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 #3

General comments:

In the paper the spatial and temporal characteristics of the Storfjorden polynya for the winter seasons of 2002-2014 are described based on thermal infrared satellite imagery. This 12 years data set is the major contribution of the paper. The created data set can be utilized as a reference set to other Arctic polynya statistics and also in the climate simulations. The method to calculate ice thickness from MODIS is well-known generally, and also used by the authors in other papers.

The only significant deficiency in the paper is that the trend and fluctuations observed in the polynya statistics are not set in any manner to a more general context. E.g. connections to the ice conditions in the surrounded seas like the Barents Sea and Fram Strait (or the effect of the Arctic Sea ice retreat generally) are not discussed. Neither any comparisons to other Arctic polynyas, e.g. in the Kara Sea or the Laptev Sea, are made. When these omissions and some other minor points are addressed the paper is worth to be published. I agree with the other referees that the paper is well written and easy to follow.

I have read the reviews by the referees #1 and #2. They raised several important points and questions. I tried to avoid to duplicate the comments already made. Hence I have just a few additional remarks.

We would like to thank the third referee for her/his valuable comments and suggestions for an improved version of the original manuscript. We thoroughly went over the specified parts in the manuscript and we will answer her / his comments in the following.

Specific comments:

P. 5765 (5766?) L5-15*: How does the thermodynamic ice production from the Storfjorden polynya compare to other Arctic polynyas, e.g. polynyas in the Kara and Laptev Seas (see e.g. Kern 2005, 2008 for the Kara Sea and your own publications for the Laptev Sea).*

First, we would like to highlight that a direct comparison to other Arctic polynya systems is challenging, due to a variety of different retrieval methods, strategies and physical parametrizations. Taking this into consideration, the following numbers are worth to be highlighted:
In comparison to other Arctic polynya systems, the Storfjorden polynya is on average quite small (e.g. $POLA_{CC}$ = 4555.7 km² (STO) vs. 21.2 * 10³ km² ± 9.1 * 10³ km² for winters (Jan.–Apr.) 1996/97 to 2000/01 (KARA SEA). Similar differences can be found for the thermodynamic IP derived by either remote sensing techniques (Willmes et al. (2011) → 55.2 km³ (Laptev Sea); Tamura et al. (2011) → 342 ± 71 km³ (Kara Sea); Iwamoto et al. (2014) → 186 ± 34 km³ (North-Water polynya)) or modelling approaches (e.g. Bauer et al. (2013) → 30-73 km³ (Laptev Sea)). Absolute numbers for each region vary dependent on the applied technique and / or regarded spatial margins.
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 majority of important Arctic polynya-regions, based on almost the same TIT-retrieval scheme as in the here presented manuscript.

P. 5771. L9-28*. A crucial feature in your approach is the scaling approach. You mentioned it increases the ice volume estimates about 30 %. Hence it is important to have some estimate for the accuracy of the proposed method. This is not difficult to do. Pick a cloud free day, mask 45 % of the polynya area randomly and apply the scaling. When the procedure is repeated several times, you should have understanding how well the approach works. Using three consecutive cloud free days you can get an accuracy estimate for the interpolation procedure. Add the uncertainty estimates to the text and discuss their effect on the results.*

Thank you for this valuable remark and suggestion. As proposed 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.

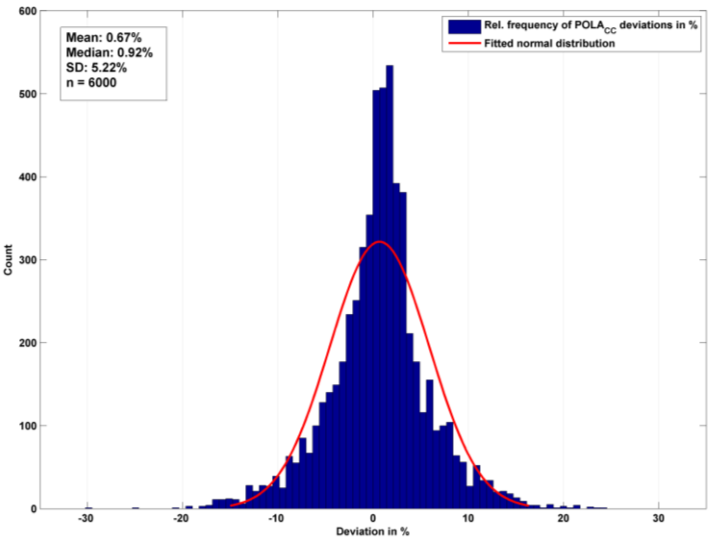

*Figure 1 Histogram of $POLA_{CC}$-deviations, based on six near clear-sky case studies from January 2009 (DOY: 002, 020, 024, 025, 026, 030). For each case study, the coverage-correction was repeated several times (n=1000*6), after randomly removing 45% of the pixels within the applied polynya mask.The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

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.

***P. 5773**. You write in the introduction that time series like this increase our understanding about the Arctic ice conditions. However, you have not linked in any way volume and area estimates of the polynyas to the ice conditions surrounding the Svalbard area, e.g. to ice cover in the Barents Sea and in Fram Strait. Especially interesting these comparisons would be when the IP is very low or very high relative to the mean IP during the covered time period.*

We agree that setting our time series into the context of the sea ice conditions of surrounding areas, other Arctic polynyas, atmospheric conditions (e.g. NAO, AO) would be very interesting. But this is also a little bit beyond the scope of our paper, which should be seen in comparison to related studies in the Storfjorden area.

***P. 5774 L. 7-14**. You should analyze the results in Table 2 in more detail. After all those results are one of the main contributions of your paper. When I looked at Table 2 the following points drew my attention: The increase per decade is 7.7-9.5 km3 for the IP estimates (no CC) and 16.1-17.7 km3 per decade for the IP volume estimates with CC. There occur large increases in the IP from winter 2003/2004 to 2004/2005 and again from 2011/2012 to 2012/2013. During the years from 2004 to 2011 the variation in the IP production (with or without CC) is relatively small.*

Thank you for these welcome additions. We will add some more words about that topic at the appropriate parts of the manuscript.

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.

An alternative version of Fig.8 which highlights seasonal differences in IP is shown below.

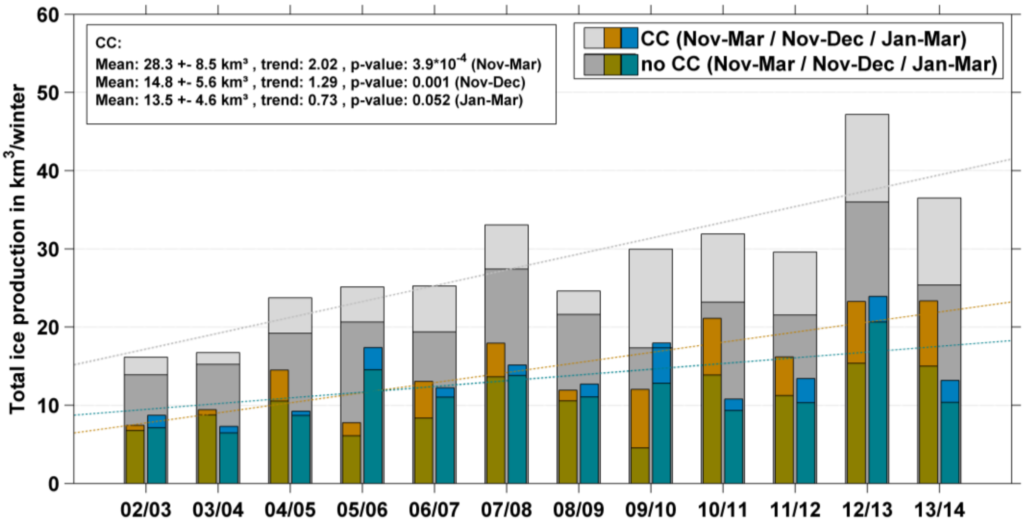

Figure 2 Annual wintertime accumulated ice production in the Storfjorden polynya, given in km³/winter. Estimations are based on daily heat flux calculations using the daily derived TIT- composites. Special emphasis is given to the effect of an applied coverage correction (CC). Dotted lines show linear trend estimations for IP_{CC}. Colored bars are additionally given for a seasonal comparison between November-December (yellowish) and January-March (blueish).

P. 5775 L 10 *"…the here presented last 12 winter-seasons show a positive trend of 20.2 km3." Remove decadeˆ(-1). Add "during the analyzed period". See my earlier comment.*
We fixed that, thank you for your suggestion.