 26th, when it spanned more than 60,000 km² (Fig. 5). Afterwards, the area decreases almost linearly with time until the now refrozen polynya is not identified as open water any more on March 8th. Note that the area of the opening is still visible as dark/new ice in the Sentinel-1 mosaic.

There are areas (Fig. 5a,g) where leads and 100 % SIC are directly next to each other. This happens when there are no MODIS SIC available for the merging. In this case, the merged SIC are equal to the AMSR2 SIC which show 100 % SIC for sea ice thicker than 10 cm.

In the next section, we investigate the driving mechanism behind the polynya and the environmental conditions throughout the event.

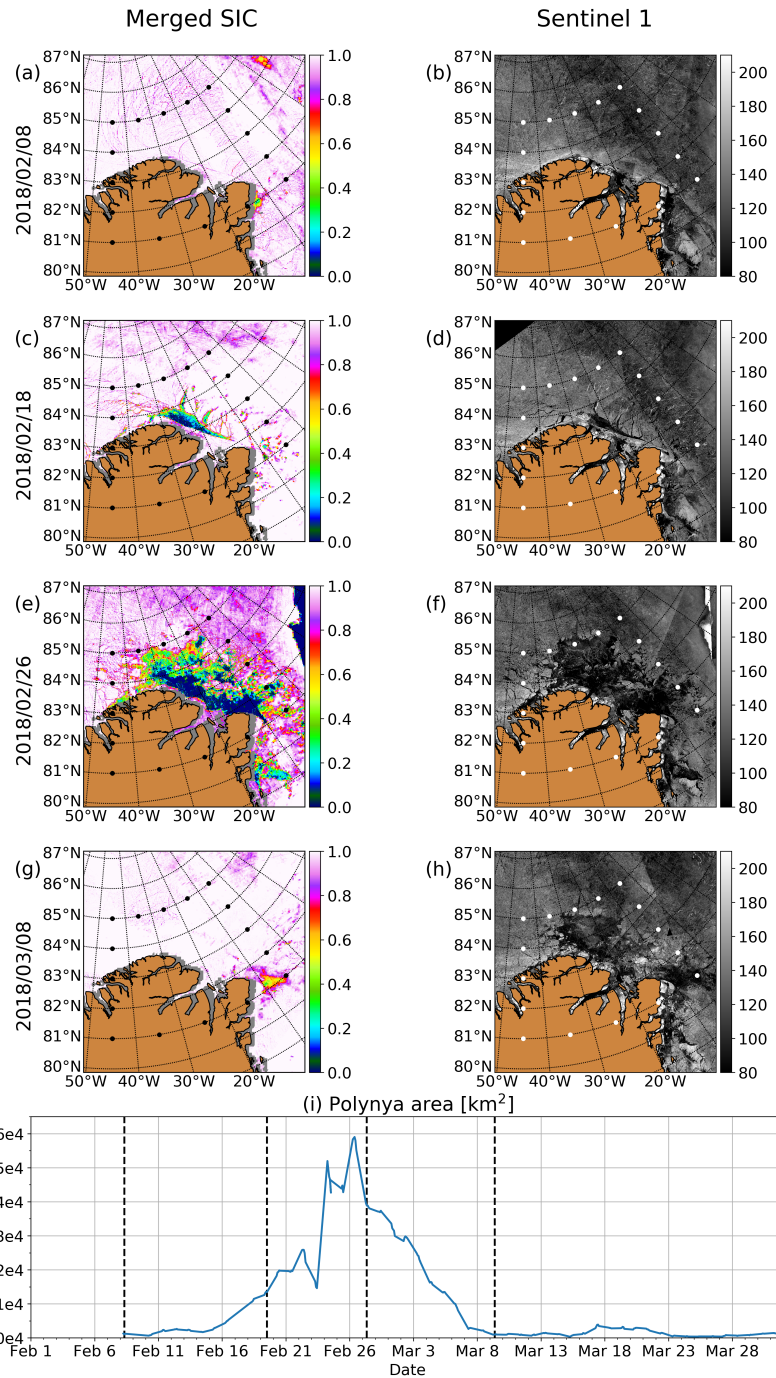


Figure 5. (a), (c), (e) and (g): Merged SIC before, at the beginning, at the maximum and after the refreezing of the polynya. The MODIS/AMSR2 pairs were acquired at 07:50/07:44 on February 8th, at 11:45/11:39 on February 18th, at 09:15/09:11 on February 26th and at 11:30/11:28 on March 8th. All times are a.m. and UTC. (b), (d), (f) and (h): Corresponding Sentinel-1A/B daily mosaics. [The colorbar units are greyscale values.](#) (i): Time series of the polynya area. The polynya area is calculated as sum of the open water fraction (1 - merged SIC) in the map area, multiplied with the respective grid cell size. All available granules are shown. The acquisition times of (a), (c), (e) and (g) are marked by the vertical dashed lines.

5 Environmental conditions

There are two possible reasons for the polynya: The sea ice could have drifted away, which would be typical for a latent heat polynya or it could have melted, which would be typical for a sensible heat polynya. This section describes and analyses the 2 m air temperature and surface air pressure (subsection 5.1) and the ~~sea-ice~~sea-ice drift pattern (subsection 5.2) associated with the polynya.

5.1 Air temperature and surface air pressure

Local air temperatures (Fig. 6) at the autonomous weather station in Cape Morris Jesup in 2018 were above the 2010–2017 average from February 15 to March 8. This is in line with the breaking up and refreezing of the polynya. The air temperature increased rapidly at the beginning of the polynya period. During the formation of the polynya, the air temperature varied by more than 10°C from day to day and crossed the freezing point on nine out of ten days between February 16th and 25th. The air temperature decreased as soon as the polynya started to refreeze and reached the average value on March 8th. Above-average air temperatures during this time of the year have occurred before, for example in 2011 and 2013. However, those lasted only up to five days and not ten days like during the event studied here. On a larger spatial scale, Fig. 7 and Fig. 8 show the air temperature and surface air pressure distribution during the formation phase (February 22nd to 26th) and the refreezing phase (March 2nd to 4th) of the polynya. During the formation, the air temperature was up to 20°C and more than two standard deviations above the average in the polynya region. This was not only a local phenomenon, but associated with a warm-air intrusion from the Atlantic Ocean which caused anomalously high air temperatures until beyond the North Pole (Fig. 7a). The surface air pressure distribution completes the picture: There was a high-pressure system over the Barents and Kara Sea which persisted until February 26th. The surface air pressure was 30–40 hPa above average, which is more than two standard deviations (Fig. 7f). This is the period when the polynya opening rate increased (Fig. 5i). The high-pressure system caused northward winds over the Greenland Sea which contributed to the opening of the polynya. Furthermore, it caused the advection of warm air from the mid-latitudes towards the Arctic region. Ten days later, the atmospheric state had changed substantially (Fig. 8). The air temperature dropped down to the mean of the previous year. The surface air pressure was high over the Central Arctic and lower over the Eurasian Arctic. This caused southward winds which contributed to the closing of the polynya, together with the Transpolar Drift. Although the air temperature was far above average, it was not high enough to explain the polynya. It only crossed the freezing point for some hours, but can not have melted the thick multiyear ice north of Greenland. We conclude that the sea ice must have been broken up by ~~sea-ice~~sea-ice drift. This is consistent with the study of Moore et al. (2018). They found that the thermodynamic ~~sea-ice~~sea-ice production was always positive, while the ~~sea-ice~~sea-ice motion caused the net loss of sea ice. The warm-air intrusion between February 13th and ~~March 3rd~~March 3rd (Fig. ~~6 and March 3rd~~6 and 7) contributed to maintaining the polynya open. The next section describes the ~~sea-ice~~sea-ice drift pattern throughout the polynya event.

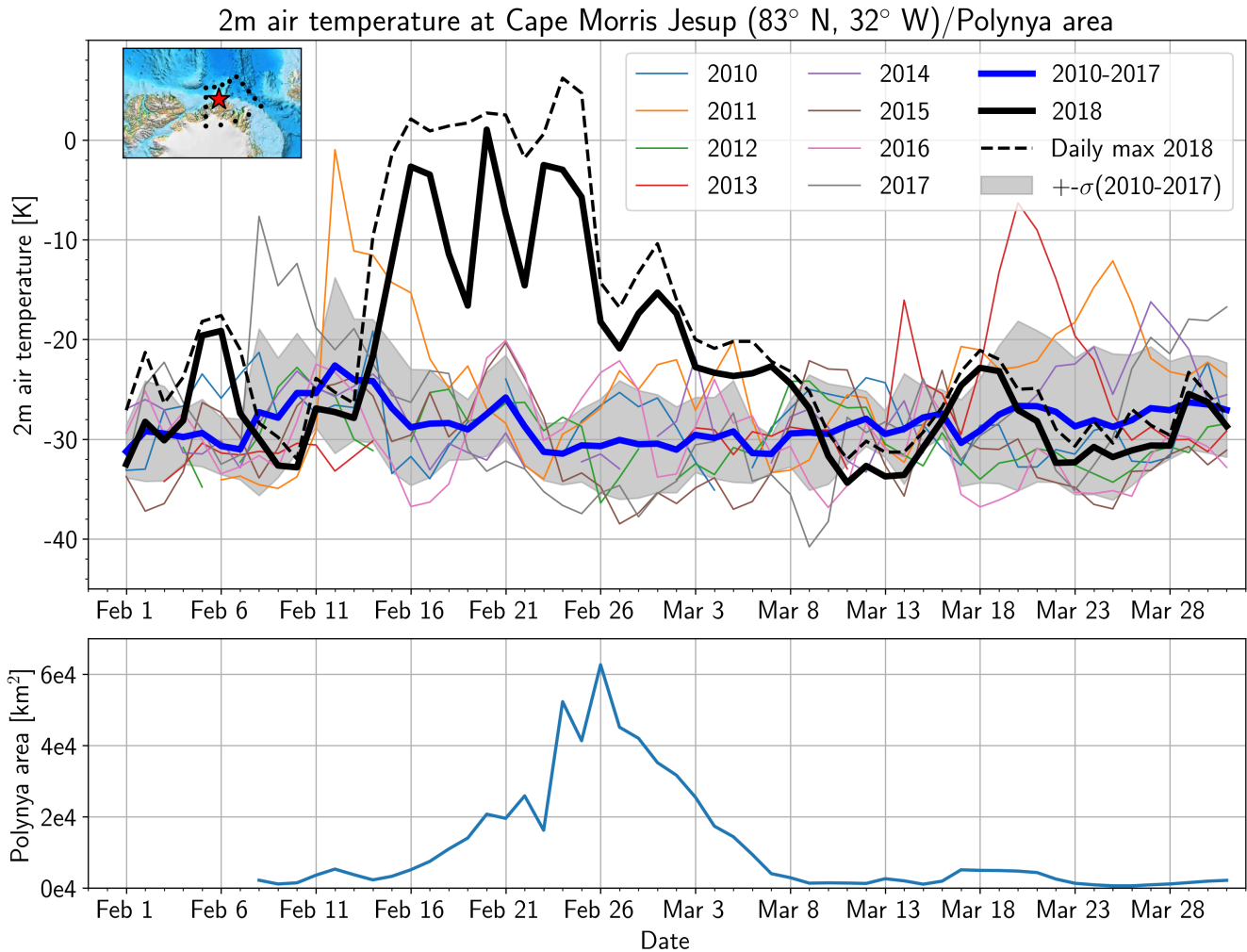


Figure 6. Upper plot: Daily average of 2 m air temperature data at the Danish Meteorological Institute’s weather station at Cape Morris Jesup since 2010. The blue line shows the mean air temperature of the years 2010–2017, the black line shows the air temperatures in 2018. The thin lines represent the single years. The shades indicate the standard deviation of the air temperatures ~~until 2018~~. in the years 2010-2017. The box and star in the map mark the region of the polynya event and the location of the Cape Morris Jesup Station, respectively. Lower plot: Time series of the polynya area from Fig. 5, but with daily means instead of all granules.

5.2 ~~Sea-ice~~ Sea-ice drift

OSI-SAF ~~sea-ice~~ sea-ice drift data between the opening of the polynya (February 14th) and the end of our study period (March 31st) are used to investigate the dynamic drivers of the polynya. In general, the Transpolar Drift exports the sea ice to the Atlantic Ocean via Fram Strait. ~~This year~~ During the polynya event, however, this ~~sea-ice~~ sea-ice drift pattern was reversed.

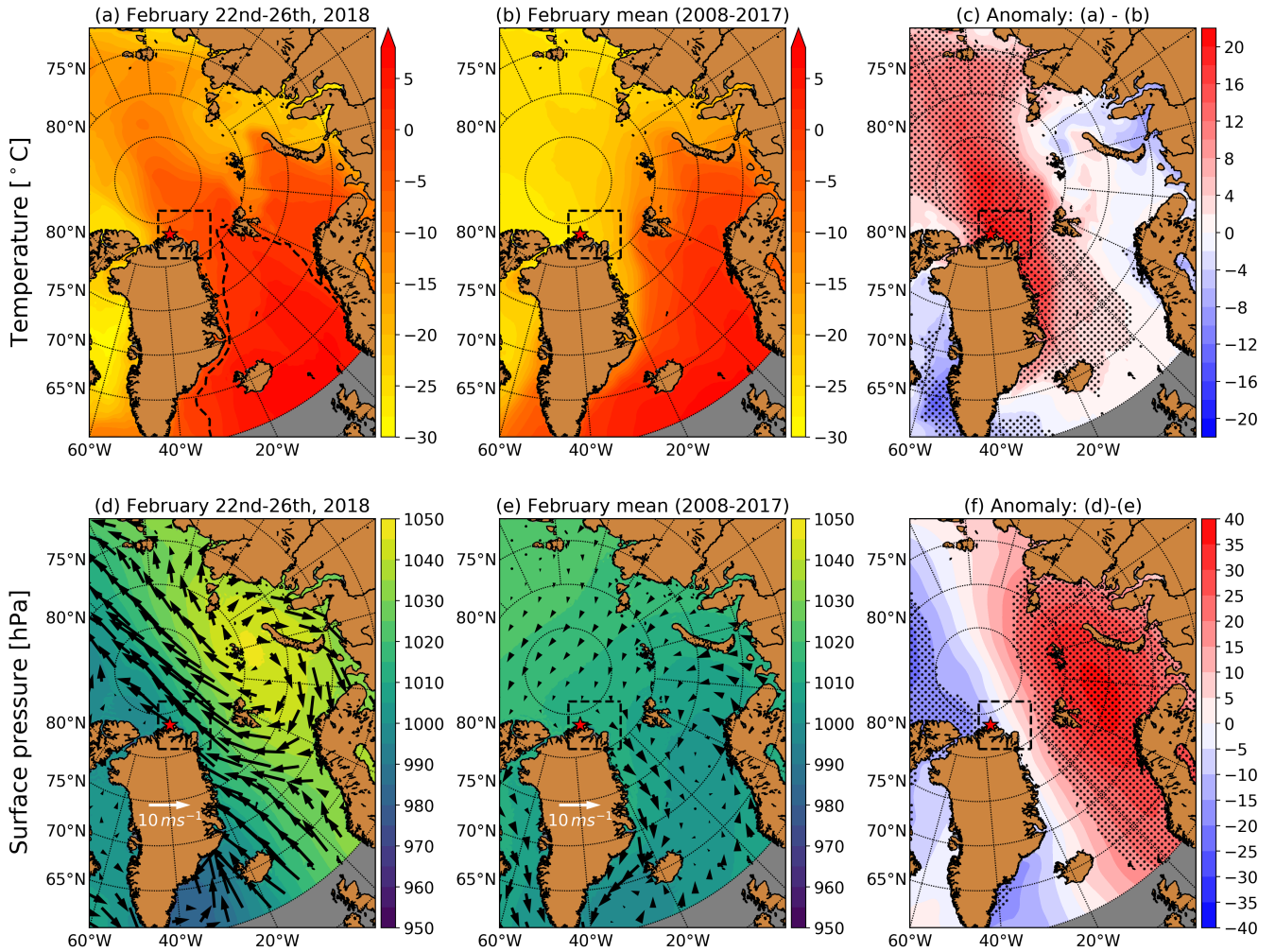


Figure 7. (a) ERA5 2 m air temperature from February 22nd to February 26th, 2018, together with the 0°C isotherm. The box and star in the map mark the region of the polynya event and the location of the Cape Morris Jesup Station, respectively. (b) February mean ERA5 2 m air temperature between 2008 and 2017. The 0°C isotherm is shown as dashed line. (c) Difference between (a) and (b). Black dots mark points where the air temperature in 2018 was more than two standard deviations above/beneath the 2008–2017 average. (d) ERA5 surface air pressure distribution from February 22nd to February 26th, 2018. The black arrows give the ERA5 10 m wind. (e) Same as (d), but for the February mean surface air pressure between 2008 and 2017. (f) Difference between (d) and (e). Black dots mark points where the surface air pressure in 2018 was more than two standard deviations above/beneath the 2008–2017 average.

Where there is normally southward flow, there was northward flow while the polynya opened (Fig. 9a,b). The [sea-ice-sea-ice](#) drift was not only to the opposite direction than usual, but also stronger: The sea ice moved by more than 14 km d^{-1} over a period of almost two weeks. This is 50% more than normal (Table 1). Afterwards, the [sea-ice-sea-ice](#) drift direction changed

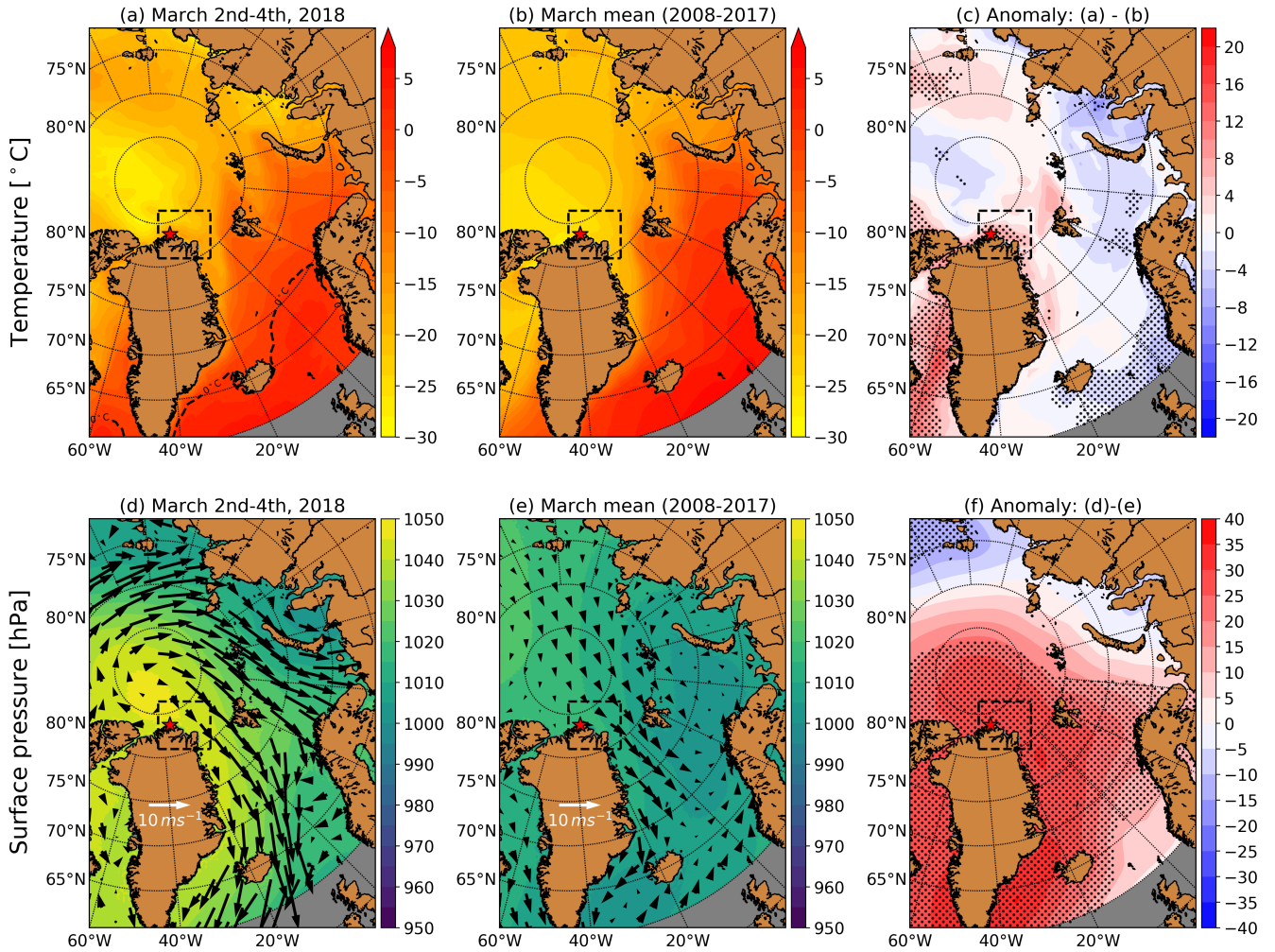


Figure 8. (a) and (d): Same as Fig. 7, but for March 2nd–4th. (b) and (e): Same as Fig. 7, but for the March mean. (c) and (f): Difference between (a) and (b) respectively (d) and (e)

to normal conditions, i.e. southeast and there was below-average displacement in the first half of March (Fig. 9c,d). During the second half of March, the [sea-ice-sea-ice](#) drift was about average (Fig. 9e,f). The mean [sea-ice-sea-ice](#) displacement and the [sea-ice-sea-ice](#) drift angle for [this year 2018](#) and 2010–2017 are given in Table 1. The [sea-ice-sea-ice](#) drift angle is the orientation of the [sea-ice-sea-ice](#) drift towards North and is counted counter-clockwise, so that a sea-ice drift angle of 90° means westward movement. Because of the south-southwestern [sea-ice-sea-ice](#) drift direction, the sea ice was not completely exported towards the Fram Strait in south-east direction. Instead, it partly returned to the polynya region. Here, it got rafted and ridged with the newly formed sea ice in the polynya. This matches the observation of strong southwestern [sea-ice-sea-ice](#) drift between March

	2018	2010–2017	2018	2010–2017
	Displ.[km]	Displ.[km]	Angle[°]	Angle[°]
Feb 14th – Feb 27th	14.4	8.9±1.9	359.4	186.5±8.2
Feb 28th – Mar 16th	4.9	8.7±1.9	157.9	187.5±6.2
Mar 17th – Mar 31st	8.7	8.7±1.8	165.5	194.8±12.9

Table 1. Mean daily displacement and [sea-ice-sea-ice](#) drift angle in the dashed box shown in Fig. 9(a)–(f), calculated based on the OSI-SAF drift product. For the period 2010–2017, the standard error (defined as the standard deviation divided by the square root of the number of years) is given as well. The angles give the mean orientation of the [sea-ice-sea-ice](#) drift vectors towards north. The counting goes counter-clockwise, so that a [sea-ice-sea-ice](#) drift angle of 0°/90°/180°/270° corresponds to purely north-/west-/south-/eastward [movementsea-ice drift](#), respectively.

16th and March 20th (Fig. 9g). We therefore expect a mix of thermodynamically grown, flat sea ice and rough sea ice grown due to [sea-ice-sea-ice](#) deformation at the end of March.

The event can be summarised as follows: In February, the sea ice broke apart and was transported northwards. In the first half of March, the [sea-ice-sea-ice](#) drift was weak and there was rapid thermodynamic [sea-ice-sea-ice](#) growth in the resulting open water of the polynya since air temperatures were almost 30°C below the freezing point (Fig. 6). In the second half of March, parts of the sea ice which had moved northwards in February returned to the area, mainly during one event between March 16th and March 20th, where the [sea-ice-sea-ice](#) drift was strong and directed towards Southwest, i.e. towards the Northern Greenland coast.

6 Processes

10 This section is dedicated to the processes in the polynya: We estimate the amount of sea ice grown in the polynya and the heat released to the atmosphere. To estimate [sea-ice-sea-ice](#) growth, we calculate the accumulated thermodynamic [sea-ice-sea-ice](#) growth assuming calm, snow-free conditions. We employ the freezing degree day parameterisation of Lebedev (1938). The calculations start on February 14th, when the first leads were visible in the merged SIC product. This is compared to airborne electromagnetic (AEM) [ice-sea-ice](#) thickness measurements taken on March 30th and 31st and to the simulations of thermodynamic growth by the NAOSIM model. Also, the estimates of thermodynamic growth are compared to the SMOS/SMAP [sea-ice-sea-ice](#) thickness product of the University of Bremen (Pařilea et al., 2019). For a consistent comparison despite the different grids, we define the polynya area as the area of all pixels which had less than 50 % SIC on the respective grid at least once during the event as described in Sect. 2.

15 The accumulated [sea-ice-sea-ice](#) growth calculated from the freezing degree days increased strongly over the first days while the polynya [opens-opened](#) and then slowed down (Fig. 10). This is expected because the heat flux decreases non-linearly with [sea-ice-sea-ice](#) thickness once the [sea](#) ice starts to grow. As air temperatures decreased, [sea-ice-sea-ice](#) growth increased until the accumulated [sea-ice-sea-ice](#) growth at the end of March was 65 cm. The NAOSIM accumulated [sea-ice-sea-ice](#) growth

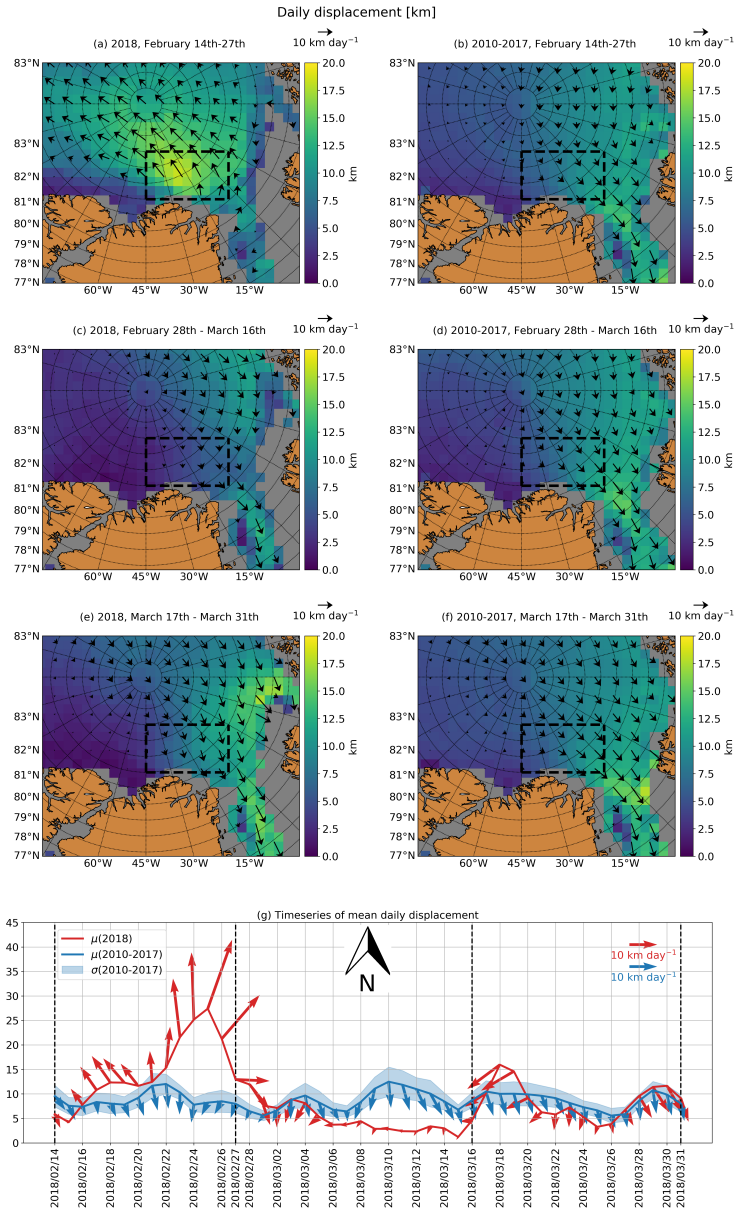


Figure 9. Daily displacement based on the OSI-SAF drift product in the polynya region between February 14th and March 31st. The periods February 14th–27th, February 28th–March 16th and March 17th–31st in 2018 are considered in (a), (c) and (e). The same periods, but for the mean between 2010 and 2017 are considered in (b), (d) and (f). The vectors in (a)–(f) show the mean [sea-ice-sea-ice](#) drift velocity in the corresponding periods, where velocity is defined as displacement per day. (g) shows a time series of the displacement (lines), the standard error of the [sea-ice-sea-ice](#) drift between 2010 and 2017, defined as standard deviation divided by the square root of the number of years (blue shades) and the [sea-ice-sea-ice](#) drift velocity (vectors). The orientation is such that an upward-pointing vector points towards North. The arrows in the top right give the scale of the arrow length. Displacement and [sea-ice-sea-ice](#) drift velocity are the averages in the black dashed boxes in (a)–(f).

increased slowly during the opening of the polynya. Then, it increased strongly from February 25th to March 1st. After that, the accumulated [sea-ice-sea-ice](#) growth increased slowly to 60 cm at the end of March. During the opening of the polynya, the SMOS/SMAP [sea-ice-sea-ice](#) thickness is dominated by dynamic processes. Also, the SMOS/SMAP algorithm assumes 100 % SIC (Pařilea et al., 2019; Huntemann et al., 2014), which is not the case here. In this phase, it can therefore not be compared
5 to the estimates of pure thermodynamic growth. After the refreezing started, it evolved synchronously to the accumulated thermodynamic [sea-ice-sea-ice](#) growth from the freezing degree day parameterisation until both datasets showed [sea-ice-sea-ice](#) thicknesses of 50 cm. Since the SMOS/SMAP algorithm does not retrieve [sea-ice-sea-ice](#) thicknesses above 50 cm (Huntemann et al., 2014; Pařilea et al., 2019), we can not compare the two thermodynamic estimates to the SMOS/SMAP [sea-ice-sea-ice](#) thickness product after March 20th (Fig. 10).

10 In addition to [sea-ice-sea-ice](#) growth, we estimate the thermodynamically produced [sea-ice-sea-ice](#) volume by multiplying the accumulated growth rates from Fig. 10 with the maximum area covered by the polynya. For the maximum area, we again consider all points where the [sea-ice-sea-ice](#) concentration dropped beneath 50 % at least once during the polynya event. The freezing degree day parameterisation yields a [sea-ice-sea-ice](#) volume of 33 km³, NAOSIM yields a [sea-ice-sea-ice](#) volume of 15 km³. The lower [sea-ice-sea-ice](#) volume by NAOSIM is because the area of the polynya in the model was only half as big
15 compared to the observations.

Figure 11 compares the accumulated thermodynamic [sea-ice-sea-ice](#) growth to the [sea-ice-sea-ice](#) thickness measured by three AEM flights on March 30th and 31st. Their modal/mean value was 1 m/1.94±1.83 m with a smaller mode at 5 cm. The small mode is caused by refrozen leads covered with dark and light nilas [which were observed visually during the flights](#). This explains the presence of classes of very thin [sea](#) ice adjacent to the open leads. The tail of the frequency distribution in Fig. 11
20 represents deformed [sea](#) ice rather than purely thermodynamically grown flat [sea](#) ice. We note that there is a difference of the main mode of the AEM measurements of 1.0 m which normally represents the thickness of the most abundant, thermodynamically grown [sea](#) ice (e.g. [Haas et al. \(2010\)](#)[Haas et al. \(2010\)](#)), and the 0.60 m and 0.65 m obtained by the NAOSIM and FDD models, respectively. This difference can be due to insufficient heat flux assumptions in the models, in particular unrealistic ocean heat flux, or it can indicate that much of the level [sea](#) ice in the polynya was also formed by rafting, which could increase
25 level [ice-sea-ice](#) thickness much above the thermodynamically achievable thickness. However, the much larger mean AEM [sea-ice-sea-ice](#) thickness of 0.94 m above the modal [sea-ice-sea-ice](#) thickness demonstrates the importance of dynamic [ice-growth by sea-ice-sea-ice growth by sea-ice](#) convergence and compression as a result of the closing of the polynya. The heat released to the atmosphere calculated by the NAOSIM model (Fig. 10b) is closely coupled to the opening and closing of the polynya. It is negative, i.e. directed from the ocean to the atmosphere, throughout the entire event. The average/maximum daily heat flux
30 was -40/-124 W m⁻². The time-integrated heat flux was -866 W m⁻².

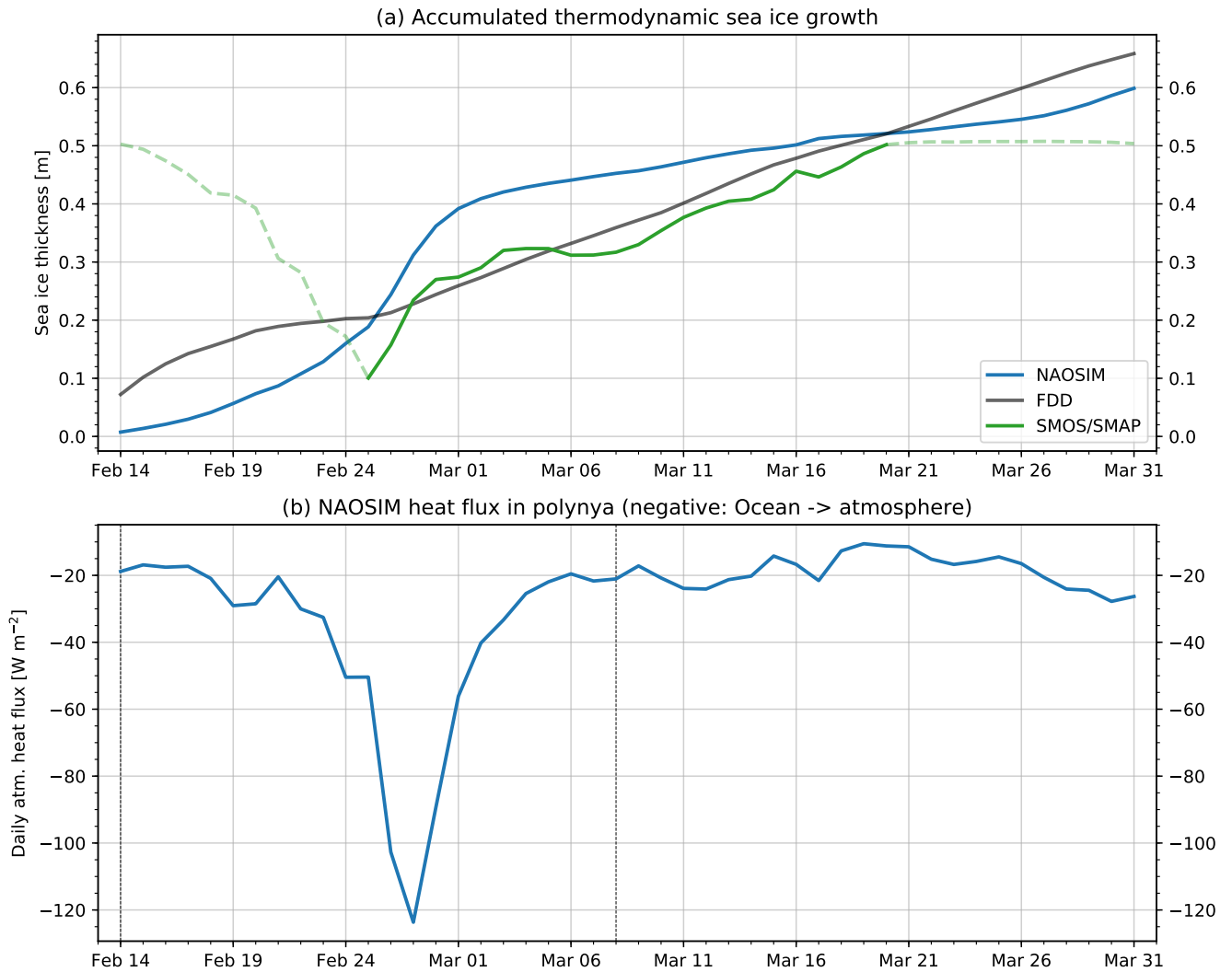


Figure 10. (a) Accumulated thermodynamic sea-ice-sea-ice growth after February 14th modeled by NAOSIM and estimated using the freezing degree day parameterisation. The SMOS/SMAP passive microwave sea-ice-sea-ice thickness product of the University of Bremen is shown for comparison. Days before the refreezing started are marked by the faint dashed line, the same holds for the days after the algorithm reached its maximally retrievable sea-ice-sea-ice thickness. (b) Spatially averaged atmospheric heat flux, defined negative upward (blue line) during the polynya period (vertical dashed lines).

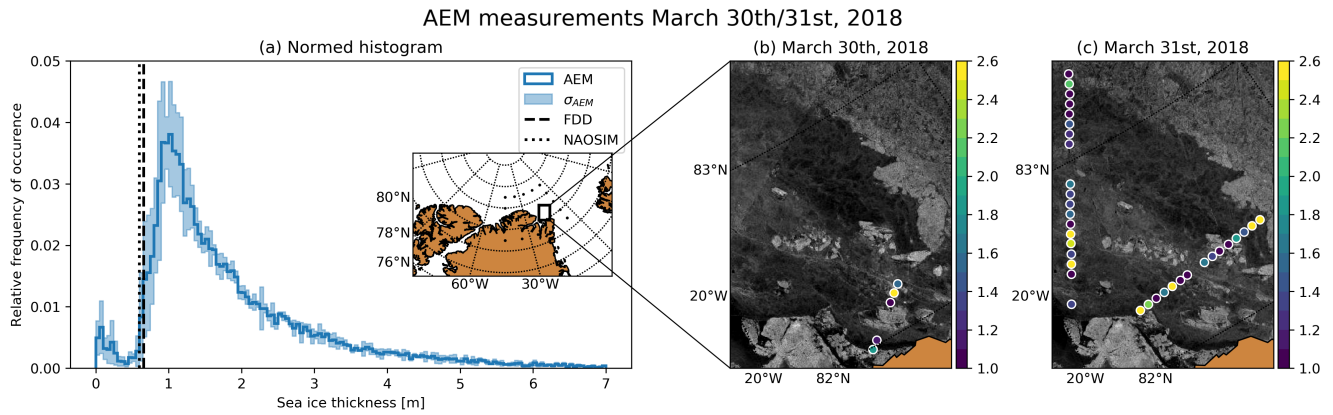


Figure 11. AEM measurements of the thickness of young first year ice formed in the polynya until the end of March. (a): Normalised histogram of the AEM measurements. The shades indicate the standard deviation of the three single flights. The black vertical line shows the mean [sea-ice-sea-ice](#) thickness calculated based on freezing degree days since February 14th. The dotted polygon shows the region of the polynya. The small black rectangle shows the region of the AEM flights. (b) and (c): AEM flights on March 30th and 31st. The dots show the AEM measurements, averaged every 5 km. The background shows a Sentinel-1 mosaic for the respective day.

7 Discussion

Comparing the 2018 polynya north of Greenland to the climatology between 1979 and 2017, we find that the SIC in the polynya area during the peak period between February 25th and February 27th were the lowest observed during any day between November and April since 1979. This confirms the findings of Moore et al. (2018) who showed that the mean February SIC 2018 was smaller than any mean February SIC between 1979 and 2018. ~~Our statement is even stronger~~ [We confirm and further strengthen the findings of Moore et al. \(2018\)](#) as we include the entire winter season in our comparison. The 2018 winter polynya thus was a first-time event which had influence on the regional [sea-ice-sea-ice](#) production and ocean-to-atmosphere heat flux as [will be](#) discussed below. An event as strong as this never happened before during the satellite period. The 1979–2017 all-time minima curve accumulates all potential polynya events during that period. We identify clear but smaller polynya events like in 1986 in mid December. Improved monitoring of these events is possible with the high-resolution, spatially continuous SIC dataset which we present in this paper.

By comparing the merged, MODIS and AMSR2 SIC, we find that AMSR2 SIC is higher than MODIS for high SIC. As the merged SIC preserve the AMSR2 SIC mean, this also holds for the merged SIC. The differences between the MODIS and the AMSR2 SIC arise because the algorithms have different sensitivities to [sea-ice-sea-ice](#) thickness: AMSR2 is based on the polarisation difference which is independent of the [sea-ice-sea-ice](#) thickness if the sea ice is thicker than 10 cm (Heygster et al., 2014). MODIS SIC is based on the local [sea-ice-sea-ice](#) surface temperature anomalies and assumes a bimodal [sea-ice-sea-ice](#) thickness distribution (Drüe and Heinemann, 2004). If the [sea-ice-sea-ice](#) thickness varies while the SIC is 100%, the [SIC concentration](#) of thin sea ice will thus be reported as reduced SIC. Within the 48 by 48 km window used for the derivation of

the [sea-ice-sea-ice](#) tiepoint, the [sea-ice-sea-ice](#) thickness is expected to vary. This is also the reason why the MODIS SIC are lower than the merged SIC before and after the maximal extension of the polynya (Fig. 3). The SIC underestimation is tolerated by Drüe and Heinemann (2004) because the algorithm was designed to derive the thermal surface conditions rather than the physical surface conditions and the oceanic heat flux depends on [sea-ice-sea-ice](#) thickness. However, the SIC underestimation causes a discrepancy when compared to AMSR2 SIC. The described dependence of the MODIS SIC on [sea-ice-sea-ice](#) thickness and the fact that the SAR SIC also is close to 100 % let us conclude that the AMSR2 SIC are closer to the true SIC here. Thus we merge the AMSR2 SIC and MODIS SIC keeping the AMSR2 SIC on a larger scale but adding the higher resolution of the MODIS SIC to resolve smaller leads and openings.

Comparing the histograms of the SIC datasets, we find that the leads west of the polynya tend to be smeared out by the AMSR2 SIC. This is caused by the lower spatial resolution of AMSR2 and not a deficiency of the algorithm. It illustrates that the merged SIC are better than AMSR2 or MODIS SIC alone. Using only MODIS SIC would mean an underestimation of the SIC in many cases, as described above, and would be limited to cloud-free scenes. Using only AMSR2 SIC would result in smearing out narrow leads. Also, refrozen leads which are covered by snow or sea ice which is thicker than 10 cm would not be identified. The merged product's magnitude is closer to the SAR SIC than the MODIS SIC and at the same time it preserves most of the high-resolution spatial information of the MODIS data. The SAR SIC themselves are well-suited as a reference product above the region west of the polynya due to their high spatial resolution. However, larger open water areas like the polynya itself can be misclassified due to, e.g., wind roughening effects. Also, SAR data are only available locally. Thus, the merged SIC are the only product which combines high spatial resolution, spatial coverage and daily Arctic-wide coverage.

Over the polynya region, we find that the SAR and MODIS SIC are higher than the AMSR2 SIC. As the air temperatures were still below freezing, it is likely that [sea-ice-sea-ice](#) production started shortly after the opening. The wind and [sea-ice-sea-ice](#) drift patterns hindered the evolution of a homogeneous [sea-ice-sea-ice](#) cover and the newly formed sea ice was turned into grease ice. Under these circumstances, it may be that AMSR2 does not retrieve the grease ice. The grease ice would, however, change the backscatter signature so that the polynya is no longer recognised as such by the SAR SIC. Additionally, a rough water surface can be misinterpreted as ice by the SAR SIC algorithm as it was trained to retrieve small leads which generally have a smooth surface. The grease ice also shows up as increased MODIS SIC. Another reason for higher MODIS SIC is that the [sea-ice-sea-ice](#) tiepoint is derived based on the local [sea-ice-sea-ice](#) surface temperature anomaly. If the surrounding [sea-ice-sea-ice](#) surface temperature is only slightly below freezing, the range between the dynamic [sea-ice-sea-ice](#) tiepoint and the fixed water tiepoint gets small and small [sea-ice-sea-ice](#) surface temperature variations cause high SIC variations. The described sensitivity of the MODIS and SAR SIC towards to very freshly grown [sea-ice-sea-ice](#) is also the reason why they are lower during the maximal extension of the polynya (Fig. 3). It may be that we underestimate the SIC here by tuning MODIS SIC to the AMSR2 SIC as we get SIC between 0 % and 20 %, although the actual concentration of grease ice is probably higher. We tolerate this as a [tradeoff-trade-off](#) because the approach allows better retrieval of higher SIC and a spatially continuous field. The advantage of the higher resolution of the merged SIC product was shown in Figure 4. It was most pronounced during the early break-up ; [when the open water extent of the merged SIC was up to 60, higher than that of the AMSR2 SIC and less pronounced towards the end of the opening phase](#). The reason is that small leads which are formed while the polynya breaks up

are resolved by the merged product, but not or only hardly by the AMSR2 SIC. This is caused partly by the higher resolution of the merged product and partly because the MODIS SIC can retrieve refrozen leads which are not retrieved by the AMSR2 SIC any more.

5 Strictly speaking, a refrozen lead should not be visible in a SIC product, i.e. have a SIC of 100% as soon as it refreezes.
While the sea ice is thin (approximately thinner than 10 cm), a lead will likely be shown as reduced SIC in our merged product as the AMSR2 SIC are influenced by sea-ice thickness (Heygster et al., 2014; Wiebe et al., 2009). For new sea ice in leads, the brine on top of the ice and the thin sea-ice thickness influence the brightness temperatures measured by the passive microwave radiometer, which can lead to a reduced SIC retrieval. While the sea ice is growing, this effect gets reduced and when the sea-ice thickness exceeds approximately 10 cm, the lead would appear as 100% SIC in a pure AMSR2 SIC product. In our
10 merged product, however, it may still appear as reduced SIC. This is due to the influence of thin sea ice on the MODIS SIC (Drüe and Heinemann, 2004) which is stronger than the influence on the AMSR2 SIC. In this case, we could set the SIC to 100% to be fully consistent with the definition of SIC, but we decided to keep this additional lead information. The rationale for this is that for many applications and processes, e.g. navigation or heat flux calculations, the presence of leads is highly relevant. We thus accept being slightly inconsistent with the definition of sea-ice concentration as a trade-off for conveying the
15 lead information to the user. A step forward in future could be to add a flag to our product which tells the user that the AMSR2 SIC at the respective pixel is 100%, meaning that the lead is already refrozen. This flag would also convey information about the sea-ice thickness: It would indicate that the sea ice is thick enough to be retrieved as 100% SIC by AMSR2, i.e. thicker than approximately 10 cm, but still thin enough to be retrieved as reduced SIC by MODIS.

Next, we look into the spatial and temporal evolution of the polynya and the environmental conditions. At its maximal
20 extent, it spanned more than 60,000 km². The mean size during the opening was 11,000 km². This is slightly larger than the average size of 17 recurring Arctic polynyas reported by Preußner et al. (2016). They find sizes between 400 and 43,600 km². The opening of the polynya was driven by anomalous ~~sea-ice~~ sea-ice drift. It was directed northwards where it is normally directed southwards. Besides, the ~~sea-ice~~ sea-ice drift speed was 14 km d⁻¹, which is 50% stronger than in the eight years before. Also, other studies (Kwok et al., 2013; Vaughan et al., 2013) find typical ~~sea-ice~~ sea-ice drift speeds between five and
25 10 km d⁻¹ in this region. During the second half of the opening period, the ~~sea-ice~~ sea-ice drift anomaly was caused by a persistent high-pressure system above the Eurasian Arctic. The sea-ice drift pattern during the polynya event has also been analysed by Moore et al. (2018). They use data of the Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS, ~~Zhang and Rothrock (2003)~~ Zhang and Rothrock (2003)). We can only compare our findings indirectly because they look at the ~~sea-ice~~ sea-ice thickness change due to ~~sea-ice~~ sea-ice motion while we look at the ~~sea-ice~~ sea-ice drift directly. Still, the
30 temporal evolution is consistent: They identify a first peak on February 16th and a second, stronger one on February 23rd and 24th. In our ~~sea-ice~~ sea-ice drift time series, the peaks are one to two days later. The event on March 3rd during which the sea ice was partly returned to the polynya area is also visible in their data. Since their time series ends on March 5th, further comparison is not possible. We found that the ~~surface-air-pressure~~ surface-air-pressure distribution during February and March was coincident with the opening and closing of the polynya. Moore et al. (2018) identify the surface pressure
35 distribution and the associated warm-air intrusion as surface response to a sudden stratospheric warming which occurred in

early February. The high-pressure system caused northward winds in the polynya area and increased the opening rate. The warm-air intrusion from the mid-latitudes featured air temperatures up to 20° C above the average, visible in both reanalysis data and local measurements. The heat released by the polynya contributed to the anomaly. Other studies (Graham et al., 2017; Woods and Caballero, 2016; Moore, 2016; Mewes and Jacobi, 2018) report that such winter warming events have occurred since the 1950s, but did not last as long and were weaker than in recent years. Also, they were not related to polynyas. Even if the 2 m air temperatures in our case were exceptionally high, they were below/only slightly above the freezing point. The advected air temperature anomaly contributed to the polynya development only indirectly: It slowed the ~~sea-ice-sea-ice~~ growth, but did not prevent ~~sea-ice-sea-ice~~ growth totally and did not melt the sea ice. This is again consistent with the results of Moore et al. (2018) who show that the thermodynamic ~~sea-ice-sea-ice~~ production was always positive, i.e. no ~~sea-ice-sea-ice~~ melt occurred. After the air pressure distribution changed, the ~~sea-ice-sea-ice~~ drift was directed towards Fram Strait as usual and air temperatures were 20° C below the freezing point. The polynya refroze and closed quickly. ~~While it was opened, it contributed to the air temperature anomaly due to heat release.~~

We identify two periods of enhanced ~~sea-ice-sea-ice~~ drift directed towards the Northern Greenland coast in the beginning and in the second half of March (Fig. 9). These closing events have caused deformation of the newly formed sea ice in the polynya. At the end of March, the polynya was covered by a mixture of second and multiyear ice from before the event, deformed newly grown young ice and flat new ice (Fig. 11). Our estimate of thermodynamic ~~sea-ice-sea-ice~~ growth (60 cm modeled by NAOSIM, 65 cm estimated by the freezing degree day parameterisation) for March 31st is thus likely an underestimation of the actual ~~sea-ice-sea-ice~~ thickness due to the ~~sea-ice-sea-ice~~ thickening by deformation. This is confirmed by comparing these estimates to AEM ~~sea-ice-sea-ice~~ thickness measurements at the end of March, which found a modal ~~sea-ice-sea-ice~~ thickness value of 1 m as well as a tail towards higher ~~sea-ice-sea-ice~~ thicknesses due to deformation.

The SMOS/SMAP algorithm assumes 100 % ~~sea-ice-sea-ice~~ concentration. This was not always the case during the event. In fact, our SIC curves in Figure 3 show SIC down to 65 %. This contributes to the SMOS/SMAP ~~sea-ice-sea-ice~~ thickness decrease before February 25th. Especially for very thin sea ice, passive microwave retrievals of ~~sea-ice thickness and sea-ice sea-ice thickness and sea-ice~~ concentration are ambiguous and it is hard to disentangle the influence of the two quantities on the signal (Ivanova et al., 2015; Heygster et al., 2014). A quantitative estimate of how much the lower ~~sea-ice-sea-ice~~ concentration influenced the ~~sea-ice-sea-ice~~ thickness retrieval would be beyond the scope of this paper. We note that the SMOS/SMAP ~~sea-ice-sea-ice~~ thickness during the opening and early refreezing are less reliable than at a later stage of refreezing. The SMOS/SMAP ~~sea-ice-sea-ice~~ thickness is only valid until a ~~sea-ice-sea-ice~~ thickness of 50 cm (Huntemann et al., 2014; Pařileia et al., 2019). Therefore, we can only compare the SMOS/SMAP ~~sea-ice-sea-ice~~ thickness to the other products between February 25th, when the refreezing starts and March 20th, when the SMOS/SMAP ~~sea-ice-sea-ice~~ thickness reaches 50 cm. The agreement between the freezing degree day parameterisation, the SMOS/SMAP ~~sea-ice-sea-ice~~ thickness and the NAOSIM ~~sea-ice-sea-ice~~ thickness in this period is good. For SMOS/SMAP and the freezing day parameterisation, this is partly because the SMOS/SMAP algorithm was trained using this parameterisation (Huntemann et al., 2014; Pařileia et al., 2019). The influence of the warm-air intrusion on the quality of the ~~sea-ice-sea-ice~~ thickness retrieval was probably negligible. The air temperature was

only above 0° C during the opening of the polynya. During the refreezing phase which we analyse here, the air temperature was beneath 0° C and therefore did not influence the [sea-ice-sea-ice](#) thickness retrieval.

By comparing the estimates of the thermodynamically produced [sea-ice-sea-ice](#) volume, we find a discrepancy between the freezing degree day parameterisation (33 km³) and the NAOSIM model (15 km³). The discrepancy is because the polynya in the model is only half as large as in the observations. A similar finding was presented in Moore et al. (2018), who find that the polynya in the PIOMAS model was significantly smaller than in the observations. Since our observations agreed well with the outline of the polynya in the SAR images, we conclude that the 33 km³ are the better estimate. Preußer et al. (2016) give January-March accumulated [sea-ice-sea-ice](#) production rates of 52 km³ on average for 17 Arctic coastal polynyas. According to Tamura and Ohshima (2011), the ten major coastal polynyas in the Arctic produce between 130 and 840 km³ per year. Total winter-accumulated [sea-ice-sea-ice](#) production in Arctic polynyas has been estimated between 1811 km³ (Preußer et al., 2016) and 2940 km³ (Tamura and Ohshima, 2011). However, given that normally [sea-ice-sea-ice](#) production north of Greenland is negligible and that the 2018 polynya was only open for three weeks while the values of Preußer et al. (2016)/ Tamura and Ohshima (2011) are given for three months/an entire year, the event is still remarkable on a regional scale. Finally, we estimate a mean/maximum heat flux of -40/-124 Wm⁻² during the time when the polynya was opened. This is small compared to the heat fluxes given by Morales-Maqueda et al. (2004). They report mean heat fluxes between -38 and -105 Wm⁻². We attribute this to the warm-air intrusion. When the polynya was opening, the air temperatures were around -10° C, so that the heat flux was comparably small. When the air temperatures decreased to -30° C, the polynya had already started to refreeze, which dampened the heat flux.

8 Summary & Conclusions

This paper uses a new SIC product at 1 km resolution from merged passive microwave (AMSR2) and thermal infrared (MODIS) data. The product comprises the high spatial resolution of the thermal infrared data and the spatial coverage of the passive microwave data. Its benefit is demonstrated by means of the polynya which opened north of Greenland in winter 2018. We show that the merged product detects more leads than the passive microwave data and at the same time allows continuous monitoring of the event.

The polynya opened in the second half of February. The open water area expanded over 12 days, reached its maximal extent of more than 60,000 km² on February 26th and decreased linearly until it closed on March 8th. The closing was due to fast refreezing after the warm-air intrusion abated. Additionally, there was dynamic closing by southward [sea-ice-sea-ice](#) drift. The merged SIC ~~show closed sea-ice~~ [shows closed sea-ice](#) cover after March 8th. Nonetheless, the area of freshly grown sea ice is still distinguishable in SAR images on March 31st.

The evolution is driven by the [sea-ice-sea-ice](#) drift in the polynya region. The [sea-ice-sea-ice](#) drift was directed northwards instead of the usually dominating southward direction during the polynya opening. Furthermore, it was 50 % stronger than usual. The [sea-ice-sea-ice](#) drift was weak during the first half of March, allowing for undisturbed thermodynamic growth of new sea ice. Two convergent events at the end of February and mid March brought back sea ice which was exported from the

polynya area during the formation. Therefore, there is a mixture of flat, thermodynamically grown and rough sea ice grown due to ~~sea-ice~~ sea-ice dynamics at the end of March.

Temperatures during the opening of the polynya were more than 20° C above average. This was caused partly by a high-pressure system above the Kara Sea which brought in warm air from the Atlantic. However, the air temperatures still remained
5 below freezing. They were not high enough to melt the sea ice, but slowed down the refreezing process. Only locally, the daily maximum air temperature exceeded the freezing point several times, but not long and strong enough to cause substantial melting. The polynya also contributed to this air temperature anomaly due to the heat released from the ocean to the atmosphere.

The questions which we raised in the beginning can be answered as follows:

1. Does merging MODIS thermal infrared and AMSR2 passive microwave SIC allow additional insights about the forma-
10 tion of the polynya?

Before the opening of the polynya, leads were visible in the merged, high-resolution SIC product which would have been smeared out by the AMSR2 SIC due to the coarse resolution. Generally, the merged SIC showed more SIC values between 60 % and 90 % than the AMSR2 SIC, indicative of the leads which are identified due to the higher resolution. Over regions with 100 % SIC, an underestimation of the merged SIC compared to the AMSR2 SIC may occur, which we tolerate as a tradeoff
15 for the possibility to resolve more leads. ~~During the opening of the polynya, the merged SIC retrieve up to 60 more open water than the AMSR2 SIC alone~~ The benefit of the merged SIC is most pronounced during the opening of the polynya.

2. Was the polynya opened thermodynamically or dynamically and how unusual were the environmental conditions?

The polynya was opened by an anomalous ~~sea-ice~~ sea-ice drift event in the end of February, which confirms the findings of ~~Moore et al. (2018). The sea-ice~~ Moore et al. (2018). The sea-ice drift was directed northwards for 12 days where it is normally
20 directed southwards. Also, it was 50 % stronger than usual. A high-pressure system over the Eurasian Arctic kept the polynya open. It was accompanied by local air temperatures more than 20° C above average, caused partly by advection due to the high-pressure system and partly by heat release from the opening polynya. Although the air temperature was exceptionally high, it was not high enough to melt the sea ice. Events like this have occurred before ~~and-~~ , but not with the same magnitude. They are expected to occur more frequently in future due to the expected thinning of the ~~sea-ice~~ sea-ice cover.

25 3. How much sea ice grew in the polynya and how much heat was released to the atmosphere?

Two estimates of thermodynamic ~~sea-ice~~ sea-ice growth show accumulated growth of 60 cm (NAOSIM model) and 65 cm (freezing degree day parameterisation) on March 31st, i.e. much lower than the modal AEM thickness of 1.0 m. This could indicate that thermodynamic ice growth was strongly underestimated by the models, despite the fact that we have observed a thin snow cover which would have reduced ice growth but was not considered by the freezing degree day parameterisation.
30 On the other hand, the larger observed modal ~~ice~~ sea-ice thickness could also have been due to rafting which would double the resulting ~~ice~~ sea-ice thickness compared to the level ~~ice~~ sea-ice thickness of the undeformed ice at the time of deformation. However, the much larger mean AEM ~~ice~~ sea-ice thickness of 0.94 m more than the modal ~~ice thickness showed~~ sea-ice

thickness shows that deformation played a strong role for ice growth in addition to thermodynamic growth considered by the models. According to the freezing degree day parameterisation, 33 km³ of sea ice were produced. The modeled heat release from the ocean to the atmosphere was on average 40 Wm⁻² while the polynya was open.

9 Outlook

5 The merged SIC product is presented here for the first time. The benefit ~~towards~~over single-sensor SIC is demonstrated. However, more validation is needed and planned in future work. This could be done by using for example high-resolution optical data from the European Union Copernicus Sentinel-2 or the US Landsat satellite. Also, other methods for merging SIC should be tested and compared to the method presented here. For example, Dasgupta and Qu (2006) use a wavelet-based approach to merge MODIS and AMSR-E data for vegetation moisture retrieval and Ricker et al. (2017) use an optimal interpolation scheme
10 to merge CryoSat-2 and SMOS (Soil Moisture and Ocean Salinity) ~~sea-ice~~sea-ice thicknesses. In principle, their approaches should also be applicable for merging SIC. The combination of passive microwave and thermal infrared data is not expected to work in summer as both of them can not distinguish melt ponds from open water and thus underestimate the summer SIC. Data in the visible wavelength range provide the possibility to detect melt ponds separately (Rösel et al., 2012). Including them into the merging procedure could thus improve the product's performance in summer. Higher resolution can also be achieved
15 by including SAR data as suggested by Karvonen (2014).

At the moment, potential atmospheric effects on the AMSR2 ~~sea-ice~~sea-ice concentration over sea ice are not considered. Work on correcting these effects is currently undertaken (Lu et al., 2018). It is planned to include this in the future development of our product.

We found that events like this have occurred before north of Greenland. Future research could focus on investigating when,
20 where and how often such events occurred and how strong they were. A polynya was observed in the same spot in August 2018. It could be investigated whether the event described here preconditioned the event in August 2018.

The freeze-up period ~~should~~could also be analysed in more detail. We show that the modal ~~sea-ice~~sea-ice thickness at the end of March can be approximately reproduced by rather simple approaches neglecting dynamic processes. More research could clarify how much flat and how much rough sea ice there was at the end of March and how the remaining discrepancy
25 between our two estimates and the AEM ~~sea-ice~~sea-ice thickness of 35 cm can be explained.

Code and data availability. The code and data needed for reproducing the Figures are available upon request from VL (vludwig@uni-bremen.de). FK (frank.kauker@awi.de) may be contacted for the NAOSIM model code and output. DM (murashkin@uni-bremen.de) may be contacted for the binary Sentinel-1 lead maps. VL may be contacted for the AEM sea-ice thickness data as well as for the AMSR2, MODIS and merged SIC code and data. The merged SIC product will be publically available at <https://www.seaice.uni-bremen.de> in near
30 future. The availability of the other datasets is given in the Acknowledgements.

Author contributions. VL, LI and GS designed the research. DM contributed the SAR SIC dataset. FK performed the NAOSIM run. CH contributed the AEM data. VL wrote the paper, except for Sect. 2.2.2 (DM), Sect. 3.4 (CH) and Sect. 2.2.7 (FK). All authors critically discussed the contents and agreed to the submission.

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References

- Ackerman, S., Frey, R., Strabala, K., Liu, Y., Gumley, L., Baum, B., and Menzel, P.: MODIS Atmosphere L2 Cloud Mask Product. NASA MODIS Adaptive Processing System, Goddard Space Flight Center, USA., https://doi.org/http://dx.doi.org/10.5067/MODIS/MOD35_L2.061, 2017.
- 5 Beitsch, A., Kaleschke, L., and Kern, S.: Investigating High-Resolution AMSR2 Sea Ice Concentrations during the February 2013 Fracture Event in the Beaufort Sea, *Remote Sensing*, 6, 3841–3856, <https://doi.org/10.3390/rs6053841>, <http://www.mdpi.com/2072-4292/6/5/3841>, 2014.
- Castro-Morales, K., Kauker, F., Losch, M., Hendricks, S., Riemann-Campe, K., and Gerdes, R.: Sensitivity of simulated Arctic sea ice to realistic ice thickness distributions and snow parameterizations, *Journal of Geophysical Research: Oceans*, 119, 559–571, <https://doi.org/10.1002/2013JC009342>, <http://dx.doi.org/10.1002/2013JC009342>, 2014.
- 10 Comiso, J. C.: SSM/I sea ice concentrations using the bootstrap algorithm, vol. 1380, National Aeronautics and Space Administration, Goddard Space Flight Center, 1995.
- Copernicus Climate Change Service: (C3S): ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate . Copernicus Climate Change Service Climate Data Store (CDS), November 30, 2018., 2017.
- 15 Dai, A., Luo, D., Song, M., and Liu, J.: Arctic amplification is caused by sea-ice loss under increasing CO₂, *Nature communications*, 10, 121, 2019.
- Dasgupta, S. and Qu, J. J.: Combining MODIS and AMSR-E-based vegetation moisture retrievals for improved fire risk monitoring, in: *Remote Sensing and Modeling of Ecosystems for Sustainability III*, vol. 6298, p. 62981B, International Society for Optics and Photonics, 2006.
- 20 Drüe, C. and Heinemann, G.: High-resolution maps of the sea-ice concentration from MODIS satellite data, *Geophysical Research Letters*, 31, 2004.
- Drüe, C. and Heinemann, G.: Accuracy assessment of sea-ice concentrations from MODIS using in-situ measurements, *Remote Sensing of Environment*, 95, 139–149, 2005.
- EUMETSAT Ocean and Sea Ice Satellite Application Facility: Global sea ice concentration climate data record 1979-2015 (v2.0, 2017), [Online]. Norwegian and Danish Meteorological Institutes. doi: 10.15770/EUM_SAF_OSI_0008 , 2017.
- 25 Gao, Y., Xie, H., Lu, N., Yao, T., and Liang, T.: Toward advanced daily cloud-free snow cover and snow water equivalent products from Terra–Aqua MODIS and Aqua AMSR-E measurements, *Journal of Hydrology*, 385, 23 – 35, <https://doi.org/https://doi.org/10.1016/j.jhydrol.2010.01.022>, <http://www.sciencedirect.com/science/article/pii/S0022169410000545>, 2010.
- 30 Graham, R. M., Cohen, L., Petty, A. A., Boisvert, L. N., Rinke, A., Hudson, S. R., Nicolaus, M., and Granskog, M. A.: Increasing frequency and duration of Arctic winter warming events, *Geophysical Research Letters*, 44, 6974–6983, <https://doi.org/10.1002/2017GL073395>, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2017GL073395>, 2017.
- Haas, C., Lobach, J., Hendricks, S., Rabenstein, L., and Pfaffling, A.: Helicopter-borne measurements of sea ice thickness, using a small and lightweight, digital EM system, *Journal of Applied Geophysics*, 67, 234 – 241, <https://doi.org/https://doi.org/10.1016/j.jappgeo.2008.05.005>, <http://www.sciencedirect.com/science/article/pii/S0926985108000682>, airborne Geophysics, 2009.
- 35

- Haas, C., Hendricks, S., Eicken, H., and Herber, A.: Synoptic airborne thickness surveys reveal state of Arctic sea ice cover, *Geophysical Research Letters*, 37, <https://doi.org/10.1029/2010GL042652>, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2010GL042652>, 2010.
- Haid, V. and Timmermann, R.: Simulated heat flux and sea ice production at coastal polynyas in the southwestern Weddell Sea, *Journal of Geophysical Research: Oceans*, 118, 2640–2652, <https://doi.org/10.1002/jgrc.20133>, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/jgrc.20133>, 2013.
- Hall, D. and Riggs, G.: MODIS/Aqua Sea Ice Extent 5-Min L2 Swath 1km, Version 6.[20180214-20180308], <https://doi.org/http://dx.doi.org/10.5067/MODIS/MOD29.006>, 2018.
- Hersbach, H. and Dee, D.: ERA-5 reanalysis is in production, *ECMWF newsletter*, p. 7, 2016.
- 10 Heygster, G., Huntemann, M., Ivanova, N., Saldo, R., and Pedersen, L. T.: Response of passive microwave sea ice concentration algorithms to thin ice, in: *Geoscience and Remote Sensing Symposium (IGARSS), 2014 IEEE International*, pp. 3618–3621, IEEE, 2014.
- Hibler, W.: A dynamic thermodynamic sea ice model, *Journal Geophysical Research*, 9, 815–846, 1979.
- Hibler, W. I. and Bryan, K.: A diagnostic ice-ocean model, *Journal Physical Oceanography*, 17, 987–1015, 1987.
- Huntemann, M., Heygster, G., Kaleschke, L., Krumpen, T., Mäkynen, M., and Drusch, M.: Empirical sea ice thickness retrieval during
15 the freeze-up period from SMOS high incident angle observations, *The Cryosphere*, 8, 439–451, <https://doi.org/10.5194/tc-8-439-2014>, <https://www.the-cryosphere.net/8/439/2014/>, 2014.
- Ivanova, N., Johannessen, O. M., Pedersen, L. T., and Tonboe, R. T.: Retrieval of Arctic Sea Ice Parameters by Satellite Passive Microwave Sensors: A Comparison of Eleven Sea Ice Concentration Algorithms, *IEEE Transactions on Geoscience and Remote Sensing*, 52, 7233–7246, <https://doi.org/10.1109/TGRS.2014.2310136>, 2014.
- 20 Ivanova, N., Pedersen, L. T., Tonboe, R. T., Kern, S., Heygster, G., Lavergne, T., Sørensen, A., Saldo, R., Dybkjær, G., Brucker, L., and Shokr, M.: Inter-comparison and evaluation of sea ice algorithms: towards further identification of challenges and optimal approach using passive microwave observations, *The Cryosphere*, 9, 1797–1817, <https://doi.org/10.5194/tc-9-1797-2015>, <http://www.the-cryosphere.net/9/1797/2015/>, 2015.
- Kaleschke, L., Lüpkes, C., Vihma, T., Haarpaintner, J., Borchert, A., Hartmann, J., and Heygster, G.: SSM/I sea ice remote sensing for
25 mesoscale ocean-atmosphere interaction analysis, *Canadian Journal of Remote Sensing/Journal Canadien de Teledetection*, 5, 526–537, 2001.
- Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M. Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, R., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K., Ropelewski, C., Wang, J., Jenne, R., and Joseph, D.: The NCEP/NCAR 40-year reanalysis project, *Bulletin of the American meteorological Society*, 77, 437–471, 1996.
- 30 Karvonen, J.: A sea ice concentration estimation algorithm utilizing radiometer and SAR data, *The Cryosphere*, 8, 1639–1650, 2014.
- Kauker, F., Gerdes, R., Karcher, M., Köberle, C., and Lieser, J.: Variability of Arctic and North Atlantic sea ice: A combined analysis of model results and observations from 1978 to 2001, *Journal of Geophysical Research Oceans*, 108, 3182, <https://doi.org/10.1029/2002JC001573>, 2003.
- Kwok, R., Spreen, G., and Pang, S.: Arctic sea ice circulation and drift speed: Decadal trends and ocean currents, *Journal of Geophysical Research: Oceans*, 118, 2408–2425, <https://doi.org/10.1002/jgrc.20191>, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/jgrc.20191>, 2013.

- Lavergne, T., Eastwood, S., Teffah, Z., Schyberg, H., and Breivik, L.-A.: Sea ice motion from low-resolution satellite sensors: An alternative method and its validation in the Arctic, *Journal of Geophysical Research: Oceans*, 115, <https://doi.org/10.1029/2009JC005958>, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2009JC005958>, 2010.
- Lavergne, T., Sørensen, A. M., Kern, S., Tonboe, R., Notz, D., Aaboe, S., Bell, L., Dybkjær, G., Eastwood, S., Gabarro, C., Heygster, G., Killie, M. A., Brandt Kreiner, M., Lavelle, J., Saldo, R., Sandven, S., and Pedersen, L. T.: Version 2 of the EUMETSAT OSI SAF and ESA CCI sea-ice concentration climate data records, *The Cryosphere*, 13, 49–78, <https://doi.org/10.5194/tc-13-49-2019>, <https://www.the-cryosphere.net/13/49/2019/>, 2019.
- Lebedev, V.: Rost l'da v arkticheskikh rekakh i moriakh v zavisimosti ot otritsatel'nykh temperatur vozdu kha, *Problemy arktiki*, 5-6, 9–25, 1938.
- 10 Lindsay, R. W. and Rothrock, D. A.: Arctic sea ice leads from advanced very high resolution radiometer images, *Journal of Geophysical Research: Oceans*, 100, 4533–4544, <https://doi.org/10.1029/94JC02393>, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/94JC02393>, 1995.
- Lu, J., Heygster, G., and Spreen, G.: Atmospheric Correction of Sea Ice Concentration Retrieval for 89 GHz AMSR-E Observations, *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, PP, 1–16, <https://doi.org/10.1109/JSTARS.2018.2805193>, 15 2018.
- Marcq, S. and Weiss, J.: Influence of sea ice lead-width distribution on turbulent heat transfer between the ocean and the atmosphere, *The Cryosphere*, 6, 143–156, <https://doi.org/10.5194/tc-6-143-2012>, <https://www.the-cryosphere.net/6/143/2012/>, 2012.
- Markus, T. and Cavalieri, D. J.: An Enhancement of the NASA Team Sea Ice Algorithm, *IEEE Transactions on Geoscience and Remote Sensing*, 38, 1387–1398, 2000.
- 20 Martin, S., Robert, D., Ronald, K., and Benjamin, H.: Estimation of the thin ice thickness and heat flux for the Chukchi Sea Alaskan coast polynya from Special Sensor Microwave/Imager data, 1990–2001, *Journal of Geophysical Research: Oceans*, 109, <https://doi.org/10.1029/2004JC002428>, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2004JC002428>, 2004.
- Mewes, D. and Jacobi, C.: Heat Transport Pathways into the Arctic and their Connections to Surface Air Temperatures, *Atmospheric Chemistry and Physics Discussions*, 2018, 1–14, <https://doi.org/10.5194/acp-2018-636>, <https://www.atmos-chem-phys-discuss.net/acp-2018-636/>, 2018.
- 25 MODIS Characterization Support Team (MCST): MODIS Geolocation Fields Product. NASA MODIS Adaptive Processing System, Goddard Space Flight Center, USA, <https://doi.org/http://dx.doi.org/10.5067/MODIS/MOD03.006>, 2015.
- Moore, G.: The December 2015 North Pole Warming Event and the Increasing Occurrence of Such Events, *Scientific Reports*, 6, <https://doi.org/10.1038/srep39084>, 2016.
- 30 Moore, G. W. K., Schweiger, A., Zhang, J., and Steele, M.: What Caused the Remarkable February 2018 North Greenland Polynya?, *Geophysical Research Letters*, 0, <https://doi.org/10.1029/2018GL080902>, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2018GL080902>, 2018.
- Morales-Maqueda, M. A., Willmott, A. J., and Biggs, N. R. T.: Polynya Dynamics: a Review of Observations and Modeling, *Reviews of Geophysics*, 42, <https://doi.org/10.1029/2002RG000116>, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2002RG000116>, 2004.
- 35 Murashkin, D., Spreen, G., Huntemann, M., and Dierking, W.: Method for detection of leads from Sentinel-1 SAR images, *Annals of Glaciology*, p. 1–13, <https://doi.org/10.1017/aog.2018.6>, 2018.
- OSI-SAF: Global Sea Ice Concentration Climate Data Record, http://osisaf.met.no/docs/osisaf_cdop3_ss2_pum_sea-ice-conc-climate-data-record_v2p0.pdf, last access: 03 July 2019.

- Parkinson, C. L. and Washington, W. M.: A large-scale numerical model of sea ice, *Journal Geophysical Research*, 84, 311–337, 1979.
- Pañile, C., Heygster, G., Huntemann, M., and Spreen, G.: Combined SMAP–SMOS thin sea ice thickness retrieval, *The Cryosphere*, 13, 675–691, <https://doi.org/10.5194/tc-13-675-2019>, <https://www.the-cryosphere.net/13/675/2019/>, 2019.
- Preußner, A., Heinemann, G., Willmes, S., and Paul, S.: Circumpolar polynya regions and ice production in the Arctic: results from MODIS thermal infrared imagery from 2002/2003 to 2014/2015 with a regional focus on the Laptev Sea, *The Cryosphere*, 10, 3021–3042, <https://doi.org/10.5194/tc-10-3021-2016>, <https://www.the-cryosphere.net/10/3021/2016/>, 2016.
- Ricker, R., Hendricks, S., Kaleschke, L., Tian-Kunze, X., King, J., and Haas, C.: A weekly Arctic sea-ice thickness data record from merged CryoSat-2 and SMOS satellite data, *The Cryosphere*, 11, 1607–1623, <https://doi.org/10.5194/tc-11-1607-2017>, <https://www.the-cryosphere.net/11/1607/2017/>, 2017.
- 10 Rösel, A., Kaleschke, L., and Birnbaum, G.: Melt ponds on Arctic sea ice determined from MODIS satellite data using an artificial neural network, *The Cryosphere*, 6, 431–446, <https://doi.org/10.5194/tc-6-431-2012>, <http://www.the-cryosphere.net/6/431/2012/>, 2012.
- Saha, S., Moorthi, S., Wu, X., Wang, J., Nadiga, S., Tripp, P., Behringer, D., Hou, Y., Chuang, H., Iredell, M., Ek, M., Meng, J., Yang, R., Peña Mendez, M., van den Dool, H., Zhang, Q., Wang, W., Chen, M., and Becker, E.: The NCEP Climate Forecast System Reanalysis, *Bulletin of the American Meteorological Society*, 91, 1015–1057, <https://doi.org/http://dx.doi.org/10.1175/2010BAMS3001.1>, 2010.
- 15 Saha, S., Moorthi, S., Pan, H., Wu, X., Wang, J., Nadiga, S., Tripp, P., Kistler, R., Woollen, J., Behringer, D., Liu, H., Stokes, D., Grumbine, R., Gayno, G., Wang, J., Hou, Y., Chuang, H., Juang, H., Sela, J., Iredell, M., Treadon, R., Kleist, D., Van Delst, P., Keyser, D., Derber, J., Ek, M., Meng, J., Wei, H., Yang, R., Lord, S., van den Dool, H., Kumar, A., Wang, W., Long, C., Chelliah, M., Xue, Y., Huang, B., Schemm, J., Ebisuzaki, W., Lin, R., Xie, P., Chen, M., Zhou, S., Higgins, W., Zou, C., Liu, Q., Chen, Y., Han, Y., Cucurull, L., Reynolds, R., Rutledge, G., and Goldberg: The NCEP Climate Forecast System Version 2, *Journal of Climate*, 27, 2185–2208, <https://doi.org/http://dx.doi.org/10.1175/JCLI-D-12-00823.1>, 2014.
- 20 Schledermann, P.: Polynyas and Prehistoric Settlement Patterns, *Arctic*, 33, 292–302, <http://www.jstor.org/stable/40509028>, 1980.
- Semtner, A.: A Model for the Thermodynamic Growth of Sea Ice in Numerical Investigations of Climate, *Journal of Physical Oceanography*, 6, 379–389, 1976.
- Smith, S. D., Muench, R. D., and Pease, C. H.: Polynyas and leads: An overview of physical processes and environment, *Journal of Geophysical Research: Oceans*, 95, 9461–9479, <https://doi.org/10.1029/JC095iC06p09461>, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/JC095iC06p09461>, 1990.
- 25 Spreen, G., Kaleschke, L., and Heygster, G.: Sea ice remote sensing using AMSR-E 89-GHz channels, *Journal of Geophysical Research: Oceans*, 113, <https://doi.org/10.1029/2005JC003384>, 2008.
- Steele, M., Morley, R., and Ermold, W.: PHC: A global ocean hydrography with a high-quality Arctic Ocean, *J. Clim.*, 14, 2079–2087, <http://www.scopus.com/scopus/inward/record.url?eid=2-s2.0-0035324968&partnerID=40&rel=R7.0.0>, 2001.
- 30 Sumata, H., Lavergne, T., Girard-Ardhuin, F., Kimura, N., Tschudi, M. A., Kauker, F., Karcher, M., and Gerdes, R.: An intercomparison of Arctic ice drift products to deduce uncertainty estimates, *Journal of Geophysical Research: Oceans*, 119, 4887–4921, <https://doi.org/10.1002/2013JC009724>, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2013JC009724>, 2014.
- Sumata, H., Kauker, F., Karcher, M., and Gerdes, R.: Simultaneous Parameter Optimization of an Arctic Sea Ice–Ocean Model by a Genetic Algorithm, *Monthly Weather Review*, 147, 1899–1926, <https://doi.org/10.1175/MWR-D-18-0360.1>, <https://doi.org/10.1175/MWR-D-18-0360.1>, 2019a.
- 35 Sumata, H., Kauker, F., Karcher, M., and Gerdes, R.: Covariance of optimal parameters of an Arctic sea ice-ocean model, *Monthly Weather Review*, <https://doi.org/10.1175/MWR-D-18-0375.1>, <https://doi.org/10.1175/MWR-D-18-0375.1>, 2019b.

- Tamura, T. and Ohshima, K. I.: Mapping of sea ice production in the Arctic coastal polynyas, *Journal of Geophysical Research: Oceans*, 116, <https://doi.org/10.1029/2010JC006586>, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2010JC006586>, 2011.
- Tonboe, R. T., Eastwood, S., Lavergne, T., Sørensen, A. M., Rathmann, N., Dybkjær, G., Pedersen, L. T., Høyer, J. L., and Kern, S.: The EUMETSAT sea ice concentration climate data record, *The Cryosphere*, 10, 2275–2290, <https://doi.org/10.5194/tc-10-2275-2016>, <https://www.the-cryosphere.net/10/2275/2016/>, 2016.
- 5 Vaughan, D., Comiso, J., Allison, I., Carrasco, J., Kaser, G., Kwok, R., Mote, P., Murray, T., Paul, F., Ren, J., Rignot, E., Solomina, O., Steffen, K., and Zhang, T.: Observations: Cryosphere. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.
- 10 Vavrus, S. J.: The Influence of Arctic Amplification on Mid-latitude Weather and Climate, *Current Climate Change Reports*, 4, 238–249, <https://doi.org/10.1007/s40641-018-0105-2>, 2018.
- Wernecke, A. and Kaleschke, L.: Lead detection in Arctic sea ice from CryoSat-2: quality assessment, lead area fraction and width distribution, *The Cryosphere*, 9, 1955–1968, <https://doi.org/10.5194/tc-9-1955-2015>, <https://www.the-cryosphere.net/9/1955/2015/>, 2015.
- 15 Wiebe, H., Heygster, G., and Markus, T.: Comparison of the ASI ice concentration algorithm with Landsat-7 ETM+ and SAR imagery, *IEEE Transactions on Geoscience and Remote Sensing*, 47, 3008–3015, 2009.
- WMO: WMO sea-ice nomenclature: Terminology, codes and illustrated glossary, Tech. rep., Geneva: Secretariat of the World Meteorological Organization., 1970.
- Woods, C. and Caballero, R.: The role of moist intrusions in winter Arctic warming and sea ice decline, *Journal of Climate*, 29, 160314091706008, <https://doi.org/10.1175/JCLI-D-15-0773.1>, 2016.
- 20 Zhang, J. and Rothrock, D. A.: Modeling Global Sea Ice with a Thickness and Enthalpy Distribution Model in Generalized Curvilinear Coordinates, *Monthly Weather Review*, 131, 845–861, [https://doi.org/10.1175/1520-0493\(2003\)131<0845:MGSIIWA>2.0.CO;2](https://doi.org/10.1175/1520-0493(2003)131<0845:MGSIIWA>2.0.CO;2), [https://doi.org/10.1175/1520-0493\(2003\)131<0845:MGSIIWA>2.0.CO;2](https://doi.org/10.1175/1520-0493(2003)131<0845:MGSIIWA>2.0.CO;2), 2003.