Reply to Interactive comment on "Thin-ice dynamics and ice production in the Storfjorden polynya for winter-seasons 2002/2003–2013/2014 using MODIS thermal infrared imagery" by A. Preußer et al.

Received from anonymous referee #2

The MS presets an application of the previously developed algorithm (Adams et al., 2013) of deriving thin sea ice thickness (<20cm) from MODIS SIT products and other datasets, for the Storfjorden polynya for the winter season of 2002-2014 period. The tech is clear and results are compared with others, and showing clear advantage and reliability of the results. I can recommend the paper to be published only after authors address those comments below and maybe more in the revision stage.

We would like to thank the second referee for her/his valuable comments and suggestions that will definitively help to improve the original manuscript (MS). We carefully went over the specified parts in the MS and we will answer her / his comments in the following.

Specific comments:

(1) *In page 5767, line 1, you mentioned the MODIS SIT is for daytime only, no nighttime validation has been done. But you used this data for the winter season which is nighttime only (no daytime), right? So how you can use those data? Am I wrong? I realized this same data was used in the Adams et al. (2013) paper.*

Thank you for this valuable comment, which motivated us to review the cited studies by Hall et al. (2004) and Riggs et al. (2006) more carefully.

First of all, it is correct that we only used nighttime scenes in our investigation to exclude ambiguities originating from the inclusion of shortwave radiation. Regarding the nighttime validation of MODIS IST, we discovered that apparently there is a small error in the study of Riggs et al. (2006). Hall et al. (2004) present an accuracy assessment using both Arctic (buoys and meteorological data from tide stations) and Antarctic (South Pole station) validation data sets. Thereby, an IST-accuracy (RMSE) of 1-3 K is given, which depends on location, sample size, a certain temperature bias and different criteria for cloud screening. In addition, it is clearly stated that also nighttime cases are included (especially for the Antarctic IST-validation: 255 cases which are primarily nighttime cases (April–December 2001)). Therefore, we have no reason to assume a worse IST-accuracy / sensor-calibration for nighttime MODIS swaths than during daytime, besides an increased tendency to be affected by undetected cloud signals / decreased performance of the MOD35 cloud mask (lack of visible channels for the cloud mask). The used coefficients in the split-window approach to calculate IST from satellite measured brightness temperatures are not dependent on day-/nighttime conditions.

Consequently, we will leave out the sentence about a missing nighttime validation and correct the accuracy range to 1-3 K, as it was done in several comparable studies using nighttime MODIS IST data.

(2) *In page 5768 line 20, there is an assumption of $Q_{atm} = Q_{ice}$, I would like authors to address this for possible error and why this assumption stands.*

First of all, this is exactly what the surface energy balance requires. The critical question is, if a bulk approach for heat conduction can be used.

By using an upper threshold of 50 cm for TIT-calculations (Yu and Rothrock, 1996; Drucker et al., 2003), the vertical temperature gradient in the ice can be assumed to be linear according to Stefan's law (Stefan, 1891). Yu and Rothrock (1996) state: "This assumption (i.e. linear temperature profile) is supported both by field observations (Nakawo and Sinha, 1981) and by a theoretical study (Maykut, 1982)."

(3) *Page 5771 equations 4,5, you have one assumption, assuming the polynya area has the same proportion under cloud cover and no cloud cover; and your correction was only applied to coverage (make clear what coverage?) over 0.5. I think both of these will cause errors and I hope you can discuss them.*

Thank you for your remark. This topic was also mentioned by the other two referees, so we decided to perform and include an error analysis as proposed by anonymous referee No.3.

We selected a total of six case studies from January 2009, which feature more or less clear-sky conditions (≥ 99%; IST-coverage → percentage of pixels within the polynya mask that feature at least one valid IST-value from all MOD/MYD29 swaths covering the Storfjorden region at a given day). The coverage-correction has been iteratively (n = 1000) applied for each case study after randomly removing 45% of the pixels within the polynya mask. The resulting deviation (in %) from the "true" polynya area (POLA) from all case studies combined is shown in the Figure below. These $POLA_{CC}$-deviations almost perfectly follow a typical normal (Gaussian) distribution, with a mean value of 0.67% (in a hypothetical case of 100% IST-coverage we expect it to be ± 0) and a standard error of ~ 5-6 % of the daily POLA. This may help to quantify the error of our method.
Alternatively, we think that interpolating between bounding days with better IST-coverage (> 50%) is so far the best solution of handling large cloud-gaps in the daily composites. For future studies, we are working on a more advanced solution which incorporates a spatial feature reconstruction algorithm.
We will add this information in the revised manuscript in Ch.2.3.3 and plan to include a short appendix.

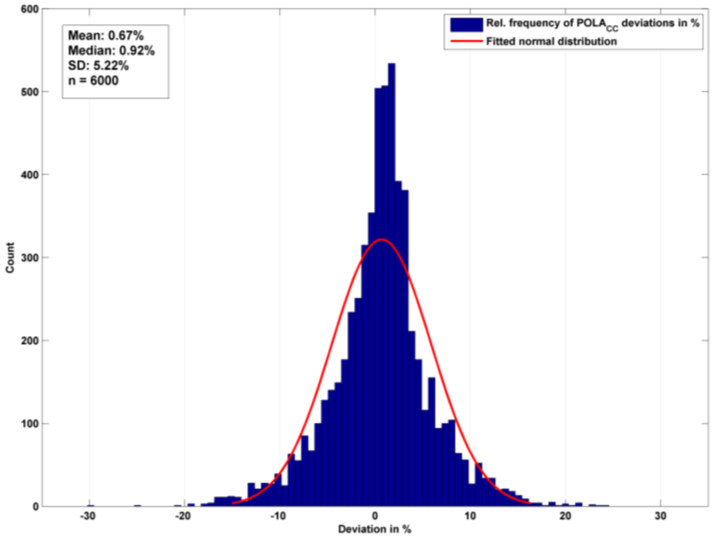

*Figure 1 Histogram of $POLA_{CC}$-deviations, based on six near clear-sky case studies from January 2009 (DOY: 002, 020, 024, 025, 026, 030). For each case study, the coverage-correction was repeated several times (n=1000*6), after randomly removing 45% of the pixels within the applied polynya mask.The red curve illustrates a fitted normal distribution.*

(4) *Page 5773 line 15, you mentioned years 2004, 2005, 2007 and 2011, but my checking with the figures, I found they should be 2003, 2004, 2005, 2009 and 2011. Please check.*
We checked your comment and indeed, 2003 and 2009 are also fitting to that context. We will add these years in the revised manuscript.

(5) *Fig 4 and 5, why only up to 50%?*
To enhance the contrast between low and high frequencies, the color-bar is limited to range from 0 to 0.5 (0 - 50% of the days in Nov.-Dec. / Jan.-Mar.).

(6) *I guess those areas of 0 TIT frequency in figure 4, 5 are of thicker ice (>0.2m), I hope you can use the AMSR-E ice concentration maps to support you.*

Thank you for your suggestion. We had a look into daily AMSR-E and AMSR2 SIC-maps for the regarded time period. Due to the coarser spatial resolution and potential ambiguities from land spill-over effects in the comparatively narrow/small Storfjorden area, we decided to leave out the PMW-data in the framework of this study, as it might probably introduce new/additional error sources.

To illustrate the differences between the PMW SIC-data and our TIT-retrievals, we present the spatial distributions of TIT up to 0.2 m (a) and up to 0.5 m (b) as well as the ASI SIC (c) for the 12th of January 2009 in Fig.2 (below). Indeed, areas where pixels show values above 0.2 m compare nicely to higher SIC (more compact ice) in the AMSR-E image. Comparing Fig.2 (b) and (c), you might also notice that there seems to be no direct/simple relationship between thicker ice and higher SIC, as retrieved TIT-values are strongly varying in areas with 100% SIC.

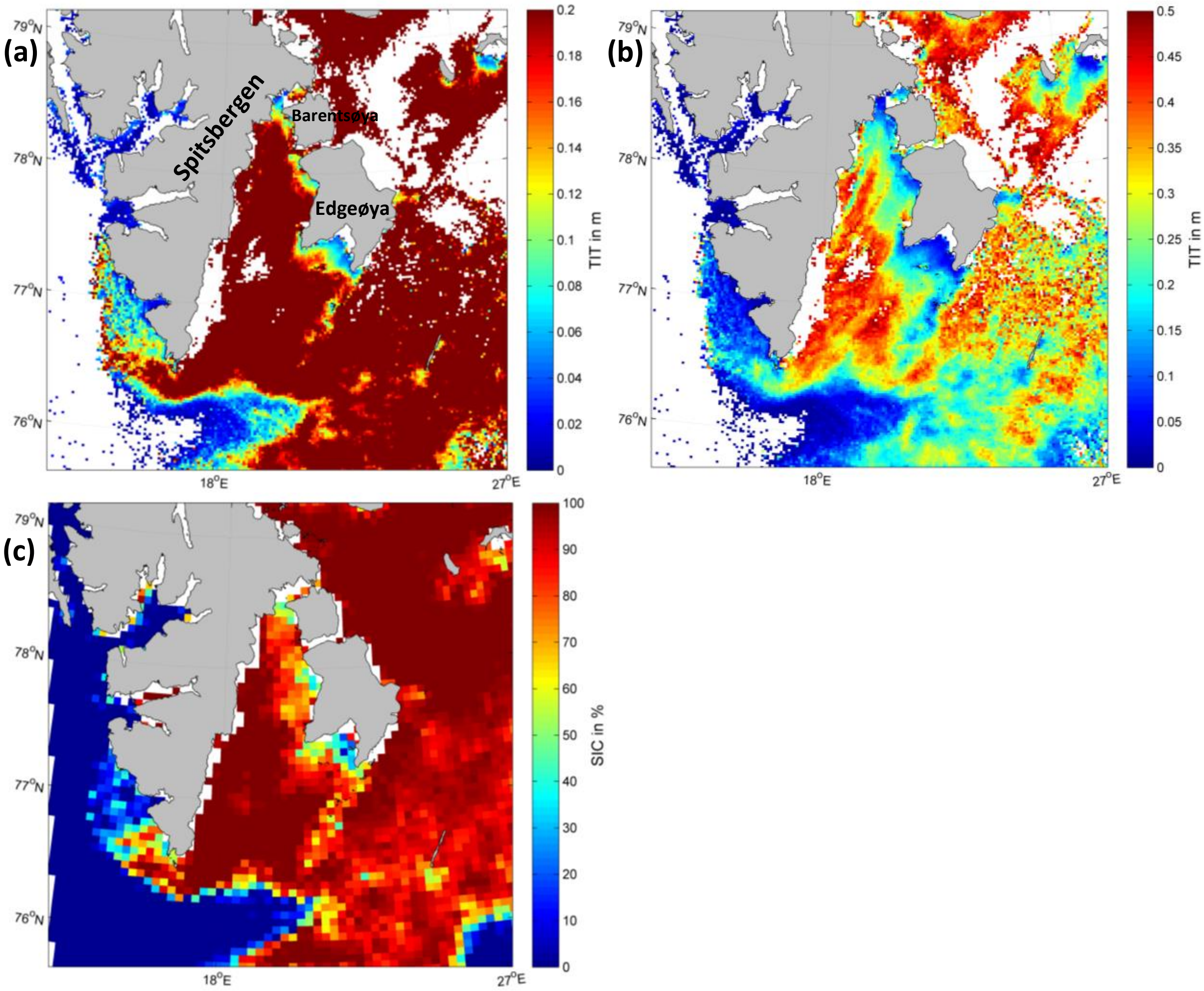

Figure 2 Spatial overview of calculated TIT ≤ 0.2 m (a), ≤ 0.5 m (b) and AMSR-E sea-ice concentrations (ASI v5; University of Bremen; (c)) on the 12th of January, 2009.

(7) *I hope to see more discussion and interpretation on the reasons or mechanisms for such pattern/trend you see from the 12 years of data.*

We find that the significant positive trend in overall (Nov.-Mar.) IP_{CC} originates primarily from a significant positive trend (CC: 1.29km³/yr, p = 9.05*10^-4) at the beginning of winter (Nov.-Dec.), while the period from Jan.-Mar. shows no significant trend (but still being positive; CC:

0.73km³/yr, p = 0.052). This could be an effect of an observable shift towards more thin-ice in Nov.-Dec., which is most probably connected to a later appearing fall freeze-up (as already mentioned in the manuscript) and therefore a lot open water / very thin ice in the southern part of the applied polynya-mask. A similar explanation can be given for the high IP in 2012/2013, where the Storfjorden area features high frequencies of TIT ≤ 0.2 m not only in Nov.-Dec., but also in Jan.-Mar. This could be related to an anomalous northerly position of the ice-edge in Storfjorden.

We will add some words about that topic in the results and discussion. An alternative version of Fig.8 which highlights seasonal differences in IP is shown below.

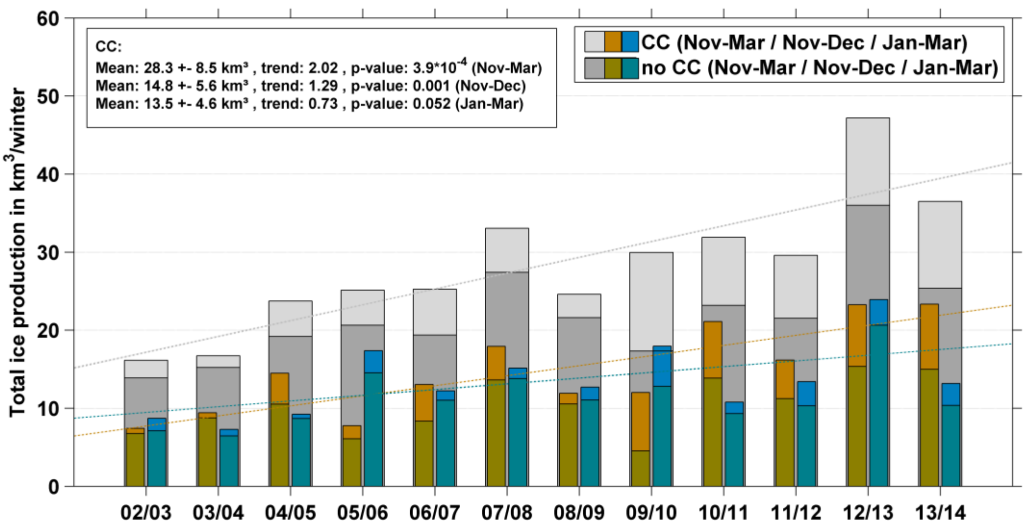

Figure 3 Annual wintertime accumulated ice production in the Storfjorden polynya, given in km³/winter. Estimations are based on daily heat flux calculations using the daily derived TIT- composites. Special emphasis is given to the effect of an applied coverage correction (CC). Dotted lines show linear trend estimations for IP_{CC}. Colored bars are additionally given for a seasonal comparison between November-December (yellowish) and January-March (blueish).