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The Cryosphere
Discussions

Interactive comment on "Reflective properties of melt ponds on sea ice" *by* Aleksey Malinka et al.

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We are grateful to the referees for their positive evaluation of our work and particularly for the detailed comments. We made corrections in the manuscript according to the referees' minor comments. In the following we give more detailed answers to their questions. The revised version of the manuscript will be submitted when we will have the answers of the reviewers.

Anonymous Referee #2:

The manuscript describes a new numerical model to calculate the spectral reflectance of melt ponds on Arctic sea ice, mostly determined by three independent variables. The authors find good agreement between simulated and observed spectra from in-situ measurements during three different field campaigns. This allows them to derive water depth, under pond ice thickness and transport coefficients for each of the ponds.

Given the ongoing changes of the Arctic sea ice cover towards longer melt periods and increasing melt pond fractions, the manuscript describes a timely topic, which is well suited for publications in The Cryosphere. Over all, I suggest publication after minor revisions, which mostly comprise some additional discussion and sharpening of the main conclusions.

Thank you.

General comments: - It is not clear to me what the NEW elements of this model are, compared to existing models and theoretical approaches. It seems that most relations and assumptions are taken from existing studies. Since this is a mostly methodological manuscript, the following aspects need to become obvious: o What are the additional and new insights into radiative transfer of melt ponds?

Actually, we don't know any existing models or theoretical approaches that relate the pond reflectance to its physical characteristics. The work of Makshtas and Podgorny relates the pond albedo to the albedo of its bottom only. In our work we show how to obtain the spectrum of the pond bottom albedo through the radiative transfer characteristics of under-pond sea ice. To do so we use the approaches, developed by the authors for light scattering by non-spherical particles within the WKB approximation (Malinka, 2015) and for radiative transfer within the two-stream approximation (Zege et al, 1991). We show which particular parameters determine the pond bottom albedo. These parameters are really the transport scattering coefficient and ice thickness. Besides, we pay particular attention to two more points: the bi-directional reflectance, which is of great importance for remote sensing techniques when processing satellite data, and the atmospheric correction of in situ measured data, which is hardly made by anyone for in situ measurements. As far as we're concerned, we think that all these points are stated in the Introduction. Also, according to your advice, we added these points to the Abstract.

o How can or should this model be used in future (the outlook at the very end is rather unspecific and too general)? o What kind of scientific merit do the authors expect from this and following studies (applications of the model).

Of course, we cannot predict all possible merits. But some applications are obvious: such a model is absolutely necessary for satellite data processing in remote sensing of Arctic ice. Particularly, this model has served as a basis for the MPD (Melt Pond Detector) algorithm for melt pond fraction and sea ice albedo retrieval from MERIS data (Zege et al., 2015).

- The authors conclude that only three independent parameters are needed to characterize melt ponds and thus to retrieve an appropriate optical characterization from them. They do discuss and show results of pond depth and substrate thickness, but I am missing an analysis and more discussion and details on the transport coefficient. In that respect, the role of the three main parameters should be discussed in the discussion and be concluded at the end of the manuscript. How do they impact the model (not only in equations) and what sensitivity do we expect and receive?

We consider all three parameters, z, H, and σt , as independent ones. All these three values are retrieved for every spectrum. In Table 2 we show only two of them just for comparison with the in situ measured values of z and H. Nobody measures σt , so we don't show its values. Additionally, we can add that the transport scattering coefficient is mostly variable due to air bubbles in sea ice. We appended the section dedicated to the dual pond measured in SHEBA expedition with the transport coefficient values for the light and dark parts, which gives the idea of the effect of the transport coefficient on the pond albedo.

- The comparison with in-situ observations show differences of under-pond ice thickness and water depth of 50% and some even significantly higher. I do not follow the argumentation that this is satisfactory, in particular since there is very little discussion about this (see comments below). I consider these differences as more significant than the discussion reveals. In particular with respect to the under-pond (substrate)

thickness, which should be the most important parameter to determine pond albedo.

Actually, the most important parameter that determines the pond albedo is the transport optical thickness of under-pond ice τt that is a product of the transport scattering coefficient σt and ice thickness H: τt = σt H . Partially this explains the retrieval error: τt is retrieved with much higher accuracy, however there is no way to compare it with a measured value. There could be also other different sources of error. First, the under-pond ice might not be flat, especially its lower boundary. In this case the optical retrieval gives some average value, while the in situ measurement gives a random value taken in some particular point. From this point of view the measurement makes a mistake, rather than the retrieval. The second source can be the presence of some impurities that affect the absorption spectrum. Additional absorption can affect the retrieval of the scattering coefficient and, consequently, of H. Besides, there could be other sources of uncertainties, like finite pond size, presence of snow in the receiver FOV, clouds in the sky etc. In view of that, the RMS error of 37% seems to us more than reasonable, especially given the fact that the microwave sounding methods fail absolutely in ice thickness retrieval, when ice is covered with a thin water layer.

Note: I am puzzled about the term “substrate”. Why not under-pond ice thickness?

Thank you for the prompt. As we already mentioned, we are not native English speakers. We have changed this term.

Specific comments: Abstract: The abstract may be significantly improved by adding more results and a statement that explicitly names the additional benefit and further applications of the model: - Page1/Line15 (P1/L15): . . . are examined: What is the result of the examination?

We added: “We find that atmospheric correction is necessary even for in situ measurements. Thus, an atmospheric correction procedure has been used in the model verification”

- P1/L16: several => three field campaigns

Changed

- P1/L17: “good performance” this is rather relative, good in what measure?

How can we measure the adequacy of a model or a theory? This is rather quality, than quantity measure.

- Why are the three main parameters not mentioned in the abstract? How do they perform?

We added some details into the Abstract. Now they are mentioned.

- What does this model stand out for and what is the (likely) future benefit of this study/model?

The model is needed to get and study a quantitative relationship between the physical characteristics of a melt pond and its reflectance. This quantitative characterization will be helpful in retrieving melt pond fraction from space and thereby quantifying the atmosphere–sea ice–ocean heat fluxes relevant for climate research.

Introduction - Recent studies by different groups show the increasing fraction and importance of melt ponds. Also shifts in melt onset and melt season duration are observed and discussed in various ways. I am missing this aspect in the introduction, while this would add to the motivation of this study and model development.

We added these facts into the Introduction, together with the reference ‘Markus et al., 2009’.

- In addition, there are various approaches to parameterize melt ponds in circulation models of various complexities. This should also be included and could even link to the role of light transmittance into and through sea ice (the remaining after reflection). This could also well link the introduction to the final part of the conclusions (see comments below)

We added the phrase about light transmittance to the Conclusion

- P2/L4: Include also “water” properties.

If we understand correctly, this comment refers to the sentence “This solution has required the detailed consideration of the inherent optical properties of sea ice, which forms the pond bottom.” If so, we don’t think it is worth including ‘water properties’, because this would mean ‘sea water’ IOPs, which is a very elaborated problem that is very separate from ‘sea ice’ IOPs.

Model descriptions - This section is most detailed. It could be improved by distinguishing better between existing models and theories and highlighting new ideas and findings.

It is stated in the Introduction: “Subsection 2.1 presents the derivation of the formulas for pond reflectance, given by Makshtas and Podgorny (1996) expanded to various incident conditions.” All other findings throughout the manuscript are original. We do not see how to distinguish better.

- The role of the resulting three main parameters should be highlighted.

These parameters determine the pond spectral reflectance. The coincidence of measured and modeled spectra allows us to state that on more parameters can improve the model and make it closer to reality (unless we see real difference in spectra, which we attribute to some sediments). (we added this to conclusion, also, see below). Additionally, we added the explanation to the end of Sec. 2.4: “So, in the absence of pollutants just three parameters determine the pond spectral reflectance: namely, the transport scattering coefficient and geometric thickness of the under-pond ice and water layer depth . This statement is confirmed by the coincidence of measured and modeled spectra demonstrated below.”

- It would add value to the manuscript if the model is made available for other users. How is the model implemented? How (numerically) costly are the simulations?

The model is very simple in the implementation, because it is entirely based on analytical formulas. The only numerical cost is the calculation of functions fin and fout (integrals in Eq. (14) and (22)). However, these functions can be calculated once for given set of wavelengths and then used as a look-up-table to speed up the simulation. As for the rest, all the formulas are given in the manuscript and can be used straightforwardly. We added this aspect to the end of Sec.2.1 and to the Conclusion.

Model verification - P13/L16-19: The realization of the validation and comparison should be described in more detail.

To find the best fit solution we use the multidimensional Newton-Raphson method with the singular value decomposition of the pseudo-inverse matrix. We really think that the discussion of the method lies far beyond the paper scope, but the method name is added to the manuscript. Adding computational details will make the understanding of the work only harder. Also we are sure that the particular method of searching solution doesn't matter for model verification. It is enough that we find such values of the three pond parameters that give the best fit of spectra in the sense the least squares.

o How did the authors derive that these are the three main parameters. What other parameters were analyzed?

See above our answer about the role of these three parameters. Additionally we can note that refractive indices and absorption spectra of ice and water were not analyzed, because they are fixed, and sediment concentration was not analyzed, because we have no information about polluting substances. So, no more parameters can be analyzed from the point of view of albedo spectrum. Another question is that the transport scattering coefficient consists of the contributions of air bubbles and brine inclusions and thus is determined by their concentrations. Their relationships are considered in detail in Sec. 2.2c and 4.3.

o What about the transport coefficients? How were they studied/discussed? o How are the thicknesses retrieved?

All three parameters are retrieved in the same manner. They comprise a 3d-vector, which is varied to provide the best fit of spectra. We added this phrase to Sec. 4.1.

- It is a disadvantage that most ponds were not open ponds as it is assumed in the model development. I do see the constrains through the given data set, but this weakens the verification and needs more consideration. Why is there e.g. no thin surface ice in the model?

For the same reason we are also not quite satisfied with the dataset, but that's what we have. We made computations for the model with frozen surface. Adding a thin ice layer on top changes almost nothing in the results however makes formulas much more tremendous, so we decided not to include them into the manuscript. This overloaded model was formulated in our internal report. At first, we planned to attach this report to the manuscript as a supplement, however the editorial refused it. And we agree with them, because it gives too little new information.

- P14/L14: Add the year (2008) into the main text.

Added.

- Section 4.4 should be the main discussion of the comparisons. This is too short and somewhat superficial. o Where do these rather large differences of 50% come from? I do see various reasons in e.g. pond depth distributions, non-planar interfaces, footprint of sensors compared to pond properties. But this needs to be discussed in more detail. o What precision may/can be expected in such models? o What determines the uncertainties? Which of the given assumptions might not be ideal, but what would it mean to adapt this? It is most likely not realistic within this study, but some additional discussion would be useful and interesting for further studies.

Throughout the manuscript, making the derivations, we stated the assumptions we use in the model. Surely, every assumption is some approximation or idealization and any of them can limit applicability and accuracy of results. However, the perfect fit of the measured and modeled spectra is a proof that these assumptions were reasonable.

- With respect to those differences: As discussed, impurities are mostly low in the ponds, so the result is mostly based on scattering (not absorption). In this case, the retrieved spectral shape may be expected to be in good agreement, while amplitude is the main aspect of evaluation. But if then the simulated differences are still around 50% for the under-ice thickness this is somewhat surprising to me. I agree that the RMSE match is quite good if not excellent, but may be not because of the right thicknesses, but other parameters in the model. This should be discussed more.

We think this question is answered in the section 'General comments' (the 4th question). (Also note that the mean error for ice thickness is 37%, not 50%).

Conclusions - Given that ponds may be described by the three parameters: How would future applications look like? What is the main benefit from this conclusion? (P16/L16)

It is just a scientific statement. Actually, reducing the number of key physical parameters down to three is indeed the main benefit.

- P16/L27: This raises the question: How much of the model has been used before and what is new (see above)?

This model was almost fully used in the MPD algorithm described in Zege et al., 2015, but a detailed description hasn't been published until now. The new modification is that the two-stream approximation is used now instead of the radiative transfer asymptotic formulas for weak absorption. This allows widening the scope of the applicability to significant absorption, what is important in the red and near IR range. The second one is that the scientific justification is given for the sea-ice IOPs and, consequently, to the role of the transport scattering coefficient.

- P16/L30: "can be useful": This is somewhat vague. How can it realistically be used?

For example, for a better understanding of the Arctic energy budget the quantitative characterization of melt pond reflection is needed. At least, it is needed for satellite

retrieval of melt pond fraction.

- The last lines of the manuscript are not convincing to me. How would these improvements be implemented? What are the next applications or which part of these results is most promising. This needs a more thoroughly discussion and a more specific outlook.

The most promising is the relationship between the physical and optical parameters of a melt pond. We think this relationship is needed to study, e.g., the process of ice melting, which is highly determined by its radiative budget.

- The conclusions section misses a conclusion on the uncertainties and deviations from the field measurements (Section 4.4). At the same time, I suggest to highlight that the validation was done against quite a suite of field measurements and variable pond conditions. This is a valuable aspect and could be stressed more. Many studies limit their validation to a single data set (e.g. one field experiment).

We think that most of the facts are performed in the main text. We added the names of expeditions once again to the conclusion.

Table 1 - I think that this is not needed.

The purpose of the table is clarifying for the reader which parameters are variable (and, consequently, are varied in the retrieval) and which are fixed in the model.

Table 2 - The pond code names seem to be an internal coding with almost no use for other studies. Using station names and dates as identifiers that link to field reports, Polarstern station numbers, and Pangaea data sets is suggested.

We put the station number in the case of Polarstern expedition.

- I suggest to re-arrange the columns and group retrieved/measured/difference (absolute, and %) for each: ice thickness and water depth. This eases evaluation of the performance.

Done.

- RMSD values could be given in units of e.g. 10ˆ-3 to save space and ease reading

Done.

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