RC3: Interactive comment on "Circumpolar polynya regions and ice production in the Arctic: Results from MODIS thermal infrared imagery for 2002/2003 to 2014/2015 with a regional focus on the Laptev Sea" by Andreas Preußer et al.

Received from Anonymous Referee #3 on August 24, 2016

General comments

Coastal polynyas play a crucial role in altering a variety of physical, biological and chemical processes at the boundary between the atmosphere and the ocean. In the case of Arctic Ocean, polynya ice production is a key component for understanding the maintenance and variability in ocean stratification (cold halocline) and ice-ocean interaction, as well as the seasonal sea-ice mass budget. This paper provides the circumpolar mapping of polynya area (POLA) and its ice production (IP) in the Arctic Ocean, with fine spatial resolution of about 2 km. This resolution is much finer than the previous mapping with satellite microwaves. The authors have accomplished the creation of the dataset of POLA and IP by treating massive amount of 143000 MODIS data, with well-refined procedures. As well, the paper provides 14-year dataset of POLA and IP, which will be the basic data for understanding of drastically changing Arctic Ocean. The paper is overall logical, well-organized, and the presentation/writing is refined. Although the results might have some bias arising from that the calculations were made only for clear-sky and nighttime conditions, this is mainly because of limitation of satellite (MODIS) data. I think that the authors have done a best to create the circumpolar data set with a high spatial resolution. I believe that the paper surely contributes to the community of Arctic and climate sciences. But there still remains some points that should be improved, all of which are minor ones. Some figures can be a bit improved for clarity (see comments 7, 8, 12, 14, 15 for details). In brief, the paper should be published in Cryosphere after a minor revision. The specific points are the followings.

We highly appreciate the valuable and constructive comments and suggestions from Referee #3 and would like to thank her/him for her/his efforts. The overall quality of our submitted manuscript will certainly benefit from the listed specific comments, all of which we will respond to in the following.

Specific comments

1. MODIS clear-sky data can be obtained rarely in the polar cloudy condition. Thus most of researchers including me think that it is difficult to obtain seamless (daily) surface dataset from the MODIS data. For example, in investigation of landfast ice (Fraser et al., 2012, J. Climate) from MODIS, data set was made only for 20-day interval because of cloudy condition. At first I could not believe the average coverage fraction of 70-80% per day (Table 1) in this study. However, if the MODIS image can be obtained for one area several tens of times per day, composite of clear-sky portion could offer the daily data. I guess this is the case and explain why such high fraction of coverage is possible. If this is true, the authors should clearly explain why such high fraction of coverage is possible. For example. How many times per day can MODIS cover a certain area? What percentage can we obtain the cloud free scene? I think that such explanation enhances the creditability of this study.

It is understandable that this circumstance might be surprising at first glance, as thermal infrared data is strongly influenced / limited by the presence of clouds – especially in the polar-regions. We are certainly aware of these difficulties. However, the calculation and usage of daily median composites of IST / TIT enables a vastly increased spatial coverage of these quantities, based on the principle/assumption that clouds move over sub-daily timespans. Of course this assumption can be violated as clouds also tend to behave rather stationary. In those cases, cloud-gaps cannot be avoided completely.

As already written in the manuscript (P.5, L.11), an average of around 73 MODIS swaths per day is available for the Arctic domain. The absolute amount of overpasses for a certain region increases with latitude due to the polar-orbit configuration of the MODIS sensors onboard Terra and Aqua. Therefore, regarding the request of the referee, we **included an additional column in Table 1 that features the average amount of MODIS scenes per day and per region**.

2. Although the MODIS data provide high resolution data set, POLA and IP can be obtained only in clear-sky condition. The atmospheric condition and accordingly surface heat flux in clear-sky condition would be different from those in cloudy condition. Thus it is likely that POLA and IP obtained all from clear-sky condition have some bias compared to those from cloudy condition or pure average irrespective of atmospheric condition. I understand that evaluation of such bias is not easy and no further analysis is needed. But ***more discussion or clear statement of such bias should be made in the revision****. At least such drawback should be stated in conclusion section.*

The exclusive usage of clear-sky pixels is a prerequisite of our approach and can't be avoided using TIR data. The evaluation of such a potential bias is certainly an interesting aspect for further improvements to our TIT retrieval scheme, but at the same time (as you already mentioned) quite challenging**. In this regard, a potential bias might originate from both sub-daily as well as daily timescales.**

On a sub-daily timescale, the POLA retrieval can be assumed to be only little affected by the bias to clear-sky and nighttime conditions, since the TIT (taken as the daily composite) will not change that much, if clouds are present. This is different for the IP, which is computed from energy fluxes. While the turbulent fluxes of sensible and latent heat over polynyas are relatively insensitive to cloudiness, the increase in longwave downward radiation will cause a lower IP in reality. This will lead to a systematic overestimation of IP in our method. However, this is the case mainly for low-level clouds, which emit at a relatively high temperature. Heinemann and Rose (1990)[1] show that this effect can amount up to 50 W/m². König-Langlo and Augstein (1994)[2] show that the effective emissivity (ε_{atm}) increases from 0.765 (clear sky) to 0.985 (fully cloudy), taking the 2m-temperature in the Stefan-Boltzmann law for the computation of the downward longwave radiation ($L\downarrow$). For typical $L\downarrow$ values of about 200 W/m², the increase by 0.22 for the emissivity would also result in an increase of around 50 W/m², thereby impacting the total energy balance considerably. For an estimation of the actual error on a sub-daily basis, $L\downarrow$ would have to be weighted with the percentage of cloudy overpasses.

Regarding a bias originating from the SFR-approach/cloud-interpolation, further sophisticated comparisons with cloud-insensitive active or passive microwave remote sensing data could be helpful, but certainly go beyond the scope of the here presented manuscript.

We augmented the **conclusions** to read: "Compared to the most recent study on ice production in Arctic polynyas by \citet{iwamoto2014}, our estimate on the average total ice production is about 52-54\% larger, although differences in the regarded time frame, reference areas, sensor-specifics **as well as a potential biases due to cloud cover and/or the exclusive assumption of clear-sky conditions** certainly contribute to this discrepancy."

[1] Heinemann, G., Rose, L., 1990: Surface energy balance, parameterizations of boundary layer heights and the application of resistance laws near an Antarctic ice shelf front. Boundary Layer Meteorol. 51, 123-158.

[2] König-Langlo, G. and Augstein, E. (1994): Parameterization of the downward long-wave radiation at the Earth's surface in polar regions , Meteorologische Zeitschrift, N.F.3, 343-347.

Further, also in **Sect.3.3** it now reads: "(…) Since low-level clouds reduce the net radiative loss by about 50 \unit{W/m^2} in polar regions (Heinemann and Rose 1990, König-Langlo and Augstein 1994), the restriction to cloud-free conditions in the daily composites results in a positive bias in IP. Considering the fraction of average MODIS coverage of 75\% (COV2; Tab.~\ref{tab:tab01}) and assuming that not all clouds are low-level, the overestimation of net energy loss by our method can be estimated to be less than 10 \unit{W/m^2}, which corresponds to less than 0.4 \unit{m} IP per winter."

3. Similarly, POLA and IP can be obtained only in nighttime and thus POLA and IP obtained all from nighttime likely have some bias compared to those from daytime or pure average. Although a brief statement was made in page 9, it may be better to evaluate such bias even in a brief way. For example, difference in heat budget on thin ice for nighttime and daytime under a typical wintertime condition can be evaluated.

We appreciate the referee's remark on a possible bias due to the exclusive analysis of nighttime conditions. While we do agree that the influence of shortwave radiation and albedo effects could be rather significant, we do not think that a bias evaluation would contribute in a meaningful way to the here presented study due to the following reasons: Currently, our method does not feature a shortwave radiation parametrization, as (our) previous studies showed that the implementation of such can be rather problematic and connected with ambiguities. In addition, the implementation of such would introduce further error-sources that would make it even more complicated to evaluate a possible bias.

4. The study does not include the results of October and April when the polynya activity starts and continues, which is one of the drawback of this study. According to Iwamoto et al. (2014), for example, these two months provide 10-30 % of total annual ice production (IP). Particularly in NEW, Laptev, Archipelago, IP becomes maximum in October. Such drawback should be stated in IP section and conclusion.

Including the months of October and April would be problematic since the amount of suitable clear-sky and nighttime scenes decreases with increasing amounts of solar radiation.

5. Abstract: "Overall, our study contains the most accurate characterization of circumpolar polynya dynamics and ice production to date". This statement is ambiguous and overvaluing. The authors should state more specifically in what points this study provides the most accurate characterization? Probably, high spatial resolution is strong selling point. On the other hand, this study still has the drawback of data gap by cloud.

We admit that this statement might have been too unspecific in that context. This was also a remark from Referee #1. Therefore, we changed this part and a similar formulation in the conclusions-section to read:

"Abstract: *Overall, our study **presents a spatially highly accurate characterization** of circumpolar polynya dynamics and ice production which should be valuable for future modeling efforts on atmosphere- sea ice - ocean interactions in the Arctic.*"

and

"Conclusions: (…) *we think that this new data set of 13 consecutive winter seasons is a huge step forward for a **spatially** accurate characterization of Arctic polynya dynamics and the seasonal sea-ice budget in general.*"

Regarding the mentioned drawback of our applied method, we refer to the limitations of thermal infrared data at several parts of the manuscript (e.g. Sect.2, Sect.3, Conclusions), as we are absolutely aware of them.

6. P3, L15-16: "west of Novaya Zemlya is excluded in our investigations due to a variety of potential ambiguities originating from ocean heat fluxes": I understand the situation. But, as described in the textbook by Martin (2001, Polynyas. In: Encyclopedia of Ocean Sciences. vol 3. Academic Press,), the Novaya Zemlya polynya is one of the most active polynya, and other studies (e.g., Iwamoto et al., 2014) includes the Novaya Zemlya polynya in their tables. Similar situation by the effect of ocean heat also occur in the polynyas of Storfjorden, Franz-Josef Land. Why only the Novaya Zemlya polynya is excluded?

In recent years, the area at the northern tip and western coast of Novaya Zemlya was rarely fully enclosed by sea ice during winter. Initially, this was one of the main reasons why we decided to exclude this region as seemed to more fulfill MIZ characteristics in our opinion.

Nevertheless, motivated by the reviewers comment we took a closer look at this region and decided to include it in an updated / revised version of the manuscript. Following Årthun et al. (2012), at the least the influence of the eastern branch of Atlantic water spreading into the Barents Sea seems to be lower as expected in this region. It remains up for debate if those regions with changing ice conditions in recent years can be considered as a polynya region in a textbook sense, but in order to increase consistency regarding the considered polynya regions to Tamura and Ohshima (2011) and Iwamoto et al. (2014) the manuscript was changed accordingly with an additional polynya mask "**Western Novaya Zemlya**" (WNZ). Necessary changes can be found to the marked up version of the manuscript.

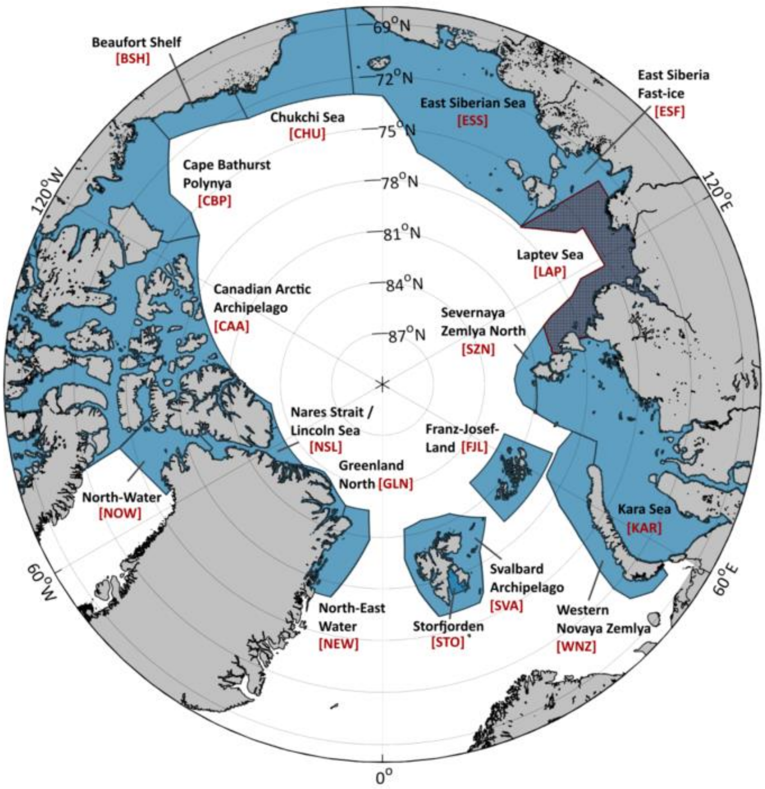

Figure 1 Map of all investigated areas of interest located in the Arctic, north of 68 ◦ N. Except for the Laptev Sea (red frame), all other applied polynya masks are marked in blue and enclose the typical location of each polynya in wintertime.

***Årthun et al. (2012)[3]:** "The inflow of Atlantic water between Norway and Bear Island [the Barents Sea Opening (BSO); e.g., Ingvaldsen et al. 2002] is the Barents Sea's main oceanic heat source. The inflow consists of several branches (Fig. 1a; Loeng 1991) but mainly follows a counterclockwise circulation **before exiting the Barents Sea between Novaya Zemlya and Franz Josef Land** (Schauer et al. 2002). **During its passage through the Barents Sea, the Atlantic water loses most of its heat to the Arctic atmosphere** (Häkkinen and Cavalieri 1989; Årthun and Schrum 2010), and the **heat transport through the northern exit is consequently small** (Gammelsrød et al. 2009). The dominant role of the Atlantic inflow on the Barents Sea heat budget and its intimate link to surface heat fluxes are further evident from the close correspondence between observed volume transport through the BSO and thermal water mass transformation in the western Barents Sea (Segtnanet al.2010)."*

7. In some figures (Figs. 4, 7, and 8), coast lines are not visible.

It is understandable that the line-width of the coast-lines might seem a tad small/narrow, although still visible in several test-print outs. The small width was chosen on purpose for these pan-Arctic overviews, in order to not distract the readers view from polynya-activities close to the coastline.

8. P6, Figure 3: The scale in the right bottom should be enlarged.

Fixed, thank you for this remark.

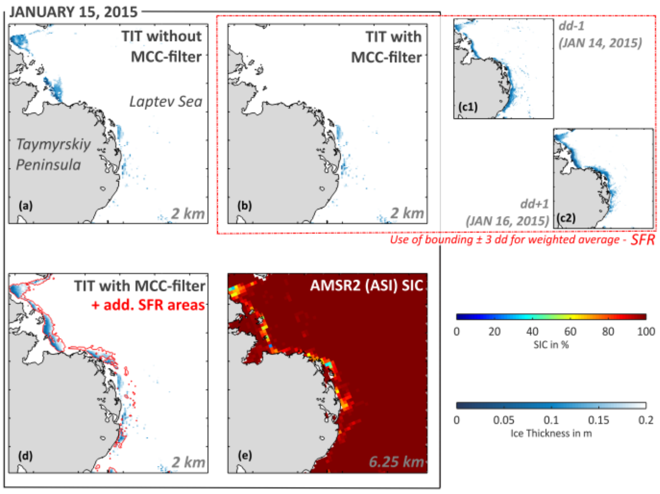

Figure 2Different stages in the MODIS thin-ice thickness (TIT up to 0.2 m) processing chain for a single exemplary day (January 15, 2015). Sub-panels (a), (b), (c1/c2) and (d) all feature a subset (north-western Laptev Sea) from daily pan-Arctic TIT composites, with (a) showing the daily TIT without any cloud-treatment besides the MOD35 cloud mask and (b) the resulting TIT distribution after applying the ERA-Interim medium cloud cover (MCC) filter. Two bounding days with a better coverage of TIT are featured in panels (c1) and (c2) as a reference for the highest relative contribution in the spatial feature reconstruction (SFR) algorithm. The resulting spatial distribution of TIT after application of SFR is shown in panel (d), with new additional / reconstructed areas (up to 20 cm) marked in red. A comparison with Advanced Microwave Scanning Radiometer-2 (AMSR2) ASI sea-ice concentrations (Spreen et al. (2008); Beitsch et al. (2014); University of Bremen) from the same date is given in (e). The respective grid-resolution is given in the lower right corner of each sub-panel.

9. P7, L14-20: I understand the former part of this paragraph, but I do not understand well that why a pixel-wise persistence index (PIX) becomes the ratio between the total number of MODIS swaths that feature thin-ice and the total number of swaths that feature clear-sky conditions.

We understand that our formulation here might be a bit misleading. Calculated PIX values refer to the "*ratio between the total number of MODIS swaths that feature thin-ice **at a given pixel-location** and the total number of swaths that feature clear-sky conditions **at the same pixel-position**.*" In other words: the persistence index is meant to give a sense how frequently thin-ice was detected on a given

[3] Årthun, M., Eldevik, T., Smedsrud, L. H., Skagseth, Ø., & Ingvaldsen, R. B. (2012). Quantifying the influence of atlantic heat on barents sea ice variability and retreat*. *Journal of Climate*, *25*(13), 4736-4743.

day and pixel. The higher the index, the more likely it is that this thin-ice signal in the daily composite is related to a persistent polynya-occurrence and not to erroneously inherent clouds.

We slightly modified the definition as depicted above.

10. P7, L25-28: "a probability of thin-ice occurrence is derived using a weighted composite of the surrounding days", "by a weighted average of the surrounding six days". Please describe the weight (function) specifically.

As in the studies by Paul et al. (2015b) and Preußer et al. (2015b), we once more applied the following set of weights: *w3 = 0.02, w2 = 0.16 and w1 = 0.32*. The probability threshold is fixed at *th= 0.34*. Paul et al. (2015a) showed that this combination yielded the highest spatial correlation for case studies in the Brunt Ice shelf region (Antarctica) and it is at the same time less restrictive in terms of missing coverage in close proximity of the initial day of interest. **We added information on the used weights in Sect. 3.2**, but refer then to the original description of the setup and a more detailed analysis of the SFR approach in Paul et al. (2015a).

11. P9, L19-24: This paragraph is hard to understand. How does the coverage-correction (CC) carry out the extrapolation? What's mean by "the additional SFR areas (COV4)".

We agree that this formulation was not precise enough to avoid confusion. Hence, we rephrased it to:

"In case of very persistent cloud cover inside the respective reference areas and a resulting daily MODIS coverage below 50\% (i.e. COV4 < 0.5), both daily POLA and IP are linearly interpolated from bounding days. "

12. P15, Figure 7: Most of the IP area are colored by nearly same color, blue, implying the production of 0.8-2.5 m. These high frequency ranges should be better resolved using stronger color gradient to discriminate the difference.

Thank you for this comment. You are right that several areas are quite hard to discriminate. As there is a related comment to Fig.7 by Referee #1 (Dr. Stefan Kern), we tried to fix this in a **new version of Fig.7 (see updated manuscript and below)**. Figures 4, 8 and 11 were also improved with your comment in mind **(see updated manuscript)**.

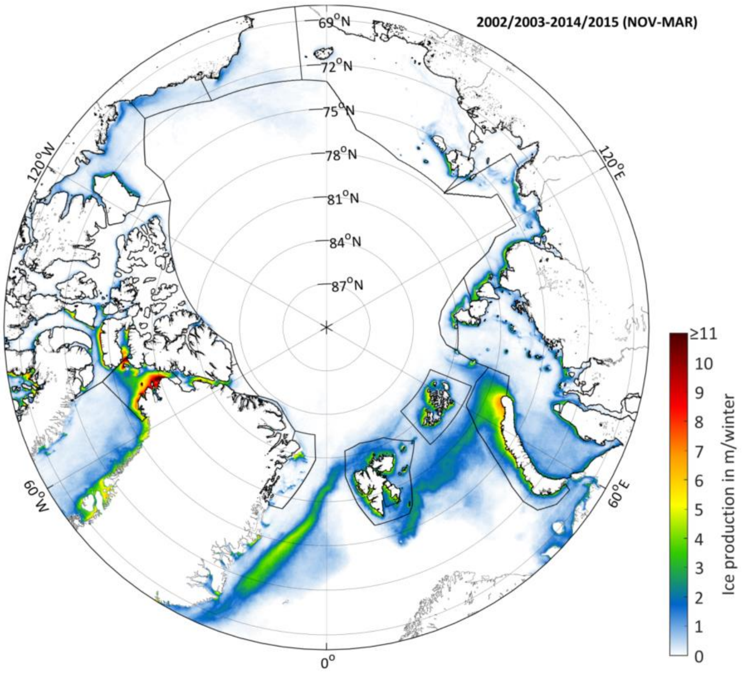

Figure 3 Average (2002/2003 to 2014/2015) accumulated ice production (m per winter) during winter (November to March) in the Arctic, north of 68°N. The margins of applied polynya masks (Fig. 1) are shown in black dashed lines.

13. P17, L7-9: "a tendency towards a diminishing fast-ice extent", "retreating-behavior of fast ice": Which part corresponds to these features? It is better to describe the location of these areas specifically.

This is a very good suggestion. As this part was also mentioned by Referee #1 (Dr. Stefan Kern), the sentence is slightly changed so that it now reads:

"(…) *and (2) the spatial structure of opposing negative / positive IP-trends* ***along the coasts of the Laptev Sea and Kara Sea*** *suggests a tendency towards a potentially diminishing fast-ice extent over the presented 13 years. (…)*"

14. P18, Figure 9: The inset map at the upper right is not effective at all. Rather, range of Fig. 9 (Laptev Sea area) should be indicated in Fig.1 with the name of Island.

Some comments from the other two referees pointed towards specifics on the Ice Area Export (IAE) and the geographical location of the flux gates by Krumpen et al. (2013). With the here mentioned suggestion in mind, we chose to make Fig.9 with its inset more meaningful by adding some additional regional specifics (see below). In our opinion, adding more information to Fig.1 (except for a better identification of the Laptev Sea through a different color) would have potentially become a bit overwhelming as there are already a lot of location names indicated.

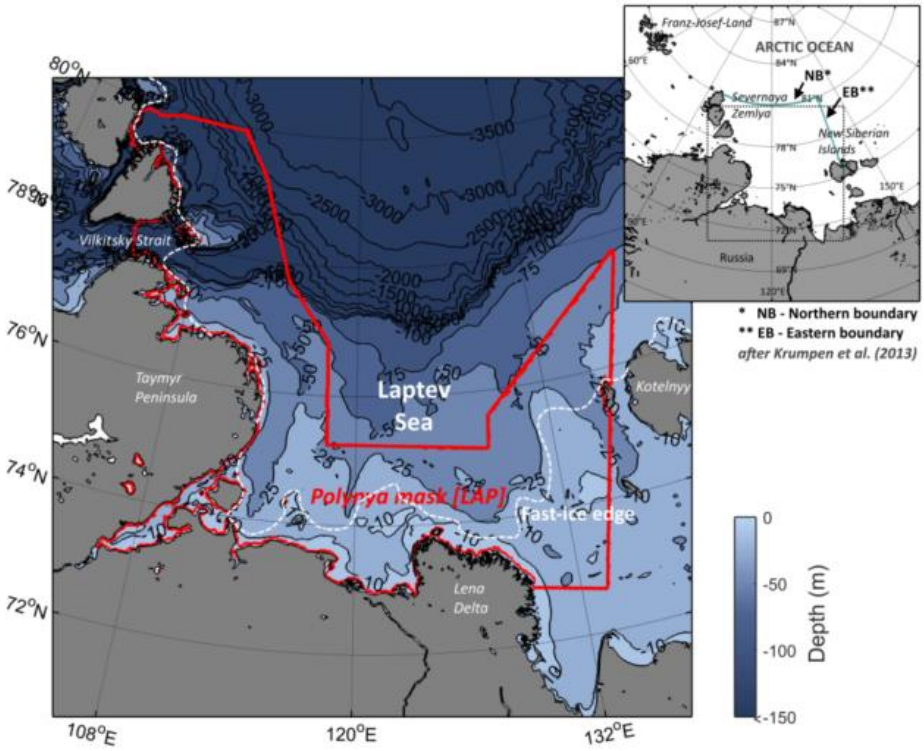

Figure 4 The geographical location of the Laptev Sea in the eastern Arctic. The applied polynya mask is marked in red, enclosing the locations of typical polynya formation along the coast and fast-ice edge (dashed white line; position derived from long-term thin-ice frequencies in March (Fig. 4)). Flux gates from the study by Krumpen et al. (2013) at the northern (NB) and eastern (EB) boundary of the Laptev Sea are shown in the inset map (grey solid lines). Bathymetric data by Jakobsson et al. (2012) (IBCAO v3.0).

15. P19, Figure 10: This is not usual Hovmoeller plot. Hovmoeller plot is generally used to see the spatial vs. temporal variations to examine the propagation characteristics. There is no temporal continuation in the vertical direction of Fig.10 and thus the contours should not be used in the vertical direction. This figure should not be drawn as Hovmoeller plot. The contours can be used in the lateral direction (seasonal evolution). I propose the following figure. The polynya area ratio (strength) is represented by the contours and color in the lateral direction (seasonal evolution) separately for each year. Then such horizontal long graphs are lined up in order from 2002 to 2015. Namely the contour procedure is only used for the lateral direction when compared to the original Fig.10.

We followed the reviewer's suggestion and modified Fig.10 as can be seen below. It features an improved color-contrast and omits the usage of contours. However, we decided against a presentation of a polynya area ratio (i.e. relative sizes), as this would require a lot of additional information for the reader.

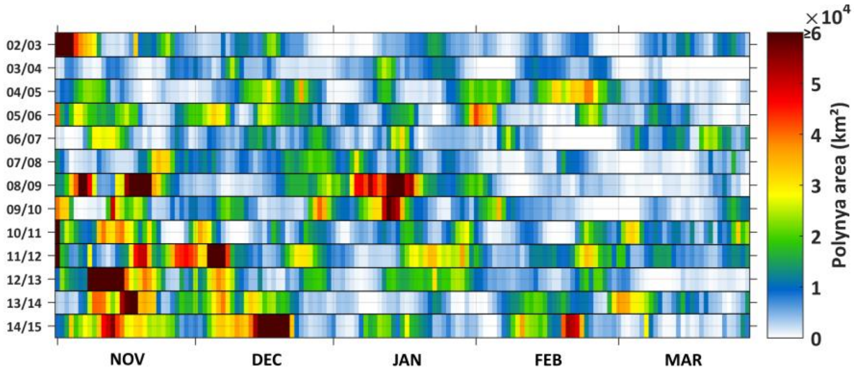

Figure 5 Daily polynya area (TIT ≤ 0.2 m) in the Laptev Sea region between 2002/2003 and 2014/2015. Values are calculated within the margins of the applied polynya mask (Fig. 1) and saturated at a level of 6 x 10^4 km^2 for a better discrimination of lower values.