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 #1

This paper describes the spatial and temporal characteristics of the Storfjorden polynya over a time period of more than 10 years using thermal infrared satellite imagery. The paper is well written and easy to follow. The method to calculate ice thickness from MODIS is well-known, and already published in other papers. However, the statistical analysis of polynya using MODIS data over such a long time period is valuable and the method could be extended to other regions with frequent polynya openings and respective ice production which are important for the ocean circulation. Therefore, the paper is worth to be published with minor revisions.

We would like to thank the first referee for her/his valuable comments and suggestions that will definitively help to improve the original manuscript, most importantly the discussion and the specification of error-margins. We carefully went over the mentioned parts of the manuscript and we will answer specific and general comments in the following.

Specific comments:

P. 5764, L. 11-13. *It is not clear to me, if "an increasing frequency" is meant for one freeze-up period or a trend in the 12 years period here.*

The number of larger polynya events in Nov.-Dec. increases over the regarded 12-yr period, not one single freeze-up period.

We slightly changed the formulation in the Abstract to make that more clear.

P. 5765, L. 11. *Please add references after "model approaches".*

We added Ebner et al. (2011), Krumpen et al. (2011) and Bauer et al. (2013) as reference.

P. 5765, L. 15-21. *There are also other regions with frequent polynya openings and active ice production in the Arctic (e.g. Laptev Sea). Why is the Storfjorden region so important that you choose this region for the statistical analysis?*

The selection of our study area followed several distinct requirements: 1) A comparatively small areal extent to profit from enhanced resolution imagery. 2) A region that is well studied to compare our estimates. 3) More or less stable formation-mechanism with limited error-sources (e.g. oceanic heat input). 4) Significant importance considering total IP and deep water formation. 5) Part of the study area during the aircraft-based campaign LEAST (March 2014)

We will add some statements to the revised manuscript.

P. 5765, L. 26-29. *How do you intend to distinguish the sea ice transported into the Storfjorden area from thermodynamically induced ice growth? Could this be a factor of uncertainty in your estimates?*

Sea ice that is advected from the south into Storfjorden may play a role in the total ice thickness distribution. But, as our ice production estimates are based on the "as is" daily mean thin-ice thickness distribution below 20 cm ice thickness, these processes are included in our estimates as long as the total ice thickness in a certain grid cell does not exceed 20 cm.

P. 5766, L. 24. *"IST swath"→ "Swath-based IST"*

We fixed that, thank you for your suggestion.

P. 5767, L. 5. *Please emphasize here that only nighttime scenes are used in this study.*

We changed it to "(…) resulting in 27 individual swaths per day on average for later composite generation. These composites solely consist of nighttime scenes to exclude the influence of incident shortwave radiation (Yu and Lindsay (2003), Adams et al. (2013); compare Ch. 2.3 and 2.3.1). (…)".

P. 5767, L. 11. *Please add references after "previous studies".*

Added Skogseth et al. (2004, 2005) and Jardon et al. (2014) as reference.

P. 5769, L. 29. *The uncertainty of the retrieved TIT caused by neglecting a snow layer should be discussed here.*

First, we think that this assumption is valid for very thin ice (compare Adams et al., 2013: "*we neglect snow on the thin ice, which is in accordance with in situ observations [in the Laptev Sea] during the TRANSDRIFT XV expedition*"). Similar observations could be made in March 2014 during the aircraft-based campaign LEAST in Storfjorden. Of course these are only airborne observations for a few cases, so we can't exclude any possible snow layer in general. Mäkynen et al. 2013 applied a snow layer thickness in the TIT-retrieval, based on a statistical relationship to the ice thickness. Although this approach seems to work reasonably well, we decided not to use it as (to our best knowledge) there are no reference / validation measurements for snow on thin ice (below 0.2 m) available.

As we are currently not trying to develop a new procedure of handling a possible snow cover, we decided to stick to the assumption formulated by Drucker et al. (2003) and Adams et al. (2013).

P. 5772, L. 16. *"SD are highest'→ "SD is highest"*

We fixed that, thank you for your suggestion.

P. 5772, L. 1. *Please define the "relative TIT-distributions".*

We changed the mentioned part into: "The bars in Fig.3 show the mean relative contribution of each ice-thickness class from the total number of pixels with a TIT-value ≤ 0.2 m between the winter-seasons 2002/2003 to 2013/2014."

Section 4 Discussion

Question 1: *What could be the potential reason of positive trend in IP in the Storfjorden region during the last 12 winter-seasons? Fig. 8 shows an extremely high IP during the winter season of 2012/2013. Do you have any explanation?*

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.

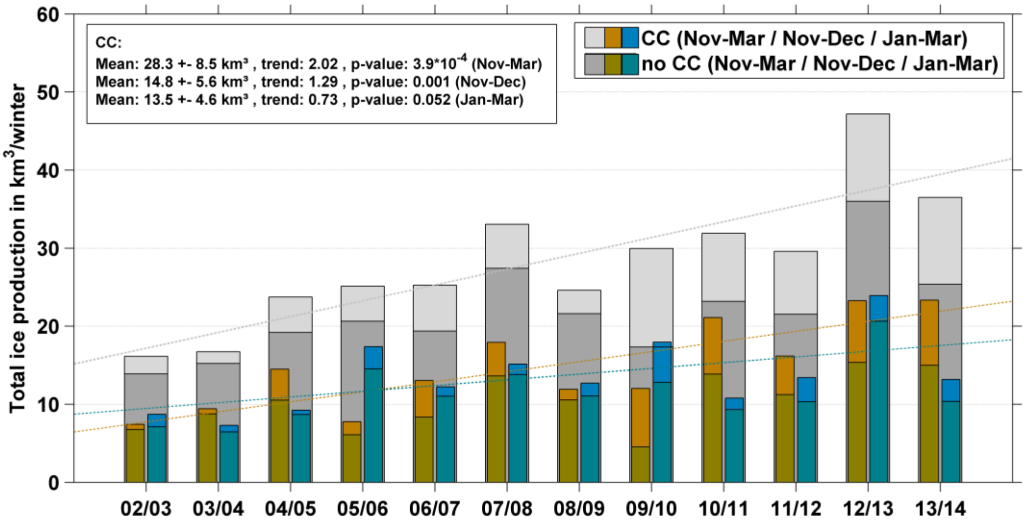

Figure 1 Annual wintertime accumulated ice production in the Storfjorden polynya, given in km³/winter. Estimations are based on daily heat flux calculations using the daily derived TIT- composites. Special emphasis is given to the effect of an applied coverage correction (CC). Dotted lines show linear trend estimations for IP_{CC}. Colored bars are additionally given for a seasonal comparison between November-December (yellowish) and January-March (blueish).

Question 2: *Does the coarse resolution of sea ice concentration derived from passive microwave sensors lead to the overestimation of IP in this region? If yes, what is the reason?*
It leads for sure to a higher uncertainty, while the sign of the bias cannot be determined here. It will depend on the distribution of thin ice within the sensor's footprint and potential land spillover effects.

Question 3: *As you mentioned, MODIS data has a strong limitation due to the cloud coverage. Please discuss in more detail how large is the uncertainty of IP estimate due to the cloud coverage.*

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.

To test the performance of our coverage-correction scheme, which aims at compensating cloud-induced data gaps, 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.

As the correction / upscaling of IP-values uses the same scaling-factor F, the retrieved error-margins can also be regarded as the uncertainty of our IP_{CC} estimates.

We will add this information in the revised manuscript in Ch.2.3.3 and plan to include a short appendix.

Question 4: *Only from this paper, I could not conclude that the Storfjorden polynya has special contribution to the overall ice production in the Arctic. Could you give an approximate estimation of the contribution of IP from Storfjorden to the Arctic-wide IP?*

According to Iwamoto et al. (2014), the Storfjorden polynya contributes with 4 % to the average total ice volume produced in Arctic polynyas between 2002/2003 and 2010/2011 (September-May), which appears to be a minor contribution. Despite that, the Storfjorden polynya is highly relevant due to its importance on deep water formation and the connection of the water masses in Storfjorden to the larger-scale ocean dynamics in the Barents and Greenland Seas. Estimations by Skogseth et al. (2004) show that the Storfjorden polynya supplies between 5-20% of all the newly formed dense water (BSW) which enters the Arctic Ocean, although its spatial extent is comparatively small.

We will add some additional words dealing with the pan-arctic context / relevance in the discussion. In addition, we would like to mention at this point that we are currently preparing a follow-up study dealing with pan-arctic TIT-retrievals and IP-estimates. This will enable us to do direct comparisons between the most important Arctic polynya-regions.