

Point by point authors response

to the reviewers comments during the 2nd review iteration of the manuscript by Istomina et al.

“The melt pond fraction and spectral sea ice albedo retrieval from MERIS data I and II”

The authors are sincerely grateful to the reviewer and editor for the comprehensive comments and patient correction of the grammar and references format! it gave the manuscript a great deal of improvement.

The following is the point by point response to the comments of both the reviewer and the editor; the page and line of the correction correspond to the page and line of the comment and are not repeated. These are only given if the correction has been introduced at a difference place of the manuscript. The author’s response is shown in yellow.

Minor issues (I part):

Title: Missing comma – change to: The melt pond fraction and spectral sea ice albedo retrieval from MERIS data I: validation against in situ, aerial, and ship cruise data

done

P.3, l. 7-9: please rewrite the sentence. Or just split it up in 2 sentences.

The sentence has been rewritten and split, resulting in “These details of melt evolution are responsible for the spatial variability of MPF and sea ice albedo. The temporal variability of MPF is driven by air mass transport and changing air temperature.”

P.3, l. 9-11: the need is the knowledge of the albedo and the MPF – not a satellite retrieval. With a satellite retrieval you can solve these question and gain a dataset. Rewrite to make it clear.

The sentence was changed to “This introduces complications in the MPF modeling and creates the need for an MPF and sea ice albedo dataset of possibly high temporal and spatial resolution, which can be retrieved from satellite data.”

P.3, l. 22 delete the “new” (if somebody is reading the paper in 3 years the algorithm isn’t new anymore)

done

P.3, l.24: replace “other” with “previous developed”

done

Chapter 2 or somewhere else (e.g. Conclusions): I miss a little bit the discussion on submerged ice. It occurs quite often in the pack ice due to ice dynamics, and the spectral response is like melt ponds.....of course for the albedo, it makes no difference, but for the MPF. It would be nice if the submerged ice is mentioned here. This can also lead to the weak validation results for MPF.

P6,1,10 Inserted sentence ”Submerged sea ice or water saturated ice surface are optically identical to melt ponds and are retrieved as those.”

P. 7, l.28/29: change to “the clouds have a lower albedo than the bright surface and may be seen as melt ponds....”

done

Chapter 3.2: Albedo validation was only performed on FYI. Please discuss this and the differences that may occur for MYI

p 11, l, 22ff inserted text:

“Due to the lack of field data the validation has not been performed over MYI, however, the MPD has been designed for MYI, namely sea ice of high ice concentrations with light melt ponds. FI is a deviation from this case at least in the melt pond type, and possibly in the surface albedo, but as MPD performed well even in this case, we expect it to perform at least as well over MYI of high ice concentrations.”

Minor issues (II part):

The authors refer at least 2 times to a follow up publication, which is not really necessary, or otherwise the reader is asking, why the follow up publication is not included since the paper has only 27 pages in manuscript format.

P6 l 27 - reference to a follow-up publication is not relevant and has been removed.

in the Conclusions, however, the reference to the ice type study is kept to emphasize the open point.

Title: change pond to ponds

done

P 1, l 15: sea ice albedo on spatial....

not changed as it would distort the sentence structure.

P 1, l 17: to air surface temperature reanalysis data,

corrected.

P 1, l 24: of both, MPF and Albedo:

do not agree with capital Albedo, comma added.

P 1, l 24-25: please formulate a proper sentence.

sentence reformulated and split in two.

P 2, l 9: where 96 % of the ...

done

P 2, l 11-12: context of a changing Arctic due to the sensitivity.....for the global climate

done

P2, l 14-15: The maximum this year was in February!

the text was written before the maximum, corrected in text.

P 3, l. 3: Use “This publication” instead of current work

changed throughout the manuscript.

Be consistent: write either MPF or melt pond fraction (line 7, p. 3)

changed throughout the ms, but consciously kept in figure captions as “melt pond fraction”.

P 4, l 4: delete one .

done

P. 4, l. 9, l. 13: avoid ()cloud covered regions with up to 80% cloud cover throughout the year....

done

P. 4, l. 21: the results are presented

done

P. 5, l 16: change to: MPF decrease due to freezing and snowfall events.

done

p 6, l 6. If you label the lines in the figure properly you can avoid the parenthesis here in the text.

as figure caption is now more consistent, the text in parentheses was removed.

p. 6 l 18, melt pond formation followed by a rapid drainage

corrected

p. 7 l. 3: evolution of melt ponds

done

p. 8, l 17-19. The explanation is not clear – please reword the sentence

the sentence is split and reformulated.

p. 8, l 22f. The Meris MPF algorithm produces 10-15% bias as far as I understood. Please clarify it here.

correct, there may be a bias of up to 15% due to unscreened clouds - the explanation is added into the description of the MPD product to make it more comprehensive p4 l 14ff.

p. 8, l. 26 delete one "that"

done

p. 8, l. 30 date format – please be consistent throughout the manuscript

done

p. 10, l. 7, which affects

do not agree - "clouds affect" - left unchanged

p. 10, l. 12, Please formulate in proper sentences and not in enumerations (it will be easier for the reader)

done

Chapter 3.3 Trends: I miss here the discussion of Figure 8 (significance)....

p 10 l 25ff - discussion added.

References (p 14):

l. 16: check DOI

checked - it does look horrible, but it is correct like this.

l. 17: Mäkynen, Rösel (correct spelling of author's names!)

done

l. 19: give the doi, not a link!

done

p. 15, l. 14. Delete "Received"

done

Figure 1, p. 16, l 4: ")" is missing

done

Figure 2; p. 17, label FYI and MYI!

explanation added in the figure caption

Figure 4; p. 19, l 3: of weekly MPF averages

done

Editor's comments:

Paper 1

General comment

One issue that needs to be resolved and discussed in the text concerns your definition of melt ponds in the late season and how this corresponds to relevant satellite data. In figure 16 you indicate that the estimated pond fraction is 0.5.

this value is obtained from the ship data - there is no satellite value for this image due to cloud cover. Clarification is added in the figure caption of Fig.16.

However, this is based on the assumption that you can identify former ponds that are now frozen over by their former outlines. When does such a pond turn from "pond" to "sea ice"? Early in the season, temporary ice cover on ponds may be discounted since this typically melts back within a day or so. However, late in the season (i.e. September) it makes more sense to clearly draw the line between ponds and a solid ice surface that was formerly a pond.

This is more than semantics. If you look at your figure 3, the retrieved pond fraction remains high (>0.1) throughout September and into early October. Are you implying that MERIS is actually detecting former ponds? Depending on what the geographic coverage of Fig. 3 is, I don't quite follow how you can have a remaining pond fraction of 0.1 or more in late September unless this includes frozen, former ponds.

this is a very important point - the MPD continues to retrieve some values MPF as long as the albedo of frozen over ponds is smaller than that of surrounding sea ice. The MPF retrieved in these conditions is the “effective” MPF which basically tells how much of the open ponds one would need to obtain this kind of top of atmosphere signal. The sea ice albedo of course also reacts to frozen over ponds in a similar way, which makes both albedo and MPF complementary products. For the studies of radiative balance this should not be an issue as it represents darker surface which is really the case in case of frozen over ponds. If one wants to exclude them anyway, reanalysis air temperature can be used. Clarification is added p16 l 4ff.

The way the curves oscillate around a stable (?) mean in September suggests that this is some type of bias in the data rather than a real feature. This is quite important because it may also apply to data in May (if a similar bias exists for unponded ice early in the season).

Please be sure to discuss the implications and confirm the definition used for pond observations & validation (re Fig 16).

The bias in the data (Fig. 3 red curve) comes from unscreened clouds, whereas the blue curve is the “perfectly” cloud screened data. However, given the remark on the frozen ponds, it is hard to say how large is an actual retrieval bias because the study region includes the whole Arctic ocean to the north of 65°N.

A discussion on this is added on p8 l 4ff.

Specific comments

p. 1; l. 1: remove “The” from title to read “Melt pond fraction...”

done

p. 1, l 22: change to “consequences for the heat” (here and below the suggested edits will be listed in quotation marks”

done

p. 1, l 23: “from ME^{DI}um Resolution”

done

p. 2, l .6: Please write out the acronym ASPECT and be sure to address the comment made for p. 15, l. 12)

done

p. 2, l. 16: Here and throughout the manuscripts replace “melting season” and “melting temperatures” with “melt season” and “melt temperatures”

done

p 2, l 26: “, e.g. Rösel et al. (2012) or Tschudi et al. (2008)” - i.e., only place the year in parentheses here and throughout the manuscript when referring to specific studies in the text.

Corrected throughout the paper.

p 3, l. 21: “Zege et al. (2015)” - see previous comment

corrected.

p. 7, l. 28/29: “clouds have lower albedo”

done

p 11, l 5: Abbreviation for fast ice (FI) needs to be introduced here, not further down in the text.

done

p 13, l 18: What is “thrashed ice” ? are you referring to brash ice?

Yes, brash ice is meant, this is changed throughout the manuscript.

p 14, l 8: Again, “thrashed ice” needs to be corrected, there is no such term in the glaciological nomenclature (at least not based on WMO nomenclature).

Changed to brash ice.

p 15, l 12: Referring to ASPECT protocol raises several issues. First, ASPECT needs to be written out, but more importantly it needs to be confirmed that ASPECT protocol was in fact used. My

understanding is that on recent Polarstern cruises the IceWatch protocol has been followed (<http://www.iarc.uaf.edu/en/icewatch>) which differs in important details, in particular with respect to melt pond fractions and typology from ASPECT. Maybe this was not yet the case in 2011, but needs to be confirmed for the two cruises that you reference. A general statement such as “most often performed according to ASPECT protocol is not sufficient. For HOTRAX my understanding is that an early version of the IceWatch protocol was used. Also, you should provide a reference, either in a publication or a website to the specific protocol that was employed.

The 2011 Polarstern cruise is still ASPeCt (at least so it says in Pangaea dataset where the data is published), in 2012 changed to ASSIST. For the HOTRAX 2005 it was ASPeCt as well - so stands at the HOTRAX data page.

ASPeCt spelled out on p15, l.18 and p2, l 5.

p 15, l 24: “available”

done

p 19, l 22: delete “, .”

done

p 19, l 25: “Richter-Menge, J.A.”

done

p 20, l. 6: De Abreu, R.A.”

done

p 20, l 19: Use consistent abbreviation for Edition (see l 1 on same page); preferably write it out fully. Changed to “Second Edition”, “Third Edition” and “Prentice Hall Inc” in both cases.

p 20, l 21/22: “Klyukov, D.A.”

done

p 20, l 31: The Lehmann reference is missing bibliographic information. Is this a report, a thesis or something else? Also please be sure to correct the orthography “Messungen für Nordostgrönland” corrected and added “scientific report”

p 21, l 10: “University Press,”

done

p 21, l 25: delete extra “,”

done

p 21, l 31: both initials “A” need to be upper case

done

p 25: In the result column of Table 3, what is the reference to “Not a number” (NaN) meant to indicate? Are you saying that the total albedo could not be retrieved? If so, N/A (not available) would be the term to use.

Changed to N/A

p 26, l 4 “shown in red” instead of “marked with the red color”

changed

p 29, l 2: deleted “from”

done

p 29: In the figure caption for Figure 3 please indicate what region this time series represents. Are these all swaths for a particular near-synoptic acquisition?

Text inserted: “The region covered is the Arctic Ocean to the north of N 65° (land masked out). All available swaths from May 1, 2009 to September, 30, 2009 have been taken.”

p 31: The standard deviation shown by the color scale on the right looks very low; if i interpret this correctly you are seeing a standard deviation of of less than 0.005 in albedo for many of the aerial survey measurements? Please check and make sure this is correct and not a potential shift in the decimal point. How long are the transects over which this st. dev. is calculated? The text doesn’t provide any details on this as far as I can tell.

This is really so – the measured albedo varied very little on the scale of 1km (satellite pixel size). Also, there was a threshold on STD. We explained this in the figure caption:

p31, inserted text: “STD is calculated from all collocated aerial measurements for a given satellite pixel. Only pixels with STD smaller than the mean STD are used.”

p. 35: Please provide a scale bar or a description as to the size of the scene.

The image width is approximately 400m, it has been added into the figure caption.

p 40, l 6: “thrashed ice” - unclear what you refer to here, see comments above.

Changed to brash ice.

Paper 2

General comments

Given the importance of seasonal evolution of ponds in the context of your paper, it would be important to clearly separate different stages of melt in the paper. At present, it appears as if you equate the onset of visible, expansive ponding with the onset of melt, for example in Section 3.3 of the paper and other spots throughout (e.g., Figure caption for Fig. 4). As outlined in the comments for paper 1, a clear distinction between different seasonal stages of melt on FY and MY ice is important to avoid confusion or misinterpretation of satellite data. For pond evolution (which is different from the different stages of melt!), it may help to refer to the literature (such as Polashenski et al., 2012 or the paper by Eicken et al., *J. Geophys. Res.*, 107(C10), 8046, doi:10.1029/2000JC000583, 2002 - which delineates different stages of pond evolution based on pond coverage and ice processes) to discuss findings from MERIS/MODIS data in terms of pond evolution stage. It needs to be made clear that onset of melt will occur well before any ponds can be detected in MERIS or MODIS data. Hence, some of the low pond coverages in May shown in Figure 2 may be due to bias (see discussion by Roesel et al. 2012 on this topic) rather than indications of ponding.

Thank you for this important comment; it addressed yet another important issue. The definition of melt stages and a small discussion on how the MPD treats the incoming top of atmosphere signal is added on p. 3, 18ff. Yes, we do equate onset of positive air temperature to increase of MPF because in case of MPD this is really the case - the retrieval reacts to surface properties change and may in some cases give an increased MPF in case of water saturated ice. This, as well as the reference to Eicken et al., 2002, have been added into the text.

The bias demonstrated by MPD comes from the above mentioned issue and from unscreened thin clouds, which is the main reason for the MPF behavior in May where there should not be open ponds. In September, one more source of bias is added - frozen over ponds which are darker than regular sea ice and are still detected as some small MPF (not equal to the actual MPF).

At the same time, your findings shown in Fig. 3 for wide spread melt ponding in Week 2 of 2007 are not associated with onset of melt but represent the last phase of Stage 1 of pond evolution before the transition into Stage 2 (as outlined in Eicken et al. 2002). Please clarify in the text.

Completely agreed, it has been changed accordingly throughout Sect. 3.1

In Figure 1 you should a large area north of Barrow labeled as FY ice. Does the white circle correspond exactly to the area studied or is this merely a schematic. In 2007 much of that area shown in Fig. 1 was a mixture of multiyear and first-year ice. This is important to highlight because it may explain some of the differences observed between 2007 and 2011 and the regional contrasts in melt onset between Beaufort and eastern Chukchi Sea and the central/western Chukchi Sea.

it is a schematic - the labels are only that large to give an instant impression, the real sizes of studied areas are smaller, depending on the case 50km to 100km around the center. The center of that area is at 75N,155W (clarified in text and in the caption of Fig. 2) and ice at the white FYI label disappears completely on the first of August (red curve in Fig 2), so we are relatively sure it is mostly FYI. Also,

the area used for 2007 vs 2011 time series is shown with the yellow tags W and E (Fig. 1). The explanation on why these areas are used is added in the caption of Fig. 5, p20, l 4ff. Clarification on the schematis and on the size of area is added on p16, l3.

Specific comments

p 1, l 14: “current state and trend of the climate”

done

p 1, l 16: “Melt Pond Detection (MPD) retrieval scheme for MEdium Resolution Imaging Spectrometer (MERIS) satellite data.”

done

p 1, l 17: This section of the abstract is difficult to follow. While I’m not sure what exactly you are stating here, one suggestion to change (if my interpretation is correct) would be to write: “This study compares sea ice albedo and MPF to reanalysis air surface temperatures, compares MPF retrieved from MERIS to those obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS), and examines albedo and MPF trends. Weekly averages of MPF for 2007 and 2011 showed different MPF dynamics while summer sea ice minimum was similar for both years. The gridded...”

changed as suggested

p 1, l 24ff: “a negative MPF trend in ... connected to a change of the absolute MPF value at its peak, but no temporal shift, and a positive trend around the Queen ... onset, with the peak MPF values unchanged.”

changed as suggested

p 2, l 1ff: “as opposed to the Queen Elizabeth Islands where MPF dynamics react to an earlier seasonal onset of melt.”

done

p 2, l 10: Here and throughout ms change “melting season” to “melt season”

done

p 2, l 11: “of a changing Arctic due to the sensitivity”

done

p 2, l 17ff: “can help improve understanding of the current state and trends of the energy balance”

done

p 2, l 18&19: Delete the sentence “One of the evidence...” it is confusingly worded, repeats a point stated earlier and is hence not needed.

done

p. 3, l 2: As mentioned for paper 1, if you cite a reference in the context as done here, you need to write it as “Schröder et al. (2014)”, this needs to be corrected through the manuscript, such as later on the same page where you refer to Roesel and Kaleschke.

changed throughout the manuscript

p. 3, l 5 and l 9 and l 26: Please write out MERIS, NCEP and NSIDC in full the first time you introduce them in the main body of the text so that the acronyms are clear.

done

p 3, l 12: “dynamics have been”

done

p 4 l 4: delete extra period at end of sentence

done

p 4 l 10: “will still affect the gridded”

done

p 4 l 14: “assigned not a number value” OK, this explains NaN in the previous paper; N/A may still be better in the table in Paper 1 but you can leave the NaN reference here.

done

p 4 l21: The last sentence is missing a verb but I'm wondering whether it's even necessary since the same thing is expressed in the section captions.

true, the sentence has been deleted.

Also, there is a problem with Section 2.1 - this is the only subsection in Section 2 and I'm not sure what exactly the case studies are. From what I can tell, you really only need one section 2 which would be titled something like: "Comparisons between surface air temperature and time series of MPF and albedo: Case studies for FYI and MYI"

Section renamed correspondingly, and also on p 3 l 24 corresponding change in ms structure has been given.

p 8 l 22: "Comparison to MPF from MODIS data (Roesel et al., 2012)

done

p 9, l 10: "it is apparent that for June"

done

p 9 l 16ff: this sentence is difficult to follow, suggest reword to "The primary reason for this difference is likely the contrast in cloud screening between the two datasets, with MODIS much better suited to cloud screening over snow, resulting in differences in the fraction of unscreened clouds between both datasets."

done

p 9 l26: "suggest that the bias ... from possibly inaccurate assumptions about sea ice optical"

done

p 9, l28/29: Delete the text in parentheses ("in some locations..."), it is confusing and not necessary.

done

p 9 l 30: "18 June 2011"

done

p 9 l 31: "slight differences in"

done

p 10, 17: "are sensitive"

done

p 10 l5 and l12: The use of (1) and (2) so widely spaced apart and with a semicolon in front of (2) is confusing; please eliminate the numbers, they are not needed. Also, please delete the semicolon in front of the last sentence in the paragraph.

done

p 10 l 15: Garbled sentence, do you mean to say "with the NCEP surface air temperature data"?

yes, corrected

p 10 l 21: "are the most"

done

p 10, l 23: "and a positive trend of 1-2% during the early melt season is found near the Queen"

done

p 10 l 25: "explanation for this finding is not the increase in the absolute value of the MPF, but rather the earlier melt onset ... to early season data" - last part of the sentence was unclear, I'm assuming "beginning of the dataset" refers to early season data, if not then please modify.

reformulated

p 11 l 19: "warm air masses"

done

p 11 l 26ff: "i.e. an increasing trend for MPF yields a decreasing trend of the albedo. A decreasing... around the ... to dynamics of the apparent MPF weekly trends"

done

p 12 l 24ff: "a negative MPF trend ... connected to a change ... shift, a positive MPF trend around the Queen but with peak ..."

done

p 12 1 29: “opposed to the Queen Elizabeth Islands ... dynamics react to earlier onset of melt.”

done

p 16 1 4: “Greenland”

done

p 17: Please indicate in the figure caption that Barrow data are shown in red and MYI data shown in blue.

done

1 **The ~~m~~Melt pond fraction and spectral sea ice albedo**
2 **retrieval from MERIS data I: validation against in situ,**
3 **aerial, and ship cruise data**

4
5 **L. Istomina¹, G. Heygster¹, M. Huntemann¹, P. Schwarz², G. Birnbaum³,**
6 **R. Scharien⁴, C. Polashenski⁵, D. Perovich⁵, E. Zege⁶, A. Malinka⁶, A. Prikhach⁶**
7 **and I. Katsev⁶**

8 [1]{Institute of Environmental Physics, University of Bremen, Bremen, Germany }

9 [2]{Department of Environmental Meteorology, University of Trier, Trier, Germany }

10 [3]{Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research,
11 Bremerhaven, Germany }

12 [4]{Department of Geography, University of Victoria, Victoria, Canada }

13 [5]{Cold Regions Research and Engineering Laboratory, Engineer Research and
14 Development Center, Hanover, New Hampshire, USA }

15 [6]{B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk,
16 Belarus }

17 Correspondence to: L. Istomina (lora@iup.physik.uni-bremen.de)

18
19 **Abstract**

20 The presence of melt ponds on the Arctic sea ice strongly affects the energy balance of the
21 Arctic Ocean in summer. It affects albedo as well as transmittance through the sea ice, which
22 has consequences ~~on-for~~ the heat balance and mass balance of sea ice. An algorithm to
23 retrieve melt pond fraction and sea ice albedo from ~~the~~-MEDium Resolution Imaging
24 Spectrometer (MERIS) data is validated against aerial, ship borne and in situ campaign data.
25 The results show the best correlation for landfast and multiyear ice of high ice concentrations.
26 For broadband albedo R^2 is equal to 0.85, with the RMS being equal to 0.068, for the melt

1 pond fraction: R^2 is equal to 0.36 with the RMS being equal to 0.065. The correlation for
2 lower ice concentrations, subpixel ice floes, blue ice and wet ice is lower due to ice drift and
3 challenging for the retrieval surface conditions. Combining all aerial observations gives a
4 mean albedo RMS of 0.089 and a mean melt pond fraction RMS of 0.22. The in situ melt
5 pond fraction correlation is $R^2=0.52$ with an RMS=0.14. Ship cruise data might be affected by
6 documentation of varying accuracy within the [Antarctic Sea Ice Processes and Climate](#)
7 [\(ASPeCt\)ASPECT](#) protocol, which may contribute to the discrepancy between the satellite
8 value and the observed value: mean $R^2=0.044$, mean RMS=0.16. An additional dynamic
9 spatial cloud filter for MERIS over snow and ice has been developed to assist with the
10 validation on swath data.

11 1 Introduction

12 Melt ponds on the Arctic sea ice affect the albedo, mass balance and heat balance of the ice
13 (e.g. Perovich et al., 2009) by translating the increase of air temperature into drastic and rapid
14 surface type changes. They introduce a positive feedback within the sea ice albedo feedback
15 loop (Curry et al., 1995) thus facilitating further ice melt. In the context of changing Arctic
16 climate (Shindell and Faluvegi, 2009), knowledge of melt pond fraction (MPF), its spatial
17 distribution and the length of the [meltingmelt](#) season is required to reflect and predict the role
18 of the sea ice cover in the radiative balance of the region. Schröder et al. (2014) show the
19 potential of predicting the minimum sea ice extent in autumn by the spring MPF. In addition
20 to applications in climate studies, e.g. global circulation modeling, knowledge of the MPF can
21 be helpful for navigation purposes. Findings from numerous in situ campaigns (Barber and
22 Yackel, 1999; Hanesiak et al., 2001; Yackel et al., 2000) provide data of excellent quality and
23 detail, but unfortunately lack in coverage. To fill in this gap, a remote sensing approach needs
24 to be employed.

25 The present work is dedicated to validation of a MPF and sea ice albedo retrieval algorithm,
26 the Melt Pond Detector (MPD), described by [Zege et al., \(2015\)](#). The algorithm differs from
27 existing satellite remote sensing algorithms, e.g. [Rösel et al., \(2012\)](#) or [Tschudi et al.,](#)
28 [\(2008\)](#), by 1) utilizing a physical model of sea ice and melt ponds with no a priori surface
29 spectral reflectances, and 2) providing daily averaged MPF instead of weekly averaged MPF,
30 which is beneficial in case of rapid melt evolution. Field observations (Figure 1) show faster

1 melt evolution on first year ice (FYI) as compared to multiyear ice (MYI). Due to the fact that
2 MPF depends not only on air temperature and available melt water volume but also on the ice
3 topography (Eicken et al., 2004; Polashenski et al., 2012), the melt evolution is different for
4 FYI and MYI. Melt onset proceeds rapidly to the MPF maximum on FYI with rapid pond
5 drainage and moderate MPFs afterwards. On multiyear ice, the evolution of melt up to the
6 melt maximum takes longer. The peak MPF value is lower and the MPF decrease is slower
7 than that on FYI (Figure 1). A detailed description of melt stages and melt water distribution
8 mechanisms can be found in ~~(~~Polashenski et al., (2012). These details of melt evolution are
9 responsible for the ~~create~~ spatial variability of MPF and sea ice albedo, ~~and a~~ The temporal
10 variability of MPF is driven by air mass transport and changing air temperature, ~~are the main~~
11 ~~drivers of the temporal variability of the MPF.~~ This introduces complications in the MPF
12 modeling and creates the need for ana satellite retrieval of MPF and sea ice albedo dataset of
13 possibly high temporal and spatial resolution, which can be retrieved from satellite data.

14 The manuscript is structured as follows: in Section 2 the MPD algorithm, its input and output
15 data are described. Section 3 is dedicated to validation of the cloud screening (Sect. 3.1),
16 albedo (Sect. 3.2) and MPF (Sect. 3.3) products. The additional cloud screening developed for
17 the purpose of quality validation is presented in Section 3.3.2. The conclusions are given in
18 Section 4.

19 **2 Data used**

20 The data used for the present study are the pond fraction and broadband sea ice albedo swath
21 data products retrieved from MERIS swath Level 1b data over the ice covered Arctic Ocean
22 using the MPD retrieval. The present chapter presents a short summary of the MPD retrieval.
23 The full description of the algorithm can be found in ~~(~~Zege et al., (2015).

24 The MPD is an new algorithm for retrieving characteristics (albedo and melt ponds fraction)
25 of summer melting ice in the Arctic from data of satellite spectral instruments. In contrast to
26 other previously developed algorithms (Rösel et. al, 2012; Tschudi et al., 2008) MPD does not
27 use a priori values of the spectral albedo of constituents of the melting ice (melt ponds,
28 drained surface, etc.).

29 The retrieval algorithm is based on the observations of optical properties of constituents of
30 sea-ice (Perovich, 1996). A sea ice pixel is considered as consisting of two components: white

1 ice and melt ponds. The reflection properties of surface are described by the spectral bi-
2 directional reflectance distribution function (BRDF) $R(\theta, \theta_0, \varphi, \lambda)$, where θ and θ_0 are the
3 zenith angles of the observation and illumination directions, respectively, and φ is the
4 azimuth angle between them, λ is the wavelength.

5 The white ice is considered as an optically thick weakly absorbing layer. The BRDF of this
6 sub-pixel $R_{ice}(\theta, \theta_0, \varphi, \lambda)$ is determined by its optical depth τ_{wi} , the mean effective grain size
7 a_{eff} , and the absorption coefficient α_{yp} of yellow pigments, which could arise due to
8 sediments suspended in the seawater. The spectral dependencies of optical characteristics of a
9 layer are determined by the spectrum of the complex refractive index of ice by (Warren and
10 Brandt, 2008) and spectral absorption of yellow pigments by (Bricaud et al., 1981). The used
11 analytical approximation for $R_{ice}(\theta, \theta_0, \varphi, \lambda)$ has been developed on the base of the
12 asymptotic solution of the radiative transfer theory (Zege et al., 1991).

13 The BRDF of a melt pond $R_{pond}(\theta, \theta_0, \varphi, \lambda)$ is determined by the melt water optical depth τ_p
14 and by the spectral albedo of its bottom. The pond bottom is an ice layer, which in turn is
15 characterized by the transport scattering coefficient σ_{ice} and the optical depth τ_{ice} . Thus, the
16 BRDF of the melt pond is calculated as reflection of the water layer with a semi-translucent
17 bottom.

18 It is supposed that the pixel surface consists of white ice (highly reflective) and melt ponds
19 with area fraction S . The BRDF of the whole pixel is a linear combination:

$$20 \quad R(\theta, \theta_0, \varphi, \lambda) = (1 - S)R_{ice}(\theta, \theta_0, \varphi, \lambda) + SR_{pond}(\theta, \theta_0, \varphi, \lambda) \quad (1)$$

21 The body of the retrieval algorithm comprises of the following steps.

22 1. The input to the algorithm is the MERIS level 1B data, including the radiance
23 coefficients R_i at channels $i=1, 2, 3, 4, 8, 10, 12, 13, 14$ (correspond to the central
24 wavelengths of 412.5, 442.5, 490, 510, 681.25, 753.75, 778.75, 865 and 885nm), and
25 the solar and observation angles (zenith and azimuth). Also the relevant information
26 on atmosphere and surface state can be entered from an input file.

27 2. The data is sent to the three independent blocks:

- 1 a. The atmospheric correction preprocessing block. The atmosphere reflectance
2 r_i and transmittance t_i are calculated for the used set of wavelengths (i is the
3 channel number). Atmospheric correction is performed with regard to the
4 surface BRDF.
- 5 b. Separation of the sea-ice pixels. In this procedure the ice pixels are separated
6 from the cloud, land and open water pixels, using a brightness criterion on the
7 channels R_2, R_3 , and R_4 , spectral neutrality criterion on the ratio of the
8 channels R_1 and R_2 , MERIS differential snow index (Schlundt et al., 2011) and
9 the threshold on the ratio of the MERIS oxygen-A band (R_{11} and R_{10}). The
10 first two criteria separate white surfaces, which can be snow, ice, or cloud. The
11 MERIS differential snow index and oxygen-A band threshold discard cloudy
12 pixels over snow.
- 13 c. Setting the bounds for ice and pond parameters. These border values serve to
14 stabilize the algorithm and are set to correspond to values observed in nature
15 (obtained by analyzing the field data from the Polarstern cruise (Istomina et al.,
16 2013) and from the CRREL field observations (Polashenski et al., 2012)).
- 17 3. The main part of the algorithm is an iterative procedure to retrieve ice and pond
18 parameters and the pond fraction S . The procedure is based on the Newton-Raphson
19 method (Press et al., 1987) that provides the search of the minimum of the functional
20 $\sum_i (R_i^{meas} - R_i^{calc})^2$ in the space of ice and ponds characteristics and fraction S .
- 21 4. The resulting characteristics and the value of S are used to calculate the spectral
22 albedo of the pixel.
- 23 5. Output is the melt pond area fraction, the spectral albedo, and the estimation of the
24 retrieval error in the pixel. The spectral albedo is retrieved at six wavelengths
25 specified by the user. For the validation studies presented in this paper, the broadband
26 sea ice albedo has been calculated as an average of the six spectral albedo values at
27 400-900nm in steps of 100nm.

28 A satellite scene is processed pixel by pixel, producing an hdf5-formatted map of output
29 values.

1 The MPD algorithm has been preliminarily verified numerically, using a synthetic dataset of
2 top of atmosphere radiances from melting Arctic ice as the input of a satellite spectral
3 instrument. This dataset was computed with software developed based on the radiative
4 transfer code RAY (Tynes et al., 2001; Kokhanovsky et al., 2010) for calculating signals
5 reflected by the melting sea ice-atmosphere system. Thus the radiances in the MERIS spectral
6 channels were simulated for a set of ice pixels for a few typical situations, including
7 ‘standard’ white ice, bright ice (snow covered), dark and light blue melt ponds. The numerical
8 experiment showed that the melt pond fraction can be retrieved with high accuracy (error less
9 than 1%) for the most common case of ‘standard’ white ice and light blue (young) melt pond.
10 The retrieval error increases with deviation from the ‘standard’ case, e.g. the retrieved pond
11 fraction can be underestimated more than twice for the case of bright (snow covered) ice and
12 dark (mature) melt pond. However, this situation is rare, because in the case of an open
13 (exposed) mature pond snowfall only affects the surrounding ice surface for a short time due
14 to ~~melting~~melt temperature. The case of lid covered melt pond is a separate topic, which is
15 discussed in detail in Sect. 3.3.3. Submerged sea ice or water saturated ice surface are
16 optically identical to melt ponds and are retrieved as those. At the same time the MPD
17 algorithm provides accurate retrievals of the spectral albedo in all considered cases, even in
18 the situations when the error of the pond fraction retrieval is high. The spectral albedo is
19 retrieved much better with the MPD algorithm than with ~~the~~ the conventional algorithms using
20 the Lambert approximation for surface reflection, which underestimates the albedo at about
21 0.05 all over the spectral range, whereas the error of the MPD retrieval in the worst case
22 (‘bright ice – dark pond’) is 0.01 and lower in all other considered cases.

23 **3 Validation**

24 The datasets used for the validation of the MPD algorithm are shown in Table 1.

25 These validation datasets contain a wide range of pond fractions and were obtained over
26 landfast ice, FYI and MYI of various ice concentrations. Therefore the performance of the
27 satellite retrieval can be thoroughly tested for a variety of conditions and conclusions on the
28 more or less suitable conditions for the application of the MPD retrieval can be drawn. Such
29 conclusions are especially important as the MPD retrieval was initially designed for a limited
30 set of ice and pond parameters, namely for the conditions of the melt evolution with open

1 melt ponds surrounded by dry white ice within the pack ice. A sensitivity study based on
2 modeled input data shows the algorithm's better performance for bright melt ponds as
3 opposed to dark melt ponds (Zege et al., 2015). Therefore, it is expected that the MPD
4 algorithm shows the best performance over MYI of high ice concentrations. The performance
5 over lower ice concentrations, in case of subpixel ice floes, saturated wet dark ice or thin
6 ponded ice is compromised due to the limitations of the retrieval (Zege et al., 2015). We,
7 however, perform the comparison to the in situ data for all available conditions anyway in
8 order to evaluate the performance of the algorithm at the global scale.

9 Unfortunately, MERIS only features VIS and NIR channels, whereas for effective cloud
10 screening over snow, IR and TIR channels would be more suitable. Therefore MERIS is not
11 the best instrument for cloud screening over snow and ice, and there remains a risk of cloud
12 contamination in the swath data and final gridded product. To avoid this, an additional cloud
13 screening (Sect. 3.3.2) was implemented which proved to give a much better result on swath
14 data. For the gridded product, a restriction on the amount of valid data pixels to form one grid
15 cell was applied to screen out cloud edges. These issues will be addressed below.

16 The summary of dataset locations is shown in Figure 2. Among the above mentioned datasets,
17 the airborne measurements and transect estimates are more accurate than visual estimations;
18 in case of ship cruise bridge observations or visual estimations of melt ponds fraction in the
19 field, the measurement accuracy is hard to evaluate.

20 **3.1 Validation of the cloud screening**

21 | In order to test the performance of the cloud screening presented in (Zege et al., (2015), we
22 have employed data from the AATSR sensor aboard the same satellite platform. The
23 advantage of this sensor is that it has suitable IR channels for cloud screening over snow and
24 ready procedures to perform this task. For this study, a cloud screening method for AATSR
25 | developed by (Istomina et al., (2010) is used. For that, the swath data of both MERIS and
26 AATSR was collocated and cut down to only AATSR swath. Then, the two cloud masks (the
27 reference mask by AATSR and test mask by MERIS) have been compared as follows: for
28 each swath, an average pond fraction in cloud free areas as seen by AATSR (Figure 3, blue
29 curve) and by MERIS (Figure 3, red curve) has been derived. This has been done for the

1 period from May 1, 2009 to September 30, 2009. The resulting Figure 3 shows the effect of
2 clouds on the MERIS MPD swath data: before the melt season, ~~the~~ clouds ~~are~~ have ~~the~~ lower
3 albedo than the bright surface and ~~are~~ may be seen as melt ponds by the MPD retrieval. In the
4 case of developed melt, the situation is the opposite: the melting surface is darker than clouds,
5 and unscreened clouds are taken as lower pond fraction by the retrieval. Overall, the
6 unscreened clouds in the MPD product result in smoothing out of the pond fraction toward the
7 mean value of about 0.15. However, the temporal dynamics is preserved even in swath data.
8 Partly the problem of unscreened clouds can be solved at the stage of gridding swath data into
9 daily or weekly averages, by constraining the amount of valid pixels that form a valid grid
10 cell so that cloudy areas which are only partly unscreened in the swath data are still not
11 included in the gridded data (see Sect. 2 in the companion paper Istomina et al., 2015). It is
12 important to note the positive MPF bias even in the data cloud screened with the reference
13 AATSR cloud mask (blue curve in Figure 3) both in May and in September 2009 where no
14 melt ponds should be present. One of the reasons for the bias in September might be the
15 specifics of the MPD retrieval which detects also frozen ponds as MPF (see Sect. 3.3.3 for
16 details). Another reason might be the actual accuracy issues of the MPD retrieval for dark
17 ponds (see Zege et al., (2015) for details). Given the geographical coverage of the study
18 region (Arctic Ocean to the north of 65°N), the positive MPF bias in May can appear due to
19 water saturated sea ice (after the onset of positive air temperature but before the actual
20 widespread melt).

21 **3.2 Validation of the albedo product**

22 **3.2.1 In situ validation**

23 Validation of the sea ice albedo satellite retrieval is a non-trivial task due to high spatial
24 variability. In summer this variability is even more pronounced as each given duration and
25 intensity of melt or refreeze creates an optically unique surface type (various grain sizes of sea
26 ice and snow, drained, forming, overfrozen melt ponds, deep or shallow ponds on MYI or
27 FYI, intermediate slushy areas, etc). For a satellite pixel size of 1.2 km x 1.2 km the surface
28 types and their fractions from field observations are in the best case only known for a 100-200
29 m long transect. In order to obtain the in situ sea ice albedo, a linear mix of all surface

1 fractions is constructed. The availability of such comprehensive field measurements is very
2 limited, and for those available, the question of how representative the chosen transect is for
3 the whole area is anyway present. In this study, we use a transect data taken in the Canadian
4 Arctic in June and July 2006 as part of the joint Finnish Institute of Marine Research and
5 University of Calgary Cryosphere Climate Research Group polar ice POL-ICE research
6 project (Geldsetzer et al., 2006), where the uniform pond distribution was confirmed using
7 helicopter images (not shown here).

8 During POL-ICE 2006 the spatio-temporal evolution of surface features and their spectral
9 reflectance properties were monitored by collecting a series of transect measurements on
10 landfast FYI (FI) also in the vicinity of Resolute Bay, Nunavut between June 26, 2006 and
11 July 11, 2006. For each transect, a 200m transect line was established perpendicular to the
12 predominant major-axis pond direction to maximize the frequency of changes between ponds
13 and snow/bare ice patches. For the relatively uniformly distributed network of ponds and
14 snow/bare ice patches characteristics of smooth FYI, this orientation yields a representative
15 areal fraction of cover types (Grenfell and Perovich, 2004). A total of 12 transects were
16 collected with surface cover types classified as: melt pond, snow/bare ice, or mixed at 0.5 m
17 intervals. The mixed cover type was introduced to classify the slushy mixture of water
18 saturated ice that could be neither classed as discrete pond or snow/bare ice. The data is
19 shown in Table 2.

20 For 8 of POL-ICE 2006 transects when lighting conditions were suitable, cosine-corrected
21 downwelling and upwelling radiance (0.35 m height) measurements were made at 2m
22 intervals using a TriOS RAMSES spectrometer (320-950nm). Spectral data were processed
23 using the calibration files and software bundled with the RAMSES spectrometer, with
24 radiation measurements integrated across the bandwidth of the instrument to create integrated
25 albedo measurements from each sample. Each albedo measurement was matched to a surface
26 class, and average broadband albedo statistics by class and for each transect were derived. For
27 these locations, the MPD retrieval has been performed and the broadband albedo average
28 within 5km around the location has been produced. Satellite overflights closest in time to the
29 field measurements were taken. The result is shown in Table 3, the comparison itself in the
30 last column „Results“. The NaNs in the retrieved data are gaps due to cloud cover. Only four
31 cases were cloud free. Overall, slight overestimation of the satellite albedo is visible. The

1 discrepancies between the field and satellite albedo can be explained by difference in the
2 spatial resolution of the two datasets and varying melt pond distribution within the studied
3 area.

4 **3.2.2 Aerial validation**

5 The validation has been performed for selected cloud free satellite swaths at the reduced
6 resolution of the retrieval (MERIS data, reduced resolution, 1.2 km x 1.2 km).

7 The aircraft campaign MELTEX („Impact of melt ponds on energy and momentum fluxes
8 between atmosphere and sea ice“) was conducted by the Alfred Wegener Institute for Polar
9 and Marine Research (AWI) in May and June 2008 over the southern Beaufort Sea (Birnbaum
10 et al., 2009).

11 The campaign aimed at improving the quantitative understanding of the impact of melt ponds
12 on radiation, heat, and momentum fluxes over Arctic sea ice. For determining broadband
13 surface albedo, the BASLER BT-67 type aircraft POLAR 5 was equipped with two Eppley
14 pyranometers of type PSP measuring the broadband hemispheric down- and upwelling
15 shortwave radiation. The radiation sensors were mounted on the aircraft in a fixed position.
16 For clear-sky conditions, data of the upward facing pyranometer, which receives direct solar
17 radiation, were corrected for the misalignment of the instrument (based on a method described
18 by Bannehr & Schwiesow, (1993)) and the roll and pitch angles of the aircraft to derive
19 downwelling hemispheric radiation flux densities for horizontal exposition of the sensor (see
20 Lampert et al., 2012).

21 Weather conditions in May 2008 were characterized by warming events interrupted by cold-
22 air advection from the inner parts of the Arctic towards the coast of the southern Beaufort
23 Sea. A warming event on May 23 and May 24, 2008, caused the onset of melt pond formation
24 on ice in a large band along the coast from the Amundsen Gulf to Alaska. On May 26, 2008,
25 numerous melt ponds in a very early stage of development were overflowed. However, from
26 May 27 to June 1, 2008, a new period with prevailing cold-air flow caused a refreezing of
27 most melt ponds, which were still very shallow at that time. During the last week of the
28 measurements, a tongue of very warm air was shifted from Alaska to the Beaufort Sea. It

1 reached its largest extension over the ocean on June 4 and June 5, 2008, which again strongly
2 forced the development of melt ponds.

3 The available validation data consist of 5 flight tracks for 5 days on May 26, and June 3, June
4 4, June 6 and June 7, 2008. Only the cloud free data is selected. The measurements were
5 performed at different altitudes, as low as 50m and reaching 400m, with correspondingly
6 different numbers of measurement points for each satellite pixel. The collocation of such an
7 uneven dataset with the satellite data has been performed by calculating an orthodromic
8 distance of every pixel within a satellite swath to a given aerial measurement point, and
9 collecting those aerial points lying at the minimum distance to the centre of a given satellite
10 pixel. This ensures that aerial measurements performed at any height are collocated to the
11 corresponding satellite pixel correctly. The number of data points per flight is in the order of
12 tens to hundreds of thousands with up to 500 points per satellite pixel.

13 The validation effort has been done on swath satellite data. The quality of retrieval conditions
14 for the MPD algorithm differs for each overflight depending on weather conditions, ice
15 concentration and ice type. In addition, time difference between the satellite overflight and
16 aerial measurements affect the comparison (Table 4) due to ice drift.

17 An example of such different conditions is shown in Figure 4, where the flight tracks over FI
18 and over separate ice floes are shown.

19 The time difference between the aerial measurement and satellite overflight varies for the
20 presented cases, which adds to the validation data uncertainty for cases with lower ice
21 concentrations due to drifting separate floes. Where possible in case of drift, the time
22 difference was limited to 1.5 hours around the satellite overflight. Two exceptions with time
23 difference 2^h-3^h are marked in Table 4. Figure 5 shows the altitude and the correlation of the
24 measured and retrieved broadband albedo for the only flight over FI on June 06, 2008. The
25 rest of the flights were flown over separate floes. As no screening of albedo data was possible,
26 it was decided to limit the time difference to 1.5 hour around the satellite overflight for the
27 asymmetrically distributed flights. Some points of low measured albedo but high retrieved
28 albedo feature time difference up to 2h and are most probably connected to the drift of
29 separate ice floes. These are flights on June 04, 2008, May 26, 2008, June 03, 2008 and June
30 07, 2008. They are shown in Figure 6, Figure 7 and Figure 8. Due to ice drift, the aerial

Field Code Changed

1 measurements are displaced relative to the satellite snapshot which causes different areas to
2 be compared to each other. The resolution differences of the two sensors may increase this
3 difference even more. Therefore, slight over or underestimation due to the ice concentration
4 difference of aerial and satellite measurements is visible. As the numerical experiment shows
5 that accuracy of the albedo retrieval in all cases is high (Zege et al., 2015), and the case of no
6 drift shows high correlation of retrieved and measured albedo (~~fast ice(FI)FI~~ case shown in
7 Figure 5), we conclude that the discrepancy is due to the specifics of data used for validation
8 and not a weak point of the MPD retrieval. To conclude, the best correlation for albedo
9 retrieval is observed for the landfast ~~and multiyear ice of high ice concentrations~~, which are
10 the conditions of the best algorithm performance with $R^2=0.85$, $RMS=0.068$. Due to the lack
11 of field data the validation has not been performed over MYI, however, the MPD has been
12 designed for MYI, namely sea ice of high concentration with light melt ponds. FI is a
13 deviation from this case at least in the melt pond type, and potentially in the surface albedo,
14 but as MPD performed well even in this case, we expect it to perform at least as well over
15 MYI of high ice concentrations. Correlation for lower ice concentrations, subpixel ice floes,
16 blue ice and wet ice is lower due to complicated surface conditions and ice drift. Combining
17 all aerial observations gives a mean albedo RMS of 0.089.

18 3.3 Validation of the melt pond product

19 3.3.1 Aerial validation

20 For the validation of the melt pond product, the aerial photos from the same airborne
21 campaign MELTEX 2008 have been used. Although the flight tracks are the same, the criteria
22 for data selection are different for albedo and melt pond measurements. This is why the
23 validation data for melt pond and albedo data not to overlap entirely for the same flight. The
24 number of points per flight is in the order of hundreds with about 5 images per satellite pixel
25 (example photograph is shown in Figure 9). Additionally, one more flight over MYI near the
26 coast of North Greenland during the aerial campaign NOGRAM-2 2011 has been used.

27 For the evaluation of the aerial photographs a supervised classification method (maximum
28 likelihood) was applied. For every pixel x , the probability D of belonging to every class c is
29 calculated. The pixels get assigned to the class with the highest probability (Jensen, 2008). If

1 the training data is normally distributed, the maximum likelihood is expressed as follows
2 (Gonzalez and Woods, 2002):

$$3 \quad D = \ln(a_c) - [0.5 \ln(|Cov_c|)] - [0.5(X - M_c)^T (Cov_c^{-1})(X - M_c)]. \quad (2)$$

4 where D is the quantities weighted distance (likelihood), c is a particular class, X is the
5 measurement vector of the candidate pixel, M_c is the mean vector of the sample of class c, a_c
6 is the a priori probability of class c (set to equal values for all classes), Cov_c is the covariance
7 matrix of the pixels in the sample of class c, T is the transposition function.

8 More than 10,000 aerial photographs were recorded during the MELTEX campaign during
9 the different flight tracks. As the quality of the data was not uniform, only images which meet
10 the following requirements were chosen: images taken during horizontal flight tracks (to
11 minimize the geometric distortions) and clear sky flight tracks (to prevent a wrong
12 classification because of fog, clouds and shadows of the clouds). The camera was operated
13 with a non-constant exposure, so that the sea ice in images with a large fraction of open water
14 was overexposed and useless for further evaluation. To simplify the automated classification,
15 images of each day were separated into different flight tracks with similar exposure, ice
16 conditions and same flight level. Nevertheless almost 3000 images were classified and
17 evaluated for the MELTEX campaign. Two suitable flight tracks of the NOGRAM-2
18 campaign that contain about 1000 images were chosen to complement the quantification of
19 the melt stages. Depending on the flight level, each image covered an area between 0.2 km²
20 and 3 km².

21 Overall the validation data used features four types of sea ice: thin and thick FYI as well as
22 ~~fast ice~~ (FI) for the MELTEX images, and MYI for NOGRAM-2. Most of the investigation
23 area of the MELTEX campaign was covered by thin FYI or FI. Only on June 07, 2008, the
24 most northerly part of the flight track contained a notable amount of thick FYI. This part
25 showed a different behavior during the melting process and contained different surface classes
26 than the thin FYI or FI.

27 Most flight tracks of the campaign were subdivided in several subflight tracks. For every
28 subflight track a representative image was chosen, which contained all classes. In cases where
29 there were no representative images with all classes for a given subflight track, two or more
30 images were merged for the determination of the training data. The threshold for the

1 maximum likelihood method was set to 0.95. This means that the probability of belonging to
2 a defined class must be 0.95 or higher. Otherwise the pixels were not classified. Within the
3 presented study, the amount of unclassified pixels per image is uniformly about 1-2%.

4 The sea ice conditions varied greatly for each of the studied flights, with the cases ranging
5 from land fast ice of 100% ice concentration, separate drifting ice floes to ~~thrashedbrash~~ ice
6 with subpixel ice floes (example in Figure 10). The cases with no separate ice floes and no ice
7 drift are shown in Figure 11 (FI) and Figure 12 (left panel, MYI) with quite good
8 correspondence of the retrieved and measured pond fractions. Right panel in Figure 12, on the
9 other hand, shows higher retrieved MPF than measured from the aircraft. The reason for this
10 discrepancy is twofold: relatively large time difference and the challenging surface
11 conditions. The surface state at the time was as follows: the reported cold air intrusion in the
12 area on June 01, 2008 prevented the forming melt ponds from evolving further (an overview
13 on surface conditions in the area can be found in (Scharien et al., (2012)), and the large floes
14 were covered with frozen ponds at the beginning of their evolution. Frozen shallow ponds at
15 the beginning of their evolution were classified as sea ice from the aerial images, but retrieved as
16 melt ponds from the satellite. For the applications connected to the radiation budget studies (e.g.,
17 GCM), a generalization where darker types of sea ice and melt ponds are put into one class is
18 appropriate due to similar radiative characteristics of the two.

19 Figure 13 shows the flight on June 07, 2008, which features larger ice floes than the flights
20 shown in Figure 14. The MPF output of the MPD algorithm is not affected by the subpixel
21 fraction of open water because the almost constant spectrum of open water only affects the
22 amplitude and not the spectral shape of the mixture of surfaces (sea ice, ponds and open
23 water) within the pixel; however, the spectral signature of melt ponds is harder to resolve in
24 case of lower ice concentrations. Subpixel ice floes, ~~thrashedbrash ice, with inclusions of~~ blue
25 ice are not appropriate conditions for the MPD algorithm application, hence the overestimated
26 pond fraction for both flights in Figure 14. Overall, the best correlation can be seen for the
27 cases of landfast and multiyear ice of high ice concentrations $R^2=0.36$, $RMS=0.065$.
28 Combining all aerial observations gives mean melt pond fraction RMS equal to 0.22.

Field Code Changed

1 3.3.2 Cloud screening for in situ and ship cruise validation

2 As the aerial validation has been performed on cloud free data, the problem of cloud clearing
3 did not arise. For in situ and ship cruise data, cloud contamination may increase the
4 uncertainty of the satellite retrieved values and in these cases this problem has to be addressed
5 additionally. With the gridded product, the unscreened cloud edges and partly screened out
6 clouds are cut out with the criterion for minimum valid data pixels allowed within one grid
7 cell. For the swath data, such criterion is not applied and the existing cloud filtering proved to
8 be not sufficient for a quality validation. Therefore, an additional spatial dynamic filter was
9 introduced for ship cruise and in situ data. An example is shown in Figure 15.

10 The dynamic spatial filter consists of dividing the swath into boxes of 10x10 pixels with all
11 the surface and cloud screening criteria applied except the oxygen A filter (Eq. 5 in Zege et
12 al., (2015)); due to MERIS bands specifics, all these filters are imperfect and are subject to
13 misclassifying certain types of clouds (e.g. thin clouds and ice clouds) as ice and snow. Then,
14 within a given box, the oxygen A filter is applied. If this additional oxygen A filter screened
15 out some additional pixels, then the box is potentially cloudy and the imperfect cloud filters
16 surely left some unscreened clouds. Such a box is discarded completely. If the additional
17 oxygen A filter (which is more sensitive to high and thick low clouds than the other applied
18 cloud filters, so in the case of clouds it would screen out more pixels than the other filters) did
19 not screen out any additional pixels, the scene is either uniformly filled with just clouds to
20 which none of the filter are sensitive (improbable) or it is a cloud free scene. The boxes where
21 this happens are kept and used for validation.

22 This method proved to be successful for the case studies on single swaths which do not
23 undergo gridding with a threshold on the minimum allowed amount of cloud free pixels
24 which helps to screen out cloud edges or partly screened clouds. For our MERIS gridded
25 products, the gridding procedure tends to introduce a similar cloud screening effect as the
26 above mentioned filter. High thin clouds, however, may still be present within both swath
27 data and gridded products. The consequences are discussed in the Section 3.1.

3.3.3 Ship cruise validation

The visual estimations of various sea ice parameters, including MPF during the ship cruises ~~(most often performed according to ASPECT protocol)~~ differ in accuracy from aerial measurements, transect measurements, or visual estimations during in situ campaigns which are dedicated to such measurements. As opposed to the in situ campaign, hourly bridge observations are performed by many observers with different estimation experience and skill, which introduces additional noise to the observed value. The two studied cruises – The Healy-Oden Transarctic Expedition (HOTRAX), 19 August – 27 September 2005 (Perovich et al., 2009), and RV Polarstern cruise ARK-XXVI-3 (TransArc2011), 04 August 2011 – 6 October 2011 (Nicolaus et al., 2012), - both travelled across the Arctic Ocean at the end of ~~melting~~melt season, August-September. ~~The occurrence of frozen over, snow covered or entirely melted through melt ponds was therefore high. The ice observations during both cruises have been performed within the Antarctic Sea Ice Processes and Climate (ASPeCt) protocol. The limited scope of the ASPECT specifics of ASPeCt ice watch protocol leads to lack of fields for detailed description of the state of melt pond. During observations for the TransArc2011 such details did not allocate a specific field for details of this kind and they were sometimes (but not always) mentioned in the field for comments, and for HOTRAX cruise such information was not available at all. Where available these details are helpful for the validation of the MPD algorithm. Spectral reflectance of frozen and snow covered ponds are close to that of sea ice can be represented as a linear mixture of dark pond and sea ice within the MERIS spectral range, and melted through ponds have the spectral behaviour of open water. Both surface types are no longer melt ponds in the original sense of the word and have to be excluded from the retrieved MPF for energy budget or climate modelling applications. As the MPD algorithm utilizes the difference in spectral behaviour of melt ponds, open water and sea ice, it will retrieve the true fraction of open melt ponds with sea ice underneath the meltwater. In case of melted through or frozen over ponds documented as melt ponds in the ship based observations, a discrepancy between the ship cruise data and the MPF retrieval will occur. This is illustrated for the case of the frozen snow covered melt ponds in Figure 16. The MPD will continue to retrieve some MPF also in case of frozen ponds as long as their albedo is lower than the albedo of surrounding sea ice. Typically a few centimeters of snow is already enough to even out this albedo difference, but horizontal snow~~

1 [redistribution due to winds can prolong the period of apparent pond presence according to the](#)
2 [MPD retrieval. This explains the positive MPF bias in September \(after the melt season\) in](#)
3 [Figure 3.](#)

4 Within this work, we apply the MPD algorithm without limitations other than cloud screening
5 (original as described by Zege et al., (2015), and dynamic spatial filter described in Sect.
6 3.3.2) to illustrate the effect of the above mentioned underestimation. In cases not dedicated
7 to the study of the algorithm accuracy, it is recommended to use the MPD MPF product in
8 combination with the reanalysis air surface temperature to apply the algorithm only when the
9 melt ponds are not frozen over. Otherwise the (supposedly low) MPF value is ambiguous and
10 could indicate both low MPF of open ponds or high MPF of frozen ponds.

11 Both cruises TransArc2011 (Figure 17) and HOTRAX 2005 (Figure 18) had only several
12 days of cloud free collocations. The available swath data and the hourly ship observations
13 have been compared point by point without temporal averaging. The only averaging was the
14 15km spatially of the satellite data around the ship location. For both cruises, information on
15 ice concentration was available from bridge observations and the ship MP values have been
16 corrected for ice concentration to give the pond fraction relative to the visible area and not to
17 the area of sea ice. For the TransArc2011 cruise, information on MYI and FYI ice
18 concentration was available with corresponding MPFs. The total MPF was calculated using
19 the linear mix of these values. However, the resulting cloud free collocations feature mostly
20 FYI cases. For the HOTRAX 2005, such information was not available and only total ice
21 concentrations were used. The correlation between the satellite value and observed value:
22 mean $R^2=0.044$, mean RMS=0.16. The low correlation might be caused by the documentation
23 of varying accuracy within the ASPeCt protocol.

24 **3.3.4 In situ validation**

25 The in situ validation has been performed on the swath data using the three available datasets:
26 transect measurements on the FI just north of Barrow, AK, approximately 1km offshore from
27 Niksiuraq in the Chukchi sea, near 71°22' N, 156°33' W throughout June 2009 (Polashenski et
28 al., 2012), 100m transect and visual estimations on the 3x3 km area of landfast FYI
29 approximately 80 km northwest of Resolute Bay, Nunavut, 75°14' N, 97°09' W, between
30 June 18 and July 10, 2002 as part of the Collaborative Interdisciplinary Cryosphere

Field Code Changed

1 Experiment (C-ICE) 2002 project (Scharien and Yackel, 2005), and 200m transect fractions
2 on landfast FYI also in the vicinity of Resolute Bay, Nunavut, 74°44' N, 95°06' W, between
3 June 26 and July 11, 2006 (Sect. 3.2.1).

Field Code Changed

4 During C-ICE 2002 visual estimates of MPF fraction were made on a homogeneous and
5 relatively smooth zone of FI in the Canadian Arctic Archipelago approximately 80 km
6 northwest of Resolute Bay, Nunavut between June 18, 2002 and July 08, 2002 (Scharien and
7 Yackel, 2005). Visual estimates were supported by occasional 100 m transect measurements
8 taken at 0.5 m intervals to characterize surface feature types (melt pond or ice) and pond
9 depths, as well as timelapse photos taken from a tower based camera mounted at 6 m height.
10 From these data a nominal 0.1 MPF estimation error was ascribed to the visual estimates. For
11 days where transect measurements were available, the daily average of W-E and N-S transects
12 was used instead of visual estimates.

13 For the remaining two datasets, the transect measurements of MPFs were used as provided.

14 The datasets feature uniform FI and at times of extremely high pond fractions and the
15 following drainage events. As the campaigns were performed on the FI, no correction for the
16 ice concentration was needed. As in case of ship cruises, the average MPF 15km around each
17 in situ point was taken. The same cloud filtering has been applied (original as described by
18 ~~Z~~Zege et al., (2015), and dynamic spatial filter described in Sect. 3.3.2). The total amount of
19 cloud free collocated points is N=47, total RMS = 14%, total R²=0.52. The correlation plot for
20 the two datasets is shown in Figure 18.

Field Code Changed

21 **4 Conclusions**

22 Melt ponds on sea ice affect the radiative properties of the ice cover and its heat and mass
23 balance. In order to assess the change of the energy budget in the region (e.g. with GCM),
24 among other sea ice and melt pond properties, the sea ice reflective properties and the amount
25 of melt ponds on sea ice have to be known. This work has validated a retrieval of MPF and
26 broadband sea ice albedo from MERIS data (Zege et al., 2015) against aerial, in situ and ship-
27 based observations.

28 The cloud screening presented in ~~Z~~Zege et al., (2015) has been compared to the AATSR cloud
29 screening presented in ~~I~~Istomina et al., (2010) for swath data of both sensors collocated to

1 AATSR swath, for the whole summer 2009. The comparison (Figure 3) shows that
2 unscreened clouds are seen as melt ponds before melt onset and as less melt ponds during
3 melt evolution; the effect of unscreened clouds is not constant and depends on the true surface
4 pond fraction. Unscreened clouds tend to smooth out the melt pond fraction values towards a
5 mean value of about 0.15. As can be seen from the figure, this smoothing effect is most
6 prominent in the beginning of the season and during the melt maximum, and is the smallest in
7 June.

8 The albedo data from from spaceborne and airborne observations have been compared and
9 showed high correlation when there is no ice drift (Figure 5, Figure 7). Same comparison for
10 MPF highly depends on the ice conditions and melt stage: for FI and MYI in the beginning of
11 melt the correlation is high (Figure 11, Figure 12, Figure 19), for separate FYI floes the
12 correlation is worse maybe due to ice drift (Figure 13, Figure 14). The comparison of ship
13 cruise data to satellite retrieved MPF for FYI and MYI at the end of the melt season shows
14 strong underestimation of satellite retrieval. This might be connected to frozen over ponds
15 undocumented in the ASPeCt observations (Figure 17, Figure 18). At the same time,
16 comparison to ship observations show that the MPD retrieval shows ambiguity of the
17 retrieved MPF: low retrieved MPF could indicate low MPF of open ponds or high MPF of
18 frozen ponds. It is planned to resolve this ambiguity in the future versions of the algorithm by
19 introducing a decision tree based on the air temperature as a measure of surface energy
20 balance to determine whether ponds are frozen over or not.

21 The presented melt pond fraction and sea ice albedo retrieval can be applied to other
22 radiometers with sufficient amount of channels in the VIS and NIR regions of spectrum, e.g.
23 VIIRS onboard Suomi NPP and OLCI onboard the Sentinel-3 ESA mission (planned launch
24 [late 2015](#)). Thus the continuity of the MPF and sea ice albedo dataset can be achieved, which
25 is important for the dataset use as input to GCM and for studies of MPF and albedo dynamics
26 in the context of global change and Arctic amplification.

27 The case studies, time sequence analysis and trends of MPF and sea ice albedo are presented
28 in the companion paper (Istomina et al., 2015).

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2 bridge observations of the TransArc 2011 cruise, to Dr. Daniel Steinhage for providing photos
3 taken with a downward-looking camera during the aircraft campaign NOGRAM-2 2011, to
4 the C-ICE 2002 participants, J. Yackel and the Cryosphere Climate Research Group,
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19

1 Table 1. Datasets used for validation of the MPD algorithm

| Campaign and year | Method | Ref. |
|-------------------|--|--|
| Barrow 2009 | In situ field campaign, fractions along a 200m transect | (Polashenski, 2011) |
| MELTEX 2008 | Airborne measurements, supervised classification algorithm applied to geolocated quality assured aerial images | (Birnbaum et al., 2009; Schwarz, 2013) |
| NOGRAM-2 2011 | Airborne measurements, supervised classification algorithm applied to geolocated quality assured aerial images | (Lehmann, 2012; Schwarz, 2013) |
| C-ICE 2002 | In situ field campaign, visual estimation and fractions along 100m transects | (Scharien and Yackel, 2005) |
| HOTRAX 2005 | Ship cruise, hourly bridge observations, visual estimation | (Perovich et al., 2009) |
| TransArc 2011 | Ship cruise, hourly bridge observations, visual estimation | (Nicolaus et al., 2012) |
| POL-ICE 2006 | In situ field campaign, fractions along a 200m transect | (R. Scharien, Sect. 3.2.1) |

2

1 Table 2. Transect measurements of surface type fractions in the Canadian Arctic, POL-ICE
 2 2006, where the relative surface type fractions are as follows: f_1 is the snow/bare ice, f_2 – melt
 3 pond, f_3 – mixed cover, f_4 – overfrozen melt pond.

| id | date_ut | time_ut | loc_y | loc_x | n | f_1 | f_2 | f_3 | f_4 |
|----|-------------|---------|----------|-----------|-----|-------|-------|-------|-------|
| 1 | 26-Jun-2006 | 15:00 | 74.73324 | -95.10583 | 383 | 0.37 | 0.31 | 0.32 | 0.00 |
| 2 | 27-Jun-2006 | 0:00 | 74.732 | -95.10324 | 400 | 0.23 | 0.41 | 0.36 | 0.00 |
| 3 | 28-Jun-2006 | 0:00 | 74.73164 | -95.14458 | 395 | 0.21 | 0.57 | 0.22 | 0.00 |
| 4 | 28-Jun-2006 | 18:30 | 74.73079 | -95.14778 | 401 | 0.24 | 0.54 | 0.22 | 0.00 |
| 5 | 2-Jul-2006 | 15:00 | 74.73015 | -95.16151 | 398 | 0.35 | 0.26 | 0.39 | 0.00 |
| 6 | 4-Jul-2006 | 17:30 | 74.73102 | -95.15971 | 400 | 0.37 | 0.31 | 0.32 | 0.00 |
| 7 | 5-Jul-2006 | 14:45 | 74.7304 | -95.17052 | 400 | 0.24 | 0.41 | 0.35 | 0.00 |
| 8 | 6-Jul-2006 | 3:00 | 74.73097 | -95.1729 | 400 | 0.22 | 0.41 | 0.38 | 0.00 |
| 9 | 6-Jul-2006 | 17:00 | 74.7309 | -95.17329 | 400 | 0.31 | 0.30 | 0.40 | 0.00 |
| 10 | 9-Jul-2006 | 15:00 | 74.72987 | -95.17271 | 400 | 0.38 | 0.06 | 0.38 | 0.19 |
| 11 | 10-Jul-2006 | 0:30 | 74.7301 | -95.17448 | 400 | 0.30 | 0.09 | 0.61 | 0.00 |
| 12 | 11-Jul-2006 | 16:45 | 74.72998 | -95.16605 | 400 | 0.33 | 0.22 | 0.46 | 0.00 |

4

1 Table 3. Integrated (320-950nm) albedo for various surface types and total obtained from
 2 transect radiance measurements in Canadian Arctic, POL-ICE 2006, versus corresponding
 3 retrieved broadband (400-900nm) albedo averaged within 5 km around the location. n is the
 4 amount of measurements, f is the surface type fraction, α is the integrated albedo.

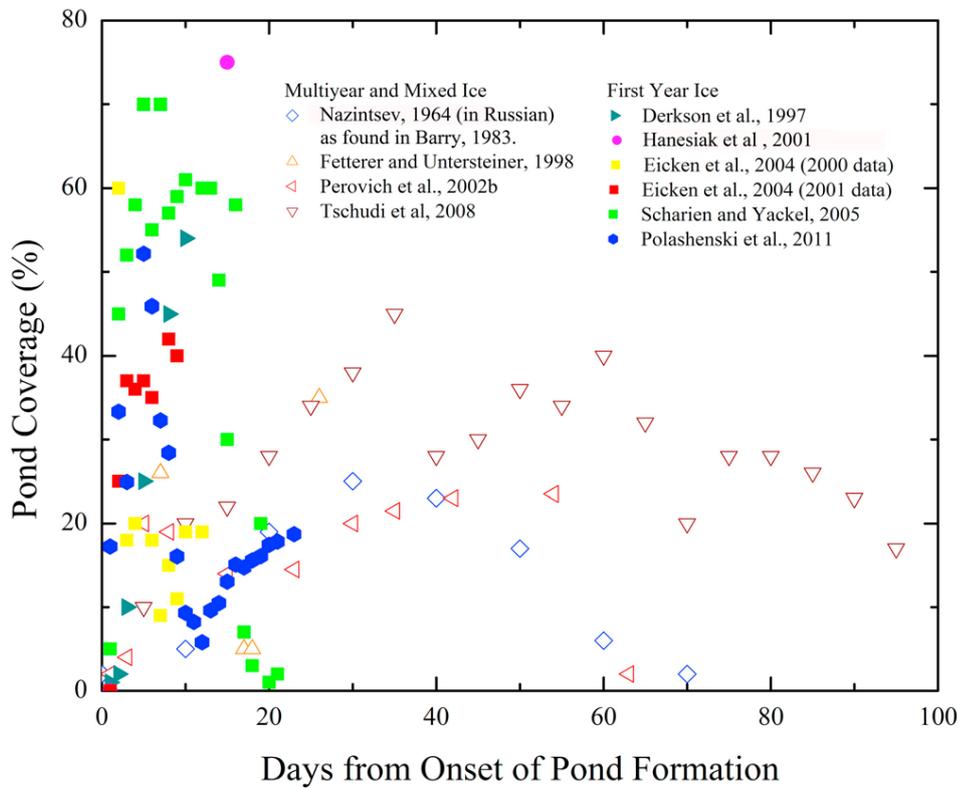
| id | SNOW/BARE ICE | | | | MIXED | | | | POND | | | | RESULT |
|----------|---------------|------|-----------------|-----------------|-------|------|-----------------|-----------------|------|------|-----------------|-----------------|------------------------------|
| | n | f | avg α | std α | n | f | avg α | std α | n | f | avg α | std α | Total α /retrieved |
| 2 | 83 | 0.21 | 0.51 | 0.07 | 86 | 0.22 | 0.31 | 0.05 | 226 | 0.57 | 0.24 | 0.03 | 0.31 / N/A |
| 3 | 94 | 0.24 | 0.62 | 0.06 | 89 | 0.22 | 0.40 | 0.13 | 217 | 0.54 | 0.23 | 0.02 | 0.36 /0.47 |
| 6 | 149 | 0.37 | 0.57 | 0.05 | 126 | 0.32 | 0.33 | 0.10 | 125 | 0.31 | 0.22 | 0.03 | 0.38 / N/A |
| 7 | 97 | 0.24 | 0.54 | 0.05 | 140 | 0.35 | 0.29 | 0.10 | 163 | 0.41 | 0.21 | 0.02 | 0.32 /0.40 |
| 9 | 122 | 0.31 | 0.58 | 0.04 | 158 | 0.40 | 0.32 | 0.11 | 120 | 0.30 | 0.20 | 0.01 | 0.36 /0.58 |
| 10 | 150 | 0.38 | 0.68 | 0.04 | 152 | 0.38 | 0.38 | 0.12 | 23 | 0.06 | 0.20 | 0.01 | 0.46 /0.48 |
| 11 | 119 | 0.30 | 0.56 | 0.04 | 244 | 0.61 | 0.30 | 0.11 | 37 | 0.09 | 0.18 | 0.01 | 0.37 / N/A |
| 12 | 132 | 0.33 | 0.71 | 0.07 | 182 | 0.46 | 0.33 | 0.16 | 86 | 0.22 | 0.20 | 0.02 | 0.43 / N/A |
| Combined | | | 0.60 | 0.08 | | | 0.33 | 0.12 | | | 0.21 | 0.03 | |

5

1 Table 4. UTC time of aerial measurements (mpf and alb) and satellite overflights (sat) for
 2 each day of available aerial measurements of MELTEX 2008 and NOGRAM 2011. Cases
 3 with large time difference (greater than 1.5^h) between satellite and field measurements are
 4 marked with the red colors shown in red.

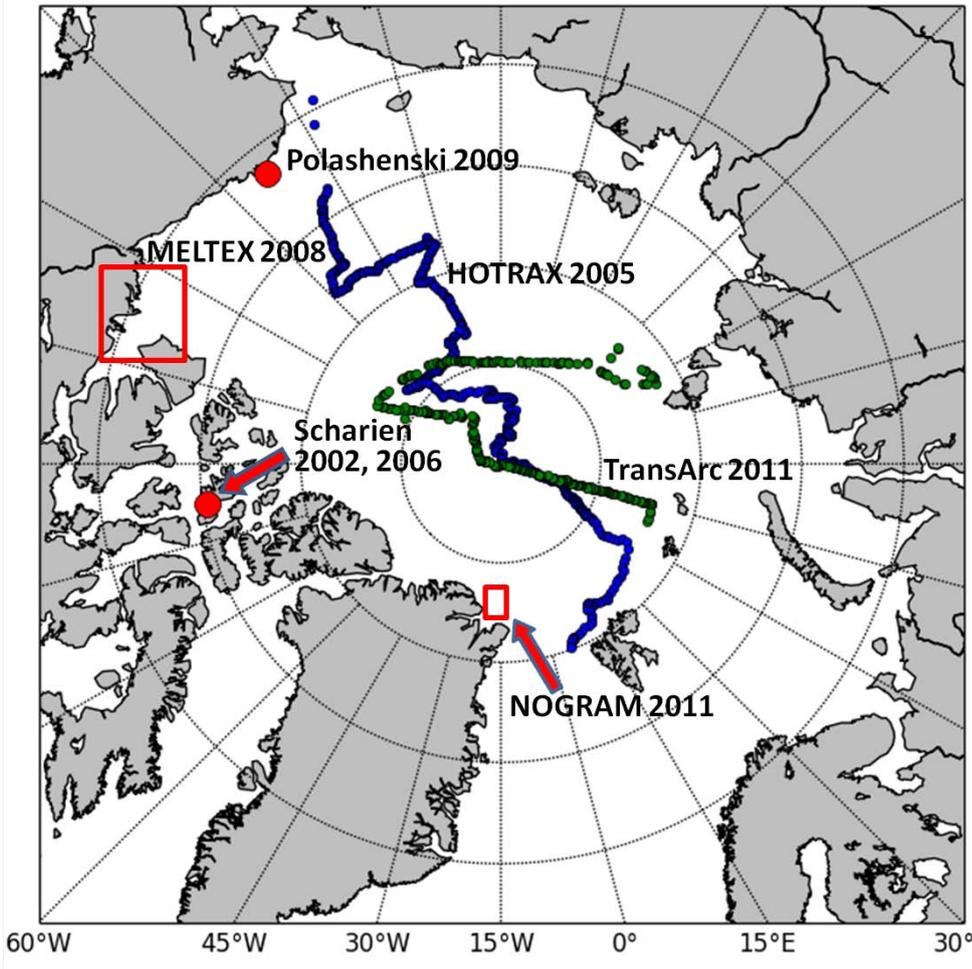
| Date | 26.05.2008 | 03.06.2008 | 04.06.2008 | 06.06.2008 | 07.06.2008 | 21.07.2011 |
|------|-------------|-------------|-------------|------------|-------------|------------|
| alb | 20:45-21:48 | 17:00-19:46 | 19:14-23:24 | no drift, | 17:08-20:17 | no drift, |
| mpf | 20:55-22:55 | 16:59-17:53 | 19:14-22:03 | FI | 17:56-19:22 | MYI |
| sat | 20:46 | 19:54 | 21:02 | | 21:08 | |

5
6

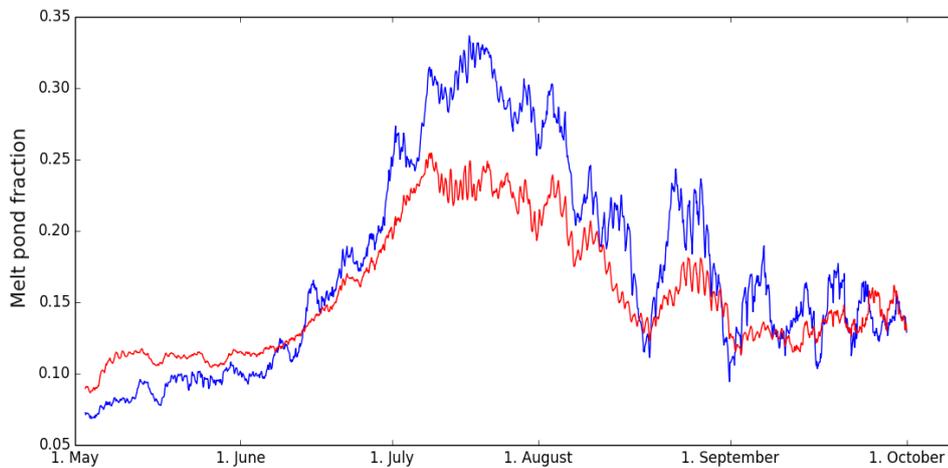


1
2
3 Figure 1. Pond coverage taken from various field campaigns (see legend) versus days from
4 onset of ponding on first year ice (filled dots) and multiyear ice (empty dots). Melt onset
5 proceeds rapidly to the MPF maximum on FYI with following pond drainage and moderate
6 MPFs afterwards; on multiyear ice, the evolution of melt up to the melt maximum takes
7 longer, the peak MPF value is lower and the MPF decrease is slower than that on FYI. Figure
8 courtesy C. Polashenski.

9
10



1
 2 Figure 2. Schematic representation of the spatial distribution of the validation data. Red dots
 3 show the location of in situ field measurements; tracks – ship cruises, rectangles –
 4 approximate area of airborne measurements. The data includes FYI and MYI.
 5

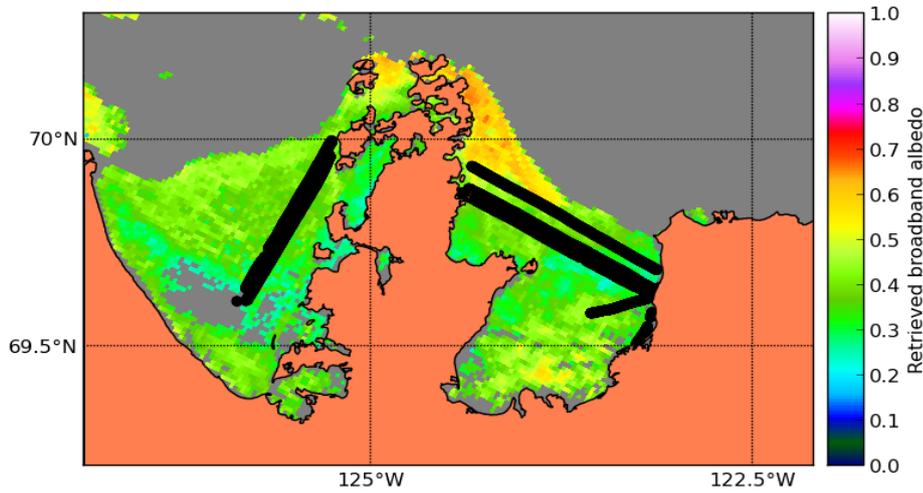


1
 2 Figure 3. Swathwise comparison of the MERIS cloud mask ~~from~~ used in the MPD retrieval to
 3 the AATSR cloud mask presented in (Istomina et al., 2010). The region covered is the Arctic
 4 Ocean to the north of 65°N (land masked out). All available swaths from May, 1, 2009 to
 5 September, 30, 2009 have been taken. Blue curve: MPF retrieved with MPD averaged in
 6 cloud free areas as seen by AATSR (reference or “perfect” cloud mask). Red curve: MPF
 7 retrieved with MPD averaged in cloud free areas as seen by MERIS (potentially cloud
 8 contaminated mask). The smoothing out effect of unscreened clouds is visible in the behavior
 9 of the red curve.

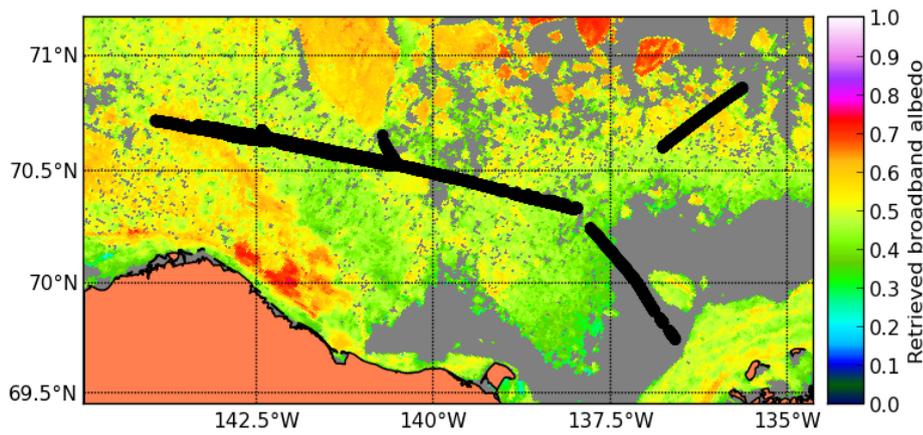
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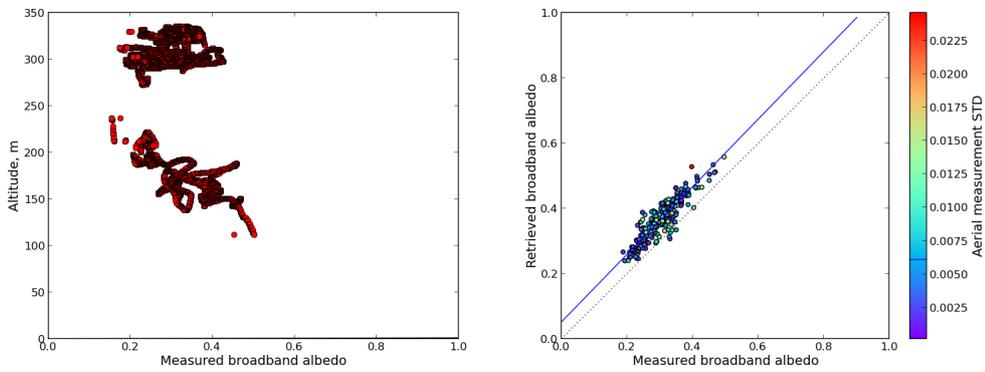


3

4 Figure 4. Examples of ice conditions present during MELTEX 2008 flights over landfast ice
5 on June 06, 2008 (top panel) and over separate ice floes of various sizes on June 04, 2008
6 (bottom panel). The black tracks depict the flight tracks with albedo measurements. The color
7 code illustrates the satellite retrieved broadband albedo. The background consists of the coral
8 filled landmask and grey filled data gaps due to cloud contamination or surface type other
9 than sea ice.

10

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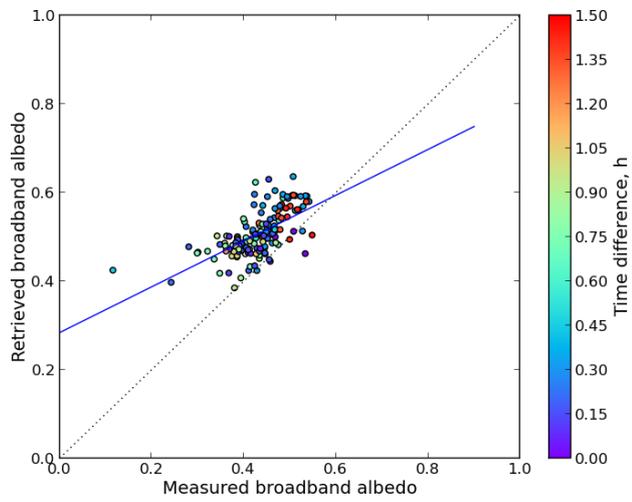
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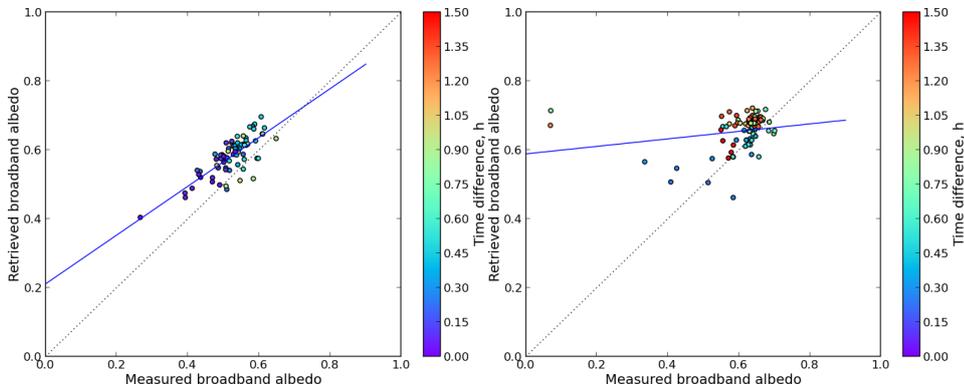
4 Figure 5. Altitude of the airborne broadband albedo measurements on June 06, 2008,
5 MELTEX campaign (left). Correlation between retrieved broadband albedo from satellite data
6 and measured broadband albedo over landfast ice (no drift) (flight track shown on the top
7 panel Figure 3). STD is calculated from all collocated aerial measurements for a given
8 satellite pixel. Only pixels with STD smaller than the mean STD are used. $N = 169$, $R = 0.84$,
9 $RMS=0.068$.

Field Code Changed

10

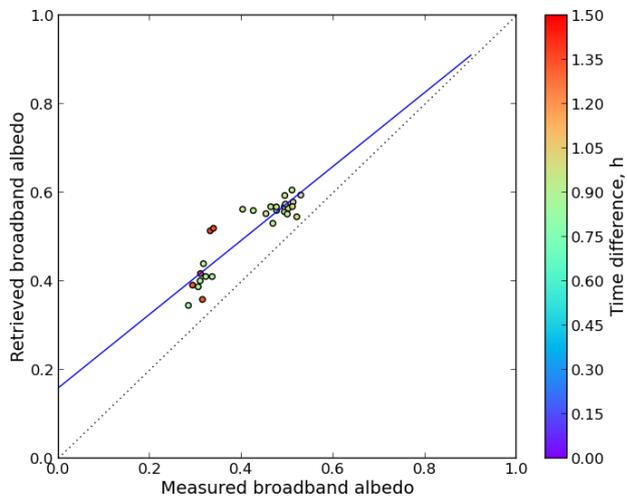


1
2 Figure 6. Correlation between broadband albedo retrieved from airborne measurements and
3 from a satellite overflight, respectively, for the June 04, 2008, MELTEX campaign (bottom
4 panel of Figure 3) with respect to time difference. $N=147$, $R^2=0.39$, $RMS=0.089$.
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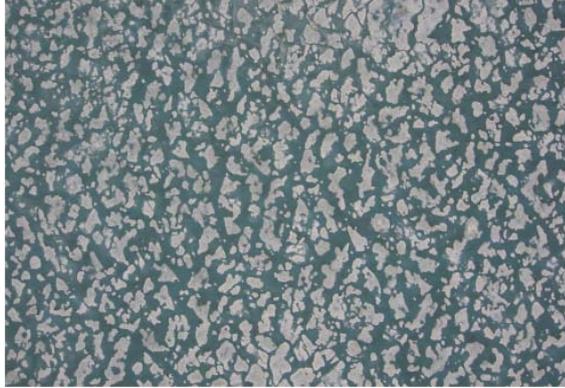
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Figure 7. Correlation between broadband albedo retrieved from airborne measurements (MELTEX campaign) and from a satellite overflight, respectively, for the May 26, 2008 (left panel), $N=73$, $R^2=0.61$, $RMS=0.07$ and June 03, 2008, (right panel), $N=78$, $R^2=0.05$, $RMS=0.121$, with respect to time difference. The flight on June 03, 2008 features the greatest time difference to the satellite overflight, therefore most of the points have been discarded due to possible drift contamination.



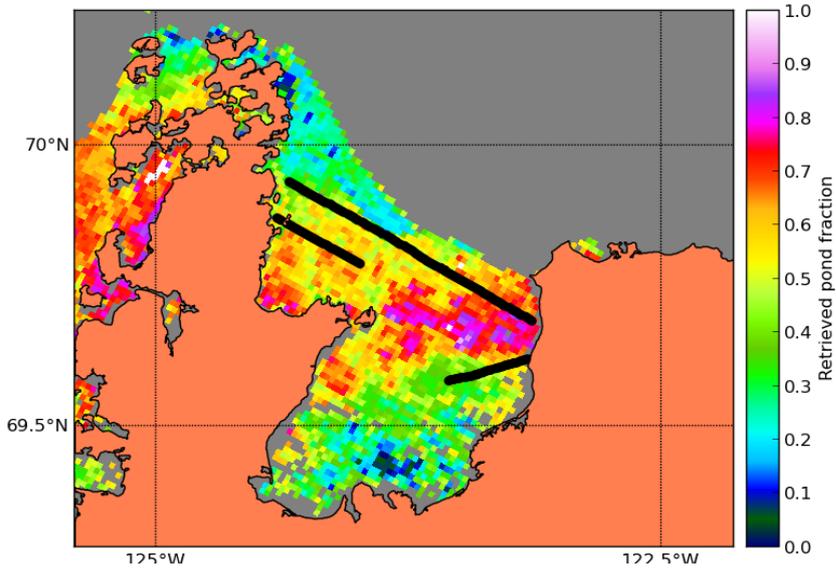
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Figure 8. Correlation between broadband albedo retrieved from airborne measurements (MELTEX campaign) and from a satellite overflight, respectively, for the June 07, 2008, with respect to the time difference. $N=30$, $R^2=0.82$, $RMS=0.096$.

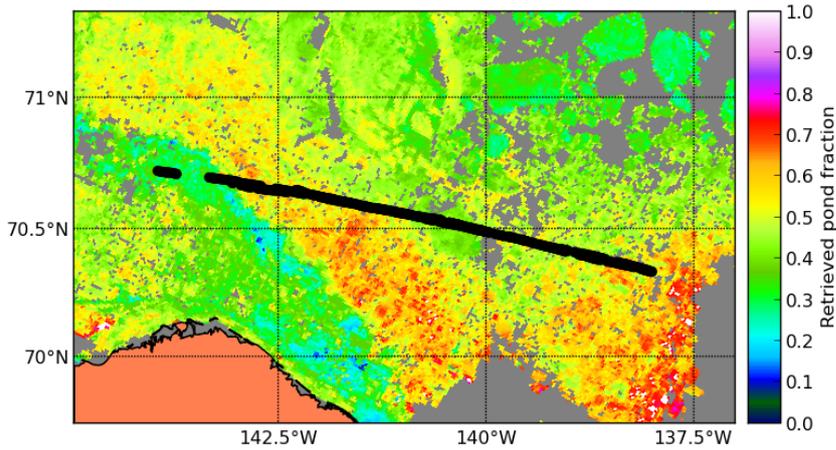


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Figure 9. Example of aerial photo from MELTEX campaign in 2008, flight over landfast ice on June 04, 2008. The image width is approximately 400 m. Only quality assessed- images were taken (see text for details).



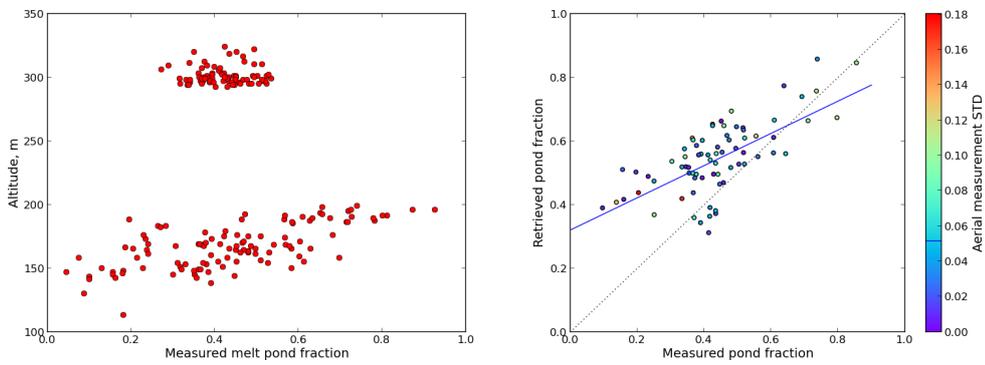
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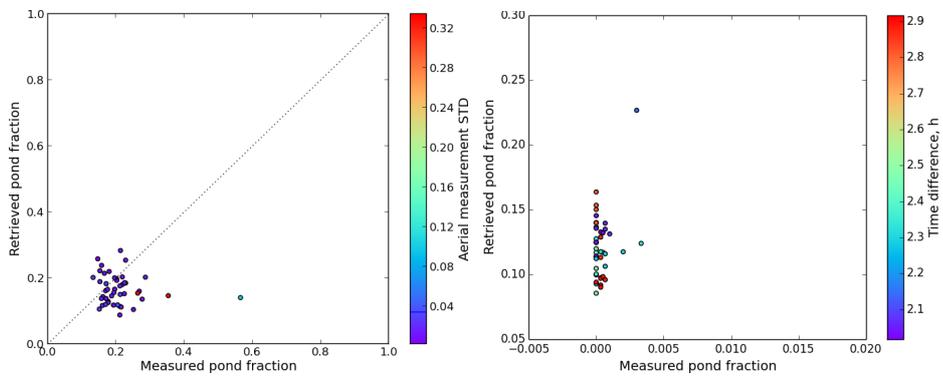
3 Figure 10. Examples of ice conditions present during MELTEX 2008 flights over landfast ice
 4 on June 06, 2008 (top panel) and over separate ice floes of various sizes on June 04, 2008
 5 (bottom panel). Black dots: the flight track. The colored filled background: the satellite
 6 retrieved melt pond fraction. The background is the coral filled landmask and grey filled data
 7 gaps due to cloud contamination or surface type other than sea ice.

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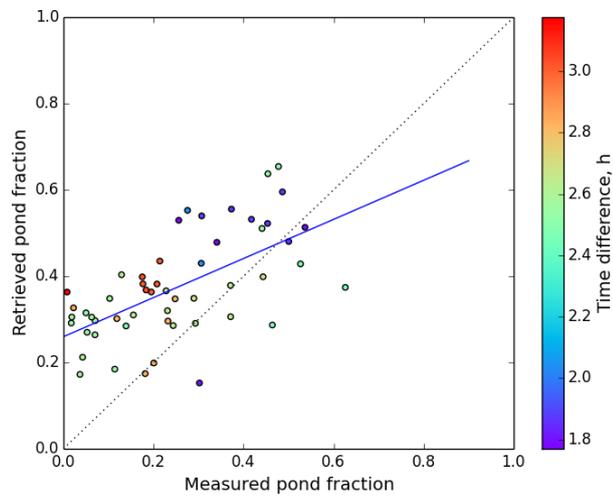
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 3 Figure 11. Altitude of the airborne melt pond measurements on June 06, 2008 (left).
 4 Correlation between retrieved melt pond fractions from satellite and airborne classified MPF
 5 over landfast ice with no drift (right), June 06, 2008 during MELTEX campaign. The flight
 6 track shown on the top panel Figure 9. $N=48$, $R^2=0.36$, $RMS=0.154$.

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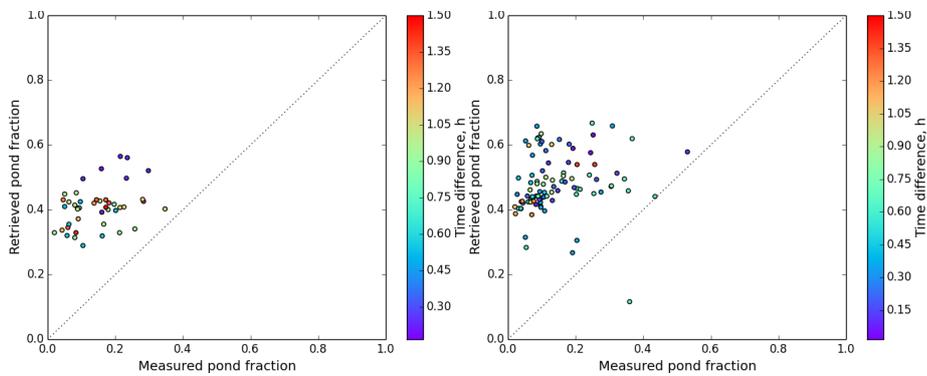
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Figure 12. Correlation between retrieved melt pond fractions from satellite and airborne classified MP over MYI (no drift, ice pack), July 21, 2011, NOGRAM-2, 2011, campaign north of Greenland (left). $N=40$, $R^2=0.004$. $RMS = 0.065$ and over FYI, June 03, 2008, MELTEX 2008 (large floes but drift + large time difference) (right), $N=44$, $R^2=0.13$, $RMS = 0.123$. See Figure 2 for locations of the NOGRAM-2 and MELTEX campaigns.



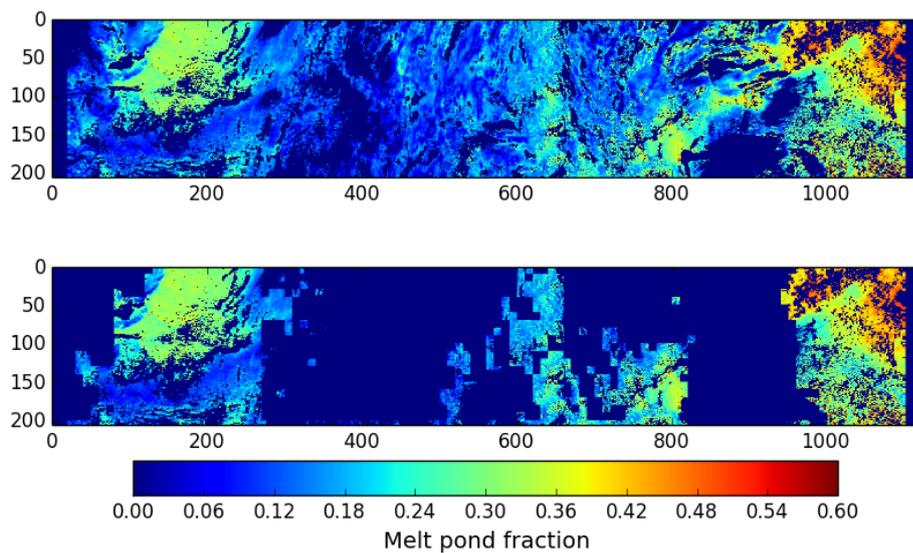
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Figure 13. Correlation between retrieved melt pond fractions from satellite and airborne classified MP over FYI, possible drift, June 07, 2008, MELTEX2008, Beaufort Sea. This case features larger ice floes than flights on June 04 or May 26, 2008. $N=53$, $R^2=0.37$, $RMS = 0.179$.



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Figure 14. Retrieved melt pond fractions from satellite versus airborne classified MP over FYI, possible drift, May 26, 2008 (left panel), $N=44$, $R^2=0.13$, $RMS=0.274$, and June 04, 2008 (right panel, the flight track is shown in Figure 9, bottom panel), Beaufort Sea, $N=93$, $R^2=0.02$, $RMS=0.361$. Both cases feature extremely thrashed brash ice with subpixel ice floes which are covered not with white ice, but with blue ice (sea ice without the scattering layer), which has spectral response similar to MP within the VIS and IR spectral range.

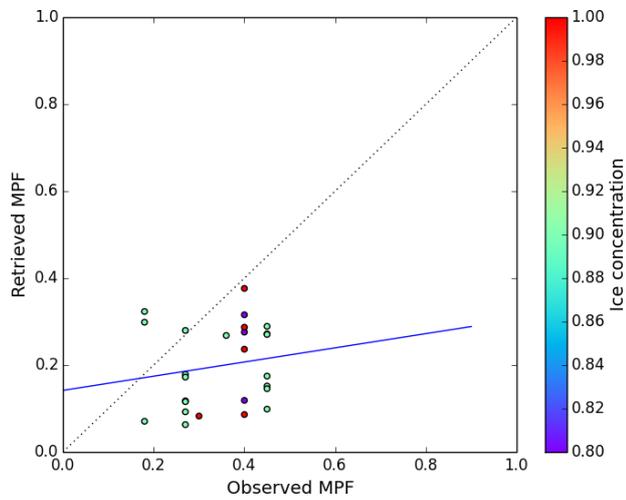


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 3 Figure 15. Example of a spatial dynamic cloud filtering for MERIS swath data: original swath
 4 subset with the cloud filters from (Zege et al., 2015) applied (top panel), same swath subset
 5 after applying the dynamic spatial filter (see text).
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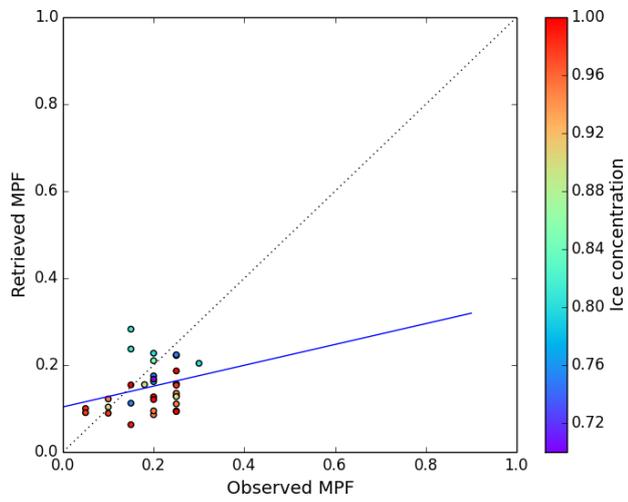
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Figure 16. An example image made from the bridge of RV “Polarstern” during the TransArc 2011 (ARK XXVI3) on the 4th of September 2011 within the course of ASPeCt observations. The ~~estimated~~ pond fraction estimated during the cruise is 0.5. The satellite retrieved pond fraction for such cases will be significantly smaller because of high albedo of frozen over snow covered ponds. Image source (Nicolaus et al., 2012).



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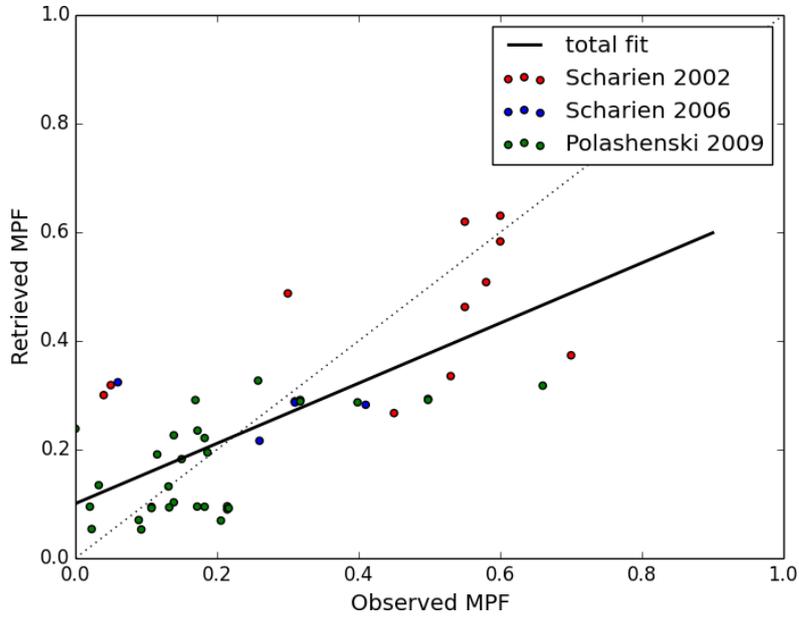
Figure 17. Retrieved MPF versus observed MPF from the hourly bridge observations during TransArc2011, 04 August 2011 – 6 October 2011. Swath data, no temporal averaging, 15km satellite average around the in situ point. All but one point is FYI. Corrected for ice concentration. Underestimation may be connected to undocumented presence of melted through or overfrozen ponds at the end of the melt season (see Figure 15). $R^2=0.026$, RMS=0.19, N=26.



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Figure 18. Retrieved MPF versus observed MPF from the hourly bridge observations during HOTRAX2005, 19 August – 27 September 2005. Swath data, no temporal averaging, 15km satellite average around the in situ point. No information on ice type. Corrected for ice concentration. Underestimation may be connected to undocumented presence of melted through or frozen over ponds at the end of the melt season. $R^2=0.067$, $RMS=0.084$, $N=32$.

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4 Figure 19. Three in situ campaigns on landfast ice: Scharien 2002 (red dots), Scharien 2006
5 (blue dots) and Polashenski 2009 (green dots). Total point number $N = 47$, $RMS = 0.14$, $R^2 =$
6 0.52 . The overestimation of the low MPF may be connected to unscreened thin clouds which
7 depending on the illumination-observation geometry may appear darker than the ice and
8 therefore cause higher retrieved MPF.

9

1 **MThe melt pond fraction and spectral sea ice albedo**
2 **retrieval from MERIS data II: case studies and trends of sea**
3 **ice albedo and melt ponds s in the Arctic for years 2002-2011**

Formatted: English (United Kingdom)

4
5 **L. Istomina¹, G. Heygster¹, M. Huntemann¹, H. Marks¹, C. Melsheimer¹, E. Zege²,**
6 **A. Malinka², A. Prikhach² and I. Katsev²**

7 [1]{Institute of Environmental Physics, University of Bremen, Bremen, Germany}

8 [2]{B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk,
9 Belarus}

10 Correspondence to: L. Istomina (lora@iup.physik.uni-bremen.de)

11
12 **Abstract**

13 The spatial and temporal dynamics of melt ponds and sea ice albedo contain information on
14 the current state and the ~~trend~~tendency of the climate of the Arctic region. ~~The current~~
15 ~~work~~This publication presents a study on ~~f~~ melt pond fraction (MPF) and sea ice albedo spatial
16 and temporal dynamics obtained with the Melt Pond Detection (MPD) retrieval scheme for
17 the Medium Resolution Imaging Spectrometer (MERIS) satellite data. ~~This~~ study ~~is~~
18 ~~dedicated to the comparison of~~ sea ice albedo and MPF to ~~reanalysis air surface~~ air
19 temperature reanalysis data, compares detailed analysis of weekly averages for 2007 and
20 2011 which showed different dynamics of MPF, but resulted in similar minimum sea ice
21 extent, comparison to the MPF retrieved from the Moderate Resolution Imaging
22 Spectroradiometer (MODIS), and ~~analysis examines of~~ albedo and MPF trends. Weekly
23 averages of MPF for 2007 and 2011 showed different MPF dynamics while summer sea ice
24 minimum was similar for both years. The gridded MPF and albedo products compare well to
25 independent reanalysis temperature data and show melt onset when the temperature gets
26 above zero, however MPD shows an offset at low MPFs of about 10% most probably due to
27 unscreened high clouds. Weekly averaged trends show pronounced dynamics of both, MPF

1 and albedo: a negative MPF trend in the East Siberian Sea ~~connected to change of absolute~~
2 ~~MPF value in its peak but no temporal shift, and a~~ positive MPF trend around Queen
3 Elizabeth Islands ~~connected to the earlier melt onset but peak MPF values staying the same.~~
4 The negative MPF trend appears due to a change of the absolute MPF value in its peak,
5 whereas the positive MPF trend is created by the earlier melt onset, with the peak MPF values
6 unchanged. The MPF dynamics in the East Siberian Sea could indicate a temporal change of
7 ice type prevailing in the region, as opposed to the Queen Elizabeth Island, where MPF
8 dynamics reacts to an earlier seasonal onset of melt. ~~melting temperatures occurring earlier in~~
9 ~~the season.~~

10

11 1 Introduction

12 In the last few decades, the sea ice extent (defined as the total area with at least 15% of ice
13 cover) and area of multiyear ice (MYI) has been declining at even faster rate than that of the
14 total perennial ice (Comiso, 2012). This tendency of the sea ice towards thinner and younger
15 ice has a strong impact on the energy balance of the system atmosphere-sea ice-ocean
16 (Perovich et al., 2011; Wang et al., 2014) where ~~.~~ 96% of the total annual solar heat input
17 through sea ice occurs during the ~~meltingmelt~~ season from May to August (Arndt and
18 Nicolaus, 2014). The above mentioned effects are of importance within the context of a
19 changing Arctic due to the sensitivity of the regional climate balance and its importance for
20 the global climate (Shindell and Faluvegi, 2009).

21 The extent of the Arctic sea ice cover has a pronounced seasonal cycle with the maximum
22 typically in March (in February in 2015) and the minimum in September. The main feature of
23 the sea ice in summer is the presence of melt ponds. Knowing their spatial and temporal
24 dynamics during the ~~meltingmelt~~ season and over several years can help improve to
25 understanding of the current state and ~~tendency trends~~ of the energy balance in the region.
26 ~~One of the evidence of the energy balance change in the Arctic is the change of the sea ice~~
27 ~~extent in the last decades.~~ The sea ice extent has been showing a general declining trend ever
28 since the beginning of continuous satellite observations in the late 1970s. This decline has
29 been stronger for the September minimum than for the March maximum (Cavalieri and
30 Parkinson, 2012; Stroeve et al., 2011). The decline of the minimum sea ice extent has become

1 very significant since 2007: in September 2007, the minimum sea ice extent of 4.15million
2 km² was about 39% below the average minimum of 1981-2000, and in 2012 the minimum
3 (3.41 million km²) was 49% below the 1981-2000 average (Perovich et al., 2012). While the
4 minima of Arctic sea ice extent were less dramatic in the other years since 2007, it has to be
5 noted that all minima after 2007 were below all yearly minima observed before 2007 (since
6 beginning of satellite observations). What is the role of melt ponds in the above mentioned
7 yearly dynamics of the sea ice cover? The clear connection between the area of melt ponds in
8 spring and sea ice extent during the sea ice minimum in autumn is highlighted in Schröder et
9 al., (2014).

10 The temporal dynamics of melt can be subdivided into 4 stages (Eicken et al., 2002). Stage 1
11 occurs after the onset of positive air temperatures and is characterized by widespread ponding
12 and lateral melt water flow. During the stage 2 both the surface albedo and MPF decrease due
13 to removal of snow cover and due to pond drainage. During the stage 3, as the meltwater
14 penetrates deeper into the ice, the pond coverage continues to evolve and MPF to grow. Stage
15 4 corresponds to freeze-up. This publication is dedicated to the application of the algorithm to
16 retrieve MPF and sea ice albedo described and validated in the companion publications
17 (Istomina et al., 2015; Zege et al., 2015). As the Melt Pond Detection (MPD) retrieval does
18 not see separate ponds, but detects the spectral signature of melt ponds in the measured top-
19 of-atmosphere signal, the retrieved MPF dynamics will somewhat deviate from above
20 mentioned stages of melt observed in the field. The reason for this deviation is the ambiguity
21 of the top-of-atmosphere signal, where e.g. the spectrum of melting sea ice (before stage 1)
22 can be represented as a linear mixture of pond spectrum and non-melting ice spectrum, as can
23 be seen from field spectra in e.g. Istomina, Nicolaus and Perovich et al., (2013). The problem
24 is addressed in MPD by setting boundary conditions on optical parameters given in Eq. 18 in
25 Zege et al., (2015). However, as the MPD uses only a limited amount of spectral bands in the
26 VIS and NIR, surfaces which are similar in these channels may all be retrieved as MPF, e.g.
27 submerged ice, blue ice and water saturated ice without yet actual meltwater on it. This may
28 introduce a bias in the MPF product (not sea ice albedo), however, it does not imply
29 limitations on the usage of the MPD product for the studies of radiative balance and global
30 circulation models. Another source of bias of the MPD product are the unscreened thin
31 clouds.

1 ~~Current work is dedicated to the application of the algorithm to retrieve MPF and sea ice~~
2 ~~albedo described and validated in the companion publications (Istomina et al., 2015; Zege et~~
3 ~~al., 2015).~~ All available Medium Resolution Imaging Spectrometer (MERIS) reduced
4 resolution data for the Arctic summers from 2002 to 2011 are processed and compiled in
5 lower resolution in daily and weekly averages to increase the coverage and quality of the data.
6 As the temporal evolution of the ~~melt-pond-fraction~~MPF and the surface albedo is naturally
7 correlated with the evolution in air temperature at the surface, a comparison to National
8 Centers for Environmental Prediction (NCEP) reanalysis temperature data for various ice
9 types was performed to check the performance of the algorithm. This has been done for
10 extended periods of time (over the whole summer); also, in the context of the above
11 mentioned connection of the MPF and sea ice extent, the MPF dynamics ~~has~~ has been studied
12 for the two years 2007 and 2011 and also compared to the data by ~~(Rösel and Kaleschke,~~
13 ~~(2012)~~ for selected cases. The performed comparisons showed clear agreement both to
14 reanalysis data and to the MPF by ~~(Rösel and Kaleschke, (2012).~~

15 The manuscript is structured as follows: Section 2 is dedicated to ~~case studies, namely~~ the
16 comparison of the MPF and albedo data to the reanalysis air temperature for various locations
17 ~~(Sect. 2.1)~~. Global applications of the MPD algorithms over the whole MERIS dataset (2002-
18 2011) are given in Section 3. There the weekly averages for 2007 and 2011 are analyzed
19 (Sect. 3.1), for these cases a comparison to another MPF retrieval is performed (Sect. 3.2),
20 trends of MPF (Sect. 3.3) and sea ice albedo (Sect. 3.4) are presented. The conclusions are
21 given in Section 4.

22 **2 Comparisons between surface air temperature and time series of MPF and** 23 **albedo: Case studies of FYI and MYI**~~Case studies~~

24 The processed swath MERIS Level 1b data obtained with the MPD algorithm as described in
25 the companion publications (Istomina et al., 2015; Zege et al., 2015) have been gridded daily
26 into the 12.5 km polar stereographic grid (the so-called National Snow and Ice Data Center
27 (NSIDC) grid) with the criterion of more than 50% valid pixels (both spatially and
28 temporally) within a grid cell to produce a valid grid cell. The standard deviation of such a
29 mixed spatial and temporal average is also provided. Thus, the resulting NetCDF file contains
30 four datasets: MPF, broadband albedo and their STDs. On average, there were around 13

1 overflights per day, with the density of overlapping swaths highest at about 80°N latitude.
2 Even from a single overflight, there are at least 100 up to about 1000 data points for averaging
3 into a single grid cell. Assuming a stable retrieval and low variations within a single day, the
4 STD gives information about the spatial variation of MPF and broadband albedo within the
5 grid cell. This kind of averaging does not provide a guarantee of a valid data point for every
6 single day and grid point. The gridding method with a threshold on the amount of cloud free
7 pixels allowed to form a valid grid cell assists with cloud screening because it does not allow
8 partly screened out clouds or potentially unscreened cloud edges to appear in the end product.
9 However, since the Arctic is one of the most cloud covered regions (with up to 80% cloud
10 covered throughout the year (Serreze and Barry, 2005)), some of unscreened clouds will still
11 affect ~~also~~ the gridded product. The amplitude of this effect tends to be the greatest (up to
12 15% MPF bias) before melt onset as it is the most challenging to separate clouds and bright
13 snow/sea ice. Later in the season the surface becomes darker due to melt, which aids the cloud
14 screening, and the bias on MPF and albedo introduced by unscreened clouds decreases.

15 The weekly resolution has been obtained by averaging the gridded daily product. As in the
16 case of daily resolution, a weekly averaged grid cell is obtained from no less than 50% of
17 valid (cloud free) pixels. Should a given grid cell contain more than 50% of invalid pixels, it
18 is assigned ~~a~~ not a number value. No weight or threshold on STDs is applied. The resulting
19 STD is then written into the resulting NetCDF file together with the averaged value for the
20 broadband albedo and MPF.

21 These weekly averages have a much higher data density since there is a higher probability for
22 the satellite to observe cloud free areas within one week than it is the case for one day.

23 The essential difference in daily and e.g. weekly averages is the data coverage due to
24 cloudiness and smoothness of the resulting product. This is why the gridded product has been
25 used for case studies and data analysis on the Arctic scale. ~~The results presented in the~~
26 ~~following sections: comparison to reanalysis air temperature for various locations on first year~~
27 ~~ice (FYI) and MYI (Sect. 2.1), weekly averages analysis for 2007 and 2011 (Sect. 3.1),~~
28 ~~comparison to MPF data from (Rösel et al., 2012) (Sect. 3.2), spatial trends of MPF (Sect.~~
29 ~~3.3) and broadband albedo (Sect. 3.4).~~

~~2.1 Comparison to reanalysis air temperature at the surface: time sequences of the daily gridded MPF and albedo for FYI and MYI~~

In order to illustrate the feasibility of the algorithm on FYI and MYI, time sequences over the summer 2009 have been produced for Beaufort Sea with mainly FYI ~~ice~~ and North Greenland with mainly MYI ~~ice~~ (Figure 1).

For this study, the daily averaged product was taken in the area 75N, 155W (Beaufort Sea) and 84.5N, 35W (North Greenland) and it was compared to the time sequence of daily averaged air temperature at the surface (0.995 sigma level) from NCEP reanalysis data (Kalnay et al., 1996). The difference between melt evolution in the selected location is mainly that melt onset happens about a month earlier in lower latitudes: beginning of June on FYI as opposed to beginning of July for MYI. Then, due to FYI roughness being much less than that of MYI, the maximum MPF on FYI can be about 4 times higher than that on MYI (maximum melt 0.2 on MYI as opposed to up to 0.8 on FYI, Figure 1 in (Istomina et al., (2015)). While the melt onset occurs rapidly on both ice types, the later stage of melt - drainage of melt ponds - happens much sooner on FYI than on MYI. On MYI, this stage is generally substituted with MPF decrease due to freezing and snowfalls events. ~~unless the MY ice is very rotten.~~

One more difference between the two chosen locations is the sea ice concentration: for the MYI the ice concentration stays very high throughout the whole summer, whereas for the FYI region the effect of ice concentration and also ice drift (in the swath data for consecutive days separate floes and their drift is clearly visible) can affect the time sequence analysis, affecting the noisiness of the retrieved values.

Overall, the comparison of the retrieved MPFs and albedos to the surface air temperature (Figure 2) shows a clear connection between these during the melt onset: as soon as air temperature assumes constantly positive values, sea ice albedo drops down and MPF increases abruptly. For both FYI and MYI the maximum MPF is around 0.35, with melt onset happening in the beginning of June for FYI and beginning of July for MYI. This corresponds to the knowledge about melt onset and dynamics from field measurements (Figure 1 in (Istomina et al., (2015)). The evolution of melt on MYI follows the air temperature dynamics and is ongoing till first snowfalls and freezing temperatures around mid August. The FYI

1 region, however, is closer to the ice edge and therefore features greater range of ice
2 concentrations within the study area. As a result, the corresponding curve appears noisier and
3 interrupts with the area becoming ice free starting 1st of August. For periods before melt
4 onset, the retrieved MPFs range from 0% to 10-15% with relatively high albedos; both might
5 be the effect of unscreened clouds which tend to increase retrieved pond fraction in case of
6 small true pond fraction and decrease it in case of high true pond fractions. The difference of
7 the sea ice type is also visible in the albedo values before the melt onset (Figure 2): higher
8 albedo of (90%, blue curve in middle panel of Figure 2) for MYI region and lower albedo of
9 about (80%, red curve in middle panel of Figure 2) for the coastal region of Beaufort Sea. For
10 MPF before melt onset, the effect of subpixel ice floes and greater open water fraction as
11 compared to the MYI region may have caused the difference in MPF offset with respect to
12 expected value near zero before melt (Figure 2).

13 **3 Temporal and spatial analysis over the whole MERIS dataset**

14 This chapter presents the main highlights of the processed MERIS data for 2002-2011.
15 Weekly averages have been used for this study due to better data coverage; therefore the
16 shown trends are produced with the weekly resolution.

17 The most striking and characteristic stage of the ~~melting~~melt season is the melt onset and the
18 first stage of melt evolution. Such dynamics are ice type specific, e.g. on FYI this is the rapid
19 melt pond formation ~~followed by a~~ with the rapid drainage, during which the MPF changes
20 drastically up and down within a scale of days to weeks. MYI features later (starts in July)
21 and slower melt onset, less extreme pond fractions with the absence of rapid melt evolution
22 stages. The pond fractions in the melt maximum on MYI are close to pond fractions of the
23 melt evolution (after melt onset and drainage) on FYI. Thus, the difference of MPF on FYI
24 and MYI is most prominent in June. Therefore in this work we study the temporal variation of
25 MPF and albedo for June of each year of the available MERIS dataset. ~~A more detailed
26 analysis of MPF and albedo for the whole summer including their parameterization will be
27 presented in a follow-up publication.~~

1 3.1 Weekly averages of June 2007 and 2011: how the record ice minimum in 2 2007 started

3 It is interesting to compare the evolution of melt ponds right after the onset of melt for the
4 record sea ice minimum in 2007 and a similar one by the ice minimum extent year 2011, to
5 see how the patterns of melt changed within these 5 years to reach the same resulting ice
6 extent during the sea ice minimum. In Figure 3 the evolution of the MPFs from the last two
7 weeks of May up to first two weeks of September 2007 and 2011 is shown. The onset ~~of~~
8 ~~melt~~ and the melt stage 1 happens-occur in the fourth week of May at the shore of Beaufort
9 Sea (2007) and East-Siberian Sea (2011).

10 The melt ~~onset-stage 1~~ during the first week of June has much more local character in 2011
11 than in 2007, being centered near point Barrow and the shore of Beaufort Sea, as opposed to
12 2007 when the melt onset began already at a more global scale. The second week of June
13 2007 featured drastic melt which corresponds to the last phase of melt stage 1 with MPF
14 values up to about 50% in the Beaufort Sea and the western part of the FYI covered Arctic
15 Ocean (top row in Figure 4), whereas in 2011 the situation was more or less stable relative to
16 the first week of June.

17 In the third and the fourth week of June 2011 large scale melt started (third week of June
18 2011, one week delay as compared to June 2007), but it is centered around the Queen
19 Elizabeth Islands. The fourth week of June 2011 shows that melting spreads from there over
20 the Eurasian Arctic Ocean, whereas in 2007 at this time these areas have already experienced
21 the maximum of melt and are now draining (melt stage 2). MYI areas to the north of
22 Greenland and Queen Elizabeth Islands for both years display ~~start-of-melting~~ the melt stage 1,
23 which continues in July. The relatively high MPFs throughout the whole Arctic Ocean are
24 interrupted with lower air temperatures in the Eurasian Arctic in the second week of July
25 2007 (bottom row in Figure 4). The lower air temperatures are evident in the time sequence of
26 daily averaged NCEP air temperatures (0.995 sigma level) and MPFs (Figure 5) for both
27 years for the characteristic location in the Barents Sea, where lower MPFs are observed in the
28 second week of July 2007 as compared to 2011 (100 km average around 85°N, 65°E). A
29 reference location north to the Queen Elizabeth Islands is also shown in Figure 5 (100 km
30 average around 83°N, 110°W). The locations of the two sites are shown with yellow square

1 tags tagged “E” and “W” respectively in Figure 1. The differences in the MPFs for the second
2 week of June and second week of July 2007 and 2011 are summarized in Figure 4.

3 The rest of July and first two weeks of August feature similar melt evolution (melt stage 3)
4 with occasional freezup and melt (Figure 3). The frequent freezups and snowfalls caused the
5 MPF decrease at the northernmost latitudes in the last two weeks of August of both 2007 and
6 2011, while the melt ponds were still present closer to the ice edge of the Arctic ocean (also
7 can be seen in Figure 5). The MPF decreases (melt stage 4) overall throughout the Arctic
8 Ocean (according to the air temperature, the ponds are frozen over and most probably snow
9 covered) in the first two weeks of September of both 2007 and 2011.

10 To conclude: the years 2007 and 2011 feature different times of various melt stages onset and
11 also different spatial patterns of MPFs, however the ice extent near the ice minimum is
12 similar. The most prominent feature is the rapid and large scale melt in the second week of
13 June 2007 associated to the melt stage 1 before transition into drainage, which was not
14 reproduced in 2011. This feature seems to be compensated by smaller MPFs in the first two
15 weeks of July 2007, whereas the MPFs during the same time period in 2011 again do not
16 reproduce this feature (Figure 4). This kind of opposite temporal MPF dynamics (2007)
17 produces the same effect as an evolution of melt uniform in time (2011). The analysis of MPF
18 time sequences (Figure 5) shows only a moderate (about 15%) MPF difference ~~of MPF~~
19 ~~amplitude~~ during the first ~~and second two~~ weeks of July between the comparison years 2007
20 and 2011. ~~However, even but such a moderate MPF difference values~~ over a large area and
21 longer period in 2011 (Figure 4) ~~produce has a significant drastic~~ effect on the minimum ice
22 extent similar to the short but extreme MPF peak in June 2007. ~~For both 2007 and 2011, the~~
23 areas of ~~higher highest~~ MPFs ~~during any phase of the melt evolution throughout the melt~~
24 season are ice free at the time of ice minimum (1st and 2nd weeks of September, Figure 3).
25 This conclusion on connection between MPF and sea ice extent during the ice minimum
26 agrees well with the findings of Schröder et al., (2014).

27 **3.2 Comparison to MPF from MODIS data by (Rösel et al., (2012)**

28 An unusual temporal and spatial dynamics of melt ponds in the Arctic Ocean in 2007 and
29 2011 has been initially discussed by (Rösel and Kaleschke, (2012) based on MODIS data and

1 | the melt pond retrieval algorithm described in (Rösel et al., (2012)). It is interesting to compare
2 | these independent data obtained from a different sensor and retrieval method to the MPD
3 | MPF, and in case of agreement to confirm the unusual melt pond dynamics for the 2007 and
4 | 2011 summers.

5 | For this comparison, two examples presented in (Rösel and Kaleschke, (2012) are taken: 8
6 | day composites starting on June 18, 2007 and June 18, 2011. These are the cases of prominent
7 | difference in melt pond patterns in 2007 and 2011. In order to compare the two datasets, the 8
8 | day composites from MODIS (pond fraction relative to ice area) available at the web page of
9 | University of Hamburg: http://icdc.zmaw.de/arctic_meltponds.html?&L=1 have been converted
10 | into pond fraction relative to pixel area using the provided ice concentration. Corresponding 8
11 | day averages have been created from the MPD daily gridded data. The selection of valid grid
12 | cells in the dataset by (Rösel et al., (2012) is the following:
13 | not less than 50% valid pixels for a valid grid cell, ice concentration greater than 25%, STD
14 | of MPF less than 15%. The comparison plot is shown in Figure 6. It is ~~visible-apparent~~
15 | for the June 18, 2007 both datasets show similar spatial patterns with higher MPF between the
16 | Queen Elisabeth Islands and Beaufort Sea, and lower MPF in the MYI region north to
17 | Greenland and eastern part of the Arctic Ocean. This pond fraction distribution seems
18 | plausible when considering the date of observation, before melt onset in the MYI region, and
19 | such a spatial distribution is confirmed by both algorithms. The MPF values slightly differ in
20 | amplitude (note the distribution of higher and lower MPF in both datasets e.g. in the Beaufort
21 | Sea). The primary reason for this difference ~~is likely the contrast maybe, firstly, the difference~~
22 | in cloud screening methods between the two datasets. with MODIS ~~being~~ much better suited
23 | ~~to for the task of~~ cloud screening over snow, ~~resultings~~ in difference cest in the fraction of
24 | unscreened clouds ~~present in the~~ between both datasets. The second reason is the different
25 | averaging method, with data by (Rösel et al., (2012) being produced as a composite (best or
26 | most characteristic observation within the period), whereas MPD data is obtained by
27 | unweighted averaging. And finally the third reason for the difference is the positive 8% offset
28 | of the dataset by (Rösel et al., (2012) as provided in the “Data quality” section at the data
29 | source http://icdc.zmaw.de/arctic_meltponds.html?&L=1. It is unclear whether this bias is
30 | constant over the whole range of MPFs and if it is possible to correct for it. (Mäakynen et al.,
31 | (2014) suggest that ~~that~~ the bias stems from ~~the~~ possibly inaccurate assumption ~~on the about~~

1 sea ice optical properties, which would mean that the bias varies not only with MPF, but also
2 with weather conditions and location in the Arctic ocean (~~in some locations the assumption on~~
3 ~~the surface was correct and in some not~~).

4 The second row of Figure 6 shows the same comparison, but for ~~June, 18.06.,~~ 2011. Here
5 again, both algorithms agree on the spatial distribution of the melt ponds, with slight
6 differences in the amplitude, and thus confirm the plausibility of results presented both in
7 Sect. 3.1 and in (Rösel and Kaleschke, (2012)).

8 **3.3 Spatial trends of MPFs for the Arctic Ocean over the whole MERIS dataset** 9 **(2002-2011)**

10 As seen from the comparison to in situ data and reanalysis temperature data, ~~(1)~~ the MPD
11 retrieval is affected by unscreened high thin clouds, to which none of the available cloud
12 filters ~~are~~ sensitive but which affect the retrieved MPF and albedo because clouds tend to
13 increase the albedo/decrease pond fraction for areas of high true MPF and increase
14 MPF/decrease albedo for areas of no or little melt. This produces an offset at the low MPFs
15 and is mainly visible at the beginning of the melt season. It affects also the maximum
16 reachable MPFs at the peak of the melt and the minimum MPFs before and after the season.
17 ~~(2)~~ The performance of the algorithm is compromised during the end of the melt season due
18 to the presence of overfrozen, snow covered or melted through melt ponds.

19 Nevertheless, for the MERIS data the temporal dynamics of the retrieved quantities compares
20 well with the NCEP ~~air at the surface~~ air temperature data and the weekly averages show
21 pronounced spatial variability of the retrieved pond fractions for different years which cannot
22 be explained by thin cloud cover. This gives us the possibility to study the trends of the
23 retrieved quantities as a potential systematic offset due to clouds would be cancelled out and
24 only the variability of the true value shows up in the trend (Figure 7). The trend significance
25 given by the map of the MPF trend p value (Figure 8) confirms this finding: the strongest
26 positive or negative trends are the most significant ones with the p value of about 0.05-0.1.
27 Given the small size of the studied sample (10 points), the statistically significant p value is
28 expected to be greater than that of the larger samples. Therefore the p values obtained here
29 can be used to select the trend candidates. One more criterion that supports the statistical

1 significance of the discovered trends is the spatial continuity of the p value that suggests the
2 non-random nature of the effect.

3 There is no trend for the first week of June throughout the years (Figure 7), except for a slight
4 positive trend of MPF near Point Barrow. This feature disappears for the second week, and a
5 ~~starting~~ positive trend of 1-2 % during the early melt season is found near the per
6 ~~investigation period is located near~~ Queen Elizabeth Islands. This trend remains until the end
7 of June. ~~Explanation for this finding is not the~~ A possible explanation for it is not the
8 ~~increased in the~~ absolute value of the MPF, but ~~rather the earlier~~ melt onset shifting towards
9 ~~spring infor~~ these areas ~~as related to the beginning of throughout~~ the MERIS dataset (Figure
10 10). A negative trend in the East-Siberian Sea has yet to be explained: either it is the opposite
11 temporal shift of melt evolution towards summer, or a shift of melt evolution towards spring
12 with e.g. drainage phase of melt observed instead of maximum melt, or a fluctuation in the
13 weather conditions or in the ice type in the area within the studied years. It is important to
14 understand that the trend of the MPF can as likely occur due to temporal shift of the melt
15 process towards spring or autumn, as well as change of maximum possible pond fraction due
16 to ice type change. The maximum and average MPFs depend not only on the air temperature,
17 but also on the sea ice roughness on various scales and other ice properties (Polashenski et al.,
18 2012), so an increasing air temperature trend in the area would not necessarily produce an
19 increasing MPF trend. The time sequence of MPF for the studied years for the location of
20 interest in the East Siberian Sea (74°N, 160°E averaged 50 km around the point) is shown in
21 Figure 9.

22 The MPF curves for different years hardly show any temporal shift, but display a change of
23 absolute MPF and of temporal behavior of the melt evolution, which is an indication of an ice
24 type change from FYI to MYI. E.g. the curve corresponding to 2011 in Figure 9 (red curve)
25 shows a clear MYI MPF dynamics. The presence of MYI in the area is confirmed by
26 analyzing the maps of ice concentration for the autumn before in the region of interest (not
27 shown here, for details see AMSR-E ice concentration maps provided by Uni Bremen,
28 <http://www.iup.uni-bremen.de:8084/databrowser.html>). At the same time, a similar plot
29 (Figure 10) for the Queen Elizabeth Islands (50 km around 78°N, 108°W) displays the exact
30 opposite: the peak of MPF for the melt onset shifts towards spring in the later years of the
31 MERIS dataset, whereas the absolute value of the MPF peak stays the same. This is the sign

1 | of warm ~~atmospheric air~~ masses appearing earlier in the summer than before, producing the
2 | positive MPF trend for the area.

3 | The MPF trend for the 4th week of June features earlier melt onset in the MYI regions and
4 | further melt overall in the Arctic ocean with occasional hints of longitudinal oscillations, e.g.
5 | in week 4 of June, Figure 7.

6 | **3.4 Spatial trends of broadband sea ice albedo for the Arctic Ocean over the** 7 | **whole MERIS dataset (2002-2011)**

8 | The MPF and the broadband albedo of the pixel are joint products, i.e. ~~an~~ increasing trend
9 | ~~of~~ MPF gives a decreasing trend of the albedo. ~~A d~~Decreasing albedo trend around ~~the~~
10 | Queen Elizabeth Islands and increasing trend in the East-Siberian Sea (see Figure 11)
11 | correspond well to ~~already seen~~ dynamics of the ~~apparent~~ MPF weekly trends (Figure 7) and
12 | are confirmed by low p-values (Figure 12). The slight differences in spatial patterns of albedo
13 | and MPF trend can be explained by different sensitivity of both retrievals to ice type and its
14 | optical properties: the albedo retrieval translates the change of ice reflectance into the albedo
15 | of the pixel, whereas the MPF retrieval only retrieves MPF. The albedo trend significance
16 | which displays similar spatial pattern as the significance of the MPF trend (Figure 8) is shown
17 | in Figure 12. As can be seen from the albedo trend significance, the remaining areas did not
18 | show clear albedo trend within the studied period of time.

19 | **4 Conclusions**

20 | ~~Current work~~ This publication presents a detailed analysis of the MPD product (Istomina et
21 | al., 2015; Zege et al., 2015) consisting of a comparison to reanalysis air surface temperatures,
22 | detailed analysis of weekly averages for 2007 and 2011 which showed different dynamics of
23 | MPF, but resulted in similar minimum sea ice extent, comparison to the data by ~~R~~Rösel et al.,
24 | ~~(2012)~~, and analysis of albedo and MPF trends. The gridded products compare well to
25 | independent reanalysis temperature data and show melt onset when the temperature gets
26 | above zero degrees Celsius (Figure 2), however MPD results show an offset at low MPF of
27 | about 10% most probably due to unscreened high clouds. This makes application of the MPD
28 | algorithm to a sensor with a more precise cloud mask desirable (VIIRS onboard Suomi NPP
29 | or OLCI onboard Sentinel3). Though absolute daily values of MPF and albedo may be

1 affected by unscreened clouds, relative MPF and albedo differences through the temporal axis
2 are significant and the temporal MPF dynamics correspond to that observed in the field for
3 FYI and MYI (Figure 2). This is also applicable to weekly averages based on analysis of MPF
4 behavior in 2007 and 2011 (Figure 3, Figure 4) and on the comparison of the MPD product to
5 data by Rösel et al., (2012) (Figure 6). Thus, the MPD products are suitable for analyzing
6 temporal and spatial dynamics of MPF and sea ice albedo.

7 Weekly averaged trends show pronounced dynamics of both MPF and albedo: a negative
8 MPF trend in the East Siberian Sea connected to a change of absolute MPF value in its peak
9 but no temporal shift, a positive MPF trend around the Queen Elizabeth Islands connected to
10 the earlier melt onset but with peak MPF values staying the same (Figure 7, Figure 9, Figure
11 10). The MPF dynamics in the East Siberian Sea could indicate a change of ice type
12 prevailing in the region, as opposed to the Queen Elizabeth Island, where the MPF dynamics
13 reacts to ~~melting temperatures occurring earlier in the season~~ earlier onset of melt. This will be
14 analyzed further in a follow-up publication.

15 **Acknowledgements**

16 NCEP Reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA,
17 from their web site at <http://www.esrl.noaa.gov/psd/>.

18 Arctic melt pond cover fractions were obtained for June 2007 and 2011 from the Integrated
19 Climate Data Center (ICDC, <http://icdc.zmaw.de/>), University of Hamburg, Hamburg,
20 Germany, March, 2015.

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22 valuable comments on the manuscript.

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24

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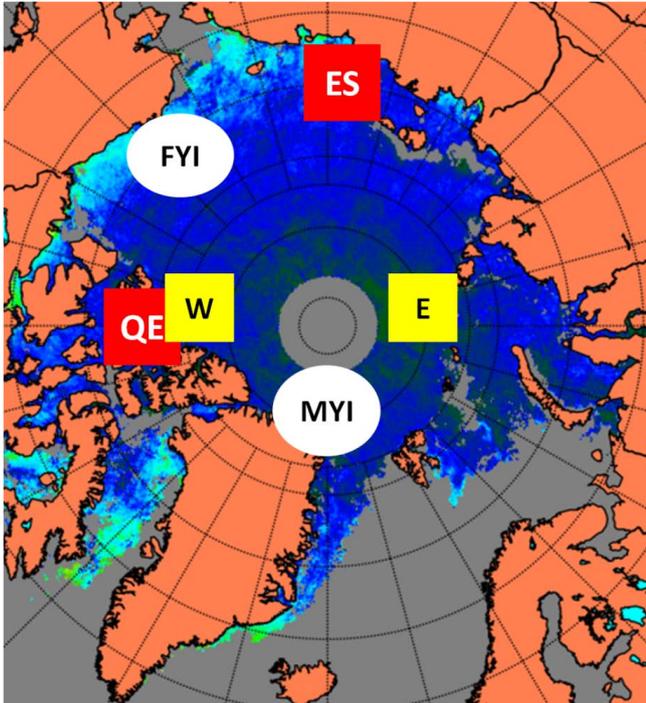
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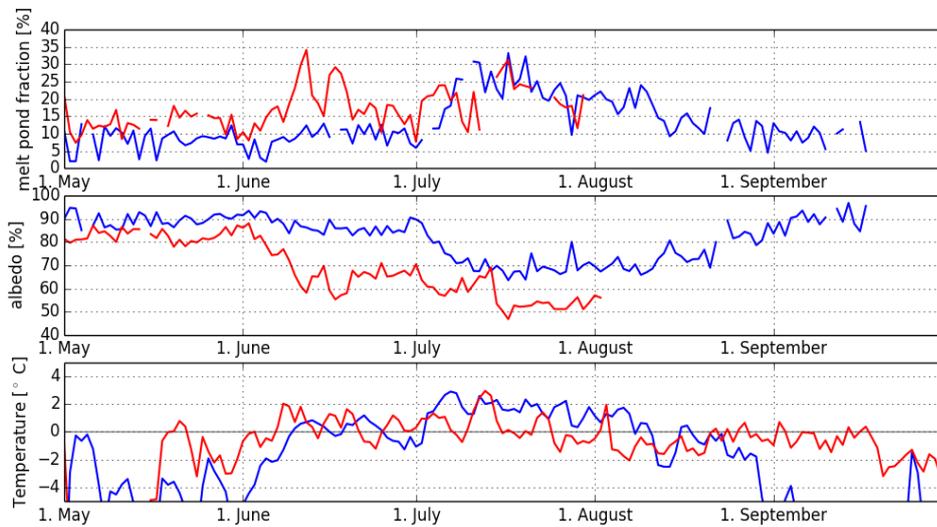
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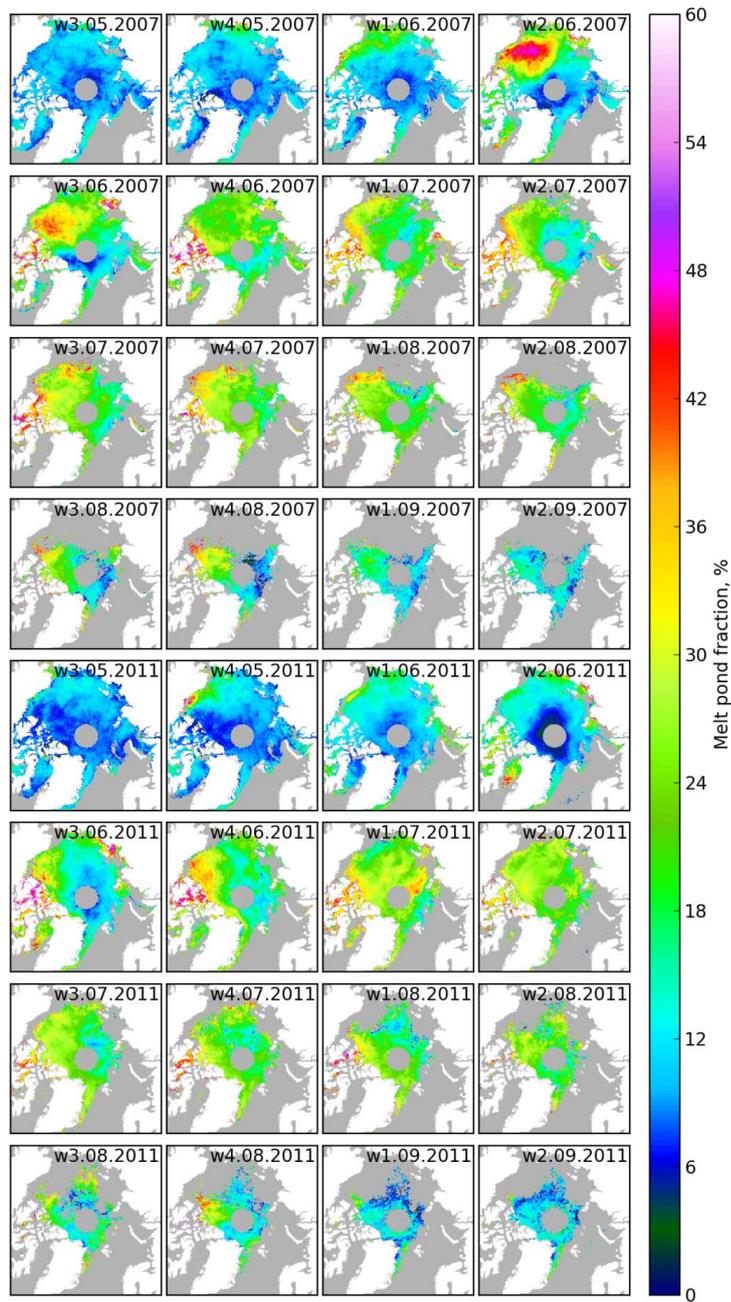
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Figure 1. The scheme of the case study locations (the size of the labels does not correspond to the real size of the studied area, see text for area sizes). White circles depict locations for the time sequence analysis in summer 2009, in the Beaufort Sea, FYI (red curves in Figure 2) and North Greenland, MYI (blue curves in Figure 2). Yellow squares show locations for two sites in both 2007 and 2011, namely in Barents Sea (E) and north to the Queen Elizabeth Islands (W) (Figure 5). Red squares depict the locations of two sites between Queen Elizabeth Islands (Figure 10) and in the East Siberian Sea (Figure 9), where the MPF temporal behavior was compared for years 2002-2011.

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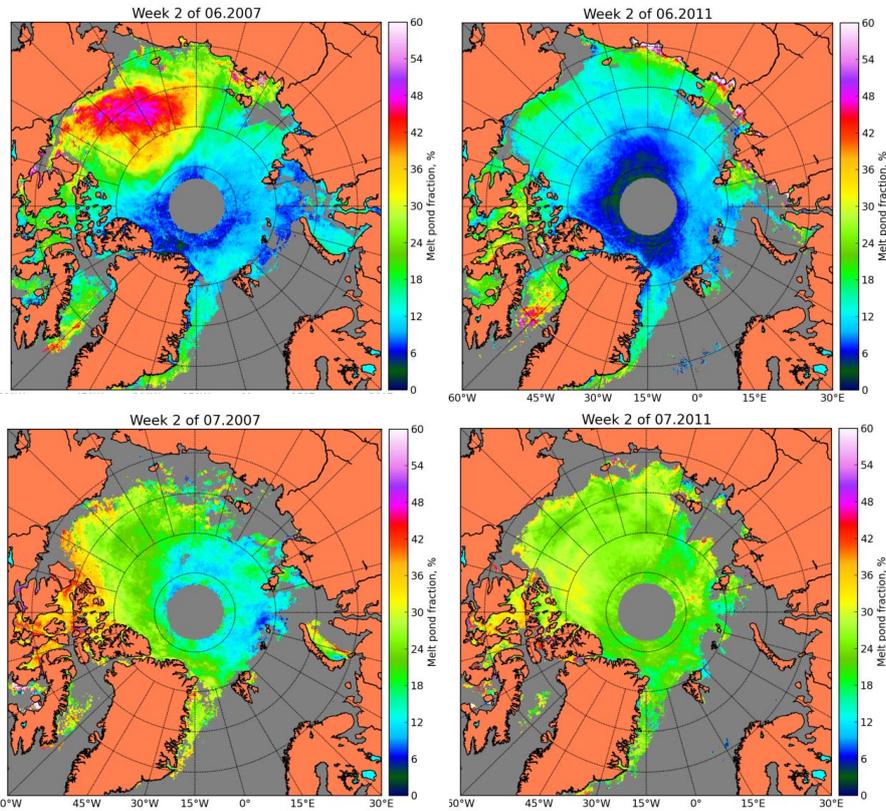


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 2 Figure 2. Time sequence of MPF, broadband albedo and NCEP air temperature at the surface
 3 for two regions: FYI area in Beaufort Sea near Barrow (75°N, 155°W, shown in red) and MYI
 4 area around North Greenland (84.5°N, 35°W, shown in blue) May to September 2009.
 5 Locations are shown in Figure 1 with white circles tagged “FYI” and “MYI”, respectively.
 6 The albedo and MPF curves in the FYI area are interrupted as the area becomes completely
 7 ice free on the 1st of August 2009.



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2 Figure 3. Retrieved weekly averaged MPF for summer 2007 and 2011.

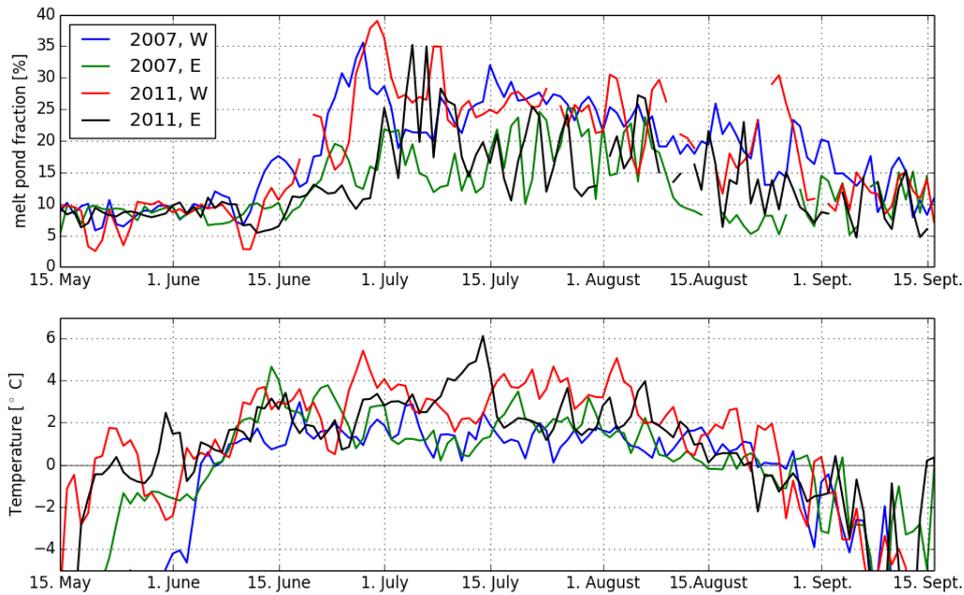


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3 | Figure 4. Main differences of weekly MPF averages 2007 and 2011 (Figure 3). Comparison
 4 of the weekly average pond fraction for the second week of June 2007 and 2011 (top row, left
 5 and right correspondingly) and for the second week of July 2007 and 2011 (bottom row, left
 6 and right correspondingly). Note the drastic melt onset in the 2nd week of June 2007, but
 7 lower MPFs in the 2nd week of July 2007 compared to 2011.

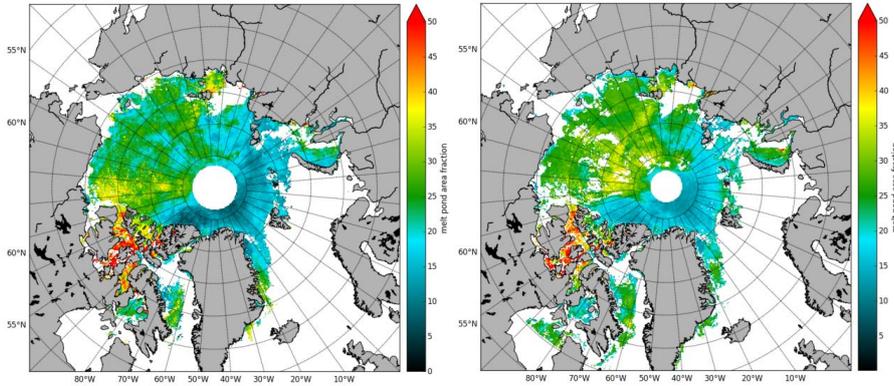
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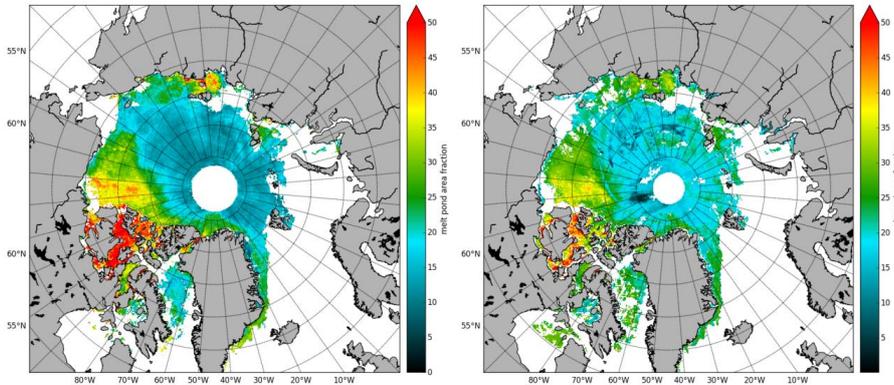
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3 Figure 5. Daily averages of MPF (top panel) and NCEP air temperature at the surface (bottom
4 panel) for two locations with the similar melt dynamics (“reference”) and diverse melt
5 dynamics (“characteristic”): reference location to the north to the Queen Elizabeth Islands,
6 83°N, 110°W (tag “W” in the legend), 2007 (blue curves) and 2011 (red curves) and
7 characteristic location in the Barents Sea, 85°N, 65°E (tag “E” in the legend), 2007 (green
8 curves) and 2011 (black curves). Locations are shown in Figure 1.

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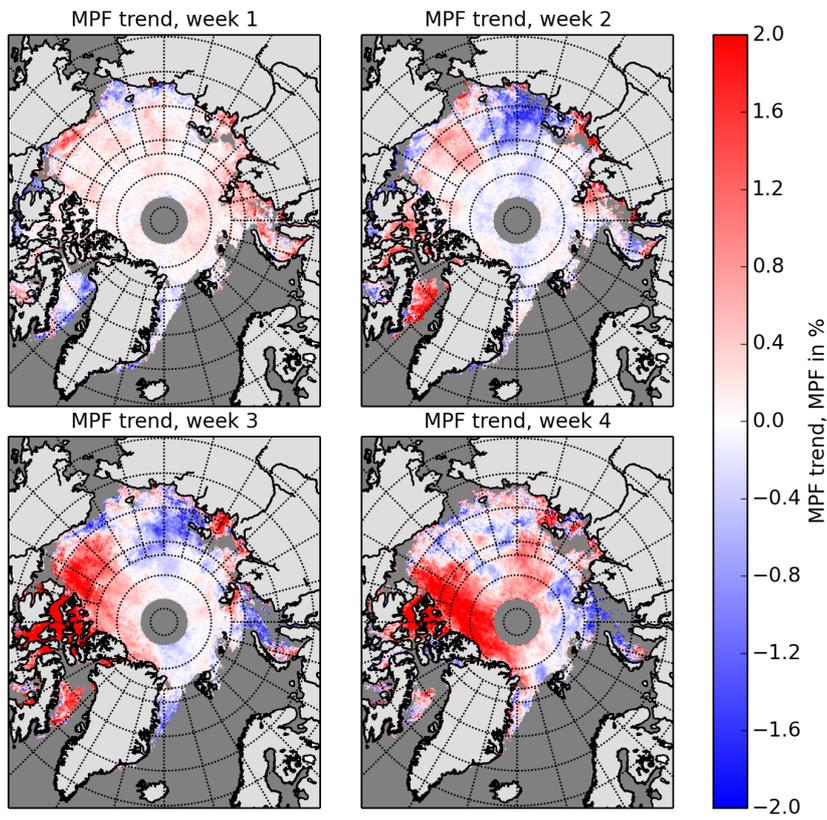


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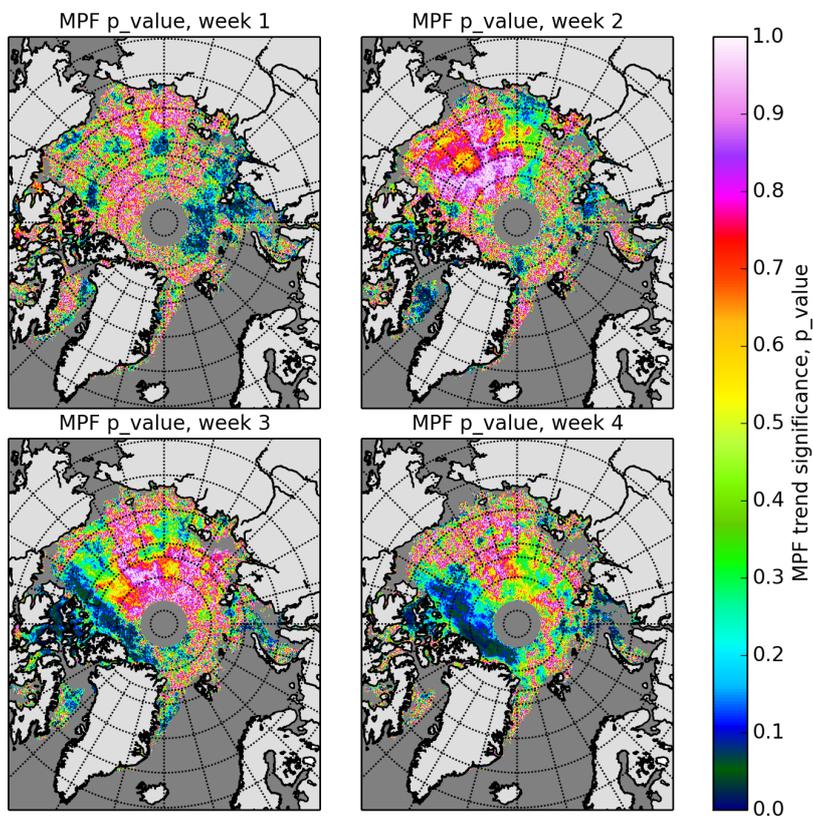


3 Figure 6. Comparison of the MPD MPF (8 day average, left column) to the MPF from (Rösler
4 and Kaleschke, 2012) (8 day composite, right column) for June 18, 2007 (top row) and June
5 18, 2011 (bottom row).

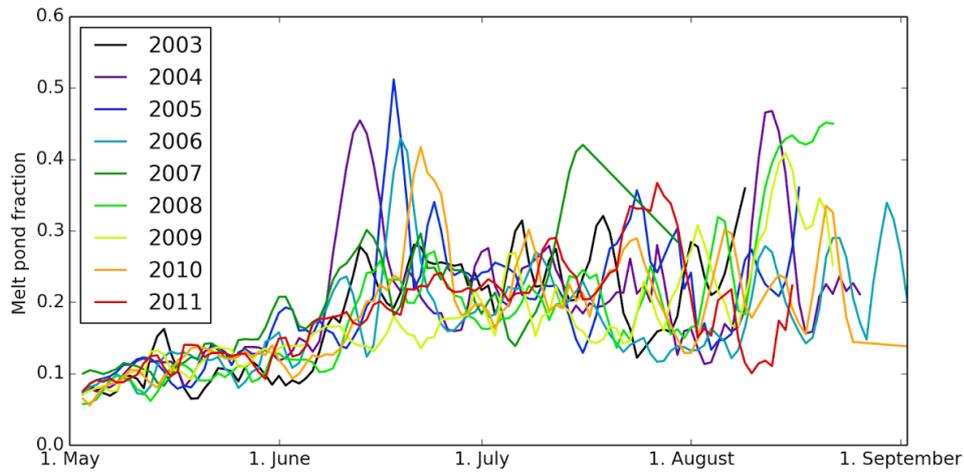
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 2 Figure 7. Melt pond fraction trends (trend in MPF %) for the four weeks of June for the whole
 3 investigation period 2002-2011.
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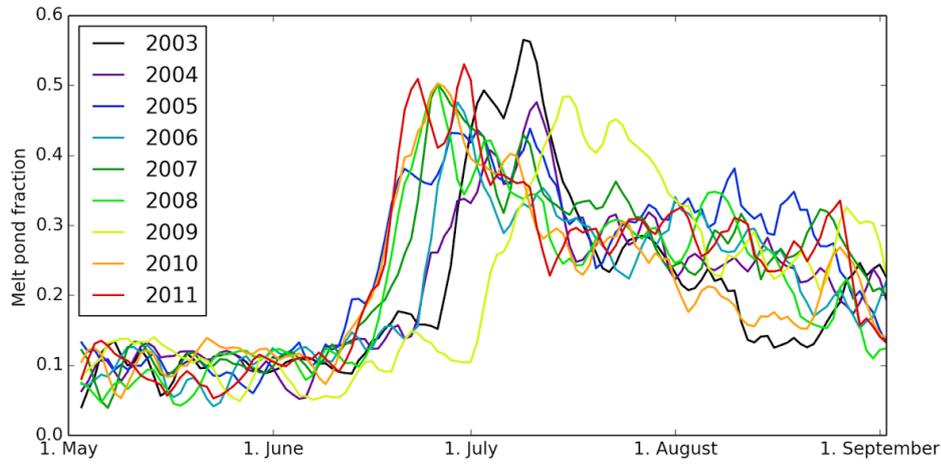


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 2 Figure 8. P values for the weekly MPF trends (see Figure 7).
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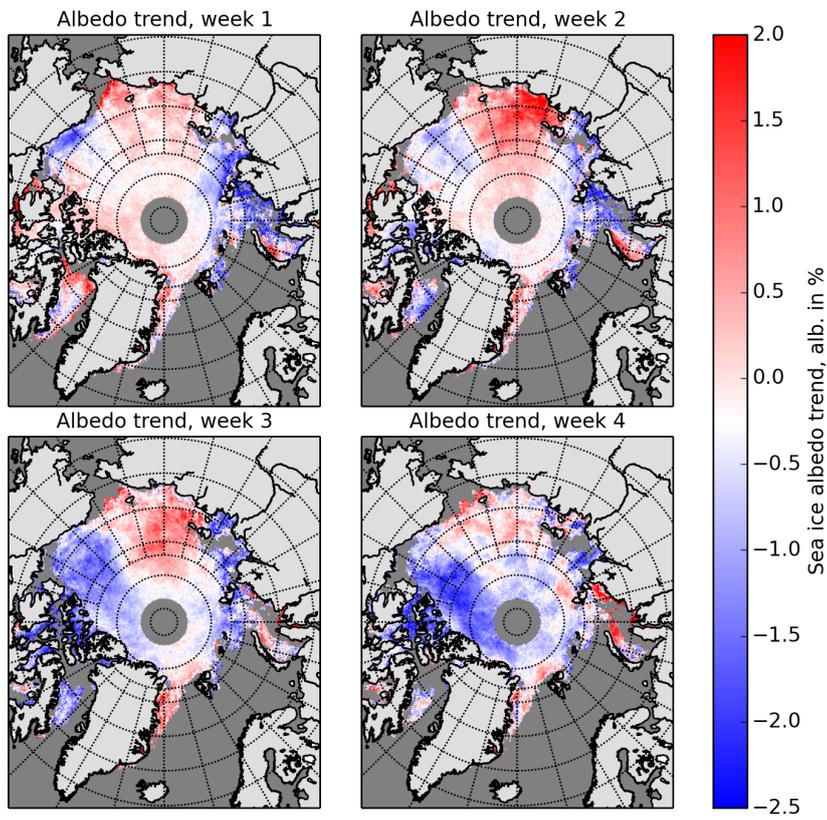


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 3 Figure 9. Time sequence of MPF for the studied years for the area of negative MPF trend in
 4 the East Siberian Sea (74°N, 160°E, marked with the red square “ES” in Figure 1). In the 2nd
 5 – 3rd week of June the MPF in the earlier years of the MERIS dataset reached high (up to 0.5)
 6 peak values as the melt onset started, which is typical for the first year ice. In the later years,
 7 however, the behavior of the MPF more resembles that on the MYI: no rapid melt onset,
 8 lower peak values of MPF. Running mean with window size 3 has been applied to the data.

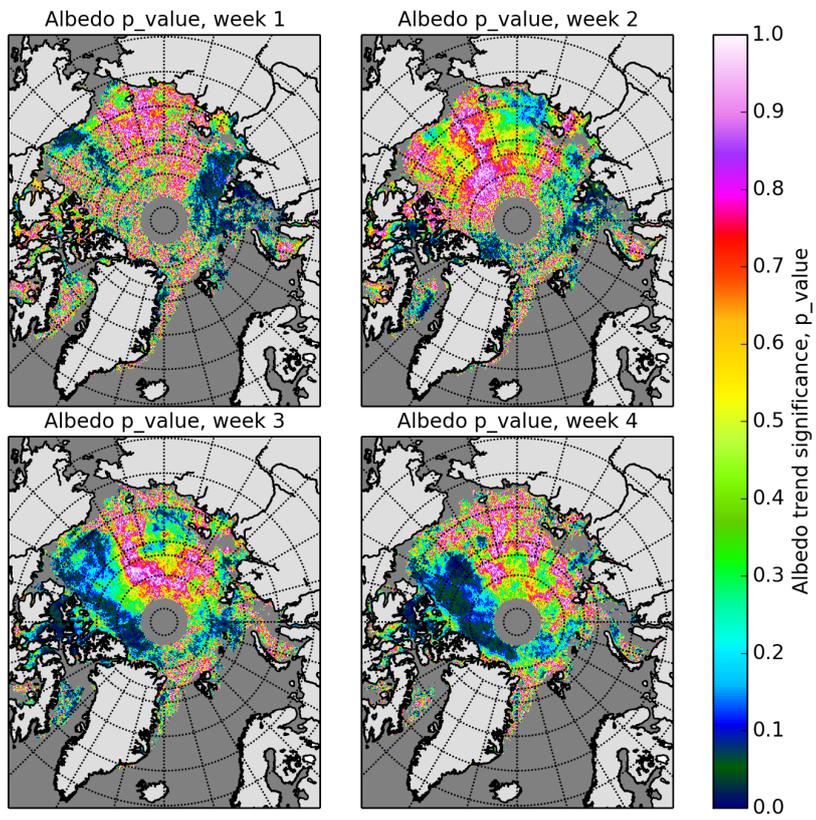
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 3 Figure 10. Time sequence of MPF for the studied years for the area of positive MPF trend in
 4 the Queen Elizabeth Islands (78°N, 108°E, marked with the red square “QE” in Figure 1). In
 5 the 3rd – 4th week of June the MPF in the earlier years of the MERIS dataset reached peak
 6 values later in the summer as compared to later years, and melt onset in the later year happens
 7 earlier than before. Running mean with window size 3 has been applied to the data.
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 3 Figure 11. Broadband sea ice albedo trends (trend in albedo %) for the four weeks of June for
 4 the whole investigation period 2002-2011.
 5



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 2 Figure 12. P values for the weekly broadband albedo trends (see Figure 11).
 3