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Interactive comment

Interactive comment on "The influence of albedo parameterization for improved lake ice simulation" *by* Alexis L. Robinson et al.

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We thank the reviewer for their time and effort in providing a constructive evaluation of our study and for their comments regarding how to improve the readability/flow of the paper. Several of the main comments revolve around the model physics that we have not explained in depth in the manuscript. In the interest of space and relevance, we did not go into great depth in some areas as the model physics are well established and our aim was to show how field data can be used to improve the representation of the ice cover in different regions, not alter the established physics. The full model description is referenced (Duguay et al., 2003) and does address much of the information the Reviewer was raising. We have identified some areas of the manuscript, as highlighted by the Reviewer (and Reviewer #2), that we can add further clarification too and also

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some areas that we can remove. Equations 1 and 2 are only included as general model description included for continuity with previously published CLIMo papers.

In general, CLIMo simulates a continuous time series, from ice formation, growth, decay, summer ice free season and into the subsequent years. Freeze up is simulated very accurately provided accurate climate and lake data is used to run the model. CLIMo does not require calibration or optimization. Our research presented here focusses on using field measurements to better describe the albedo parameterization for a specific location – temperate region where the ice is different than northern regions. We are not adjusting any of the model physics using the parameterization, only the fixed values used to represent the ice in the temperate region vs. northern regions.

Replies to each comment are provided below.

Reviewer: 1) Model description and discussion: If I understood correctly the main objective of this work is to show that the model performs better when the temporal evolution of the local albedo information is provided. While this is not a fundamental surprise that local forcing conditions are always better than global or random boundary parameters, I recognize that it is important to quantify the sensitivity of a model to such a parameter. Yet, the way the model is presented (Eqs. 1-5) is very confusing. For instance, the boundary conditions (especially the lower one at the ice-water interface) of the model are not presented. Off course, such information can be found in previous publications but the manuscript should be self-explicit. Furthermore, the authors presented 3 related equations to parameterize the albedo. They discuss optimization but it is very hard to understand what was really done. Specifically, there is no parameters in the three equations provided. It is thereby very hard to follow the changes described in the results. I think that the way the work is presented makes the study difficult for other scientists to follow and finally reproduce the findings. I thereby recommend to the authors to rewrite the results and discussion and reformulate the set of equations and finally discuss how the parameterizations have been modified to improve model's skill so that readers can understand what is modified.

Reply: To clarify – there is no temporal evolution of the albedo being used in this study. We are using an average value to better represent the whiter surface ice in the study region compared to typical ice found in northern latitudes. No equations have been modified; only the fixed values representing the snow and ice albedo were altered as an initial approach to better simulate the temperate ice cover.

The overall research compares ice cover simulations from High Arctic and temperate region lakes to illustrate the latitudinal differences in lake ice properties and presents refinements to CLIMo to better simulate ice thickness and ice-off timing in the temperate region. Where the first objective is to show the effectiveness of CLIMo for simulating ice cover regimes on High Arctic lakes, where no changes have been made to the model. The second object is to investigate and show that certain parameters within CLIMo, which were determined using High Arctic research, need to be adjusted to appropriately simulate temperate region ice cover. The results and discussion are presented in separate sections to clearly meet these objectives.

The methodology section however was written from the perspective of the unadjusted model (Section 3.4) with the modifications outlined in section 3.5. Equations 3 to 5 are important to explaining CLIMo for northern lakes (High latitude lakes), as our research supports previous studies (e.g. Ménard et al., 2002; Duguay et al., 2003; Morris et al., 2005; Brown and Duguay, 2011a, 2011b; Kheyrollah Pour et al., 2012; Surdu et al., 2014) which show that the current unadjusted CLIMo is able to model sub-Arctic and Arctic lakes (northern lakes). These equations define the current parameters and how they were derived, explaining why simulations of temperate region lakes show earlier ice-off and lower thickness estimates.

Rearranging the methodology section will greatly help clarify the modifications that were made. Currently, the changes are detailed through text in section (3.5 Simulations) but rearranging this section to relate the changes directly to the equations will aid greatly for readability and clarify the albedo differences. We see the reviewers point regarding fixed values vs. parameters, in equation 5 and thank them for bringing this to our attention. In the current form the description can lead to confusion as the specific numbers that we alter are not indicated. We will modify this to use parameters for further clarity.

By combining and rearranging section 3.4 and 3.5 a much clearer description of the model and modifications can be presented. We will re-label section 3.4 to ‘Unmodified Lake Ice Model – Northern Lakes‘ and state this section reviews the model as it was originally created for high latitude lakes; change 3.5 to ‘Modified Lake Ice Model – Temperate Latitudes’ and clearly outline here what and how the albedo values were obtained. Some relevant material from the discussion section can also be worked into this modified section to clearly show the reader the differences between the unadjusted and adjusted model. Some additional helpful advice from Reviewer #2 will also be factored into the rearranged sections here to better present the work.

Reviewer: 2) Lower boundary condition I have not understood how the flux at the lower boundary was calculated. This heat flux is proportional to the water temperature, which will evolve from let’s say 0.1C to 4C, that is a 40 times increase in the heat flux. Said differently, the heat flux will range from $< \sim 1$ W/m2 to > 10 W/m2 (without daily cycles). How is this increase over time of heat flux from the lower boundary taken into account? This boundary condition and its variability is not discussed. Without a proper quantification or at least discussion regarding the lower boundary, one may think that changes in albedo parameterization are actually also taking into account changes in heat flux at the lower boundary.

Reply: The calculation of the lower boundary conditions is not discussed in this paper as they are not directly relevant to the focus of the paper, but they are referenced in other papers concerning CLIMo – primarily Duguay et al., 2003. The one-dimensional unsteady heat condition equation (Eq 1) is subject to lower boundary conditions at the ice/water interface (underside), this incorporates the total thickness of the ice and snow (h) and the freezing temperature of fresh water (however the ice underside is always at the freezing point; Duguay et al., 2003). Growth and melt at the ice/water interface (underside) are computed from the difference between the conductive heat flux into the ice and the heat flux out of the upper surface of the mixed layer. Therefore, ice thickness is incorporated into the lower boundary conditions, since it is used to determine the penetration of shortwave radiation through the bottom of the ice slab. When shortwave radiation penetrates through the bottom of the ice slab, it is assumed to be absorbed within the mixed layer and then returned to the ice underside in order to keep the temperature of the mixed layer at the freezing point (Duguay et al., 2003). We will revise the model description to provide more basics on the required information and direct the reader to the correct place for relevant but not critical information, incorporating advice from reviewer #2 as well on this.

Reviewer: 3)Ice-on prediction I have also not understood how this model can be used to predict ice-on as discussed in the results and discussion section. How much heat must be extracted from the lake before reaching the condition T=0C? What are the initial conditions being used? The modeling approach is adapted to ice thickness and ice-off but not to ice-on.

Reply: We have addressed this point in our opening section, however, briefly, CLIMo simulates the annual cycle of a lake. Ice-on does not require adaptation for temperate regions; it is not discussed in detail within the paper since simulations are within 0 to 2 days and the ice/snow albedo has no effect other than some carry-through effects on heat storage with respect to the previous season break-up.

Reviewer: 4)Albedo I am curious why the authors did not assimilate the observed albedo using Ensemble Kalman Filters or any other approach. I also would need some clarifications regarding how albedo is actually measured. Some publications show huge daily variability (due to solar angle, melting and consequently daily changes in ice properties). It seems that you focus mostly on the seasonal variability that is the change from snow covered to snow free and further increase of the scattering with ice warming. I am curious if the daily variability is relevant or not.

Reply: While ideally a temporal series of albedo would have been used to determine the average, this was not viable at our field site as the location is used heavily for recreation and the equipment cannot be left unattended. Albedo measurements as stated in Section 3.3 Albedo, were obtained manually when site visits were made once per week. Albedo measurements are outlined in Section 3.3 'Albedo'. In 2017-2018 and 2018 – 2019)handheld measurements were made between 10 am to 2 pm, 3 were taken on each lake transect which allowed for a total of 12 measurements per site visit. The last two site visits in 2017-18 continuous shortwave radiation readings were made at MacDonald Lake between 10 am to 2 pm using a Kipp and Zonen CNR4 net radiometer (set-up detail outlined in the manuscript) and this was continued for a full season of 8 dates in 2019. We are seeking single values to best represent the snow and ice. Daily variability was not high as readings were all collected during the 10 am – 2 pm window. Examining the limited continuous data in comparison to the point data shows that the albedo averages to similar values during the overlapping collection times. Our variability is low likely as a result of the small range in hours that we are at the field site. For the purpose of this study, it was not found that variability was relevant since we were seeking an average value of albedo for temperate snow and ice conditions.

Assimilation of the observed albedo using Ensemble Kalman Filter or another approach is not required within the model, and not viable or appropriate using the limited field data collected. The model iterates daily through the entire study period using daily averages of air temperature, windspeed, relative humidity, cloud fraction, snow density and snow accumulation. CLIMo requires set values for albedo of ice, snow, melting ice, and open water. The parameterization of albedo is not an input value that would require assimilation and iteration of changing albedo values, such as what is determined using Ensemble Kalman Filters. In addition, this filter is used for large-scale datasets, and although it has been used extensively in hydrology and atmospheric sciences (Andreadis and Lettenmaier, 2006; Houtekamer and Mitchell, 2005; Roth et al., 2017; Zhang et al., 2019), the data being used in this study is limited point data and not large-scale spatial data. This study was not about using remote sensing or big data to parameterize the model, however, if you would like more detail regarding the use of big data, such as MODIS daily albedo a study completed by Svacina et al. (2014a, 2014b) provides comprehensive detail on simulated and satellite derived surface albedo of lake ice and use in CLIMo.

Reviewer: Finally, it is mentioned many times that albedo drives the melting. This is potentially misleading. Solar radiation (and air temperature) drive(s) the melting. The albedo modulates the intensity of the forcing (see for instance a very cloudy day with -20C but with very small albedo vs sunny day with +10C with larger albedo).

Reply: A valid point to raise with our terminology. In our case, we were approaching the phrase with the model in mind in such that when the albedo changes melt initiates. We will find the instances of this phrase and reword accordingly.

Reviewer: 5)Model skill metric I suggest to develop the model's skill metric as a function of the calibration parameters to show the effective improvement of the new model's version. The authors actually discuss this in section 3.6 Model Performance, but I don't see the indexes in a figure, or how the calibrated parameters achieved an optimal value. The metrics are just shown in Tables 6 and 10, so we need to assume that these are the maximum values achieved, but what are the optimal calibrated parameters?

Reply: No calibration is required for CLIMo, the model is forced with daily mean meteorological values and a 2 year spin-up period is used. The supplemental figure shows the effects of each individual modification made to the albedo values and the resulting ice simulations, however, as noted we did not provide the metrics for the model fit of each iteration. We will add the index of agreement between each modification to the in situ thickness, as well as move the supplemental figure into the main manuscript to clearly show the improvements.

R1C6 Non exhaustive specific comments *Abstract: first sentence not really attractive

Reply: Good point. We will concoct a catchier lead-in for the abstract!

*L10 “northern and temperate ice”: odd formulation

Reply: This will be rephrased for clarity. We cannot define set latitudinal ranges however as the ‘northern’ limit dips quite far south around the bottom of Hudson Bay in Canada, and the temperate region is quite different latitudinally in Europe than in North America.

*L28: why “exponentially”? More lakes up north?

Reply: Yes, this is related to distribution of lakes. Research from Verpoorter et al. (2014) show that the greatest lake abundance between 45-75° N and this is supported by the research completed by Prowse et al. (2015) where high resolution satellite imagery was used to illustrate that the highest concentration of lakes by area and perimeter are between 45-75° N. In recent work by Sharma et al. (2019) on lake ice loss in the Northern Hemisphere, found that the number of lakes experiencing intermittent winter ice cover is “projected to increase exponentially with climate warming (p. 3), and highlighted in figures within that study.

*L43 “ice melt initiation is controlled by albedo”. Please clearly stress that the drivers are solar radiation and air temperature.

Reply: This will be rephrased to include information that the drivers of albedo are solar radiation and air temperature. “ice melt initiation is controlled by albedo, where the main drivers are solar radiation and air temperature. Albedo is a surface property. . .”

*L45: Please distinguish main drivers to the secondary drivers for clarity reason

Reply: This will be rephrased to distinguish the main and secondary drivers for reader clarity. “Lake ice albedo is primarily affected by snow cover, ice type (e.g. black ice and white ice) and ice thickness, but can also be affected by the presence of impurities, cloud cover, air temperature and solar zenith angle (Leppäranta, 2015).”

*Eq 3-5: Please add parameters instead of numeric values as you will be changing them. What is “m”?

Reply: Tm is melting ice temperature; however, m (italics) alone is a typo and it should be m which is a reference to the unit m for meters. This m (italics) will be changed to m to rectify the error in the equation. Parameters will be used in

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