Anonymous Referee #1
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The paper describes an analysis of surface conditions of Arctic sea ice in summer. The images are processed from a previously developed algorithm, which is approved upon and well-described, and all methods and output are made publicly available. The paper is very well-written, logically organized, and the figures are illustrated clearly. More details need filling in for parts of the methods, which should be straight-forward to address. The largest concerns I have are the testing of the hypothesis that melt pond coverage over first-year ice is higher than that of multiyear ice and the two pathways of melt pond evolution suggested for first-year ice. These concerns can be remedied by reconsidering the argument and taking into account the following points:

>Thank you for your review of our manuscript. You have provided great insights that have helped to improve this work. We have made efforts in the revised document to better discuss the time dependent nature of melt evolution, and to reassess how we can investigate these hypotheses with the snapshots provided by our dataset.

Melt pond evolution is variant in nature, particularly over first-year sea ice. Operation IceBridge sampled melt ponds at different stages of melt given the long covered. To assume all pond formation and evolution progressed the same, for ex- ample assuming all ponds had drained (as in the discussion), is a stretch even within the same survey line. By sampling over such large, regional areas, these surveys are sampling different states of melt pond evolution.

>This is true and may actually be a point in favor of assessing regional mean melt pond fraction. While the flight lines are temporally static, their long spatial footprint means, as you point out, that we are sampling ice in many different states of pond evolution. Given that the data samples a range of ice states the fact that we did not observe any statistically significant difference in the mean melt pond fraction between ice types is suggestive. We concede that this investigation alone is not sufficient to prove or disprove the hypothesis that FYI has higher MPF than MYI, but believe these observations are an important addition to that discussion.

The bimodal pathway argument of pond evolution for FYI is a gross oversimplification. While it is an interesting idea to consider, the argument that FYI is either pond-free or heavily ponded during summer is weakly supported. Melt pond coverage on first-year ice ranges from no ponds to heavily-ponded with everything in between based on available data.

>We agree with your assessment that the bimodal pathway is an oversimplification. Early looks at this dataset led credence to this hypothesis, so we set out to test it more formally. Our results here show that the bimodal pathway is not supported, as you point out, and our intent is to show this. We have therefore reworked several sections throughout the manuscript to be clearer on this point. We want to convey the idea that FYI is more variable than MYI, exhibiting all states from low to high coverage, but that there is not a bimodal path as initially posited.

>Note the last sentence of the introduction: "This new analysis reveals that FYI pond coverage indeed exhibits both pathways, but that there is *not* a strict duality – FYI pond coverage appears to occupy all states across the near-zero to high coverage space."

Please see the following suggestions for further improvements:
L49. Relatively calm Arctic. Calm relative to what? The Arctic seas are dynamic.

>Changed this sentence to be clearer. Here we are trying to establish the well observed predominance of flat topography on FYI and not get lost in the details about ice growth mechanisms.

L57-60. The introduction would benefit from more description about melt pond evolution. One aspect that's missing is the transitory coverage of melt ponds with melt. At one stage, FYI melt ponds may have lower coverage than MYI melt ponds. At a later stage of melt, the same FYI melt ponds may have greater coverage than MYI melt ponds. Pond coverage can change substantially depending on the ice state and progression of melt.

>We have added a discussion on the four stages of melt pond evolution. We have also added additional details to this section that looks at previous author's evidence for FYI with low pond coverage.

L67-68. I recommend tweaking the language here. While the results do show low and high coverage of melt ponds on FYI, which is a valuable finding, the results do not directly link together melt pond coverage and the processes posed in Polashenski et al. 2017.

>We have added this qualification to the introduction: "While the OIB image dataset provides large spatial coverage over long flight transects, the lack of temporal coverage makes it impossible to directly link these snapshots of pond coverage to any specific pond evolution process."

L77. No flights took place during melt or freeze onset transitional phases. How was this determined?

>This categorization was determined from established knowledge on when melt onset and melt pond formation typically begins. The only summer flights were in late July, well into melting conditions everywhere in the Arctic during 2016 and 17. We have added additional details referencing passive microwave derived melt onset dates to help with this categorization.

L116-117. Were there specific cases of high-quality imagery discarded using this method? It's worth mentioning in the text in case there are any biases worth considering.

>We did not encounter this issue. This flagging system is conservative and is more likely to not flag problematic images than it is to flag good ones. This is the reason for having to supplement the flagging with manual inspection.

L131-132. Are these limits subjective to each image or is a standard value applied all? How were the limits determined?

>These limits are standard, but only applied to select images. The limit for the white reference value is 200. These limits are only applied to images that do not contain both ice and ocean, which is determined by the number of peaks in the intensity histogram and the dynamic range of the image (the difference between the darkest peak and the brightest peak). We have added these details to the text.

L134. Is a clear, binary division true for flights where freezing and recent snowfall took place?

>Yes. While we agree there is much variability in sea ice conditions – specifically that periodic freezing and snowfall events often occur in summer months – our intent here is to separate the obviously different ice conditions between March/April (prior to melt pond formation) and those of late July (after melt pond formation). As this division is solely because of melt pond detection, we feel comfortable separating the flights into “expect melt ponds to be present” and “expect no melt ponds”.

L137-140. Is there an option for using melt pond and shadow detection in the algorithm on late spring or early summer images when both conditions are present? It would be worth noting this in text here.

>The algorithm allows for this, but this was not done for the dataset described here. A new training dataset could be produced to incorporate both melt and shadow surface classifications, or even other surfaces entirely. We have added some text explaining this flexibility of the OSSP code.

L144/Section 2.3. What new information does the number of pond-free areas provide that the areal ice fraction doesn’t? It would be helpful to discuss this in a sentence or two here. For one, the distribution of pond-free ice has implications for disparate surface melt rates and the new pond-free metric would seemingly give more information in this respect.

>You are exactly right, the primary benefit here is the information it provides on the spatial distribution of melt ponds. We see a difference in this metric between certain types of FYI and MYI even if the total MPF is the equivalent between them. This is because on MYI the ponds are evenly distributed across the surface (few pond-free zones) while on FYI the ponds can be clumped in areas of high pond fraction with other regions pond-free. This metric also provides insight on different types of FYI – FYI that has many pond free areas is experiencing some difference in melt evolution than FYI with well distributed ponds.

L148/L152. 15 m and 27.5 m values are specific. How were they chosen?

>These values are misleadingly specific but were chosen to be roughly 2x and 4x the mean caliper diameter of melt ponds. We have changed the values to be 12m and 25m for clarity, rerun the analysis (results were the same) and added our justification for the threshold to the text and a citation for the mean caliper diameter value.

L170. What is meant by targeted processing?

>Here we meant tailoring a training dataset to process a specific subset of images, rather than one that performs well across a large variety of input images. We have changed the wording here to make this clearer.

L176. What are the results exactly? Are they segmented images or simply surface fractions of all images? Please clarify here.

>The results are classified images – where each image pixel has been given a value based on its classified state. These can then be readily converted into simple surface fraction numbers.

L177. Please define melt pond fraction. Is it the areal fraction of the image scene or of the sea ice? How are melted-through ponds within an ice floe classified?

>MPF is a fraction of the ice area, not image area. We have added a sentence here clarifying how melt pond fraction is determined. Melted through ponds are classified as open water following from the arguments in Wright and Polashenski, 2018. In short – we approach this from a solar radiation energy balance perspective where melted through ponds are more similar to ocean in their radiative properties. Submerged ice is classified as "melt pond" for the same reason.

L177-178. Why were images with 70% ocean area discarded? Melt pond fractions in these images would be useful information.

>A single IceBridge image typically only covers 600x400m. If 70% of this is ocean, then melt pond fractions calculated from this small area are very easily skewed by large ponds (this area is well below the "aggregate scale"). Note that the images are still processed, we just don't show the pond fraction in this plot. Even full images have a small enough area for the melt pond fraction to be skewed by large melt ponds, as shown by the orange dots in Figure 5.

L179. What is meant by low source image quality? Does this mean that there were images that had low light, were hazy, that the automation didn't catch before? If so, it would be helpful to state how many images (the fraction of the total) the automation removed. This can tell us how much work the automation saves us from doing and approximately how much work is left to do using this method.

>Yes – the manually removed images were ones with clouds/haze that were not detected by the automated system. We have added the percent caught automatically versus manually.

L180. Not enough to do what? Do the authors mean that there was usable imagery from that flight?

>There were not enough clear images to justify the effort needed to process and filter the results. A statistically relevant sample would not have been created with the small number of usable images.

L189-190. It would be useful to see the equivalent segmented image of 6c as an additional panel to the figure.

>We assume here you mean the final labelled image? Image segmentation is a specific term to describe an intermediate step of our algorithm. We have added a many of the images presented in the text as classified images in a supplemental figure.

L196-198. What's the error associated with the ice type classification? How was second-year ice classified?

>Second year ice would fall into the multiyear ice category, though it depends on the estimated surface roughness. These delineations are visually based, so the separation is between flat and undeformed ice versus textured and aged ice rather than a definitive knowledge of the ice age.

L214-215. How were the ice types distributed along the surveys? Were FYI and MYI well-mixed or was one ice type located predominantly north, east, etc.? It'd be helpful to note their distribution here.

>For flights that observed both ice types in the Beaufort/Chukchi regions there were pockets of MYI in the northern regions of a predominantly FYI pack. Otherwise the flights were only a single ice type (using our >90% estimation). We have included this information in the text.

L217-219. The first sentence needs more description. Work by Eicken et al. 2002 and Webster et al. 2015 demonstrated the same result, but what this analysis shows is that it can happen on a regional scale rather than a local scale, and that's important. The second sentence can also be expanded on. Several previous studies showed pond evolution between FYI and MYI differ. What's new with this study is the link to the large-scale variability in pond coverage. For example, one could hypothesize that there should be less spatial variability in MYI pond coverage on a regional scale because it's less variable in time relative to pond evolution on FYI. These results support that hypothesis.

>These are good insights, and we have reworked this section to better reflect what is new in this study and what has been previously observed. We have also added additional content to the discussion section to better address these concerns.

L231-232. This sentence is unclear.

>We have rewritten this sentence.

L241. How was "most" defined? Was this 51% of the ice area or more than 10 times?

>Changed to be "… that can be expected on more than half of the ice".

L243/Figure 10. This is a nice result. I was hoping to see the equivalent segmented image. It'd be worthwhile to include this either in the main text or as supplementary information.

>We have included this as a supplemental figure.

L250-253. Is this shorefast ice? It's worth stating so if it is, as it may be typical for shorefast FYI in this region.

>Yes, this ice is likely shorefast ice north of Ellesmere Island. We have changed this description: **"(e)** Shorefast level ice in the Lincoln sea. Ponds have started to drain already, as evidenced by the drainage channels visible throughout the ice. This type of relatively low coverage and consolidated ponds were infrequent in the OIB dataset, but may be common of ice in this region"

L254-255. I'd suggest rephrasing this to "infrequent" to the OIB observations, since it may be a common phenomenon.

>This is likely true, and we have added this extra information.

L256. It would be helpful to circle or highlight the sediment-laden ice as it's not apparent in this image. It also raises the question, does the algorithm also detect sediment-laden ice or is it detected as a melt pond?

>This image is actually not a great example of sediment laden ice, so we have removed this description from the text. Sediment-laden ice does not have its own classification category and would likely be put into the gray ice category, or possibly melt pond, depending on its color and darkness.

L258/Figure 11. Similar comment as Figure 10, it'd be helpful to see the segmented equivalent in the main text or supplementary information.

>We have included this as a supplemental figure.

L267-319/Section 4.1. Please see main concerns above.

>Revised discussion section, see comments in response to main concerns.

L280-281. The lack of ponds in Polashenski et al. 2017 seemed to be due to a snowfall event and freezing conditions rather than high permeability and a lack of snow.

>Polashenski et al., (2017) also discusses observations of pond-free ice that appears to have never had a snow cover (Specifically in reference to the satellite image in their Figure 15). We have added a citation to Eicken et al., 2004 here, which discussed the relationship of snow cover to pond formation.

L284-287. Do the results from earlier works using MODIS data not apply here?

>It is the authors opinion, supported by our own recent study (Wright and Polashenski, 2020), that existing MODIS melt pond products do not have the accuracy required to answer this question.

L289. How was high permeability and pond drainage determined on such a large spatial scale? Figure 10b shows no drainage features. This surface condition was classified as common in the dataset, which conflicts with the next sentence.

>If we look at the OIB dataset as a whole, the majority of the observed surface is in an advanced state of melt where the ponds have drained to sea level. This was determined empirically from looking at the dataset. This surface condition is common in reference to ice that is in a similar state of melt. In 10b, the state of melt can be described as ice that has not yet drained to sea level.

L293-294. Is this what's being suggested for the pond-free FYI areas? Before, the argument was that ponds never formed?

>We think that both pathways are possible. If the ice does not have the snow cover to support ponding (as noted by Eicken et al., 2004), or if ice permeability is too high to allow ponding (when the ice warms before surface melt begins the pore space cannot refreeze when freshwater enters, meaning ponds cannot form above sea level (Polashenski et al., 2017)), then the ponds will never form. In this section we are discussing the mechanisms required for pond free ice to emerge from ice that *did* have initial ponding.

L296. It’s not clear what is meant by if subtle topography is powerful.

>We have removed this phrase and revised this section.

L298-300. This is not clear.

>This section has been reworked for clarity.

L312-313. Is this statement in reference to the OIB data set? For previous works, this was not found to be the same. It would be worth clarifying here.

>This statement is in reference to the OIB dataset, and we have clarified this here.

L322-324. This description should be described near the beginning of the manuscript. Submerged ice may contribute to a larger proportion of pond fraction for FYI than MYI.

>We have added the official category descriptions to the introduction of this manuscript.

L333-335. Similar to the main concerns above, a snapshot of lower FYI pond coverage than MYI pond coverage does not address the hypothesis. Previous works have shown pond coverage on FYI to be highly temporally variable over summer compared to that on MYI. The temporal average of melt pond fraction for FYI and MYI over the melt period may indeed support the hypothesis.

>We have revised the conclusion section to be clearer about the conclusions that we can and cannot draw from our dataset. As you pointed out, some of our claims were too bold to address with temporal snapshot datasets.

Figure 4. It would be helpful to use a more dynamic color scheme for the melt pond fraction. It’s difficult to see the distribution along the survey lines.

>We have increased the contrast for this figure.

Figure 8. It would be helpful to know the sample size for each case.

>This has been added.

Anonymous Referee #2
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Summary
The authors provide an update to the Open Source Sea-ice Processing (OSSP) algorithm and apply it to the optical Digital Mapping System (DMS) images acquired during Operation Ice Bridge flight tracks flown in melting conditions. The OSSP derived relative surface fractions include ice, open water, and melt pond. Statistics on melt pond fraction are important for understanding sea ice evolution, light exchange, and for parameterizing models. The documented improvements to the OSSP are important since the code is being made freely available and potentially facilitates some standardization in the processing of high resolution optical datasets of sea ice during melting conditions.

In general the paper is well written and organized, and the output figures and tables concise and informative. The improvements to the OSSP are well documented, how- ever there are some problems with the analysis of the output data from the OSSP applied to the optical DMS data from the Ice Bridge flights.

>Thank you for your review of our manuscript. You have provided some insightful comments that have helped us to improve this work. In general, we have made a number of changes to better include discussions of the temporal aspects to melt pond formation and to properly place our observations in the context of known pond evolution pathways. We have attempted to remove or lessen the more speculative discussion points in the original manuscript and better incorporated previous research that supports our analyses.

The assertion that, based on the analyzed data, first-year ice (FYI) often has lower melt pond fraction than multiyear ice (MYI) is misleading. There is insufficient data analyzed, and the temporal component of melt pond fraction evolution (including a comprehensive review by one of the co-authors) is mentioned but largely ignored for the purpose of supporting the assertion.

>We do not believe this is misleading. FYI and MYI have unique pond evolutions, and it is expected that FYI will fall below MYI during certain phases of melt. According to the four stages of melt documented by Eicken et al., 2002, this happens during stage two, where FYI drains much faster than MYI. We have, however, removed the phrase “often” as we do not have the data to support this for the whole season. Observations at SHEBA found 10-30% of FYI to have zero or low pond coverage late in the melt season (Eicken et al., 2004), and our results (17%) fit right in the middle of this range.

Lines 288-293 describe the timing of the acquisition of the DMS images for this study as being in late in the melt season, when ponds have drained to sea level. In this case it can be expected that, for any sea ice that is still above sea level, the mechanically weak FYI will have likely drained and melt pond fraction will be lower than it is for MYI undergoing similar melting conditions. That is consistent with the stage of melting, not the overall behavior of FYI and MYI during melting conditions.

>At late stages in FYI pond evolution, any sea ice that is still above sea level is by definition unponded because no ponds exist above freeboard. We may be considering

different definitions of a melt pond than you because we are approaching this from an albedo and radiative transfer perspective, where submerged ice falls into the melt pond category. This is consistent with prior research where on FYI the “melt pond fraction” steadily increases in stage 3 after FYI ponds have become fully connected with the ocean (Eicken et al., 2004, Polashenski et al., 2012).

>For illustration we have included a pair of images below. Panel A of shows FYI in an advanced state of melt that can be assumed to be thin ice with ponds that are fully connected to the ocean water, yet the surface is almost entirely flooded. Contrast this with Panel B, which was taken the same day just a few km away, where the FYI has very little pond cover.

The hypotheses in the introduction are therefore poorly stated, the analysis misguiding, and the resulting conclusions are flawed.

>The hypotheses are both presented in similar form in previous work (as cited in the manuscript). We have, however, attempted to make it clearer in our manuscript that our statement of these hypotheses in the introduction does not mean that we have confirmed them to be true. Quite the opposite! For example, we did not see sufficient evidence for the duality hypothesis and rejected it (as much as it is possible to do so with this dataset).

That FYI experiences greater melt pond fraction than MYI has been more than posited, as stated on line 55, it has been well studied in the context of sea ice geophysical evolution. The authors must analyze their data in the context of the fairly well understood temporal behavior of melt pond fraction evolution on FYI and MYI, and situate their observations in the correct context (late season), using ancillary data if needed. It would make more sense to present the data as is, and evaluate the OSSP algorithm performance, without the general assertions about FYI and MYI behaviors – this not detract from some very interesting results.

>We have made a number of refinements to better include discussions on the temporal aspects of melt pond evolution and remove assertions that are not sufficiently supported by the temporal snapshots provided with this dataset.

Other comments 1. In cases where the sea ice has melted to sea level, and the ice floats below sea level, that is ocean water and sea ice – not melt pond covered sea ice. Has this been correctly specified in the algorithm and resulting statistics?
Consistent terminology regarding the season and stage of melt would make the paper clearer and easier to follow. For example, are spring conditions (line 86) actually spring when it is freezing conditions? The June 1st cut-off for categorizing freezing-melting conditions is arbitrary.

>Submerged ice is classified with the melt pond category following from the arguments in Wright and Polashenski, 2018. In short – we approach this from a solar radiation energy balance perspective where submerged ice is more similar to a melt pond in its radiative properties. Melted through ponds are classified as open water for the same reason. We have added these categorizations to the introduction and the terminology through the paper is consistent with these definitions.

>The June 1st cut off is arbitrary but is not important for the categorization. We have changed the description of the cutoff to be in reference to mean melt onset date from passive microwave datasets.

More information on the nature of the training data is required. It would be interesting if the algorithm could be trained to detect drained FYI (i.e. ice previously covered by pond which has then drained once connectivity with the ocean is achieved), since this ice has much different fluid and gas exchange properties compared to exposed ice.

>More detailed information on the training data is available in Wright and Polashenski, 2018, where this method was first presented. The training datasets here are larger but are the same in other regards as those previously described.

>The ability to detect drained FYI would be powerful but it is likely not possible from optical datasets. Drained ice in many cases does not look different than melting ice that never had a pond cover.

Once FYI and MYI are defined the full terms are not required.

>We have replaced the full terms with the abbreviations after the first use.

The assertion on line 225 is biased. Consideration of typical melt pond fraction conditions would include temporal domain, not just the spatial. This has been well documented. There could very well be low pond fraction if the FYI has drained and I would suggest that the sea ice community is aware of this.

>Bias implies some ulterior motive or misrepresentation to support a goal, which is not our intention. We agree that specifying the 'typical' melt pond cover on FYI depends on the temporal domain because the pond fraction evolves over the melt season and have therefore clarified our statement here.

>We have changed the phrasing in this section to include mention of the temporal aspect of pond formation. Our goal is to point out the prevalence of pond free ice observed in our dataset and to place this in context with previous studies, not to claim that pond free ice is a novel observation. Because our dataset is a snapshot in time we cannot determine if the pond free ice was the result of pond drainage or the result of ice that never formed ponds.

>We have also included references to previous work that have observed pond free ice.

Detailed Comments

L32: 'fine' detail instead of exquisite

>Changed.

L73-74: specify the extent i.e. ground coverage of the images

>Added this information.

L108-109: more detail on expanded training datasets is needed

>More detail is available in the publication that describes this technique. There is not much else to add beyond what is in that manuscript.

L145: Start this section by defining a pond-free ice area. Otherwise it is a bit confusing, as all areas of exposed ice (1-PF) are pond-free ice areas.

>We have moved the definition to the beginning of this section.

L185: ". . .the large the variability . . ." delete extra 'the'

>Fixed.

L217-219: There has been much work done understanding the melt pond fraction evolution for FYI and MYI, and pond evolution is likely explained by drainage mechanisms in this late period.

>We have reworked this section to include more discussion of previous work and to place it into the context of known MPF evolution for FYI and MYI.

>Drainage is a possible explanation, but there is also the possibility that ponds never formed on this ice. We cannot investigate that from this dataset because there is no temporal dimension.

L269-277: Missing from this paragraph is the occurrence of late season FYI when ponds have drained but the ice is still above sea level. In this case, FYI pond fraction would be less than MYI (likely the case in Figure 10f, for example).

>We have added a few sentences here discussing times where FYI would be expected to have lower MPF based on previous studies:

"

These effects must be balanced with the times in melt evolution where FYI is expected to have lower MPF. In the early season, MPF on FYI tends drop faster than on MYI because the meltwater is able to drain to sea level at a faster rate (Polashenski et al., 2012), and in the late season thicker FYI pond fractions would be lower than MYI because the more of the level surface sits above freeboard (e.g. Figure 10d).

"

L282-285: There should be mention of diurnal variations in pond fraction due to variable meltwater input and drainage process which, for level sea ice, can lead to dramatic changes in melt pond fraction over very short periods of time. Subtle changes in air temperature or surface energy balance can predicate these changes in melt pond fraction.

>We have added discussion of diurnal effects on melt pond fraction to this paragraph.

L331-332: This hypothesis is not investigated in the paper since it does not utilize data from early stages of melt pond coverage, when ice is relatively impermeable and differences in melt pond fraction are related to topography hence ice type.

>We have rewritten this paragraph of the conclusions to fix this issue:

>“We have investigated snapshots of melt pond coverage differences between FYI and MYI in the Beaufort/Chukchi Sea region for 2016 and the Lincoln Sea for 2017. Our results support previous findings by X and Y that FYI can have lower pond fraction than MYI under the similar forcing conditions. While the results presented herein cannot definitively confirm or refute the hypothesis that FYI has higher mean pond fraction than MYI, the high variability in FYI pond fraction over large regions suggests that the general rule of thumb that FYI should have higher ponding than MYI is too simplistic. Furthermore, the finding that FYI exhibits much larger variance its evolution indicates that there is not one path that defines the typical evolution of pond coverage. We did not find sufficient evidence that there is a strict duality in FYI pond evolution either, and we suggest future process studies investigate the mechanisms that drive FYI towards high or low pond fraction and […] ”

L443: The blue color scheme for pond fraction is difficult to interpret in the figure.

>We have adjusted the contrast in this figure.

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Major comments:
A number of questions remain about the algorithm performance and the error analysis could be strengthened:

L156. Other than haze, what are the main sources of object misclassifications?

>Haze is the main source of bulk object misclassification. Transitional surfaces (e.g. dark melt ponds, very thin ice) are the second highest source of misclassification. However, because these surfaces are typically transitioning between categories it is difficult to determine their "true" category in the first place. These and other sources are discussed in more detail in the error analysis section of the document describing the OSSP methods (Wright and Polashenski, 2018).

L156. How do object misclassifications impact the derived melt pond fraction? On Line 137, you state the shadow detection method is not applied because "typical summer solar zenith angle yields fewer shadows." The sun angle is still low in the Arctic and ridge shadows do exist in the summer. How are shadows that do exist in the imagery classified if they do not have their own category? Are they classified as melt pond? How does excluding this step impact results? How does aircraft attitude and altitude impact the impact pixels and hence, the classification algorithm and derived melt pond fraction? Have the authors re-quantified the algorithm error, given the modifications to the algorithm (Section starting at Line 107), since Wright and Polashenski, 2018?

>Previous work has determined that in spring imagery ridge shadows make up less than 0.5% of the total ice area (Webster et al., 2015) and are therefore a small source of error even if always misclassified. Their impact would be expected to be even lower in summer, where the sun angles are higher. Misclassified shadows are typically assigned a label of melt pond, and less frequently of dark or thin ice. The total impact of object misclassifications is accounted for in the error analyses described in Wright and Polashenski 2018.

>This dataset is also provided in a reprojected format that does account for aircraft pitch and roll. In this work we are assessing relative fractions and not absolute areas - the difference in calculated surface fraction between images in the corrected vs raw datasets is small. Part of the manual filtering process described in the methods section includes removing those images that were not taken at or near the nominal survey altitude.

>The algorithm adjustments were tested against the same test set as used in Wright and Polashenski, 2018, and were found to not alter the overall performance.

Designation of ice type
The authors state on L203 that the flight on July 25th 2017 covers first year sea ice. This does not seem justifiable for two reasons. a) the authors provide their own definition of a FYI flight (Line 197, that 90 % of the images in the flight are FYI). Given this definition,

and visual inspection of the DMS imagery from the flight, it is not obvious that the flight is over predominantly FYI. A larger percentage of images with pressure ridges and rubbled ice, indicating a long deformation history, and thus, MYI. Many images resemble the MYI depicted in Figure 11a-c and described as "common examples of ponded multiyear ice floes with characteristically blue ponds that are well consolidated by surface topography" (Line 258). b) the location of the flight line north of Ellesmere Island in the Central Arctic is over sea ice known to be the oldest and thickest ice in the Arctic, and highly unlikely to be predominantly FYI in origin. The 2017 Arctic Report Card found that the ice in this region in March is predominantly MYI (Figure 3c, Perovich et al., 2017). Given that it is well know that the ice in this region is some of the thickest ice in the Arctic (e.g. Figure 2b, Sallila et al. 2019), this area is highly unlikely to be predominantly FYI.
For reference: Perovich, D., Meier, W., Tschudi, M., Farrell, S., Hendricks, S., Gerland, S., Haas, C., Krumpen, T., Polashenski, C., Ricker, R., & Webster, M. (2017). Sea Ice [in Arctic Report Card 2017], http://arctic.noaa.gov/Report-Card Sallila, H., Farrell, S. L., McCurry, J., & Rinne, E. (2019). Assessment of contemporary satellite sea ice thickness products for Arctic sea ice. Cryosphere, 13(4).

>According to the sea ice age dataset (hosted at NSIDC; citation below) there are pockets of first year ice on/around July 25th 2017 in the location of this flight line. We agree that this area is typically filled by thicker multiyear ice, but that does not exclude the possibility of there being first year ice. Visual inspections of the DMS imagery show characteristics we would expect from younger, thinner ice: darker melt ponds, dark melting ice, and less surface topography.

>Tschudi, M., W. N. Meier, J. S. Stewart, C. Fowler, and J. Maslanik. 2019. *EASE-Grid Sea Ice Age, Version 4*. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi: https://doi.org/10.5067/UTAV7490FEPB.

Forcing conditions affecting sea ice floes in survey area
L212. "To investigate melt pond statistics across ice that experienced similar forcing conditions, two flights that contained both FY and MY ice were selected for further analysis" How do the authors know this ice has experienced similar forcing conditions throughout its lifetime? Considering the Beaufort Gyre is known to be an especially dynamic area, the ice observed during the flight surveys may have come from different regions. The ice in this region may, at the time of the survey, be experiencing uniform forcing conditions, but the assumption that all ice covered in a survey has experienced similar forcing conditions throughout its lifetime is invalid.

>By nature, MYI cannot experience the same forcing conditions as FYI over its complete lifetime. Here we are just referring to the current melt season, where the assumption that ice in a similar location on the same date experiences similar atmospheric conditions. We have added more qualifications to this description in the text.

Melt pond fraction calculation clarification:
L175. How is melt pond fraction calculated? If the OSSP algorithm classifies melt ponds and submerged ice in the same category, is submerged ice included in the melt pond

fraction calculation? How does the inclusion of submerged ice impact the melt pond fraction parameter?

>Melt pond fraction is calculated as: Pond area / (ice are + pond area), and we have added this information to the text. Submerged ice is included in this metric. Including submerged ice as part of melt ponds is discussed in detail in the original OSSP method document. Submerged ice is radiatively similar to melt ponds and is therefore part of the same category, and not considered a misclassification.

L177. Why do the authors choose images with open water area < 70% as a threshold for displaying melt pond fraction results? Do you include images with open water area > 70% in melt pond fraction results (Section 3.2 and 3.3).

>A single IceBridge image typically only covers 600x400m. If 70% of this is ocean, then melt pond fractions calculated from this small area are very easily skewed by large ponds (this area is well below the "aggregate scale"). Note that the images are still processed, but the pond fraction is not shown in this plot. Even full images have a small enough area for the melt pond fraction to be skewed by large melt ponds, as shown by the orange dots in Figure 5.

Minor questions needing clarification in the text:
L80 Are data collected on 15 July 2016 analyzed? This flight survey is plotted in Figure 1, but no results are shown (Figure 4).

>Yes – thank you for pointing this out. That flight was somehow missed when creating Figure 4.

L180. The authors state that data from the 20 July 2016 flight were not processed because "not enough usable images" How do the authors determine what was enough?

>Of the 1587 image frames taken on July 20, less than 30 are completely haze free. We have added these numbers to the text.

L184. Does Figure 5 follow Figure 4, and only show melt pond fraction for images with open water area < 70%?

>No – but if you look at July 24th , 2017 on Figure 4 you will see that few images in this flight were flagged as having >70% open water.

L203: Can you distinguish between the 25July2017 flight A and flight B within the text and/or in Figure 4 (where they are currently shown in the same color)?

>Yes, we have separated these flights to different colors.

L323. How is a melt pond defined in this study? Is a melt pond still a melt pond when it has melted through the sea ice? What about other features: melting snow, thaw holes, algae on ice?

>We use the definition presented in Wright and Polashenski, 2018: “Melt Ponds and Submerged Ice (MPS): applied to surfaces where a liquid water layer completely submerges the ice.”

>A melt pond is no longer a melt pond when it has melted through the ice. Melting snow falls into the ice/snow category, algae and sediment laden ice are not defined but would likely be assigned to the dark ice category depending on their color and brightness.

Figure 4. Bottom figure. For the 17 July 2017 and 18 July 2017 flights, it looks like there are no images remaining for analysis. Is that correct? Can you provide the total number of images analyzed for each flight, and total discarded? Perhaps this information could be included in a table or added to the figure.

>We have added this information in the methods section.

Comments to the Author:
Dear authors.

Thank you for your submission on a refined image-processing algorithm and its application to Operation IceBridge (OIB) Digital Mapping System (DMS) optical images for the Arctic. This work presents a valuable improvement to the existing dataset, especially with view of harvesting crucial information on Arctic meltponds. I note, however, that such work needs to be conducted rigorously and complete. As outlined by both reviewers and the public comment, your original submission showed some shortcomings with regard to those. In the meantime your responses to the three submitted comments indicates that a fully revised manuscript is likely within scope for publication in TC.

I invite you iterate on the comments the reviewers and public, together the points noted below, in order to submit your revised manuscript (ms).

General comments:

* The original submission is rather qualitative and at times handwaving. To improve the ms, pls provide quantitative information: For example, what percentage of imagery is not processed due to being cloud affected (l112); or "what is a large number" (l118).

> We have added specific numbers and percentages to section 3.1 describing the number of images that were automatically removed, manually removed, or kept for analysis. Throughout we have tried to add specific details in place of ‘handwaving’ sentences (e.g. justification for the delineation of spring/summer, size thresholds for pond free detection, etc.)

* Provide physical motivation for the choice of your tresholds: 15m (l148), 27.5m (l152).

> These values were chosen to be roughly 2x and 4x the mean caliper diameter of melt ponds. We have changed the values to be 12m and 25m for clarity, rerun the analysis (results were the same) and added our justification for the threshold to the text and a citation for the mean caliper diameter value.

* Be clearer in how you compute if underlying sea ice is First Year [FY} or Multi Year [MY] ice. I.e., what are your criteria to determine FY vs M Y (l214)?

> We have added a sentence describing the criteria used, and a reference to reflect how those criteria lead to appropriate categorization of ice age.

* The discussion section needs to better reflect the results/findings from this work/ these data and be strengthened overall. In its current form the ms leans towards a data-announcement paper (i.e., suitable for Earth System Science Data)... I recommend strongly that this ms be extended to cover suffcient scientific application and results.

> We have made significant revisions and additions to the discussion and conclusion sections to clarify the overall results from this work. We have made more direct references to the results drawn from our study specifically and reduced the discussion of the general understanding of sea ice melt pond behavior. A portion of this manuscript is

intended as a data announcement regarding the new processed Operation IceBridge data, however, we believe our finding on the more widespread prevalence of pond free first year ice than anticipated is an important discovery – even if tempered by the lack of timeseries observations in this particular dataset.

Specific comments:
l76: Your categorization into freezing and melting occurrences of OIB's DMS imagery appears rather crude, especially considering the range of locations observed. Pls justify or refine this approach.

> We have refined this description and added a reference to the mean date of melt onset determined from passive microwave remote sensing. While we agree that the strict dual categorization is crude and that there is much variability in sea ice conditions – specifically that periodic freezing and snowfall events often occur in summer months – our intent here is to separate the obviously different ice conditions between March/April (prior to melt pond formation) and those of late July (after melt pond formation). As this division is solely because of melt pond detection, we feel comfortable separating the flights into "expect melt ponds to be present" and "expect no melt ponds".

l143: Training datasets at https://github.com/wrightni/ossp:
These are shown to be from 2018 (V2): Are these the correct and up-to-date datasets relating to this late 2019-submitted ms??

> The training dataset for the IceBridge imagery has been updated on the Github page to reflect that used for this dataset (v7).

l176: Provide URL/link for the data processed for this ms at the NSIDC WWW pages.

> This has been added to the data availability section in the form of a DOI.

l250: Correct "Lincoln sea" to "Lincoln Sea".

> Fixed.

l268: There is a subsection "4.1" but no further subsection in 4: Remove by joining the 4.1 subsection title with the "4" section title.

> This has been changed.

Observations of Sea Ice Melt from Operation IceBridge Imagery

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Abstract. The summer albedo of Arctic sea ice is heavily dependent on the fraction and color of melt ponds that form on the ice surface. This work presents a new dataset of sea ice surface fractions along Operation IceBridge (OIB) flight tracks derived from the Digital Mapping System optical imagery set. This dataset was created by deploying version 2 of the Open Source Sea-ice Processing (OSSP) algorithm to NASA's Advanced Supercomputing Pleiades System. These new surface fraction results are then analyzed to investigate the behavior of meltwater on first-year ice in comparison to multiyear ice. Observations herein show that first-year ice does not ubiquitously have a higher melt pond fraction than multiyear ice under the same forcing conditions, contrary to established knowledge in the sea ice community. We discover and document a larger possible spread of pond fractions on first-year ice leading to both high and low pond coverage, in contrast to the uniform melt evolution that has been previously observed on multiyear ice floes. We also present a selection of optical images that captures both the typical and atypical ice types, as observed from the OIB dataset. We hope to demonstrate the power of this new dataset and to encourage future collaborative efforts to utilize the OIB data to explore the behavior of melt pond formation Arctic sea ice.

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1 Introduction

The extent and age of the Arctic sea ice cover has declined since the beginning of the satellite record in 1979 (Stroeve et al., 2012). Ice melt is accelerated through albedo feedback cycles initiated by surface melt decreasing the ice cover's reflectance (Curry et al., 1995; Perovich et al., 2003). Understanding changes in sea ice properties that impact albedo, particularly melt pond coverage, is important to parameterizing sea ice in global climate models (Hunke et al., 2013; Serreze et al., 2009). In-situ observations that could support developing this understanding are sparse, difficult to acquire, and may not be broadly representative (Perovich, 2002a; Wright and Polashenski, 2018). Remote sensing platforms provide a path to understanding sea ice surface change over larger scales. Newly developed computational techniques provide the means to analyze large remotely sensed datasets (Miao et al., 2015; Webster et al., 2015; Wright and Polashenski, 2018). The NASA Operation IceBridge project (OIB) has collected large amounts of high-resolution optical imagery of sea ice with the Digital Mapping System (DMS) (Dominguez, 2010, updated 2017). At ~10cm resolution, these images capture the ice surface in fine detail – but it is challenging to convert them to quantitative measures of ice conditions.

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A new technique for analyzing high-resolution optical imagery of sea ice has recently been developed and demonstrated (Wright and Polashenski, 2018). This technique, named the Open Source Sea-ice Processing algorithm (OSSP), automatically analyzes input imagery and classifies image area into four primary surface type categories: 1) snow and unponded ice, 2) dark or thin ice, 3) melt ponds and submerged ice, and 4) open ocean. Categories 1 and 2 are often combined to create a unified ice category. Several improvements and new features that define version 2 of OSSP are presented here. This version was used to create a new dataset by deploying the algorithm on a large scale to process the entirety of the NASA OIB optical image dataset. This dataset is now publicly available for community use and for other studies leveraging the IceBridge data suite. This publication is intended partially to serve as supporting documentation for those uses.

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The summer portion of the new dataset is then used to evaluate existing hypotheses about melt pond formation on Arctic sea ice. One such hypothesis describes the prevalence of ponds on first-year sea ice (FYI) versus multiyear ice (MYI). It has been widely stated that FYI has a higher average fractional pond coverage than MYI over the complete melt season (Eicken et al., 2004; Fetterer and Untersteiner, 1998a; Morassutti and Ledrew, 1996; Perovich and Polashenski, 2012). This would contribute to positive ice-albedo feedbacks, since the higher pond fraction would lower albedo of FYI, re-enforcing the transition to a younger ice pack. The reasoning most cited for expecting higher pond coverage on FYI is related to ice and snow topography (Barber and Yackel, 1999; Derksen et al., 1997; Eicken et al., 2004). When ice grows from open Arctic waters, it tends to form in flat, undeformed pans or fairly level pancake fields (Weeks, 2010). Though these pans are subsequently broken and ridged by dynamic forces, in most parts of the Arctic a large fraction of FYI remains level. When surface melt begins on level FYI floes, melt water is unconstrained by topography and spreads to cover a large fraction of the surface. On MYI, however, the ice has survived prior melt seasons that create more complex surface topography even in areas without mechanical deformation. The meltwater is then contained by the prior year's melt-formed topography into well-defined pools. The result *should be* that FYI would tend to experience greater pond coverage than MYI. Indeed, this has been presented by several authors as a likely change in the Arctic (Eicken et al., 2004; Polashenski et al., 2012).

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It is important to note that pond evolution over the melt season is highly variable and is controlled by the balance of melt water inflow and outflow rates, surface topography, and snow depth. There are four stages that characterize seasonal melt pond formation described in Eicken et al. (2002) and paraphrased as follows: (1) Initial onset of ponds above sea level with a rapid increase in areal coverage, (2) increased outflow allowing drainage to sea level with a decline in areal extent, (3) graduate increase in areal coverage due to ice melting to below ocean freeboard, and (4) refreezing. Despite a common understanding of high pond coverage on FYI, a collection of previous observations (Eicken et al., 2004; Perovich, 2002; Webster et al., 2015) have shown the possibility that FYI has lower pond coverage than MYI under certain circumstances. For example, in stage 2 areal coverage drops significantly more on FYI than it does on MYI (Polashenski et al., 2012). Observations at the SHEBA drifting ice camp found that 10-30% of the FYI in the region formed few melt ponds. Measurements there linked this observation to snow cover: Ice with little or no snow cover and with more than 0.5m snow cover had less than 1% pond coverage (Eicken et al., 2004). Webster et al., (2015) found regions where FYI started ponding much later than MYI, though the FYI ultimately developed higher pond coverage later in the summer. A new observational dataset of melt ponds on sea ice from OIB is used here to assess pond coverage differences between ice age at the height of summer melt (July), and to expand previous observations of pond-free FYI to regional scales.

A second, related, hypothesis on the behavior of FYI melt ponds suggests two summer melt evolution pathways exist: one which yields high pond fraction, and one that yields near-zero pond fraction (Perovich, 2002a; Polashenski et al., 2017), depending on early season ice permeability and the duration of surface flooding. Our new observations of pond coverage over large areas of FYI provide additional insight. Here, the OSSP-labeled OIB images were used to assess the variation in pond coverage on FYI and the prevalence of pond-free floes within the Chukchi and Beaufort Seas. To accomplish this, a method of post-processing has been developed that determines the size of sea ice areas devoid of pond coverage as a metric to quantitatively address the prevalence of low pond coverage. This new analysis reveals that FYI pond coverage indeed exhibits both pathways, but that there is *not* a strict duality – FYI pond coverage appears to occupy all states across the near-zero to high coverage space. While the OIB image dataset provides large spatial coverage over long flight transects, the lack of temporal coverage makes it impossible to directly link these snapshots of pond coverage to any specific pond evolution process.

2 Methods

2.1 Data Sources

The datasets described herein are the result of processing NASA Operation IceBridge optical DMS imagery. The DMS images were acquired with a Canon EOS 5D Mark II digital camera which has a 10cm horizontal ground resolution and a spatial footprint of ~600x400m when used at the survey altitude of 1500 feet (Dominguez, 2010, updated 2017), and is available for download at the National Snow and Ice Data Center (NSIDC). 87 IceBridge flights were processed, occurring between 2010 and 2018. The OIB flights were categorized into freezing and melting conditions, which map to the spring/fall and summer campaigns respectively. The mean date of melt onset in the Chukchi Sea, Beaufort Sea, and Central Arctic from 1979-2012 was May 17, May 28, and June 10 respectively (Bliss et al., 2014). Spring flights took place before these dates (March to mid-May, typically), and summer flights well after (mid to late

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July). No flights took place during melt or freeze onset transitional phases, making this a clean categorization: The flights between March and May were categorized as freezing condition flights (no melt ponds expected), and those taken in July were categorized as melting condition flights (melt ponds expected). One flight during fall freeze-up (October 5) was processed and was grouped with the spring set. Using this delineation, there were 9 flights during melting conditions and 78 flights during freezing conditions. Of the 9 melting condition flights, 4 occurred in 2016 originating from Utqiaġvik, Alaska, and 4 occurred in 2017 originating from Thule AFB, Greenland. There was an additional summer flight departing from Utqiaġvik on July 20th, 2016, that was not processed due to constant cloud cover obscuring the images.

A graphic of the flight tracks for all OIB sea ice flights processed, colored by freezing/melting condition status, is presented in Fig. 1. For the majority of this paper, we will focus on the melting season (summer) flights, colored in yellow. Spring data products are posted for use by the community. We anticipate that future analysis of spring flight data will help confirm lead identification in analysis of altimetry data and provide statistics on lead size and spacing and morphology useful to studies of, for example, blowing snow loss to leads or ice dynamics.

2.2 OSSP Algorithm Improvements

A number of improvements have been made to OSSP since the initial version 1 release described in Wright and Polashenski (2018). These changes can be divided into three categories: 1) Those that alter the algorithms used to classify images, 2) those which add new features, and 3) those which improve code efficiency but do not alter the core methodology. Changes that fall into category (3) reimplemented existing functions for improved performance and decreased computational resource usage. These will not be discussed in detail as they do not change the results.

2.2.1 Algorithm Refinements

OSSP is an object-based segmentation and classification image processing algorithm. In version 1, edge detection for segmentation was done by applying a Sobel-Feldman filter to the image, amplifying the resulting values to highlight strong edges, and thresholding low gradient value pixels to remove weak edges. The amplification factor and threshold value were both presented as tuning parameters that could control the number and strength of edges to detect in the image. In version 2, image edges are instead found with a Canny edge detector (van der Walt et al., 2014), which has three built-in tuning parameters: A gaussian filter with chosen radius that removes noise from the image, a high threshold which selects strong edges, and a low threshold which defines weak edges. These three parameters can be selected based on the quality of the input image and the degree of segmentation sought. The change in edge detection method does not significantly shift the behavior of the OSSP method but allows the user to better tune the segmentation to specific images. The remainder of the OSSP code uses methodology as presented in Wright and Polashenski (2018).

2.2.2 New Features

Four new features were added for processing the OIB optical image dataset: 1) An image quality analyzer which flags excessive cloud cover or haze, 2) an automatic white balance correction function, 3)

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expanded training datasets specific to OIB images, including shadow detection in spring images, and 4) orthorectification to a flat plane WGS84 spheroid.

Clouds and semi-opaque haze are common in OIB imagery. These often partly obscure the surface and prevent accurate image classification. An automated algorithm has been added that detects obscured images so that they can be removed from analysis. The quality check is based on applying a Fourier transformation to the image to detect the ratio of high and low frequency features. It is an implementation of the De and Masilamani (2013) method, where the quality score is the percent of image pixels that have a frequency greater than 1/100,000th of the maximum frequency. Poor quality images were empirically found to have a score of less than 0.025, potentially unusable images had a score between 0.025 and 0.035, and images with a score greater than 0.035 were generally acceptable.

A large number of OIB images are taken in poor surface lighting conditions. This is often a result of the aircraft flying under cloud cover or high solar zenith angles. Darker than expected and blue-shifted images are observed under these conditions. Unlike the hazy images flagged by the quality check, these can still be accurately classified. An automatic white balance correction function has been added to standardize the hue and exposure of these images and the resulting image classification. We use a single-point white balance algorithm:

$$\begin{bmatrix} R_c \\ G_c \\ B_c \end{bmatrix} = \begin{bmatrix} \frac{omax}{R_w} & 0 & 0 \\ 0 & \frac{omax}{G_w} & 0 \\ 0 & 0 & \frac{omax}{B_w} \end{bmatrix} * \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

where

$$\mathrm{omax} = \max\,(R_w, G_w, B_w)$$

and (R_w, G_w, B_w) is a chosen white reference pixel, (R,G,B) is the original pixel value triplet, and (R_c, G_c, B_c) is the corrected pixel value triplet. The reference point triplet is chosen automatically based on the image histogram of each color band; it is the smallest value that is both larger than the highest intensity peak and has less than 15% of that peak's pixel counts. This method sets the selected reference point to true white (255,255,255). All other pixels in the image are corrected with the same linear scaling which serves to both adjust the image exposure and rebalance the RGB ratios. The white reference pixel is limited to a minimum value of 200 for images with only a single surface. This prevents them from being improperly stretched so that an open water only image will remain black. The effect this color correction has on two poorly illuminated images is shown in Fig. 2.

The OIB dataset has a clear binary division between flights where melt ponds are expected (July), and those where they are not (March–May). This characteristic allows for the utilization of two specialized training datasets–one for each season. The summer training dataset is a new, larger, set than was presented along with OSSP v1.0, including additional points to encompass a wider range of possible ice conditions. The spring training dataset includes a ridge shadow surface classification class and does not include a melt pond category. The shadow detection method was not applied to melting condition images as the typical summer solar zenith angle yields fewer shadows. The algorithm allows melt pond and shadow detection to be used together given the correct training data, but this was not utilized for the creation of the dataset described here. Webster et al., (2015) found that ridge shadows make up less

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than 0.5% of the ice surface in spring, indicating that any errors due to misclassifying them are small. Removal of the melt pond category from spring images prevented occasional spurious detection of melt ponds and improved the quality of results. The training data creation followed the same technique presented in the OSSP version 1.0 documentation (Wright and Polashenski, 2018). The summer dataset was expanded to a total of 1706 training points, and the spring dataset to a total of 865 points. These training datasets can be found along with the OSSP code at (https://github.com/wrightni/ossp).

2.3 Detecting Pond-Free Ice Areas

The labeled image output by the OSSP algorithm was further analyzed to extract metrics about the spatial distribution of water features in summer. A technique was developed to find contiguous regions of pond-free ice. These regions were defined as a circle with diameter greater than 12m that does not overlap any water feature. First, the labeled image was converted into a binary image separating the snow and ice features from water (i.e. melt ponds plus ocean). Next, the distance from every snow/ice pixel to the nearest water feature was calculated, and peaks with a local maximum distance above a threshold of 12 meters were recorded. Pond free areas are the circle centered at these peaks with a radius of the distance to the nearest water feature. Any two overlapping regions were combined by adding the non-overlapping area of the smaller region to that of the larger region. These pond free regions are divided into two categories, small and large, based on a threshold of a 25 m radius. The thresholds of 12m and 25m were selected to be approximately 2x and 4x the mean caliper diameter of melt ponds (Huang et al., 2016). The number of pond free areas per image was multiplied by the ice fraction (sum of all non-ocean categories) of that image to account for differing ice concentrations between images. Figure 3 shows an example of this detection, where the location of both the small and large regions are marked with small dots and the large regions have a translucent circle showing the size of that region.

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2.4 Error

There are several sources of error in OSSP ice type classifications when applied to the DMS dataset. The established accuracy of the OSSP method, on a high-quality input image, is 96% (Wright and Polashenski, 2018). The principle source of error novel to this OIB dataset was due to lower quality images, typically from haze obscuring the surface or poor surface illumination. While automated methods standardize the quality of the input and flag bad images (Section 2.2.2), some input errors remain. The impact of uncorrected haze is twofold: First, it causes the algorithm to misclassify open water as melt pond, and second, it obscures surface type boundaries and causes insufficient image segmentation. Both issues can be understood by looking at how haze changes an optical image: It adds noise to the image, tends to brighten the pixel values, and blurs surface features. As the defining feature of open water is its uniform darkness, a layer of haze makes this surface more like a dark melt pond. The blurring impacts the edge detection algorithm used by OSSP and therefore causes a breakdown of the proper delineation of image surfaces. For the analyses of the summer dataset presented herein, images were manually sifted to remove those scenes that were not flagged by the QA analysis, but were still of questionable quality. Due to the heterogenous nature of sea ice, there is a trade-off between accuracy on a specific image and accuracy on the entire dataset – some images flagged as low quality may be usable with a training dataset tailored to those specific images. Users of this dataset should inspect their region of interest to ensure the image quality meets their desired standard.

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3 Results

3.1 Melt pond fraction along OIB flight tracks

In this paper we focus on presenting results from summer images only. Images from 87 IceBridge flights were processed with the OSSP algorithm representing over 900,000 individual images using the methods described above – these results are available for other investigations at the NSIDC archive. Figure 4 maps the track of every melt season OIB flight and plots melt pond fraction observed along these tracks. Melt pond fraction was calculated as the number of melt pond pixels divided by the total ice area (ice pixels + pond pixels). Images where more than 70% of the area was classified as open water are colored black in Figure 4 but were processed normally. Images that were automatically removed due to a low quality score (section 2.2.2) are colored orange, and images that were manually removed due to low image quality are colored red. In total, 40,672 summer images were analyzed, of which 14,876 (36.6%) were flagged with a low quality score, 5,671 (13.9%) were manually removed, and 20,125 (49.5%) were kept for this analysis. The July 20th, 2016 flight was not processed because only about 2% (30 total) of the images were haze free. Note both high variation in pond coverage along track and general regional changes between flights. Some additional variation between flights is due to temporal change, for example it appears a summer snow occurred just prior to the July 19, 2016 flight, lowering the observed pond fraction.

Figure 5 plots 300km of the along-track melt pond fraction for the July 24th, 2017 flight. This figure illustrates the large variability possible in melt pond fraction along track seen in the first half of the flight (top), with a minimum observed fraction of 10% and spikes to greater than 50%. The second half of this flight (bottom) has a more uniform melt pond fraction of ~20%. Four peaks are highlighted in orange where a large blue pond formed on the MYI (See Fig. 11d). Figure 6a zooms in to a 10km subset of this transect, and the surface corresponding to the orange highlighted section is shown in Fig. 6b. The optical image is the result of stitching 23 DMS images together. The highlighted peak in melt pond fraction occurs on a section of FYI between two multiyear floes. This case follows the prevailing hypothesis about the differences between pond formation on MYI and FYI. The relatively flat FYI section allows melt ponds to spread over the surface more evenly, resulting in a higher melt pond coverage, despite encountering the same atmospheric conditions as the MYI on either side. It is also possible that melt water from the MYI drains to the lower elevation FYI (Fetterer and Untersteiner, 1998a).

3.2 Influence of Ice Type on Melt Pond Fractions

Each summer transect was categorized into first-year ice, multiyear ice, or mixed ice based on manual inspection of those flight's images. The flights classed as a single ice type had at least 90% (estimated from visual inspection) of that type. Melt pond statistics for single ice type flights are shown as box and whisker plots in Fig. 7, where each flight is colored by its ice type categorization; blue for FYI and green for MYI. In these plots the box outline shows the 75th and 25th percentile, the middle line displays the median, the whiskers show 1.5x the interquartile range, and the red points are outliers. Generally, the 2016 flights departing from Utqiaġvik, Alaska, observed FYI while the 2017 flights departing from Thule AFB, Greenland, observed MYI. There are three exceptions to this categorization: July 13, 2016 and July 19, 2016 contain both ice types, where small pockets of MYI were included in the northern sections of an otherwise primarily FYI region, and flight A on July 25th, 2017 covers FYI. Statistics for the two mixed ice type flights are plotted separately in Fig. 8, where each flight is divided into FY or MY ice categories.

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Figure 7 reveals two insights into the difference in melt pond fractions between FYI and MYI. First, there is no obvious difference in the median pond fraction between flights, and second, there is more variance in the pond fractions on FYI. The variance is described by the interquartile range, the mean of which is 0.1 for the first-year flights and 0.05 for the multiyear flights. In other words, while FYI exhibited a wider range of possible pond fractions, the average coverage is not observed to be higher than on MYI. The difference in timing and region between OIB flights precludes drawing general conclusions about differences in median melt pond fraction between ice types. However, two flights that contained both FY and MY ice were selected for further analysis to investigate melt pond statistics across ice that experienced similar forcing conditions: July 19, 2016 and July 13, 2016. The portions of these transects that depict each ice type were manually determined. Results, delineated by ice type, for these two flights are shown in Fig. 8. The key observation here is that the two flights show opposite relationships: On July 19 the FYI has a lower median pond fraction, while on July 14, the FYI has a higher median pond fraction. Previous work has shown the possibility for FYI to have lower pond cover than MYI at local scales (i.e. individual floes) (Eicken et al., 2004, Webster et al., 2015). Our results support this observation and show that it can also happen at regional scales. That pond coverage is more variable on FYI than it is on MYI suggests that while ponds evolve differently on each type there is not a simple relationship in mean pond fraction. In other words, one cannot conclude that FYI has either higher or lower pond fractions than MYI.

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However, this comparison may not address the hypothesis that pond coverage is higher on FYI because flight lines occurring over two years and were exposed to unique forcing conditions. To investigate melt pond statistics across ice that experienced similar forcing conditions, two flights that contained both FY and MY ice were selected for further analysis:

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3.3 Observations of Pond-Free First-year Ice

The frequency at which FYI develops very low pond coverage was investigated using the pond-free region detection algorithm to find large unponded areas. Figure 9 shows the results of applying this algorithm to selected segments of the July 19, 2016 flight. Panel (a) shows the results for a portion of primarily FYI with high pond coverage, (b) shows a region of FYI that has many areas of pond-free ice, and (c) shows results from a section of MYI. The ice analyzed for Fig. 9a is what we understand would be considered as a common state for FYI in an advanced state of melt, where ponds have drained to sea level but a high portion of the ice floe remains below freeboard and yields a uniformly high pond fraction. This state coincides with the third stage of pond evolution. This contrasts with the FYI analyzed for Fig. 9b where, while melt ponds are still present, there are large open areas of pond free ice. The ponds on the MY floe are regularly distributed and the fractional pond coverage shows little variance. This could coincide with stage 2 of pond evolution, where ponds have drained and none remain above freeboard, or to a region where ponds never formed. A timeseries would be required to distinguish these paths. Expanding from these regions of this specific flight, 17% of all summer FYI images processed for this study have 3 or more large pond free regions. This reinforces previous observations by Eicken et al. (2004) that estimated 10 to 30% of FYI surrounding the SHEBA ice camp had “low or zero pond cover”. In contrast, in the MYI portion of this dataset, only 5% of images have 3 or more large pond free regions. While there is a clear difference between the MYI and FYI types, the important observation here is the large percentage of FYI that has lower than expected pond coverage.

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3.4 Snapshots of a Summer Sea Ice Cover

In processing the Operation IceBridge optical imagery dataset, we have had the unique opportunity to review a significant library of images detailing different sea ice states, looking at thousands of square km of sea ice. So few people actually observe the sea ice that notions of what is ‘typical’ or unusual are still not well known. In this section we present some examples of what we have observed to be 'representative' ice states, and examples of ice conditions that are uncommon. These are intended to serve as a qualitative summary of the extensive OIB observations, against which future campaigns can be quickly compared. For each presented image we label the noted features based on the frequency at which we have observed them. Along an arbitrary 100km transect of ice in a given melt state; *common* describes a feature that can be expected on more than half of the ice, *occasional* describes features that would be expected to show up 5-10 times, and *infrequent* describes a feature that may present once or twice.

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Sea ice scenes shown in Fig. 10: **(a)** FYI that shows a wide range of the possible melt pond fractions, ranging from pond free to high pond coverage; *occasional*. **(b)** Highly ponded level FYI scene in early melt, where ice appear as islands in a sea of water. Such ice was *common* in large areas in the Chukchi sea. **(c)** FYI with high pond fraction and very interconnected pond structure. *Common*; this represents the generally understood behavior of FYI. Here we also see that ponds preferentially form towards the middle of the floe leaving a pond-free border around the edge. The floe-edge gradients are particularly strong in this image, the pond-free border is an *occasional* feature. **(d)** Example of a floe where ponds preferentially form away from the edges. These small floes with central ponds were common in broken FYI. **(e)** Shorefast level ice in the Lincoln sea. Ponds have started to drain already, as evidenced by the drainage channels visible throughout the ice. This type of relatively low coverage and consolidated ponds were *infrequent* in the OIB dataset, but may be common of ice in this region. We speculate that deep snow dunes and thick ice are responsible. **(f)** This image shows a region that appears to have had a recent summer snowfall event. The snow serves to fill shallow ponds with slush or to completely cover them and significantly lowers pond fraction – *infrequent* in the OIB dataset as it is dependent on specific weather conditions. **(g)** A *common* example of high pond fraction FYI. **(h)** Flat and thin ice pans that are almost completely covered by melt water, this scene is *common* for late stages of melt on FYI.

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Sea ice scenes shown in Fig. 11: **(a-c)** *Common* examples of ponded MYI floes with characteristically blue ponds that are well consolidated by surface topography, showing the range of pond fractions that are possible. **(d)** Example of large reservoir-like ponds that were only observed on MYI. These are *occasional* features on large sections of MYI. **(e)** MYI with FYI inclusions from ocean that refroze during the last winter, this is *common* for MYI at lower latitudes, and *occasional* at higher latitudes. In cases of small FYI inclusions in MYI fields like this, the FYI ice is typically darker had has a higher pond coverage. **(f)** An example of low pond coverage MYI – this was *infrequent* in the OIB dataset. **(g+h)** Ponded FYI undergoing drainage, where evidence of previous ponds is still visible. The overall image represents *common* features, but the drainage pattern here is *infrequently* observed, likely due to its short lifespan.

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4 Discussion

4.1 Variation in Pond Coverage on FYI Precludes Simple Relationship with MYI

A general consensus in the sea ice community indicates that FYI has, on average, higher melt pond coverage than does MYI. While such an understanding of ponds is not universally held, it is prevalent and represents a testable hypothesis which our results above did not support. However, it should be noted that our dataset represents a single snapshot in time, and while many melt states were observed in this dataset, it is impossible to assess seasonal averages of melt pond coverage here. The reasoning for the hypothesis is two part, covering both early season FYI ponding (when meltwater sits on impermeable ice above sea level) and late season FYI ponding (after ponds have drained to sea level). In the early season case, it is argued that with limited topography, a similar volume of meltwater will flood larger areas of FYI than it would cover on rougher MYI. This is supported by observations in early melt stages, which show FYI melt pond coverage in excess of 60%. Such coverage exceeds that seen on MYI at any time (Landy et al., 2014; Polashenski et al., 2012). In the late season case, it has been argued that thinner FYI will have less buoyancy and less ice area above freeboard. In both cases, FYI ponds would be greater than MYI. These effects must be balanced with the times in melt evolution where FYI is expected to have lower MPF. In the early season, MPF on FYI tends drop faster than on MYI because the meltwater is able to drain to sea level at a faster rate (Polashenski et al., 2012), and in the late season pond fractions on thicker FYI would be lower than MYI because the level surface would have fewer depressions that sit below freeboard (e.g. Figure 10d).

An alternate hypothesis about the behavior of FYI ponds emerging in some recent papers is that FYI pond coverage is extremely variable and may have bimodal evolution driven by snow topography and permeability (Perovich, 2002b; Polashenski et al., 2017; Popović et al., 2018). FYI ponds may not form at all under certain circumstances if the ice is highly permeable or lacks snow cover (Polashenski et al., (2017) and references therein). Other observations show very high melt pond coverage that persists even after ponds drain to sea level (Polashenski et al., 2015). These divergent possibilities of pond behavior raise the possibility of bimodal behavior wherein some FYI would flood extensively and experience more ponding than MYI while other FYI might not pond at all. The image dataset analysed in this study does not support the bimodal hypothesis, but rather supports the idea that FYI pond coverage is highly variable, existing in all states from low to high pond cover. Diurnal effects can also play a large role in the melt pond fraction on FYI by significantly changing surface melt rates on short time scales, and could therefore be a cause of the high variability seen in our dataset (Eicken et al., 2004; Hanesiak et al., 1999). Understanding the distribution of MPF on basin wide scales would be key to understanding whether the transition from MY to FYI has a net increase on pond prevalence. No large scale, comprehensive observations have been available to resolve how prevalent such behaviors are.

Our image dataset provides some such information on the nature of FYI ponding, but has limitations due to each flight being a temporal snapshot. The time covered by the images is late in the melt season, when much of the FYI is fully permeable and ponds, if any formed, have drained to sea level (see Polashenski et al. (2012) or Eicken et al. (2002) for a description of the stages of pond evolution). Evidence of pond drainage features is common, and we conclude the ponds are largely at sea level. Polashenski et al., (2012) showed that ponds remaining after pond levels drain to sea level are simply those areas where the ice surface floats below sea level. The late season pond fraction is then topographically forced. If the surface of the ice is level when ponds drain, the ice surface will be uniformly above sea level, leaving pond-free ice. If, however, snow dunes or differential melt creates roughness on the surface, some of the surface will protrude from the ocean significantly and other areas will not, creating the possibility for ponds to remain at sea level. If topography is the primary driver of pond fraction, we expect FYI pond coverage late in the year would be highly variable; low on FYI that remains smooth, higher on moderately rough FYI, and lower again on the roughest FYI (see Popović et al., (2018) for more discussion). Given the range of outcomes and range of snow/ice topography on FYI, there would not be a characteristic relationship between pond coverage on FYI and adjacent MYI.

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Examining the pond coverage in more detail provides evidence that the range of possible melt states is larger on FYI than it is on MYI. In other words, FYI exhibits all possible states between low and high coverage, while MYI pond fraction typically exists within a small window. Returning to the boxplots in Fig. 7, note the larger interquartile range (IQR) of the first-year flights versus the multiyear flights. If we were to accept the traditional hypothesis that all FYI had high pond cover, we would expect the FYI to have a higher median but a similar IQR. However, this is not the case. These observations suggest pond cover on FYI is highly variable, and only in a subset of circumstances does the ice exhibit the expected higher pond fraction. Examples of each behavior are included in Fig. 8. The traditional understanding of melt pond evolution on FYI, where flat undeformed ice allows melt water to spread horizontally and create large areas of pond covered ice is often observed on landfast ice or ice attached to a multiyear floe (e.g. Barber and Yackel, 1999; Derksen et al., 1997; Fetterer and Untersteiner, 1998b; Uttal et al., 2002). For example, Fig. 6b shows a refrozen lead between two MYI floes, where the pond fraction is significantly higher on the flat FYI than on either of the adjoining MYI floes. Along the July 19, 2016 transect many of the smaller (less than 200m diameter) freely floating floes of flat FYI exhibited little to no pond cover late in the melt season (as seen in Fig. 10d). We also note many examples of floes that are pond free along their edges, such as in Fig. 10c, and floes that exhibit nearly complete pond coverage (such as 10b,g,h). This dataset, therefore, helps establish that no simple relationship between FYI and MYI ponding exists, and presents the possibility that the transition to FYI is not causing uniformly higher melt pond fraction, as has been expected. Due to the temporal variability in pond evolution, complete timeseries datasets are needed to fully analyze the relationship between MPF and ice age. The highly variable nature of FYI ponding is, however, regionally coherent, strongly suggesting that the history of conditions the ice is subject to governs ponding. Connecting conditions to pond prevalence is therefore a topic worthy of investigation for better understanding FYI albedo feedbacks.

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5 Conclusion

A new dataset quantifying sea ice surface fractions observed in Operation IceBridge DMS imagery has been created using the recently developed OSSP algorithm. This dataset classifies the surface coverage into four categories. During the melt season these categories are: 1) snow or thick ice, 2) dark or thin ice, 3) melt ponds and submerged ice, and 4) open water. In freezing conditions, the categories become 1) snow or thick ice, 2) dark or thin ice, 3) open water, and 4) ridge shadows. The dataset allows for the investigation of sea ice surface type distributions along OIB transects and opens the door for new studies, both by analysing this dataset in isolation (as demonstrated here), and by combining it with coincident OIB datasets such as ice thickness or ice roughness. This dataset is available at the NSDIC for community use. Future improvements to this dataset should include work towards a more sophisticated haze removal algorithm to apply to the OIB optical images. This will increase accuracy and increase the fraction of images that can be successfully processed.

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We have investigated snapshots of melt pond coverage differences between FYI and MYI in the Beaufort/Chukchi Sea region for 2016 and the Lincoln Sea for 2017. Our results support previous findings that FYI can have lower pond fraction than MYI under similar forcing conditions. While the results presented herein cannot definitively confirm or refute the hypothesis that FYI has higher mean pond fraction than MYI, the high variability in FYI pond fraction over large regions suggests that the general rule of thumb that FYI should have higher ponding than MYI is too simplistic. Furthermore, the

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finding that FYI exhibits much larger variance over its temporal evolution indicates that there is not one path that defines the typical pond coverage changes. We did not find sufficient evidence that there is a strict duality in FYI pond evolution either, and we suggest future process studies investigate the mechanisms that drive FYI towards high or low pond fraction and specifically note that time-series image observations and/or field studies may be necessary to unravel this question. The different trajectories that pond development can apparently take on FYI may have large impacts on sea ice modelling efforts, through albedo feedbacks. Furthermore, we suggest combining this new melt pond dataset with data available from the IceBridge Airborne Topographical Mapper to determine the relationship between sea ice topography and melt pond formation.

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Data and Code Availability. The OSSP algorithm code is available on github (https://github.com/wrightni/ossp) and the release for this manuscript is archived at zenodo (DOI: 10.5281/zenodo.3551033). The pond free detection algorithm will be archived at zenodo prior to publication and is available at github (https://github.com/wrightni/pondfree_detection) during review. Raw Operation IceBridge DMS imagery is available from the National Snow and Ice Data Center (https://doi.org/10.5067/OZ6VNOPMPRJ0). OSSP generated results are also archived at the NSDIC (https://doi.org/10.5067/1LI57H56EB7G).

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Author Contributions. NW was responsible for writing the original draft, creating the data visualizations, review and editing of the manuscript, designing and testing the OSSP software, conceptualization and programming of the pond-free detection algorithm, and formal analysis of the OSSP generated results. CP was responsible for initiating the study, contributing to writing and editing the manuscript, and contributing to methodology and result analysis. SM was responsible for implementing the OSSP software on NASA’s Pleiades system, monitoring data processing, and data archiving. RB was responsible for funding acquisition and supervision for the Ames Research Center team and for review and editing of the manuscript draft.

Conflicts of Interest. The authors declare that they have no conflicts of interest.

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References

Barber, D. G. and Yackel, J.: The physical, radiative and microwave scattering characteristics of melt ponds on Arctic landfast sea ice, Int. J. Remote Sens., 20(10), 2069–2090, doi:10.1080/014311699212353, 1999.

Curry, J. A., Schramm, J. L. and Ebert, E. E.: Sea ice-albedo climate feedback mechanism, J. Clim., 8(2), 240–247, doi:10.1175/1520-0442(1995)008<0240:SIACFM>2.0.CO;2, 1995.

De, K. and Masilamani, V.: Image Sharpness Measure for Blurred Images in Frequency Domain, Procedia Eng., 64, 149–158, doi:10.1016/J.PROENG.2013.09.086, 2013.

Derksen, C., Piwowar, J. and LeDrew, E.: Sea-Ice Melt-Pond Fraction as Determined from Low Level Aerial Photographs, Arct. Alp. Res., 29(3), 345–351, doi:10.1080/00040851.1997.12003254, 1997.

Dominguez, R.: IceBridge DMS L0 Raw Imagery, Version 1, , doi:10.5067/UMFN22VHGGMH, 2010.

Eicken, H., Grenfell, T. C., Perovich, D. K., Richter-Menge, J. A. and Frey, K.: Hydraulic controls of summer Arctic pack ice albedo, J. Geophys. Res. C Ocean., 109(8), doi:10.1029/2003JC001989, 2004a.

Fetterer, F. and Untersteiner, N.: Observations of melt ponds on Arctic sea ice, J. Geophys. Res. Ocean., 103(C11), 24821–24835, doi:10.1029/98JC02034, 1998.

Hanesiak, J. M., Barber, D. G. and Flato, G. M.: Role of diurnal processes in the seasonal evolution of sea ice and its snow cover, J. Geophys. Res. Ocean., 104(C6), 13593–13603, doi:10.1029/1999JC900054, 1999.

Huang, W., Lu, P., Lei, R., Xie, H. and Li, Z.: Melt pond distribution and geometry in high Arctic sea ice derived from aerial investigations, Ann. Glaciol., 57(73), 105–118, doi:10.1017/aog.2016.30, 2016.

Hunke, E. C., Hebert, D. A. and Lecomte, O.: Level-ice melt ponds in the Los Alamos sea ice model, CICE, Ocean Model., 71, 26–42, doi:10.1016/j.ocemod.2012.11.008, 2013.

Landy, J., Ehn, J., Shields, M. and Barber, D.: Surface and melt pond evolution on landfast first-year sea ice in the Canadian Arctic Archipelago, J. Geophys. Res. Ocean., 119(5), 3054–3075, doi:10.1002/2013JC009617, 2014.

Miao, X., Xie, H., Ackley, S., Perovich, D. and Ke, C.: Object-based detection of Arctic sea ice and melt ponds using high spatial resolution aerial photographs, Cold Reg. Sci. Technol., 119, 211–222, doi:10.1016/j.coldregions.2015.06.014, 2015.

Morassutti, M. P. and Ledrew, B. F.: Albedo and depth of melt ponds on sea-ice, Int. J. Climatol., 16(7), 817–838, doi:10.1002/(SICI)1097-0088(199607)16:7<817::AID-JOC44>3.0.CO;2-5, 1996.

Perovich, D. and Polashenski, C.: Albedo evolution of seasonal Arctic sea ice, Geophys. Res. Lett., 39(8), n/a-n/a, doi:10.1029/2012GL051432, 2012.

Perovich, D., Grenfell, T., Richter-Menge, J., Light, B., Tucker, W. and Eicken, H.: Thin and thinner: Sea ice mass balance measurements during SHEBA, J. Geophys. Res. Ocean., 108(C3), doi:10.1029/2001JC001079@10.1002/(ISSN)2169-9291.SHEBA1, 2003.

Perovich, D. K.: Aerial observations of the evolution of ice surface conditions during summer, J. Geophys. Res., 107(C10), 8048, doi:10.1029/2000JC000449, 2002a.

Perovich, D. K.: Aerial observations of the evolution of ice surface conditions during summer, J. Geophys. Res., 107(C10), 8048, doi:10.1029/2000JC000449, 2002b.

Polashenski, C., Perovich, D. and Courville, Z.: The mechanisms of sea ice melt pond formation and evolution, J. Geophys. Res. Ocean., 117(C1), n/a-n/a, doi:10.1029/2011JC007231, 2012.

Polashenski, C., Perovich, D. K., Frey, K. E., Cooper, L. W., Logvinova, C. I., Dadic, R., Light, B., Kelly, H. P., Trusel, L. D. and Webster, M.: Physical and morphological properties of sea ice in the Chukchi and Beaufort Seas during the 2010 and 2011 NASA ICESCAPE missions, Deep Sea Res. Part II Top. Stud. Oceanogr., 118, 7–17, doi:10.1016/J.DSR2.2015.04.006, 2015.

Polashenski, C., Golden, K., Perovich, D., Skyllingstad, E., Arnsten, A., Stwertka, C. and Wright, N.: Percolation blockage: A process that enables melt pond formation on first year Arctic sea ice, J. Geophys. Res. Ocean., 122(1), 413–440, doi:10.1002/2016JC011994, 2017.

Popović, P., Cael, B. B., Silber, M. and Abbot, D. S.: Simple Rules Govern the Patterns of Arctic Sea Ice Melt Ponds, Phys. Rev. Lett., 120(14), 148701, doi:10.1103/PhysRevLett.120.148701, 2018.

Serreze, M. C., Barrett, A. P., Stroeve, J. C., Kindig, D. N. and Holland, M. M.: The emergence of surface-based Arctic amplification, Cryosphere, 3(1), 11–19, doi:10.5194/tc-3-11-2009, 2009.

Stroeve, J. C., Serreze, M. C., Holland, M. M., Kay, J. E., Malanik, J. and Barrett, A. P.: The Arctic's rapidly shrinking sea ice cover: a research synthesis, Clim. Change, 110, 1005–1027, doi:10.1007/s10584-011-0101-1, 2012.

Uttal, T., Curry, J. A., Mcphee, M. G., Perovich, D. K., Moritz, R. E., Maslanik, J. A., Guest, P. S., Stern, H. L., Moore, J. A., Turenne, R., Heiberg, A., Serreze, M. C., Wylie, D. P., Persson, O. G., Paulson, C. A., Halle, C., Morison, J. H., Wheeler, P. A., Makshtas, A., Welch, H., Shupe, M. D., Intrieri, J. M., Stamnes, K., Lindsey, R. W., Pinkel, R., Pegau, W. S., Stanton, T. P., Grenfeld, T. C., Uttal, T., Curry, J. A., Mcphee, M. G., Perovich, D. K., Moritz, R. E., Maslanik, J. A., Guest, P. S., Stern, H. L., Moore, J. A., Turenne, R., Heiberg, A., Serreze, M. C., Wylie, D. P., Persson, O. G., Paulson, C. A., Halle, C., Morison, J. H., Wheeler, P. A., Makshtas, A., Welch, H., Shupe, M. D., Intrieri, J. M., Stamnes, K., Lindsey, R. W., Pinkel, R., Pegau, W. S., Stanton, T. P. and Grenfeld, T. C.: Surface Heat Budget of the Arctic Ocean, Bull. Am. Meteorol. Soc., 83(2), 255–275, doi:10.1175/1520-0477(2002)083<0255:SHBOTA>2.3.CO;2, 2002.

van der Walt, S., Schönberger, J. L., Nunez-Iglesias, J., Boulogne, F., Warner, J. D., Yager, N., Gouillart, E. and Yu, T.: scikit-image: image processing in Python, PeerJ, 2, e453, doi:10.7717/peerj.453, 2014.

Webster, M. A., Rigor, I. G., Perovich, D. K., Richter-menge, J. A., Polashenski, C. M. and Light, B.: Seasonal evolution of melt ponds on Arctic sea ice, J. Geophys. Res. Ocean., 120(9), 1–15, doi:10.1002/2015JC011030, 2015.

Weeks, W.: On Sea Ice, University of Alaska Press. [online] Available from: https://books.google.de/books?id=9S55O6WzuL8C (Accessed 18 January 2018), 2010.

Wright, N. and Polashenski, C.: Open-source algorithm for detecting sea ice surface features in high-resolution optical imagery, Cryosphere, 12(4), 1307–1329, doi:10.5194/tc-12-1307-2018, 2018.

Figures

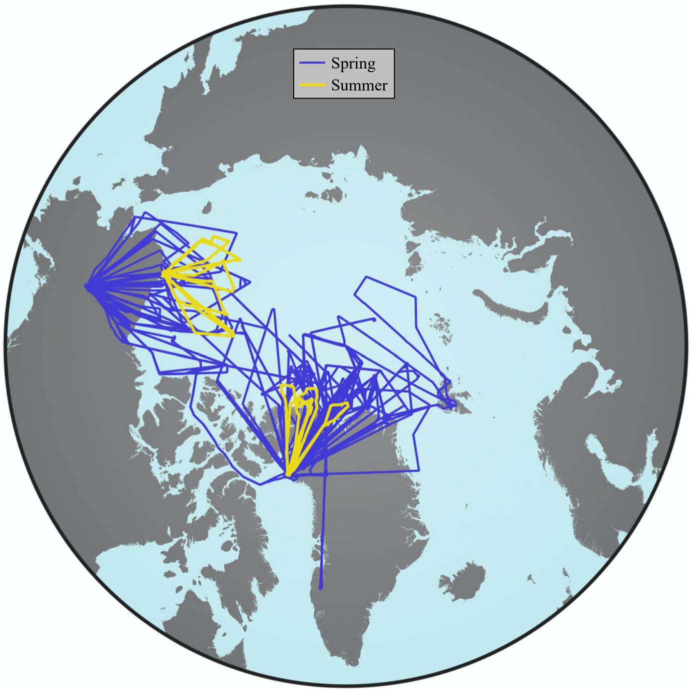

Figure 1. Plot of all flights processed with OSSP, colored by the melt conditions during the flight. Spring freezing conditions in blue, and summer melting conditions in yellow.

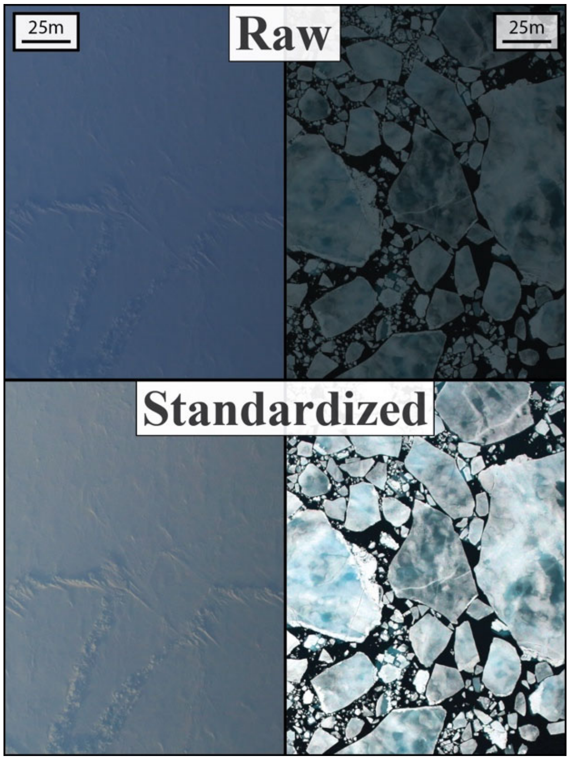

Figure 2. Demonstration of the image preprocessing steps. The raw images (top) have poor surface illumination and a blue hue, both of which have been removed in the standardized images (bottom).

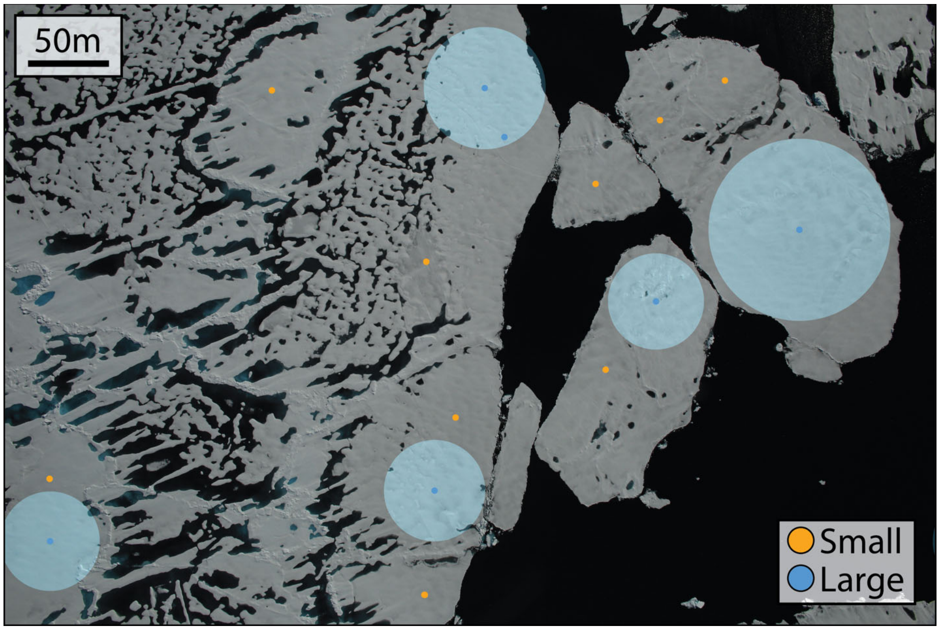

Figure 3. Example of the pond free region detection. Pond free regions are marked by small colored dots, where blue dots indicate the larger regions and orange indicates the smaller ones. Translucent blue circles are drawn with a radius equal to the size of the detected large regions. Blue dots without a translucent circle were merged with a neighboring region.

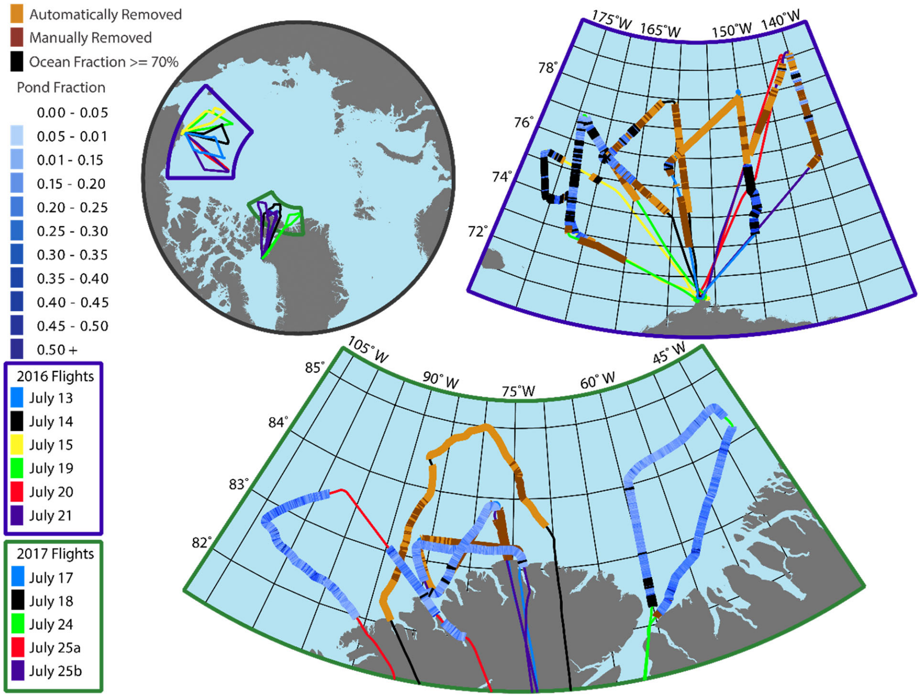

Figure 4. Melt pond fraction along OIB summer transects. Automatically and manually removed images are indicated by orange and red, respectively. 2016 flights were more prone to haze obscuring the ice surface and therefore have more deleted images.

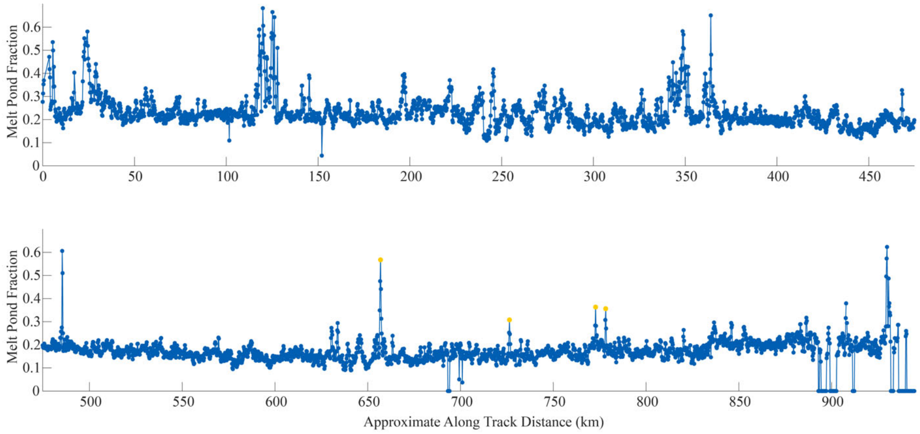

Figure 5. Melt pond fraction along track for flight July 24, 2017. The four orange highlighted points represent areas where there was a large blue pond on the multiyear ice that occupied a large fraction of the image. See Fig. 11d for an example of this feature.

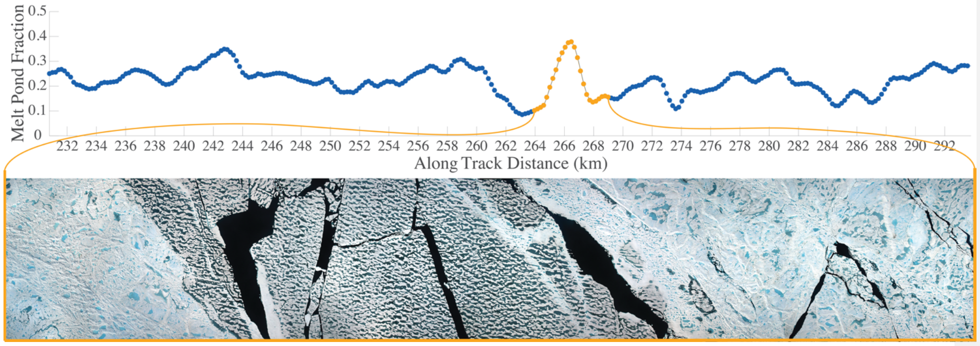

Figure 6. Melt pond fraction along a several kilometer section of the July 24, 2017 flight. The orange highlighted region is depicted as a series of stitched together DMS images that show a first-year inclusion between two multiyear floes.

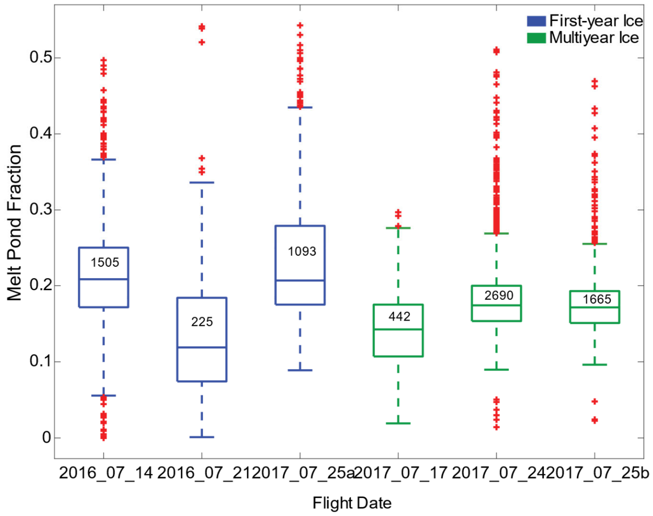

Figure 7. Melt pond statistics from summer OIB flight which contained only a single ice type. Blue corresponds to first-year ice statistics, green to multiyear ice statistics, and red crosses indicate outliers. **The number** of image frames used to calculate statistics for each flight is included inside the box. The approximate area of each image frame is 0.25 km^2.

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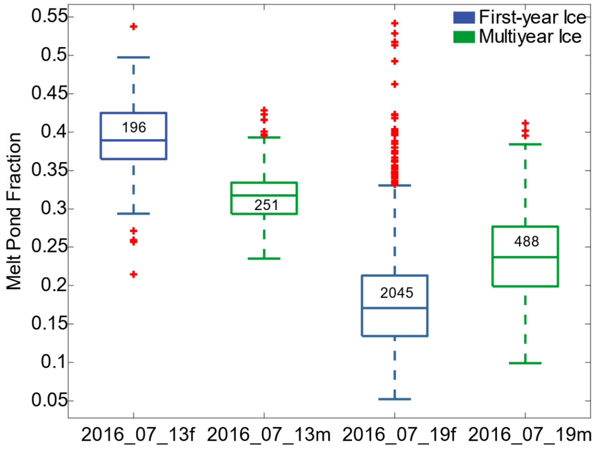

Figure 8. Melt pond statistics from two flights that contain both first-year and multiyear ice. In the July 13 case, multiyear ice has a lower pond fraction, while in the July 19 case the first-year ice has a lower pond fraction. Blue corresponds to first-year ice statistics, green to multiyear ice statistics, and red crosses indicate outliers. The number of image frames used to calculate statistics for each flight is included inside the box. The approximate area of each image frame is 0.25 km^2

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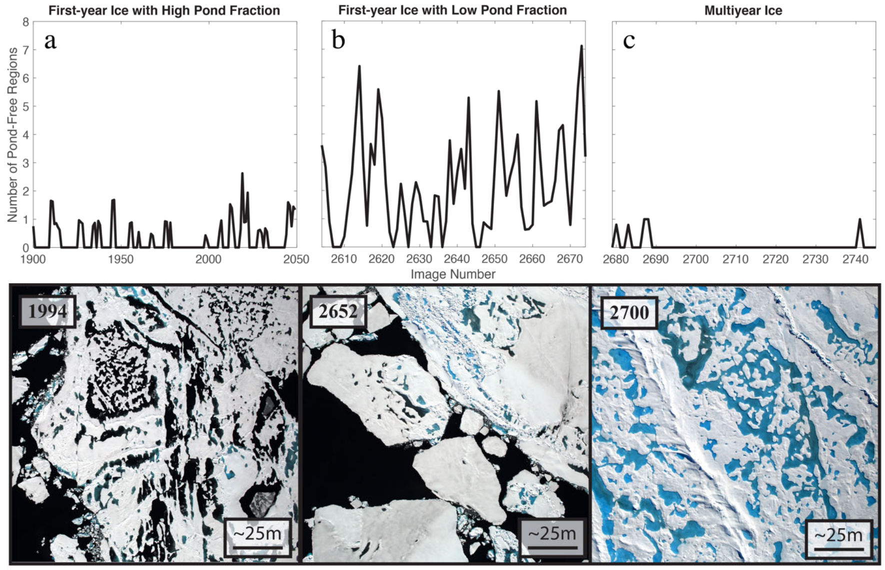

Figure 9. Number of pond-free regions on several regions of sea ice observed during the July 19, 2016 flight (top) and a sample image representing that region of ice (bottom).

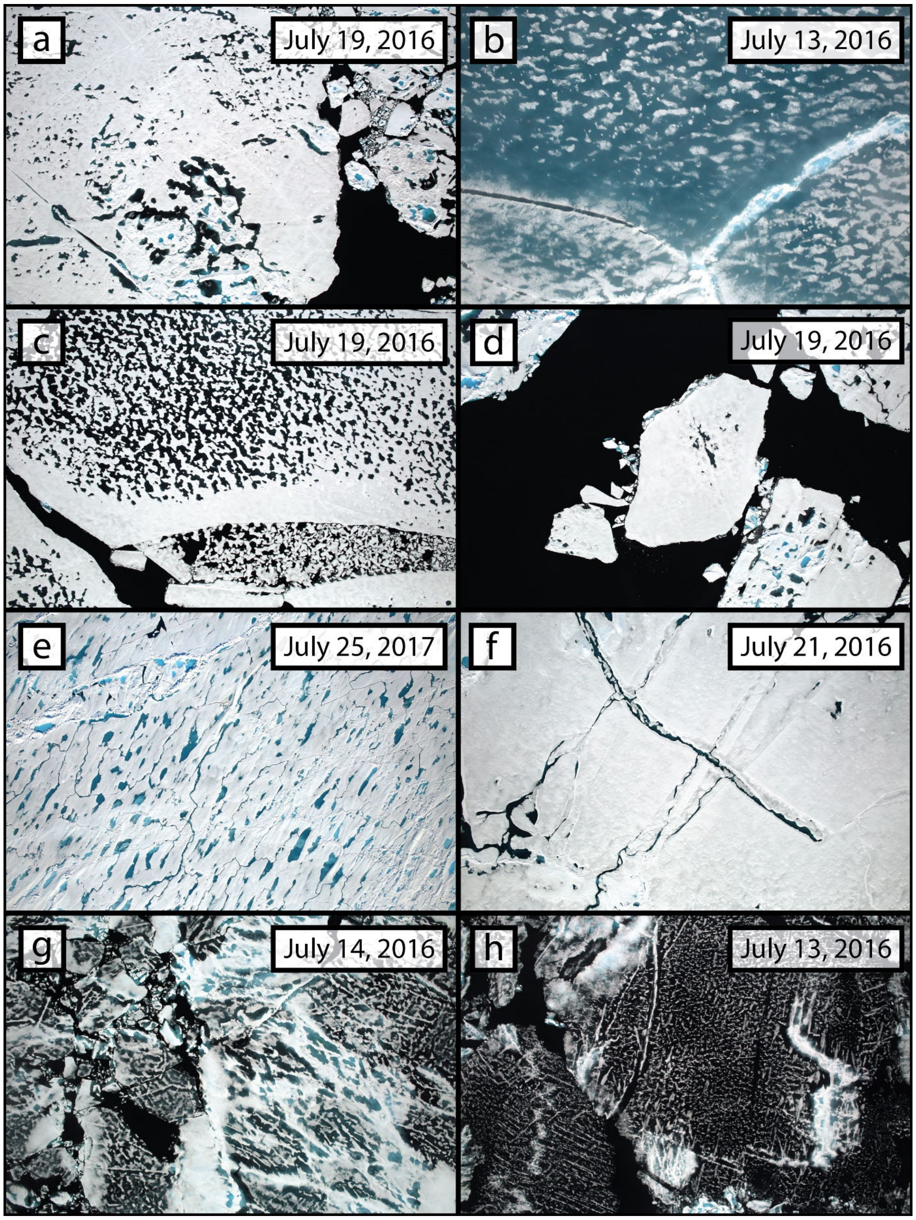

Figure 10. Exhibits of sea ice surface features as seen in the DMS dataset. Each panel is a full IceBridge image, and while flight altitude affects image resolution, each scene is approximately 600 m by 400 m. See text for full description of each frame.

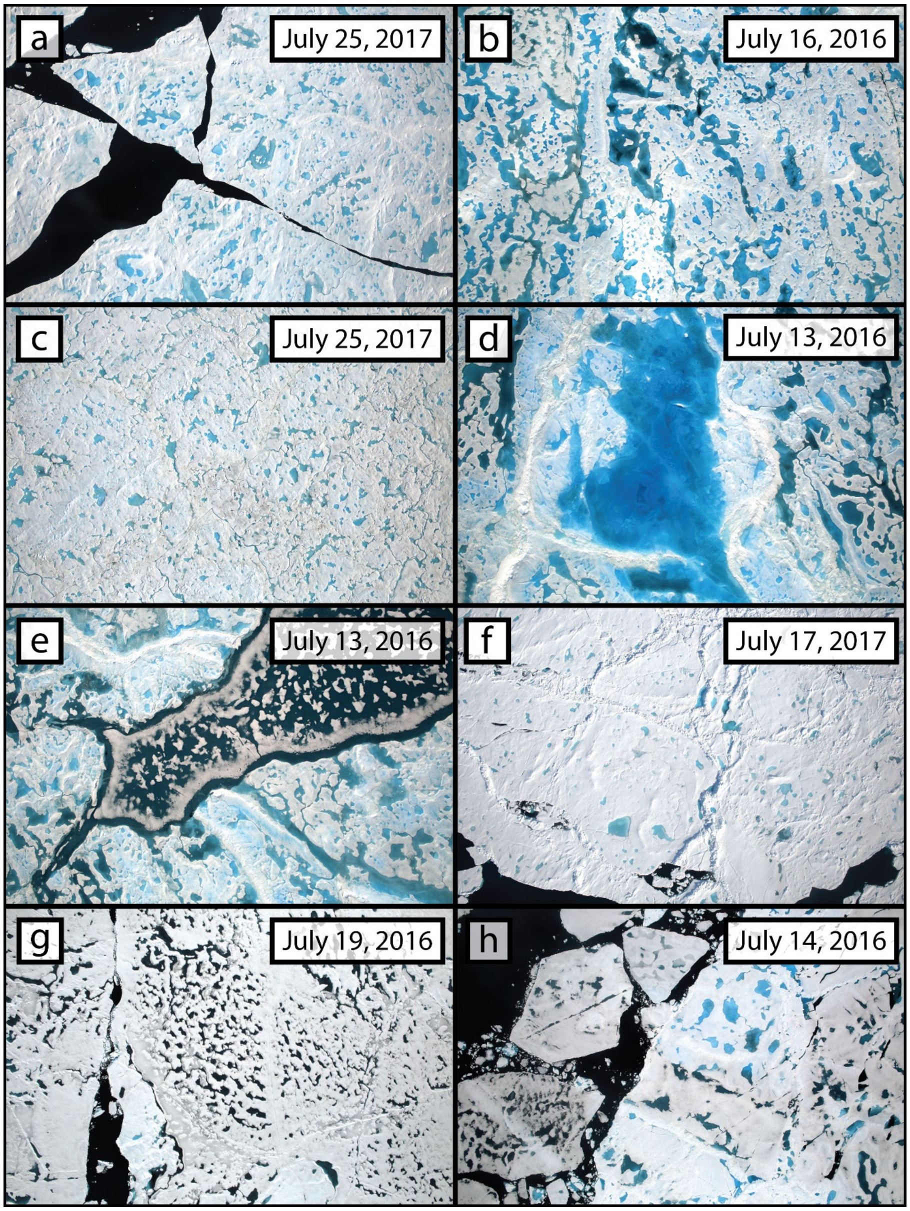

Figure 11. Exhibits of sea ice surface features as seen in the DMS dataset. Each panel is a full IceBridge image, and while flight altitude affects image resolution, each scene is approximately 600 m by 400 m. See text for full description of each frame.

Supplemental Figures:

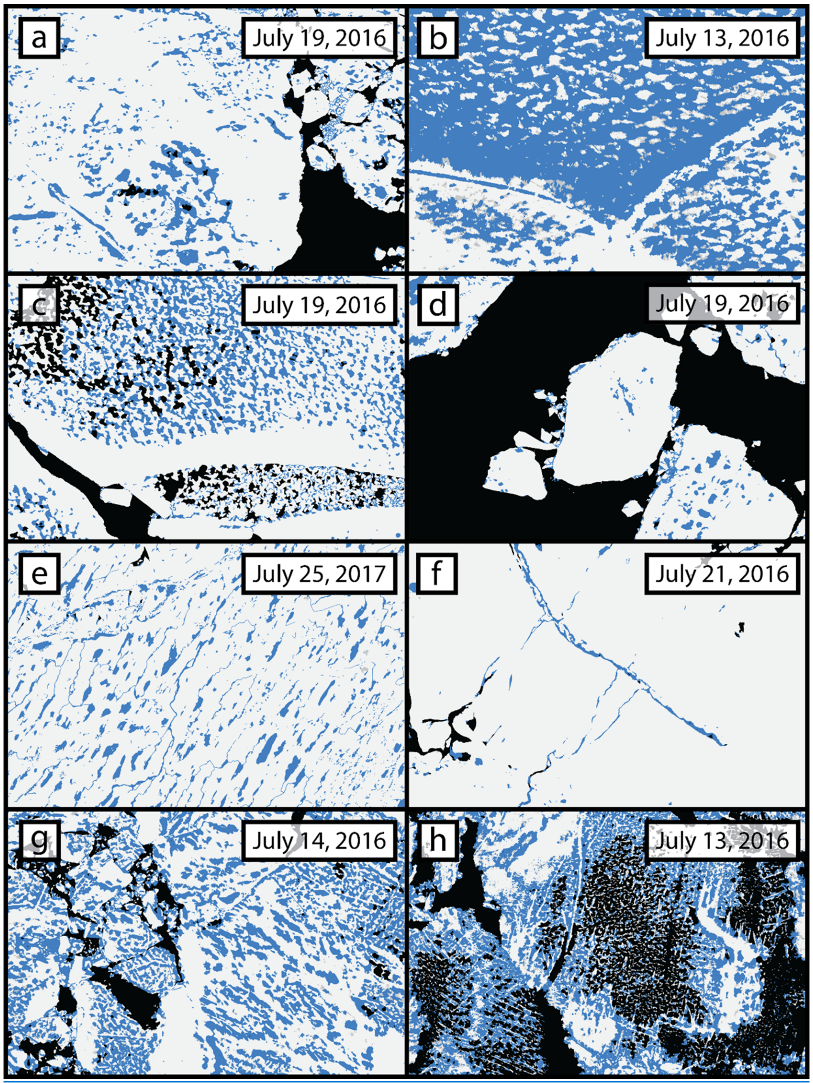

Figure S1. Classified versions of the images shown in Figure 10. White regions are snow/ice, blue regions are melt ponds are submerged ice, and black regions are open water.

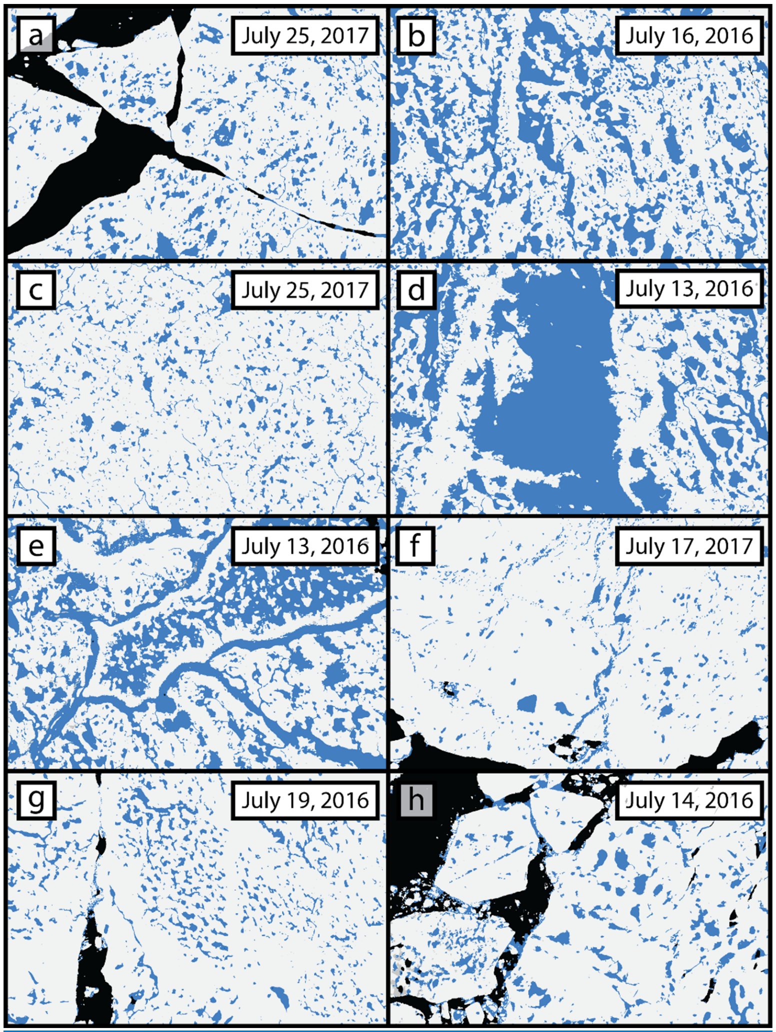

Figure S2. Classified versions of the images shown in Figure 11. White regions are snow/ice, blue regions are melt ponds are submerged ice, black regions are open water.

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