A review of "A daily basin-wide sea ice thickness retrieval methodology: Stefan's Law Integrated Conducted Energy (SLICE)" by James Anheuser et al.

The authors wish to thank the reviewer for the constructive review. We have responded in red font to individual comments below where necessary.

General Comments

The authors introduced a new method for sea ice thickness estimation from satellite snow- ice interface temperature (Tsi) by using idealized sea ice thermodynamic model. The key idea of their methodology is that thermodynamic sea ice growth rate can be calculated from upward conductive heat flux within the sea ice layer which balances with the latent heat of fusion. In their method, the conductive heat flux is a function of the Tsi under the linear temperature profile assumption. Therefore, sea ice thickness can be calculated from Tsi with appropriate initial ice thickness. Furthermore, the authors insist that the introduced method is self- correcting.

However, I have some major concerns about the introduced method. 1) There should be clarifications on the physical conditions (regions and seasons) that meet with the four assumptions they made. 2) More explanation is needed to insist that the method is "effectively" self-correcting. 3) The method seems to be a modeling approach rather than satellite retrieval. 4) Detailed procedure for the bias correction of the satellite Tsi must be provided.

Associated with the major concerns above, I think there should be significant improvements on the data and methodology before the manuscript is published to The Cryosphere. Therefore, my decision is to reconsider after the major revision. I would like to review the manuscript again after the revision.

Major comments

1. Assumptions in the SLICE method

From L202 to L208, the authors listed the four assumptions used in the SLICE retrieval method. I have concerns about the second and the third assumptions. In my opinion, the second assumption is equivalent to the statement that the temperature profile of sea ice is linear. But if you see the buoy measured temperature profiles, you will find this assumption is not always valid. Such linear profile assumption is generally valid during wintertime. Moreover, even during wintertime, sudden change in air temperature due to warm/cold advection or radiative forcing due to cloud cover can rapidly change surface temperature which makes curves in the temperature profile. The good thing is time-averaged temperature profile during wintertime is close to linear (Shi et al., 2020). The authors would consider shortening of retrieval period of the SLICE method.

The third assumption tells that there is no internal heat source associated with shortwave radiation. In other words, this assumption is valid for the regions where the solar zenith angle is maintained less than zero. The authors should check the validity of this assumption regarding the seasonal variability of the solar zenith angle. There can be sunlight in lower latitude regions during fall and spring. Otherwise, please consider the shortwave radiation effects or justify that the shortwave radiation effect is negligible for the lower latitude regions during the fall and spring seasons.

We agree that the assumptions of linear temperature profile and negligible shortwave radiation are valid during the winter time only and that SLICE is not valid outside of the sea ice growth season. As such, we will shorten the SLICE one-dimensional and basin-wide outputs to be from November 1 to March 31 only.

The other point is that the authors mentioned that the retrieval method should be applied in a Lagrangian sense in L224 but they neglected sea ice motion in the actual calculation (L262). What are the reasons for this? There must be justification for the neglect of sea ice motion. Each sea ice parcel should be tracked and matched with the nearest satellite T_{si} because the equation used in this study is a time-dependent equation. Meanwhile, the neglect of sea ice motion is not the same as focusing on thermodynamic growth. Thermodynamical growth, sea ice motion, and dynamical growth (deformation due to convergence and divergence) should be addressed separately. Consideration of sea ice motion without dynamical growth is possible.

The authors agree that sea ice motion and deformed sea ice due to convergence or divergence should be treated separately. While we are unable to include the effects of deformed ice, we will add a sea ice motion component to the basin-wide SLICE results.

The SLICE basin-wide component now includes advection of sea ice parcels using the NSIDC Polar Pathfinder daily sea ice drift product (Tschudi et al., 2019). We had planned to include this element in a future study but at the request of RC#2, we have chosen to include advection in this paper. SLICE is initialized with the CS2SMOS data or PIOMAS (interpolated to the 25 km EASE grid 2.0) from the first week of November and each 25 km x 25 km grid cell is divided into 5 km x 5km parcels, which are advected daily using the motion vectors interpolated to their position and who add sea ice thickness thermodynamically using the SLICE thermodynamic model. As before, new ice per a sea ice concentration product is initialized at 0.01 m. At any given time step, the parcels can be gridded back to the EASE grid 2.0 grid by taking the mean of parcels within each EASE grid. This process will be included in all basin-wide results shown in the revised manuscript.

In order to investigate whether SLICE can accurately capture deformed ice, we also attempted re-griding the parcels by taking the sum of parcel volume within grid cell and dividing by area. This process yielded unphysical results. Figure 1 shows an example of SLICE on March 31 2013 initialized with CryoSat-2/ SMOS on November 1 2012. The total volume of sea ice parcels within grid cell divided by grid cell area is as shown in Figure 1a. Those results are unphysical and are dominated by unrealistic convergence and divergence of parcels as shown by the total number of parcels per grid cell shown Figure 1b. The mean ice thickness of the parcels within each grid cell is shown in Figure 1c. and are the best results. The mean thickness within grid cell does not, however, capture deformed ice. Perhaps and improved sea ice motion product would allow the inclusion of deformed ice into SLICE.

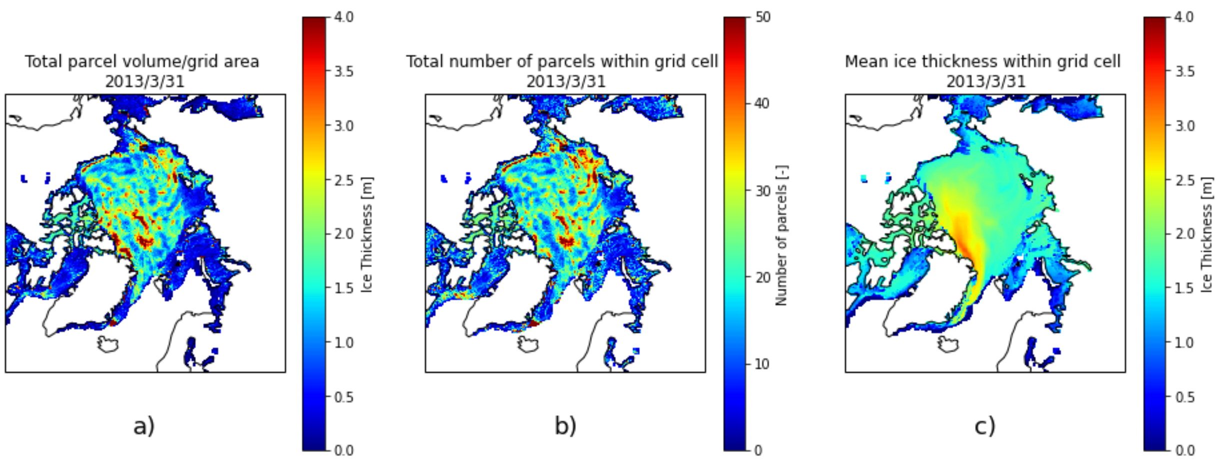

Figure 1: SLICE parcels on March 31 2013 (a) regridded using total parcel volume per grid cell divided by grid area, (b) counts within grid cell and (c) regridded mean parcel thickness within each grid cell. The volume per grid cell approach is unrealistic and dominated by erroneous convergence and divergence of parcels within grid cells.

2. Effectiveness of self-correcting characteristic

It was interesting to read the statement in L225 regarding the self-correcting characteristic of the SLICE method. Thicker sea ice indeed grows slower than thinner sea ice with a given T_{si} and vice versa according to equation (7). Therefore, the error in sea ice thickness can be relaxed by the modulation of sea ice growth speed.

However, the relaxation speed of error is important as well. If the speed of relaxation is slow, the effectiveness of self-correcting characteristics will be minor and the initial condition will be the major factor that determines the accuracy of sea ice thickness estimation. In L249-250 and Figure 2, the authors tried to show the effect of the self-correcting characteristic. Although it seems that 0.25 m deviations in the initial condition are decreasing with time, it will be better to specify the improvement quantitatively to know how fast the errors are relaxed. In addition, I suggest conducting a sensitivity test and including the result as an appendix.

Equation 7 shows that the conducted heat flux from basal sea ice growth is inversely related to sea ice thickness. All other factors being held equal, a change to sea ice thickness will be reflected by the inverse of that change to sea ice thickness growth rate. For example, a sea ice parcel that is twice as thick as a separate parcel will grow half as fast as that other parcel. We will add a +/- 0.5 m set of lines to Figure 3 and also include a quantitative assessment of how the 0.25 m and 0.5 m perturbations change of the course of the growth season.

I found some doubtful points on the self-correcting characteristic of the SLICE method. In my opinion, if the method is self-correcting, the retrieval result should fluctuate around the true state. Why is the SLICE retrieval (red solid line) the center of red shade instead of the buoy (blue solid line) which is the true state? In addition, I think the sentence “The bias grows with time as the SLICE profile moves away from its initialized thickness” makes a contradiction with the self-correcting characteristic of SLICE.

Theoretically, in the absence of any effects other than thermodynamic growth and if the SLICE assumptions are valid, initial condition errors will reduce over time. Because there are indeed other factos other than thermodynamic growth, this will not necessarily be reflected in the SLICE and buoy profiles. We will remove the sentence quoted by the reviewer regarding bias growth over time.

The significance of self-correcting characteristic is important for the algorithm extension to the past because such characteristic makes the retrieval method relatively independent from the accurate initial condition. If the self-correction is significant, SLICE sea ice thickness records initialized with PIOMAS can be constructed, and it will be more accurate than PIOMAS. To examine this, I suggest comparing the accuracy of the sea ice thickness from the PIOMAS and that from the SLICE initialized with the PIOMAS. There are some widely used independent datasets for validation such as Operation IceBridge (OIB), buoy, upward-looking sonar (ULS), and submarine observations.

The self-correcting characteristics of SLICE will not be significant enough to remove any dependence upon its initial condition. An accurate initial condition is important for SLICE’s results. With regard to long term studies, we will remove allusions to the long-term application of SLICE and instead leave that for future investigation.

There are other advantages of SLICE over PIOMAS that are more significant than the theoretical error reduction discussed here. SLICE is thermodynamically forced by satellite observations of snow-ice interface temperature rather than an atmospheric reanalysis and is a much simpler model.

3. Retrieval or modeling (significance of this study)

In some sense, the SLICE retrieval method seems to be a thermodynamic sea ice model. The reason is that it simulates sea ice thickness evolution with time, and the result of SLICE retrieval is highly dependent on initial conditions rather than observed data. I think that the SLICE method is a simplified version of the thermodynamic sea ice model introduced by Maykut and Unterstiener (1971) or the PIOMAS. It will be nice for the authors to explain why the SLICE method is satellite retrieval.

The most direct output from SLICE is a thermodynamic growth rate (and conducted flux through the ice). Much like many accepted retrievals, this output relies upon a priori information--sea ice thickness, freezing point temperature, etc. We believe this step of the process can be considered a retrieval based on a simple model. We concede that accumulating the sea ice growth into an absolute sea ice thickness is more of a modeling exercise, albeit one that is heavily observationally constrained. We will make this clear in the next revision.

Nonetheless, the novel point of this study is SLICE method is independent of the atmospheric reanalysis generally used as the forcing to sea ice model. The most relevant study to the SLICE method will be Kang et al. (2021), which simulates the physical state of a snow- ice system by using a thermodynamic equation set forced by atmospheric reanalysis and nudged by satellite T_{si}. This study has significance in terms of constructing an independent sea ice thickness record, while the physics of SLICE is very simplified compared to Kang et al. (2021) or other thermodynamic sea ice models. I recommend including an ice thickness comparison with the results of Kang et al. (2021). Their results are open to the public, and the authors can find the data repository in their paper. It is worth comparing the performance of the SLICE method with other sea ice models with more sophisticated physics and forced by reanalysis data.

We will add a comparison to the paper of SLICE initialized with CS2SMOS, PIOMAS and the model described by Kang et al. 2021 (hereafter K21) to Operation Ice Bridge (OIB) data (Kurtz, 2015).

OIB data from the month of March for the years 2013 through 2018 (including NSIDC OIB quick looks data) was first binned by SLICE grid cell and averaged across each bin to create collocated SLICE (initialized with CryoSat-2/SMOS) and OIB data. Both PIOMAS and the Kang et al. 2021 data were also interpolated to the SLICE grid. Using only SLICE grid cells with 100 or more individual OIB sea ice thickness data points within their bounds, a comparison between the datasets was created and shown below.

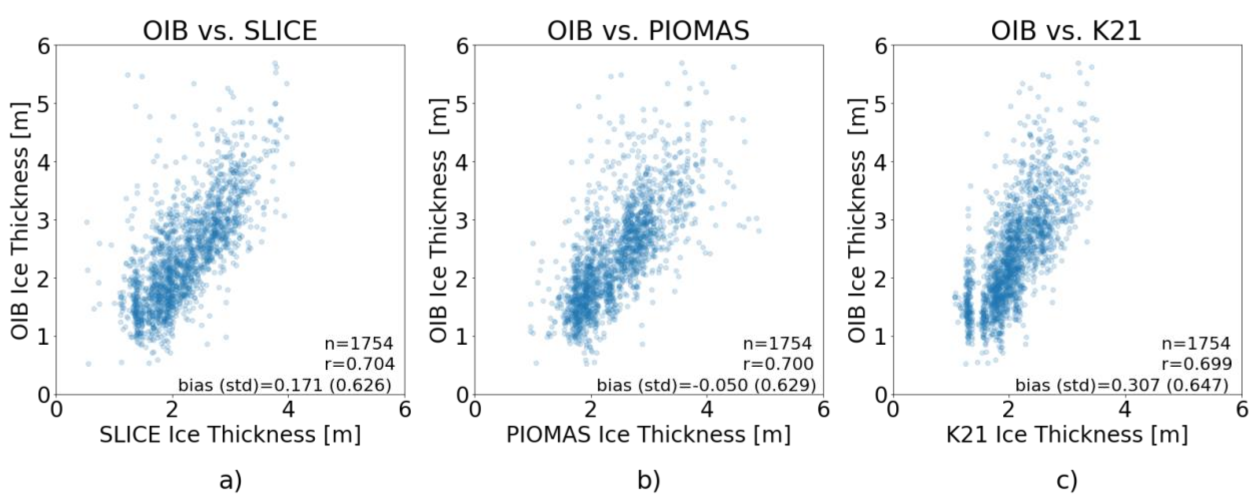

Figure 2: OIB thickness versus (a) SLICE intilialized with CryoSat-2/SMOS, (b) PIOMAS and (c) Kang et al., 2021 data including number of data points, linear correlations and bias with standar deviation. SLICE has the highest linear correlation though all three are nearly equal.

The highest linear correlation value belongs to SLICE at 0.704, however the linear correlation for PIOMAS and K21 are very near that value at 0.700 and 0.699 respectively. The smallest mean (standard deviation) bias is exhibited by PIOMAS at -0.050 m (0.629 m) followed by SLICE with 0.171 m (0.628 m) and K21 with 0.307 m (0.647 m). This analysis will be included in the revised manuscript.

These statistics show that all three models have similar performance when modeling sea ice thickness, even without SLICE including a deformation component. The differences are related to complexity of the model and reliance upon model reanalysis data. Whereas both PIOMAS and K21 require snow information and must calculate the temperature profile in the snow in order to determine the temperature profile in the ice from a reanalysis product, SLICE uses direct retrieval of the snow—ice interface temperature in order to calculate the heat flux through the ice and therefore thermodynamic sea ice growth. By assuming a linear temperature profile in the sea ice, SLICE also removes the requirement for multiple ice layers to be tracked by the model.

We don't believe SLICE to be a replacement for existing sea ice thickness retrievals, rather an additional independent dataset created using an observationally constrained very simple model that may be more applicable in certain situations.

4. Bias correction for satellite T_{si}

The authors mentioned that "The resultant snow-ice interface temperatures were found to require a bias correction of 5 K in order to match buoy snow-ice interface temperatures…"). I have read Lee and Sohn (2015) and remember that the snow-ice interface derived from AMSR- E 6.9 GHz brightness temperatures are validated with buoy measured temperature. The validation result showed that the bias was less than 1 K, which is a very different result from the 5 K bias in the manuscript. Lee and Sohn (2015) also neglected atmospheric/snow absorption.

Regarding this situation, first I thought that it is possibly due to the bias within AMSR-E and AMSR2 measurements. However, the authors stated that the AMSR2 data has been intercalibrated with the AMSR-E data so this may not be the issue. Then, may the version of L3 brightness temperature be a problem? Or simply authors failed to reproduce the T_{si} retrieval algorithm.

It is unclear why the results from Lee and Sohn (2015) seem to have not required a correction for atmospheric absorption. The physics described in that paper are valid at the surface but the brightness temperatures viewed by the satellite at 6.9 GHz will be affected by the atmosphere, which we are accounting for.

This is a very critical issue because sea ice thickness is determined by T_{si}, which is the only real observation used for the sea ice thickness retrieval. The mentioned comparison result between buoy data and T_{si} calculated by the authors showing 5 K bias must be presented (as an appendix) to justify the bias correction procedure. It will be worth reproducing figure 6 in Lee and Sohn (2015).

The "bias correction" is due to the slight absorption of 6.9 GHz radiation by the polar atmosphere. In order to better account for this, we have chosen to use a radiation transfer model (RTTOV; Saunders, et al., 2018) and pressure, temperature and humidity profiles along with skin temperature, surface pressure, 2 m temperature and humidity and 10 m winds from ECMWF ERA5 reanalysis data (Hersbach, et al., 2018) to model the effect of the atmosphere on the 6.9 GHz AMSR2 channels. For every day since 2003 and for the entirety of the Arctic basin, we have used the model to estimate the atmospheric transmission at 6.9 GHz and applied a location and time specific transmission factor to each AMSR2 radiance used in the calculation of snow—ice interface temperature. We will change equation 1 to reflect this by inserting a transmission t to the right side of the equation and remove the statement that absorption at 6.9 GHz by the atmosphere is assumed negligible. The phrase "bias correction" will be removed from the manuscript as it doesn't accurately describe this methodology. Rather, we will add a description of the new methodology described here.

Whereas we previously had used a static 5 K correction, the resulting change to 6.9 GHz brightness temperatures affected by the modeled transmission term is very consistently near 5 K. The below figure shows mean and standard deviation atmospheric correction from atmospheric transmission to a 250 K brightness temperature during December, January and February (DJF) across the years 2003-2019. The Arctic basin shows a very spatially consistent roughly 4.5 K mean with standard deviations less than 0.1 K. These results are very similar to those reported by Burgard, et al., 2020 who used a geophysical model to simulate 6.9 GHz brightness temperature at TOA using MPI-ESM output data. They report a difference of 4.49 K between the model ice surface temperature and the simulated 6.9 GHz brightness temperature at TOA for pixels with 99% or greater sea ice concentration during the summer season when accounting for columnar water vapor and columnar cloud liquid water. Though we've reported our DJF results here, our summer results are very similar. These results will not be shown in the manuscript but are relevant to this review response.

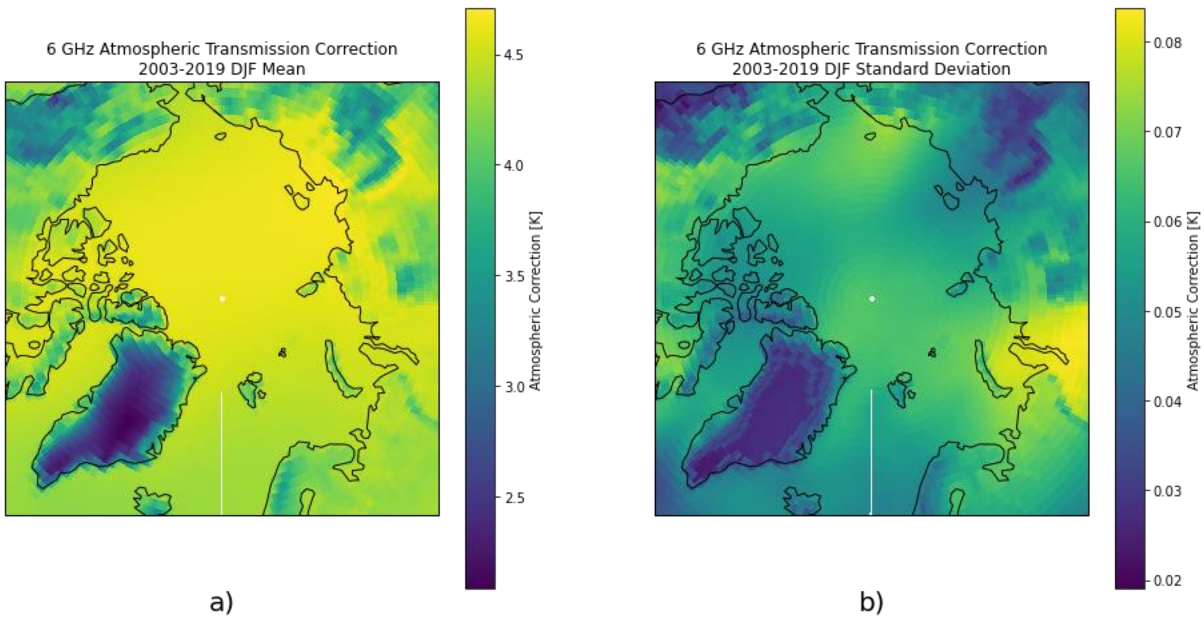

Figure 3: AMSR-E and AMSR2 6.9 GHz channels brightness temperature correction at 250 K in the 2003-2019 DJF (a) mean and (b) standard deviation calculated using a radiative transfer model and ERA5 reanalysis data.The correction is consistently near 4.5 K.

Minor comments

L29-L37: Please provide more details for relevant studies on sea ice thickness retrieval in order to emphasize the novelty or necessity of SLICE. How are the satellite altimetry methods limited in spatial coverage and temporal resolution (I think the resolution of ICESat-2 is better than passive microwave sensors such as AMSR2 6.9 GHz)? What are the limitations of the other methods? How is this study related to the existing studies?

We will add more quantitative information to this passage. In any case, while the ICESat-2 and CryoSat-2 spatial resolutions may be better than microwave instruments (which we did not and do not dispute), the orbit details, spatial coverage and temporal resolutions combine in such a way that both satellite sensors take much longer to cover the entire Arctic than AMSR2 and AMSR-E.

L63: horizontally and vertically polarized…

We will make this change.

L215: Please define negative degree-days in the manuscript and provide what happens if the temperature is positive (melting?).

The negative degree-days term is defined in L216. SLICE is not capable of capturing melt.

L221: It is hard to know which equation was used for sea ice thickness calculation. Equation (4) is too general. Did you use equation (8) which is an analytic solution for sea ice thickness, or equation (7) for change in sea ice thickness per unit time and accumulate the thickness changes?

The equations will be changed slightly in order to account for heat flux from the liquid ocean to the solid sea ice per a recommendation from RC#1. We will be sure to be more clear about which equations are used in the algorithm.

L235-237: Why the retrieval method was initialized with such condition (the day when the 14 d rolling average sea ice growth exceeded 1mm d^{-1})? Please provide the reason.

We have updated the one-dimensional results to begin with the buoy initial condition on November 1 rather than the previous definition of a start time based on ice growth exceeding a threshold. This also reflects how the basin-wide methodology works.

L400: I think uploading the data produced in this study to the public data repository more fits the data policy of TC journal.

While this step is not required for publication, we would like to increase the impact of this research in any way we can and will work to post both code and data on a publicly available repository. We will aim to provide more details along with the next revision of the article.

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