

Response to the comments of Reviewer 2

Please find our response to the comments from reviewers in **blue** font under the respective comments.

We thank the reviewers for the time and effort to thoroughly read and evaluate our manuscript, and we are grateful to the reviewers for the constructive comments and criticism about this manuscript which help us to improve our work. We have changed the content in the manuscript according to the comments and in the following we give detailed answers to the questions in the comments.

Anonymous Referee #2

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General comments

The manuscript from Zhu et al. identifies the role of ice-lead thickness, melt-pond depth, and substrate ice thickness in total and spectral albedo values of melt ponds. Melt ponds have a large impact on sea ice albedo during the summer and fall. Moreover, their characteristics also differ during the refreezing season (August-September) compared to the fast-melting period (June-July). Therefore, this study addresses relevant aspects of Arctic sea ice life cycle. Results from the observations of total and spectral albedo, along with the radiative transfer simulations, are well described with comprehensive step-by-step explanations. However, some effort is required to introduce the radiative transfer model, to avoid copying and pasting equations and text from Lu et al. (2016), and instead to highlight what was adapted in the model for this specific analysis. The discussion section will also benefit from a comparison between the observations and satellite measurements (see specific comments). The summary should be expanded to a conclusion that identifies the strengths and limitations of this study and outlines the next steps to advance the analysis.

Thanks for your positive evaluations and your constructive comments, which help us to further improve this work. We rewrote Section 2.2 to avoid meaningless repetition and to emphasize the modification we made to the model, added explanation on the underlying principles of melt pond algorithms and the potential direction of improvement and expanded the summary to a conclusion with highlights, limitations and prospects of this study. For more detailed answers to each point, please see our responses under specific comments.

Specific comments

Line 21: “and thus control the radiative forcing in the Arctic Ocean and the world (Hudson, 2011)”. Would it be possible to rephrase the sentence for more accuracy, avoiding “the world” which sounds simplistic in the context of the paper?

We rewrote the sentence to improve the accuracy: “thereby regulating the radiative forcing within the Arctic Ocean and throughout the global climate system”.

Line 65: “short-term and long-term ice stations” could these stations be identified in Table 1 or in Figure 1? Did you notice significant discrepancies in total albedo or spectral albedo due to the sampling duration?

Whether an ice station is short-term or long-term can be identified based on the third column “Date” of Table 1, where the long-term ice station spanning multiple dates (only IC2004 in this study). Besides, since all observation data used in this study were collected under overcast skies with diffusive light, the impact of solar elevation angle on albedo is negligible. Therefore, sampling duration does not significantly affect total albedo or spectral albedo.

Line 92: lambda in the equations should be defined.

Corrected accordingly.

Section 2.2 this section has to be significantly reworked to specify what differs from than Lu et al. (2016) and to clearly identify the novel elements of the present analysis.

Thank you for your comments. We rewrote Section 2.2 to avoid simple repetition of Lu et al. (2016) and to emphasize the modifications we made to the model. The revised version starts with the irradiance of each layer to introduce and highlight the role of different coefficients in the model, after which the modifications we adopted to the parameterization of origin model are introduced and the reasons and references of these modifications are explained. These changes to the parameterization of the model better represent the optical properties of the Arctic sea ice in the refreezing period, thus effectively improving the accuracy of the simulation results.

The rewritten part is attached below:

“In this model, sea ice is treated as isotropic under the assumption of diffuse incident solar irradiance. The upward and downward irradiance of each layer can be described as in (Lu et al., 2016):

$$\begin{cases} F^\downarrow(z, \lambda) = A(1 - \mu_\lambda) \exp(\kappa_\lambda z) + B(1 + \mu_\lambda) \exp(-\kappa_\lambda z) \\ F^\uparrow(z, \lambda) = A(1 + \mu_\lambda) \exp(\kappa_\lambda z) + B(1 - \mu_\lambda) \exp(-\kappa_\lambda z) \end{cases} \quad (3)$$

where z is depth in certain layer, λ is wavelength, $F^{\downarrow}(z, \lambda)$ represents downward irradiance, $F^{\uparrow}(z, \lambda)$ represents upward irradiance, A and B are constants determined by the boundary conditions, μ_{λ} represents the absorption strength (0 for purely scattering medium and 1 for purely absorbing medium), and κ_{λ} represents the attenuation coefficient. As defined in Perovich (1990), and can be written as

$$\mu_{\lambda} = \sqrt{k_{\lambda}/(k_{\lambda} + 2\sigma_{\lambda})} , \quad (4)$$

$$\kappa_{\lambda} = \sqrt{k_{\lambda}(k_{\lambda} + 2\sigma_{\lambda})} , \quad (5)$$

where k_{λ} represents absorption coefficient dependent on wavelength and σ_{λ} represents the scattering coefficient as a constant independent of wavelength. The Fresnel reflection coefficient between water and ice is neglected and the reflection at the air-water interface is taken as 0.05 for the diffuse sky, according to Perovich et al. (1990).

In this study, we adopted several modifications to the origin model. Firstly, the band of incident solar irradiance $F_0(\lambda)$ is set to 400–900 nm based on the range of in-situ measurements and the band of coefficients reported in previous studies. Secondly, the parameters of the inherent optical properties including absorption and scattering coefficients for the substrate ice are modified based on the field record to ensure the simulation to be consistent with the observation. Wang et al. (2020b) reports that the volume of bubbles and brine varies oppositely with the increasing of depth, causing inhomogeneous optical properties of the ice beneath melt pond. Here a combination of attenuation coefficient for white ice interior and pure ice in Perovich et al. (1990) is adopted, instead of that for pure ice used in original settings. According to Perovich et al. (1990), the scattering coefficient of white ice interior is 2.5 m^{-1} , while Light et al. (2015) argue that the scattering coefficient of substrate ice varies between 10 and 22 m^{-1} , and a value of 13 is taken in the multi-layer model (Light et al., 2008). In this study, as most of the melt ponds observed are dark ponds and the resulted high scattering coefficient is one order of magnitude higher than the observed, so the scattering coefficient of substrate ice is set to 2 m^{-1} , consistent with Malinka et al (2018) and Katlein et al. (2015). Besides, the incident irradiance, ice lid thickness, pond depth and substrate ice thickness are all adopted from the in-situ observation.”

Figure 3: it should be acknowledged in the figure legend that it has been adapted from Lu et al. (2016).

Corrected accordingly.

Lines 112: the equations are exactly the same than in Lu et al. (2016) along with the description until line 117. It should be acknowledged. It should also be better to

highlight how adding the ice lid is impacting the equations and what is different in the calculations compared to previous studies.

We acknowledged the equations and description from Lu et al. (2016) and added statements about our modifications adapted to the original model.

Line 119: in which equations/calculation R1 and R2 are used in the analysis?

Both R1 and R2 are parameters within the model's parameterization. In this study, they were only used in the calculation process of the modified model, and were not applied in other equations. We rephrased the sentences to clarify the features of the model and avoid confusion they may cause.

Line 167: "As a result, the calibration reduces the median deviation of CNR4 measurements from 0.2 to 0.06" is this reduction applied to all types of melt ponds? Maybe add some values in Fig. 5c and 5d to highlight the impact of the calibration.

The reduction in deviation mentioned in this sentence is the average value obtained from the three types of melt ponds (ice pond, ice-snow pond, snow pond) that underwent calibration. We added the mean values (not median value since there are only several samples for some type) of deviation between two instruments for different types before and after calibration in Figure 5 to show the impact of the calibration.

Figure 6b: what does the colorbar represent? What about the numbers and uncertainty/standard deviation in red? MP96, IA94, etc. are not defined yet.

Thank you for the comment. We apologize for the missing of explanations for annotations in Figure 6b. The colorbar in Figure 6b represents the albedo and the numbers in red represents the average value with standard deviation in certain region. Acronym such as MP96 and IA94 represents albedo in previous observations. These explanations have been added in the caption of Figure 6: "In panel (b), the colorbar represents the albedo of melt pond, the annotations in red represent mean and deviation of pond albedo in certain regions, the annotations in black represent mean and deviation of pond albedo reported in previous studies, where the acronym is as follows: GM77 – Grenfell & Maykut, 1977; IA94 – Ivanov & Alexadrov, 1994; ML96 – Morassutti & Ledrew, 1996; MP96 – Makshtas & Podgorny, 1996".

Line 278: "which is consistent with observation in Malinka et al. (2016)" Can you elaborate more on the agreement between your observations and previous studies?

There was a snow-covered melt pond (the middle panel of Figure 1 below) observed

during PS80/335 as reported in Malinka et al. (2016), with its spectral albedo between 730 and 950 nm showing a similar pattern with that of snow ponds observed in this study (Figure 8a in the manuscript). In comparison, spectral albedo of the two frozen ponds without snow (panel (a) and (b) of Figure 2 below) observed in Malinka et al. (2018) does not show this pattern in 730–950 nm. In addition, the spectral albedo of frozen ponds with snow (panel (c) of Figure 2 below) still shows the pattern, which is similar to yet less pronounced than that of snow pond and unponded ice. The simulation of Malinka et al. (2016) based on the radiative transfer theories of snow and white ice also shows the similar pattern.

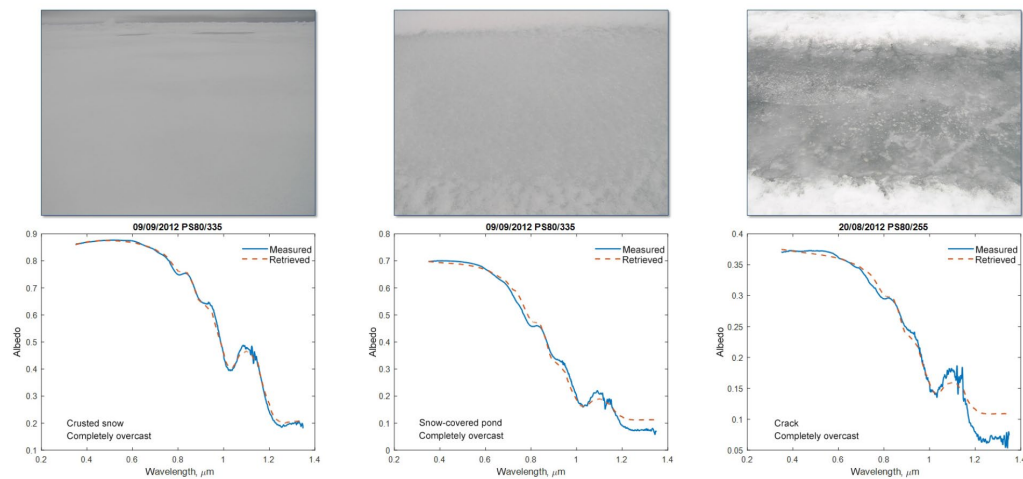


Figure 12. Three special cases: thin wind crust on top of fine fresh snow of 4 cm thickness (left panels), a frozen-over gray melt pond with snow on top (middle panels), and a frozen-over crack with air bubbles and algae inclusions (right panels). The average air temperature is $+0.3^{\circ}\text{C}$ (right panels) and -1.6°C (the others).

Figure 1. Spectral albedo of unponded sea ice and frozen ponds observed in Malinka et al. (2016).

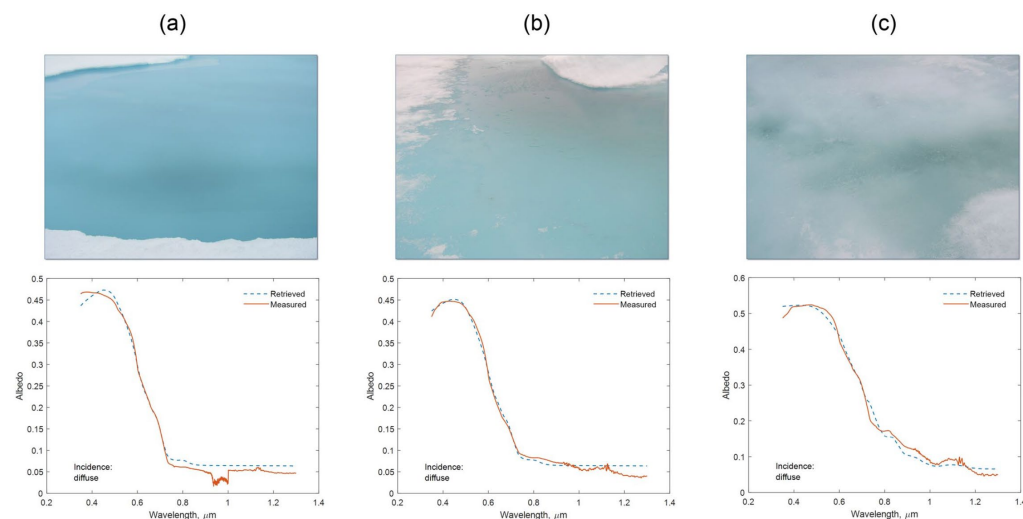


Figure 7. Frozen blue ponds. Polarstern-2012, Stations 1 (a) and 3 (b, c). The left pond is heterogeneous. The sensor was placed approximately in the center of the photograph, about 1 m from the pond edge.

Figure 2. Spectral albedo of frozen ponds observed in Malinka et al. (2018).

Based on the results mentioned above, we added statements about the agreement

between this study and previous studies in the manuscript: “The result which is also consistent with observations in Malinka et al. (2016), which reported a similar nonlinear pattern shown both in the observed albedo of snow-covered ponded or unponded ice and in the simulated albedo based on radiative transfer theories.”

Line 288: Can you better introduce $\alpha_{412}/\alpha_{667}$ as no results are presented in section 3.2 about $\alpha_{412}/\alpha_{667}$ and it is only in section 4 that references are made to this ratio.

Thank you for point out this issue. The statement is intended to emphasize the limitation of the albedo ratios caused by observation time in this study. We changed this sentence and removed the name of certain ratio such as $\alpha_{360}/\alpha_{490}$ or $\alpha_{412}/\alpha_{667}$ to avoid the confusion: “It should also be noted that the albedo ratio in this study is developed based on...”.

Line 290: “that some uncertainty remains in this result” Can you be more accurate about the uncertainties? Can the uncertainty be quantifiable?

Thank you for the comment. The major uncertainties include volume of liquid water trapped under the ice lid (Flocco et al., 2015) and the thickness of snow cover (Anhaus et al., 2021), which are reported relevant to the albedo of snow pond, thus may cause significant change on spectral distribution. In addition, minor uncertainties such as thickness of ice lid or underlying ice have effect on albedo but do not cause great change for snow pond. Those uncertainties are hard to quantify since few snow-covered melt ponds were observed and reported in previous studies, especially in the Pacific sector of the Arctic. And we will focus on the albedo measurement of snow-covered melt ponds in the future expeditions to expand the dataset for a more robust conclusion.

Line 299: “a correlation coefficient of 0.12 is found between” how is it calculated? Using values from figure 7 and figure 9?

The correlation coefficient was calculated using the albedo and depth data of 50 melt ponds (of which the depth is shown in Figure 9)—out of a total of 81 ponds (of which the albedo is shown in Figure 7)—that the depth measurements were conducted during observation.

Line 333: “a radiative transfer model” add “described in Section 2.2.

We added the words in accordance with the comment.

Line 394: “except for the influence of temperature and radiation which is discussed in section 3.2”, the influence should be reminded to complement the discussion.

We added the influence of temperature and radiation: “...except for the influence of temperature and radiation which affects the energy budget in thermal processes, causes such as precipitation and wind also have effects on the formation of them”.

Section 4 discussions:

Wavelengths corresponding to MODIS bands are selected to identify the limits of the ratio used to identify snow covered pond. The analysis would be stronger if some in situ observations were compared with collocated MODIS measurements to assess how effectively the satellite performs and under which conditions MODIS is too limited. If a case study cannot be conducted, some references to MODIS pond identification should be cited and compared with the present study.

Two melt pond retrieval algorithms developed for satellite data are applied to the observations from the present study. Although references for both algorithms are provided, it would be helpful to introduce their underlying principles and to specify if any adaptations made to use them with in situ measurements. This could be included in the Supplementary Information to complement the study’s methodology. Again, a case study comparing observations and Sentinel-2 data would be a valuable addition to extend the analysis to satellite observations.

Thank you for your constructive comment. We are regretful but it is not feasible to match or effectively compare in-situ data with satellite data due to the significant scale difference between the spatial resolution of MODIS (>250 m) and individual melt ponds (3–5 m). Besides, the Multispectral Imager (MSI) aboard Sentinel-2 has spatial resolutions from 10 m to 60 m which are closer to individual ponds, but we failed to find any image that overlaps with the snow ponds observed in this study (numbered as IC1202-2, IC1202-3, IC1204-2, IC1206-2, IC1804-1, IC1804-2, the last two of which provide spectral albedo shown in Figure 8 and Figure 13).

Therefore, case studies cannot be conducted based on current in-situ dataset and satellite product. But we will strive to compare observations and satellite data with the support of future expeditions, so as to better elaborate on the limitations of satellite observations.

To further illustrate the limitations of existing algorithms, we cited literature related to melt pond identification algorithms and added an introduction to their underlying principles before the citing two MPF algorithms: “The albedo ratio is also widely used in MPF (melt pond fraction) retrieval algorithms, which focus on deriving MPF from satellite data (Markus et al., 2002). For most algorithms, the albedo in certain bands measured by satellite sensors is operated to obtain a specific ratio, based on which

the clusters of snow/ice, melt ponds, and open water in scatter plot are determined. Albedo of certain area can be then converted to MPF based on its relative position in the plot”.

Based on the underlying principles, we analyzed the reasons why current algorithms fail to identify snow ponds as well as the potential improvement directions: “The reason behind this misidentification is surface state which causes different spectral characteristics of refreezing ponds from those ‘typical’ melt ponds. According to Figure 8, the difference between the albedo maximum (450-550 nm) and the low albedo in near-infrared (700-900 nm) reduces as the pond freezes, while most algorithms rely on those bands to distinguish ponds from unponded ice”.

Besides, although effective comparison between satellite data and in-situ data cannot be achieved with MODIS/Sentinel-2 products, we believe that as the resolution of satellite observation further improves, more detailed identification of melt ponds and even their types will become possible. The results of this study may provide theoretical support for the development of more advanced algorithms at that time.

Section 5 Summary:

The summary should be expanded into a forward-looking conclusion that clearly states the study’s limitations and outlines concrete next steps. What is still required to improve the analysis and reduce the uncertainties? What would be necessary if these observations were conducted again (e.g., meteorological data and snow depth, etc.)? How will the parametrization of the radiative transfer model be used? Is there a potential study to improve the identification of snow-covered ponds from satellite? What kind of refreezing melt pond studies does the community need to advance understanding of sea ice albedo?

Thank you for your constructive comments. We expanded the summary and added statements about the limitations and outlooks of this study.

Although observation data during 5 Arctic expeditions were used, this study is still limited by the short of sample numbers and incomplete measurements. To improve the analysis and reduce the uncertainties, the following measures are needed: recording pond types in different dates to expand the dataset of proportion of surface states; comprehensively measuring parameters such as snow depth, ice lid thickness, pond depth, and thickness of underlying ice for all ponds; documenting local weather conditions in the preceding days of pond observation to support subsequent analysis; and investigating the potential use of albedo ratios in enhancing the retrieval of melt pond fraction from satellite data. Besides, since the characteristics of typical melt ponds are well documented and studied, we argue that the process during refreezing period should be focused to further understand the albedo of Arctic sea ice.

The added sentences to the summary are as follows:

“The melt pond dataset collected from five Arctic expeditions was used in this study, but we were still limited by the incomplete measurement in some stations and the short of sample numbers for several types of ponds, especially the snow pond. Hence the uncertainties of pond albedo (i.e. weather condition, snow depth and pond water) remain unclear, requiring detailed records on meteorological and physical properties to enhance current results. Moreover, the pond classification and the modified parameterization can be adopted to large scale sea ice mode (i.e. CICE) to improve the evaluation or prediction during refreezing period in the Arctic. The albedo ratios as indicators of snow pond or unponded ice provide insight on developing MPF retrieval algorithms with advanced identification of melt ponds. The radiative energy balance of refreezing melt ponds should be focused along with enhanceive studies to further understand the Arctic sea ice.”

Technical comments

Line 92: the equations should be numbered.

We numbered the equations in the manuscript.

Line 317: More consistency should be applied for defining the acronyms to avoid confusion. Some acronyms are defined in Figure 10 legend and then used in the text without explanation: line 312 “the fitting result is close to that of ML96 and SP07”. Etc.

Thank you for the comment. We revised this part accordingly. In the revised version, the acronyms are only used in Figure 10 to avoid mess caused by excessive annotations. The previous studies in the main text are all presented in the standard citation format.

Line 416: the opposite is also observed, PCA algorithm and LinearPolar Algorithm are defined in the text line 418 but not in the Figure 13 legend.

We added citations in the caption of Figure 13.

Figure 11: unit of H should be defined.

We added definition of the unit of H in the caption of Figure 11.

Figure 13: use color-coded makers as in previous figures to help readers distinguish between the different types of melt ponds.

We added color-coded markers in Figure 8b and Figure 13 to help distinguishing different types of ponds.

References: Rösel and Kaleschke, 2011 is missing in the bibliography.

Thank you for the comment. We apologize for the missing and the citation is now added into the bibliography.

There are two references for Wang et al. (2020). They should be labeled a and b to avoid confusion, or differently to distinguish the different authors.

Thank you for point this out. We labeled a and b to distinguish the two references.