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RC1: 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 Dr. Stefan Kern (referee) on August 22, 2016

Summary:

The great potential of the combined ice surface temperature (IST) data sets derived from TERRA and AQUA MODIS infrared surface temperature observations is utilized to derive a pan-Arctic view of polynya area with unprecedented spatial grid resolution for such a long period of winters (Nov.-Mar.) spanning 2002/03 through 2014/15. Polynya area is derived by means of combining the IST with meteorological information provided by ERA Interim re-analysis data to estimate thin ice thickness (TIT). To overcome gaps due to cloud coverage an innovative, recently published approach is further developed and applied to the derived time-series of quasi-daily TIT maps. The final results: time series of distributions of polynya area, TIT and ice production are presented and discussed. The average polynya area and ice production are within the range of previous studies. Polynyas in the Eastern Arctic are found to have an increase in ice production for Nov.-Mar. over the time period considered.

General comments:

0) *The paper is very well written and it reads fluently. The figures are mostly excellent. The paper presents the retrieval and discussion of a polynya area and ice production data set of yet unprecedented spatial resolution and hence for sure warrants publication. In the current version of the manuscript a few critical definitions and questions remain unanswered, though, which I feel are required to not misinterpret this very nicely written article. The discussion of potential uncertainties and biases in the retrieved data should be improved for the same reason. Finally, the inter-comparison to other studies and discussion of the differences to other studies by means of the material the authors already have in hands could be improved.*

We would like to thank Dr. Stefan Kern (referee #1) for his valuable comments and suggestions that will definitively help to improve the original manuscript, most importantly the discussion of results and the specification of error-margins. We carefully went over the mentioned parts of the manuscript and we will answer remaining general as well as specific comments in the following.

1) *The abstract and conclusion write: "most accurate characterization of ..." I would rate it as important that the authors clearly state that they speak about spatial accuracy and not about retrieval accuracy of the thin ice thickness and ice production. In addition to that, as I write further down (in the context of the discussion with results about the polynya area from other authors), the authors could elaborate on the question whether the net effect of a finer grid resolution is solely an increase in the derived total polynya area, or whether the reduced smearing / smoothing for larger size thin ice areas when using MODIS data doesn't mean that derived polynya sizes could be also smaller.*

You are right about our formulations in the abstract and conclusions. To be more specific at these text-positions, we changed the mentioned parts according to:

"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 other remark, the net effect of the finer grid resolution, i.e. the sign of a possible bias, is really difficult to assess without actual reference / comparison data at hand. Certainly, a more precise delineation of larger polynya areas could also lead to the opposite effect regarding POLA and hence IP differences, but these effects can only be evaluated by looking at the distribution of thin-ice (and consequently heat fluxes) within the larger footprint of the passive microwave data sets.

2) *Tied with accuracy is that, to my feeling, the retrieval accuracy of the method is discussed not enough. The only notion I found about the accuracy of the thin ice thickness retrieval is the one cited by Adams et al. (2013). It does not seem that the authors did carry out accuracy investigations on their own. This starts with the validity of using coarse resolution ERA-Interim data (coarse compared to MODIS) in a pan-Artic sense. Yes, for the Laptev Sea investigations published in the literature have shown that re-analysis data fit observations quite nicely, but this is an "easy" area in terms of topography. Areas around Greenland (NEW, NOW) and the Canadian Arctic Archipelago are less "easy" and I would have hoped for a notion how good or bad ERA-Interim data might be in these, topographically more complex regions. This applies particularly to temperature and wind speed. This continues with not picking the potential latent heat effects of some of the polynyas (e.g. NOW) in the discussion of the results; ice production values could biased positive when oceanic heat fluxes are neglected. And this finalizes in a, to me, not satisfying demonstration that the cloud gap filtering approach is indeed resulting in physically realistic results plus a lack of the potential uncertainty of this approach. I have the feeling that the approach as presented here potentially misses short-lived (1-2 days) polynya closing or opening events coinciding with the passage of low-pressure systems (which are usually associated with changing wind directions and clouds). While this might not change the average polynya area it might have an impact on the overall ice production and in the variability of both, polynya area and ice production. I would have appreciated either an analysis which demonstrates that biases due to missed polynya closing or opening events are unlikely to occur, or a theoretical analysis which estimates the uncertainty in polynya area and hence ice production due to such cases.*

(1) Regarding retrieval accuracy: As the specific procedure to derive TIT (compare Sect. 3.1) has not changed significantly (besides the use of ERA-Interim instead of NCEP2 reanalysis data), we regard the accuracy assessment by Adams et al. (2013) as a valid characterization of uncertainty ranges.

(2) Regarding ERA-Interim: We appreciate the remark on this topic. In order to address this, we added the following information to Sect. 3.3:

"For topographically complex regions like Greenland and Arctic fjords, recent studies revealed shortcomings of the coarse-resolution ERA-Interim data regarding the representation of mesoscale spatial features in the wind field, such as tip-jets, channeling effects or other topography-induced phenomena related to locally increased wind speeds (e.g. Moore et al., 2016[1]). Thus, ERA-Interim shows a tendency to underestimate peak wind speeds (Moore et al., 2016) which might in some cases induce a negative bias (lower heat fluxes/ less IP) in regions where polynya formation is strongly influenced by the local topography (e.g. CAA, NOW, NEW, SZN). In our study, the usage of ERA-Interim is motivated by ensuring comparability to similar studies (e.g. Iwamoto et al., 2014) as well as the

[1] Moore, G.W.K., Bromwich, D.H., Wilson, A.B., Renfrew, I., Bai, L. (2016): Arctic System Reanalysis improvements in topographically-forced winds near Greenland. Quarterly Journal of the Royal Meteorological Society, doi:10.1002/qj.2798.

constraint that higher-resolution atmospheric data sets such as the Arctic System Reanalysis (ASRv1 – 30km; Bromwich et al., 2015[2]) are not available for the complete time period from 2002 to 2015."

Hence, we aim to investigate the potential for a future application of high-resolution (~15km) regional reanalysis /climate models such as the ASRv2 (Bromwich et al., 2015) or COSMO-CLM (Gutjahr et al., 2016) in the here presented TIT retrieval once they become available.

(3) Regarding oceanic heat fluxes:

After performing a rough estimation of the effect of an oceanic heat flux (similar to Tamura and Ohshima (2011) and Iwamoto et al. (2014)), we see that the ice production in the North Water polynya (Avg. 276.7 km³) could be reduced by around 22.5% when assuming a constant heat supply from the ocean of 50 W/m² (Bourke and Paquette [1991] and Darby et al. [1994]). This is approximately the same range as in both referred Japanese studies. However, the effect of oceanic heat on wintertime thin-ice dynamics in the Arctic is to date still not very well documented / understood and obviously a subject of recent scientific discussions (see some quotes below). For instance, the study by Yao and Tang (2003) concluded that, in case of the NOW polynya, the ocean heat flux does not reduce the ice growth rate even though there is evidence of convective mixing and entrainment by ice growth, which might trigger enhanced ocean heat fluxes in northern Baffin Bay.

Yao and Tang (2003):

"*Salt flux from ice growth is balanced by advection, from which we infer that the **exchange is predominantly horizontal** and not coastal upwelling. It appears that atmospheric heat flux compensates so that the **ocean heat flux does not reduce the ice growth rate.***"

Carmack et al. (2015)[3]:

"*In autumn and winter, ocean sensible heat is transported to the air–ocean and air–ice interfaces by upper-ocean mixing and by conduction through the ice; however, **measurements from recent years show that some of the heat gained by the upper ocean in summer is stored into the winter and can slow the growth of sea ice** (e.g., Jackson et al. 2010, 2012).*"

"*Through most of the Arctic Ocean, however, **heat input as AW and PW is separated from the surface by a layer of relatively cold and fresh water that reduces the direct impact of these heat sources on sea ice.** One notable exception is the Nansen basin where, near the Fram Strait gateway, near-surface AW heat results in a significant reduction in sea ice thickness along the continental slope north and northeast of Svalbard (Onarheim et al. 2014).*"

"*However, analyses of ITP records from the central Eurasian basin, away from steep topography, suggest that the delivery of AW heat to the overlying layers in the Eurasian basin interior can be important (Polyakov et al. 2013). Those authors showed that **the transfer of heat from the upper pycnocline to the SML is highest in winter, with an average heat loss of 3–4 W/m² between January and April.** It is likely that the increased heat loss from the AW layer to the SML in winter is caused by a combination of brine-driven convection that is associated with sea ice formation and larger vertical velocity shear below the base of the SML that is enhanced by winter storms.*"

(4) Regarding potentially missed short-lived events and SFR uncertainties: The SFR has only to do with the availability of MODIS coverage and is even most effective on short time-scales (Paul et al. 2015a). Polynyas typically appear on time ranges between 1-3 days (high autocorrelation).

[2] Bromwich, D.H., Wilson, A.B., Bai, L.-S., Moore, G.W.K., Bauer, P. (2015): A comparison of the regional Arctic System Reanalysis and the global ERA-Interim Reanalysis for the Arctic. Q. J. R. Meteorol. Soc. 142: 644–658.

[3] Carmack, E.; Polyakov, I.; Padman, L.; Fer, I.; Hunke, E.; Hutchings, J.; Jackson, J.; Kelley, D.; Kwok, R.; Layton, C.; Melling, H.; Perovich, D.; Persson, O.; Ruddick, B.; Timmermans, M.-L.; Toole, J.; Ross, T.; Vavrus, S. and Winsor, P. (2015): Toward Quantifying the Increasing Role of Oceanic Heat in Sea Ice Loss in the New Arctic Bull. Amer. Meteor. Soc., American Meteorological Society, 2015, 96, 2079-2105.

The fraction of days where the use of SFR fails to achieve an IST/TIT coverage > 0.5 is overall very low (less than 2% of all the days in 2002/03-2014/15; except CHU → ~13%). Hence, the probability to miss (or overestimate POLA) short-lived events is generally rather small, but may be higher for more frequently cloud-covered regions such as Chukchi Sea (CHU).

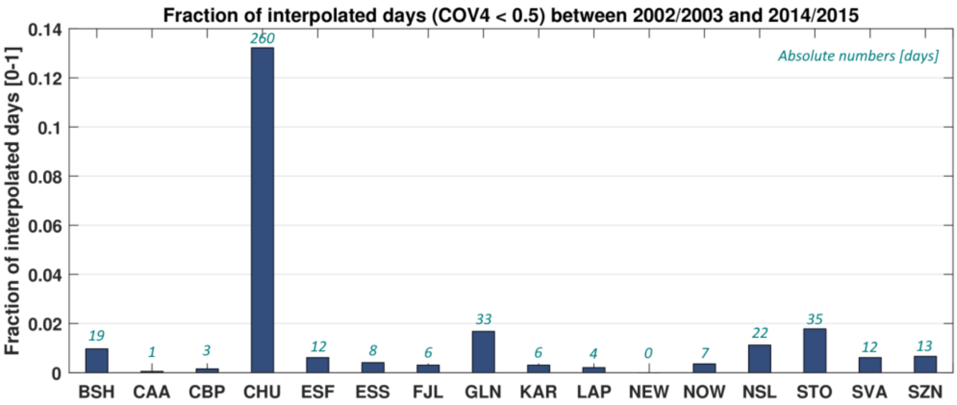


Figure 1 Overview on the interannual (2002/2003 to 2014/2015; Nov.-Mar.) fraction of exclusively interpolated days (POLA/IP values), i.e. with the best possible daily MODIS coverage (COV4) not exceeding 0.5 (50% spatial coverage). Values are given per region. The absolute amount of days is additionally listed in turquoise numbers.

3) *Not clear to me (and this refers again to comment 2) is how the metrics used in Table 1 (COV2 and COV4) works and why a fraction < 0.5 seems to be "bad" and why it seems to be "good" to have a polynya fraction close to 1. I am sure this is simply based by a misunderstanding and that reformulating sentences will clarify this issue.*

You're right in your assumption of a misunderstanding, as we are not writing about polynya fractions. COV2 and COV4 are metrics that refer to the spatial coverage of MODIS data, i.e. the availability of valid (clear-sky, HQ MCP, SFR) IST/TIT value-pairs inside a respective polynya mask area.

We will reformulate and clarify the respective parts in the manuscript, e.g. P.8 L10; Caption Tab.1; …

(…) see P.8 L.9.: "*Table 1 gives an overview on the* ***achieved MODIS coverage*** *before and after application of the SFR algorithm. On a pan-Arctic level, the average (…)*"

4) *The authors could clarify better that an observed increase in polynya area and/or ice production for the period November through March over the winters 2002/03 through 2014/15 could have one main reason: a later freeze-up. It seems as if parts of the regular fall freeze-up are included in the analysis of the authors. And since the fall freeze-up has the tendency to occur later and later it impacts the derived polynya area and associated ice production. Currently I don't see that the authors make an effort to discriminate between regular fall freeze-up and a "real" polynya event - which one could consider as a methodological hic-up. It would be, however, difficult to find a definition between the end of fall freeze-up and the beginning of the "regular" wintertime polynya-opening.*

This is actually one of the critical points when analyzing wintertime polynya dynamics, you are right. But as you also mention, separating between fall-freeze-up and regular polynya events is quite challenging for a number of reasons, especially on such a large scale as the timing varies significantly for each region in the Arctic. However, we think that for many investigated areas throughout the Arctic the complete period between Nov. and Mar. is highly interesting as potentially occurring larger heat fluxes in early winter strongly alter the atmospheric and oceanic boundary layers regardless of fulfilled textbook definitions of a polynya. Hence, we decided to use a fixed reference frame in order to ensure comparability between different regions and winter seasons, as well as to present additional and separately derived values for the period JFM, as can be seen in Fig.5 and 6 (seasonal comparisons ND vs. JFM). You are right however that we could have done a better job in referring to the influence of the freeze-up in certain regions such as STO, CAA, KAR, CHU and FJL. Therefore, in the revised version of manuscript we tried to emphasize this topic more clearly. In addition, we overhauled the former Table 2 to clearly show seasonal differences in derived average values and trends (now Tab.2+3).

5) *Into the same direction as 4) goes my final general comment. While the authors state in Figure 4 that they excluded the marginal ice zone facing the Nordic Seas I could not find a notion how this was done. The marginal ice zone could overlap with NOW, with the polynya regions facing the Bering Sea, and with SZN, KAR, FJL, and SVA and I am wondering how the authors separated events where the marginal ice zone extended into these regions from "real" polynya events.*

We apply polynya masks to exclude unlikely polynya / thin-ice locations throughout the Arctic and focus on likely and known polynya locations. The selection/definition is based on previous studies (e.g. Barber and Massom (2007)) as well as the here derived avg. TIT-frequencies between 2002 and 2015 (compare Fig.4.).

Specific comments:

I note that some of the specific comments might read as a repetition of my general comments. This is caused by the fact that I usually first go for the specific comments and afterwards decide which I rate as a general and/or major comment without deleting the specific comment. Often there are more details given in the latter as well anyways.

Abstract:

Page 1, line 4: I suggest to add "MODIS" in front of "swath-data".

Fixed.

Line 7: Acronym "POLA" is not further used in the abstract and can therefore be deleted. It needs to be introduced for the main body of the manuscript anyways.

Deleted “POLA”.

Line 13: Because the manuscript focuses on polynyas I suggest to re-formulate "thin-ice features such as large leads" into "polynyas and also large leads"

We re-formulated the sentence accordingly.

Introduction:

Page 2, line 2: Why "large". I would have considered polynyas and leads as small open water and thin ice areas - at least small compared to the entire Arctic Ocean. Perhaps "Areas of open water and thin ice, i.e. polynyas and leads, are ..." would also be an appropriate formulation?

True, this might be irritating so early on in the manuscript as these relative size-relations are depending on the context. We re-formulated the sentence as proposed.

Page 3, line 1: I agree with the authors that wind-induced stress is the main driver for most polynyas and also leads. I am wondering, however, whether the authors might also want to comment on tidal currents, which could play a role for essentially all polynyas on the shelf. In addition, entrainment and/or upwelling of warmer / saltier water masses from below or from riverine input (here just warmer and not saltier of course) could also play a role in keeping open polynyas and/or leads, and in supporting their formation. Since the authors are after sea-ice thickness retrieval using the heat-flux method and *are focusing on thermodynamic sea-ice growth assuming that oceanic heat fluxes are neglected it might be worth to at least mention that this assumption could be violated (partly) for those polynyas which are not solely a latent heat polynya but which have a substantial sensible heat polynya component.*

We are aware of the fact that polynyas and leads can also be influenced by tidal currents and/or oceanic heat fluxes. The studies of Hannah et al. (2009) and Melling et al. (2015) described these processes exemplary for the Lancaster and Jones Sound regions in the eastern part of the CAA (compare P.10 L.21). However, tidal-driven polynyas have time and space scales being much smaller than the polynyas listed in Tab.1-3. In Sect. 3.3 (P.9 L8-10) we already listed some studies which described areas (CHU, CAA, NOW), where an oceanic heat influence was either found/measured or assumed/suspected, and pointed to a potential reduction of thermodynamic ice growth. In order to make this part more concise, we added numbers on the potential influence of oceanic heat from the indicated studies.

Line32/33: What about information about meteorological parameters and heat transfer coefficients? Aren't particularly the latter quite variable and isn't it challenging to apply the correct coefficient for the different thin ice areas encountered in this manuscript? Also, I would have thought that a correct surface-to-near surface air temperature and moisture gradient as well as the correct near surface wind speed need to be known as detailed as possible. Perhaps the authors could either explain in the manuscript why these are not important or, if in fact these are, also add these here.

In a recently published study by Gutjahr et al. (2016, TCD)[4], we included a more detailed overview on the variance of the iteratively calculated heat transfer coefficient (C_H) in the Laptev Sea region. To quote the respective section on P.21:

"*Heat loss is affected by differences in the surface temperature, vertical temperature gradient, parameterization of the energy balance components, sea-ice thickness and properties, parameterization of the heat flux through the ice, and by the parameterization of atmospheric turbulent fluxes. Particularly important is the horizontal resolution of the atmospheric data set and the assumptions on the turbulent exchange coefficient for heat (C_H). […]* ***The C_H values based on MODIS data and ERA-Interim are lower than simulated by CCLM with a mean of C_H = (2.3±0.3) x 10^{-3}. A similar PDF was derived by Adams et al. (2013), who combined MODIS and NCEP.***"

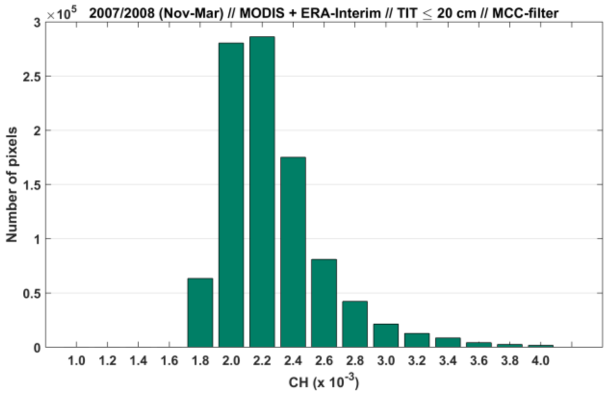


Figure 2 Frequency-distribution (class-width 0.2 x 10^{-3}) of iteratively calculated heat transfer coefficients (C_H) in the Laptev Sea polynya (TIT ≤ 0.2m) region between November 2007 and March 2008. In this particular winter, the average value of C_H was estimated with 2.3 ± 0.3 x 10^{-3}.

[4] Gutjahr, O., Heinemann, G., Preußer, A., Willmes, S., and Drüe, C.: Sensitivity of ice production estimates in Laptev Sea polynyas to the parameterization of subgrid-scale sea-ice inhomogeneities in COSMO-CLM, The Cryosphere Discuss., doi:10.5194/tc-2016-83, in review, 2016.

As the heat loss is calculated pixel-wise for each individual MODIS swath (with varying atmospheric parameters, C_H, etc.), we actually do account for differences among considered thin-ice areas.

We added some more information on this topic in the Introduction.

Data:

Page 5, line 6: Is MOD35 also used for MYD29 or does a separate cloud mask exist (and is applied) for MODIS aboard AQUA?

Thank you for this remark. The cloud mask is also generated for MODIS data from Aqua (MOD/MYD35). We added this to the manuscript.

Line 9: Could the authors perhaps motivate the grid-cell size chosen? As this to do with the decrease in spatial resolution of the MODIS pixels towards off-nadir?

Yes, we chose the grid-cell size of approx. 2km due to the decreasing spatial resolution off-nadir, resulting from panoramic distortion effects of the MODIS sensor (rotating scan-mirror; constant focal length). The study of Fraser et al. (2009)[5] referred to increase-factors of 2.01 (along-track direction) and 4.93 (across-track direction) for the marginal pixels of each MODIS scan-line.

Line 19: Please check whether you have introduced the acronym "TIT" in the text already. So far I only see it in the caption of Figure 2.

The acronym is introduced in Sect. 2.1 (P.5 L.3).

Line 26: Please note the average and maximum time difference between MODIS swath data and ERA-Interim data.

The maximum time difference can be 3 hours, as we do not perform an additional temporal interpolation as in Paul et al. (2015b). Motivated by your comment, we extracted the time difference for each single MODIS swath and the respective ERA-Interim time step (00.00, 06.00, 12.00, 18.00UTC) for all years considered. The overall average time difference amounts to **89.5 ± 52.3 minutes**, which is exactly within the range of what could have been expected when assuming normally distributed MODIS swaths around each time step.

We added this information as proposed in L.26.

Methodology:

Page 6, line 7: I encourage the authors to add a statement about the ice type which their method is able to derive the thickness for. Is is frazil / grease ice or are we talking about nilas and thicker sheet ice types like grey ice?

There were similar remarks in previous reviews of studies from the authors (STO, Weddell Sea). Our response stays the same: The presented thin-ice algorithm does not explicitly discriminate between different ice types. It follows the assumption that a linear temperature profile can be used to calculate the heat conduction through the ice. Hence, we added this information to the manuscript. Regarding the choice of constant values for the ice density and latent heat of fusion (L_f), we followed earlier studies (e.g. Willmes et al. (2011), Tamura and Ohshima (2011), Iwamoto et al. (2014)) to ensure

[5] Fraser, A. D., Massom, R. A. and Michael, K. J. (2009): A Method for Compositing Polar MODIS Satellite Images to Remove Cloud Cover for Landfast Sea-Ice Detection. *IEEE Transactions on Geoscience and Remote Sensing*, vol. 47, no. 9, pp. 3272-3282. doi: 10.1109/TGRS.2009.2019726

comparability of achieved results. These studies followed an even earlier characterization of sea-ice formation mechanisms by Martin (1981).

Section 3.1 has been complimented to now read: ***"(…) and the lower boundary of the ice (constant; freezing point of sea water) is linear. Consequently and following this assumption, the approach does not explicitly discriminate between different ice types within a polynya, as TIT are solely derived from calculating the heat conduction in/through the ice (aside from subsequent gap-filling; see Sect.~3.2).***"

Line 14/15: I understand that the authors mention March here as this month contains the spring equinox. However, November is almost as close to the winter solstice as February is. Could it be that in November the cloud coverage is the problem?

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

Page 7, Figure 3: In the case shown there were good TIT maps on January 14 and 16 (i.e. from 2 days of the surrounding 6 days used), i.e. directly adjacent in time to the TIT map from which the MCC filtering removed artificial but also correct TIT areas. I am assuming that this is a very good example. How often did the authors not find appropriate adjacent TIT maps?

You are certainly right that we picked a good example to illustrate the basic principle of our approach at this point of the paper, which combines both a meaningful correction from the MCC filter (which can often be quite subtle) as well as bounding days with a good MODIS coverage in the cloud covered/influenced/spurious regions. Frankly speaking, it is hard to quantify how frequently this "ideal" combination can be found, as it not only varies depending on the location, but also the temporal distance of available pixels for the SFR approach can vary between 1 and 3 days.

Caption, lines 7/8. I am not sure that Spreen et al. (2008) is the only reference you should use here because that paper is addressing AMSR-E while the data you used stem from AMSR2. Hasn't there been a paper by Beitsch et al., Remote Sensing, 2014, about applying the ASI algorithm to AMSR2 89GHz data for sea ice concentration retrieval? The same comment applied to page 8, lines 15/16.

This is correct. We will add the study by Beitsch et al. (2014) to the list of references and quote it, respectively.

Page 8, line 11: I have difficulties to understand Table 1 and the statement of "with certain regions performing better ... and some other regions noticeable worse" If I understood the COV2 and COV4 correctly, then this is giving the fraction of the predefined area (Figure 1) covered by thin ice as retrieved by the authors's method. What seems strange to me is that some of these show a COV4 close to 1, which would mean that the entire predefined area is covered with thin ice. I doubt that KAR is really covered to 95% by thin ice. Possibly I did misunderstand something here. I encourage the authors to clarify this issue and to better explain what their metrics is to decide which is "better" or "worse".

→Please refer to our response under general comment (3).

Line 21-23: I suggest that the authors refer more to their own earlier results (Brunt ice shelf, etc.) because I find it a bit dangerous to conclude that the correction works fine from just one example shown here.

Rewritten to read:

"All derived quality attributes (MCC-filter, cloud-cover information, PIX) are utilized in the Spatial Feature Reconstruction (SFR) algorithm (Paul et al., 2015a), which was recently successfully applied on a regional scale in both the Antarctic and Arctic to increase the information about otherwise cloud-covered areas (Paul et al., 2015b; Preußer et al., 2015a). The basic principle is that cloud-induced gaps in the daily TIT composites are compared with the TIT of the surrounding six days. In doing so, a probability of thin-ice occurrence is derived using a weighted composite **of the days surrounding an initial day of interest (DOI)**. **As in previous studies, we applied the following set of weights: $w_3 = 0.02$ (DOI ± 3), $w_2 = 0.16$ (DOI ± 2) and $w_1 = 0.32$ (DOI ± 1). The probability threshold remains fixed at *th = 0.34* and needs to be surpassed in order to assign 'new' polynya pixels. Paul et al. (2015a) showed that this combination is less restrictive in terms of missing coverage in close proximity of the initial day of interest.** The procedure is applied on all areas with identified low-quality data (low persistence, cloud-covered), so that indicated gaps can be filled with new information on potential thin-ice occurrences. For these areas, new TIT and IST values are pixel-wise allocated using a weighted average of the surrounding six days (Paul et al., 2015b; Preußer et al., 2015a). Table 1 gives an overview on the achieved IST and TIT coverage before and after application of the SFR algorithm. On a pan-Arctic level, the average (2002/2003 to 2014/2015) coverage is increased from around 0.75 (ccs and high-quality mcp) to 0.93 (including SFR areas), with certain regions performing better (e.g. CBP, LAP, NEW, SZN) and some other regions noticeably worse (CHU, GLN, WNZ).

A total of 66 case studies in the Brunt Ice Shelf region of Antarctica demonstrated the **generally** good performance of the algorithm **in comparison to more intelligible approaches** by **realistically** reproducing artificially cloud covered thin-ice areas with an average spatial correlation of 0.83 (Paul et al., 2015a). **When compared to reference runs based on equally-weighted and in some cases shorter time intervals, the SFR procedure featuring above listed weights w_3 to w_1 (DOI ± 3 days) yielded superior results both in spatial correlation and reconstructed POLA-values, regardless of the temporal polynya-evolution (e.g. opening/closing event).**

(…) while maintaining the increased spatial detail at the same time**. Based on this example and above mentioned previous works by the authors (Paul et al. 2015a, Paul et al. 2015b, Preußer et al. 2015b),** we conclude that the applied schemes to compensate and correct cloud-effects work reasonably well **on a pan-Arctic scale** and allow for a fair comparison to other commonly used remote sensing approaches to infer polynya characteristics, with limitations regarding the reconstruction of leads. "

Page 8, line 32 through page 9, line 5: This discussion about the correct sea ice salinity comes back to my previous comment about which ice type the approach can consider. I guess it is worth mentioning whether the approach primarily retrieves TIT in the frazil / grease ice domain until that area where this "unstable" ice starts to collect at the leeward side of the lead/polynya to form nilas and subsequently thicker ice types, or whether the approach primarily considers the nilas and thicker sheet ice types. Actually, if it would be frazil ice, the sea ice salinity might have chosen to be larger; studies focussing on frazil ice use salinities of 917 kg/mˆ3 (de la Rosa and Maus, The Cryosphere, 2012) or 920 kg/mˆ3 (Jordan et al., Journal of Physical Oceanography,2015).

Please refer to our earlier response. As we do not explicitly differentiate between ice types, we chose to stick to a sea ice density of 910 kg/m³ (Timco and Frederking, 1996) for the sake of comparison to earlier studies using the same value for fresh ice.

Page 9, Table 1: The "plus/minus" values in the column TIT are one standard deviation over all winters considered. How about the respective values in columns COV2 and COV4?

They also refer to the standard deviation over all winters considered. We augmented the caption accordingly.

Page 9, lines 8-10: "We do not consider an ocean heat flux ..." I agree with the authors that this would complicate the TIT retrieval substantially. I am curious, however, whether your discussion of *uncertainties will reflect that fact that some areas might have substantial oceanic heat fluxes. The authors might want to consider one further reference in this respect: Yao and Tang, The formation and maintenance of the North Water polynya, Atmosphere-Ocean, 41(3), 2003, and also cite Melling et al., 2015 here.*

Thank you for this remark (please compare general comment (4)). Including an appropriate parametrization for a varying influence of ocean heat fluxes is certainly challenging, as you correctly write above. Information on respective numbers and orders of magnitudes are sparse, and even more so during wintertime. We briefly mentioned this topic in our paper on the North Water polynya in Northern Baffin Bay (Preußer et al., 2015) with reference to the study by Yao and Tang (2003). We added this study at the referred part of the manuscript. In the same manner, the study by Melling et al. (2015) (quoted in Sect.4.1 when referring to Fig.4) dealing with 'Invisible polynyas' in the Canadian Arctic Archipelago is certainly a welcome addition at this point of the manuscript.

Page 10, line 5: I guess the authors wanted to refer to either "optical and infrared" or even only "infrared" instead of "optical" here.

Fixed, thank you for this suggestion.

Line 10: "falls below 0.5" I have difficulties to understand the authors' concept of using the fraction of the predefined polynya regions shown in Figure 1 as a quality measure. I commented on that already in the context of table 1. Here, the authors limit the fraction of thin ice in these predefined areas to be above 0.5 - if I have understood this correctly. Or, in other words, it reads as if a thin ice fraction of the predefined polynya regions in Figure 1 needs to be above 0.5, otherwise it is regarded faulty. I probably misunderstood something?

→Please refer to our response under general comment (3).

Results and Discussions:

Page 10, line 16/17: The trend in TIT mentioned in these lines are not summarized in any of the tables, am I correct? Perhaps the authors could spend a "(not shown)" or something?

You are correct, trend are not summarized/listed at any point in the manuscript. We added a '(not shown)' to avoid confusion.

Lines 29-33: I suggest the authors cite work which is related to the derivation of fast-ice extent in, e.g. the Laptev Sea like for instance: Selyuzhenok et al., J. Geophys. Res., 2015.

We added three references here, so that it now reads: *"(…) for a regular Arctic-wide mapping of monthly fast-ice extents and could thereby compliment currently existing approaches from earlier studies (e.g. Yu et al., 2014; Mahoney et al., 2014[6]; Selyuzhenok et al., 2015)."*

Page 12, Table 2: I am wondering whether the trends given are "per year" as indicated or "per decade"? If these are indeed per year, then in region ESF the increase in POLA would be 1.095 km^2 in 10 years which equals the average POLA value given. The same applies to region SZN. Perhaps the authors could check which reference period they used for their trend calculations? The authors might also consider to write how the p-values were derived, i.e. which statistical test was carried out.

[6] Mahoney, A. R., Eicken, H., Gaylord, A. G., and Gens, R. (2014): Landfast sea ice extent in the Chukchi and Beaufort Seas: The annual cycle and decadal variability, Cold Regions Science and Technology, 103, 41–56, doi:10.1016/j.coldregions.2014.03.003.

Derived and indicated trends do indeed refer to 'per year', i.e. winter-period from November to March. POLA values for the East Siberian Fast-ice mask range between ~ 0 and 3000 km², which is resulting in the average value of as depicted in Fig.5 and Tab.2.

The p-values are based on a **two-sided t-test**. We added this information at appropriate parts of the MS (e.g. Table 2; Fig.8; Text Sect. 4)

Page 12, line 11: Stylistically I would say "the large POLA values" is enough here (instead of "these") because the authors refer to NOW in the remainder of the sentence. I note in this context, that the increase in NOW POLA is not significant in the authors' study.

Thank you for these remarks. We changed the formulation and added information on the (in-) significance. It now reads:

"The study of \citet{preusser2015b} demonstrated that the large POLA values in the NOW-region are part of a (non-significant) long-term increase of average polynya extents between 1978 and 2015".

Page 15, lines 1-8: The authors inter-compare their results with Kern (2008), who only focused in the Kara Sea. Aren't there other studies about polynya area which results would be worth to compare the authors' results with?

There are certainly some other studies with information on POLA, such as the often referred Pan-Arctic studies by Tamura & Ohshima (2011) and Iwamoto et al. (2014) or many local studies. At this point of our submitted manuscript, we want to focus on one of the major regions (Kara Sea) that was not featured in our previous regional studies (STO, NOW; LAP in Sect. 4.2). Hence the comparison to Kern (2008).

Lines 8/9: "increases for" Do the authors refer to an increase in POLA or to an increase in POLA variability?

→ We refer to an increase in POLA variability.

Lines 9-20: I absolutely agree with the authors' observations written down in this part. The only concern I have here is: Where do the authors differentiate between IP during regular fall freeze-up and IP within polynyas and leads. Or in other words, when do the authors define an open water / thin ice areas to be belonging to a polynya and when is this still considered fall freeze-up? In this context: in the caption of Figure 4 the authors make a note that they discarded the regions of high TIT frequency along the marginal ice zones facing the Nordic Seas from further analysis. Wouldn't it make sense to do the same for the northern Baffin Bay (in November) and also the southern Chukchi and Beaufort Seas (in November)? Also: What was the criterion to exclude areas with a high TIT frequency? I could not find a notion how exactly these regions were defined. Did the authors used a TIT frequency threshold?

→Please refer to our response under general comment (4).

Line 23: "slight decrease" I suggest the authors add that these decreases are far from being significant.

We changed the mentioned part to read: "a slight, yet insignificant decrease…"

Line 26: "plus/minus 258 km^3" Is this an uncertainty, or is this the standard deviation from computing the average IP of the 13 winters?

As in Tab.2/3, "± 258 km³" refers to the standard deviation over the 13-yr period.

Line 30-31: I suggest that the authors comment more on this comparison. Tamura and Ohshima's results are based on SSM/I data while Iwamoto et al. base their study on AMSR-E data. The authors' *study is based on MODIS data. This implies different spatial resolutions which effect on the results could be discussed here. Actually, in the next paragraph starting in line 32 the authors carry out this discussion but without linking it to the statement in lines 30-31 and without trying to investigate (and discuss theoretically) whether 2 km instead of 6.25 km grid resolution would allow to explain the larger IP found in this study compared to Iwamoto et al. Yes, I agree, with a finer grid resolution one is able to identify smaller scale thin ice features. There is no doubt about that and this has been demonstrated in previous papers of the leading author. But at the same time POLA of larger polynyas could become smaller because the polynya edge is better defined at 2 km than at 6.25 km. Therefore there could be competing effects with the net effect being zero. In addition the period of Iwamoto et al. is much closer to the one used by the authors. By looking at the winters 2011/12 through 2014/15 the authors could check whether their larger value compared to Iwamoto et al. could be explained by considerably larger IP in these winters compared to the winters before 2011/12.*

→Please refer to our response under general comment (1).

Further, we took a closer look at the numbers from Iwamoto et al. (2014) and our numbers up until 2010/2011. It shows, that the winter seasons from 2011/2012 onwards vary considerably between low (2011/2012) IP and the largest (2012/2013) IP in our 13-yr time series. Thereby, the average value for 2002/2003 to 2010/2011 is not affected very much by leaving out the last 4 winter seasons and amounts now (incl. new WNZ region) to around 1789 km^3/winter (~ - 1-2%).

We added some more comments on that comparison at the mentioned part in Sect. 4.1.

Page 17, Figure 8: I am wondering why the map showing the significance is smaller than the one showing the trends. I suggest to make both maps the same size or, alternatively, to overplot significance levels on an even enlargened version of image a) using, e.g. dots and crosses to denote areas of >95 and >99% significance or isolines. However, what is a bit unfortunate here - as well as already in Figures 4 and 7 is the fact, that the marginal ice zone (MIZ) facing the Nordic Seas is visually dominating the Figure and distracts the eye from those regions which are really relevant for the present study. In the context of the yet unexplained way how these MIZ areas are excluded (according to the caption of Figure 4), I encourage the authors to find a way to make these areas to appear less prominent, perhaps by grey shading or similar, so that the reader can focus on the relevant areas.

We changed the overall appearance of several figures (3, 4, 7, 8, 10, and 11) according to the feedback of all three reviewers. Thereby, relevant regions are now additionally marked using the polynya masks, as can be seen below.

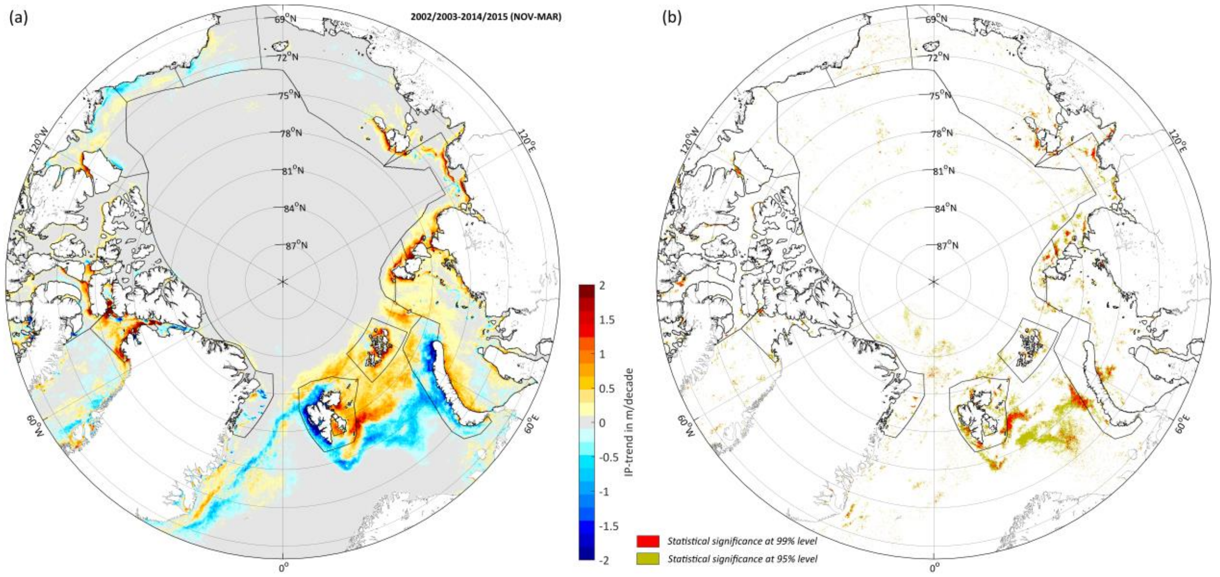


Figure 3 (a) Decadal trends (m per decade) of wintertime (November to March) ice production in the Arctic, north of 68 ◦ N. Trends are calculated by applying a linear regression on the annual accumulated IP per pixel for the period 2002/2003 to 2014/2015. Areas with statistical significance (based on a two-sided t-test) at the 95% and 99% level are depicted in (b). The margins of applied polynya masks (Fig. 1) are shown in black dashed lines.

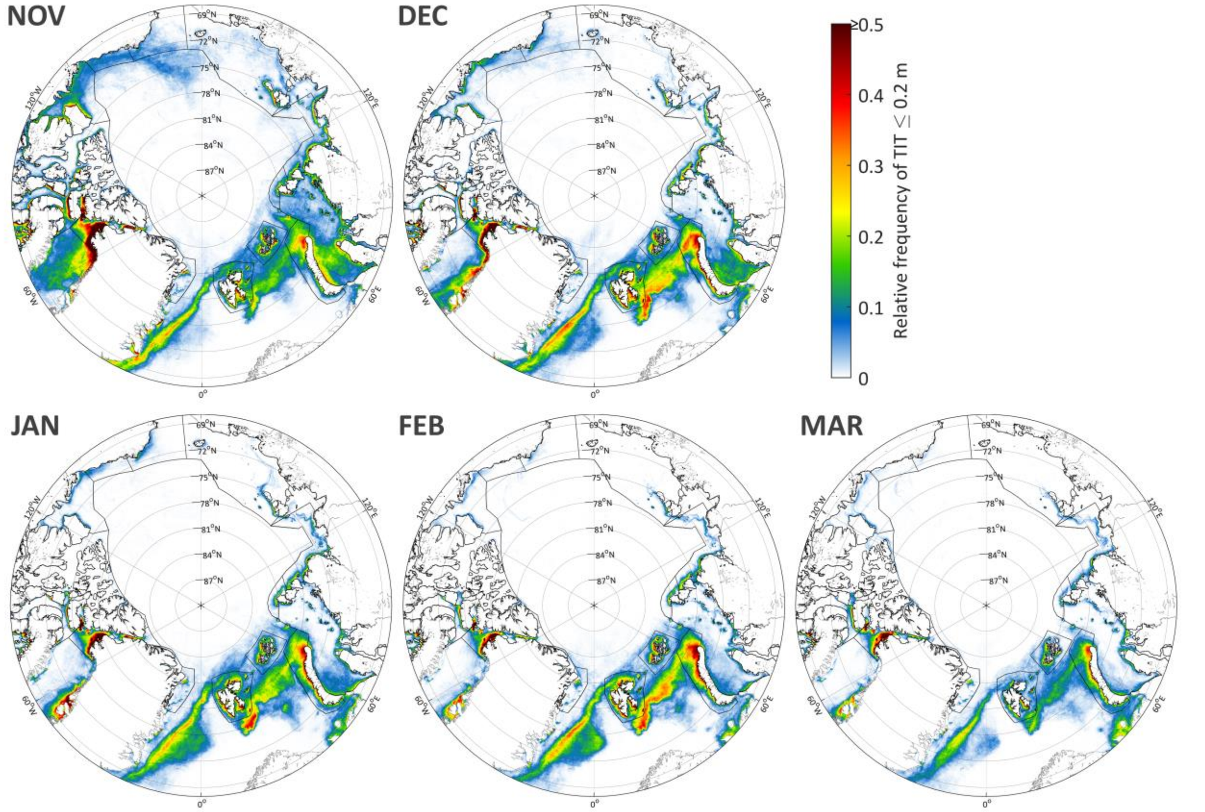


Figure 4 Average wintertime (November to March) frequencies of TIT ≤ 0.2 m in the Arctic between winters 2002/2003 and 2014/2015. Note that only thin-ice areas within the margins of a given polynya mask (dashed black lines; compare Fig. 1) are used for further analysis, while all other areas are discarded. Hence, areas with high TIT frequencies in the marginal ice zone (MIZ) around Fram Strait and northern Barents Sea are excluded from further analysis due to potential ambiguities originating from ocean heat fluxes and a high Interannual variability of the MIZ in terms of location and extent.

Line 2: "diminishing fast ice extent over the recent 13 years." I am not sure that the extent of the fast ice can be mentioned as the reason here - at least not solely. I recommend that the authors take a look at the paper by Selyuzhenok et al., Seasonal and interannual variability of fast ice extent in the southeastern Laptev Sea between 1999 and 2013, J. Geophys. Res.-Oceans, 2015 and of Yu, Y., et al., Interannual variability of Arctic landfast ice between 1976 and 2007, J. Climate, 2014 to underline or perhaps change their statement here.

Rephrased to read:

"(…) ***and (2) the structure of negative / positive spatial trends along the coasts of the Laptev Sea and Kara Sea suggests a southward shift of the fast-ice edge with potential implications for the fast-ice extent over the recent 13 years. Decreasing fast-ice extents and durations in the eastern Arctic between 1976 and 2007 were recently described by Yu et al. (2014). In addition, Selyuzhenok et al. (2015) analyzed the fast ice in the south-eastern Laptev Sea in more detail (1999 to 2013). While their study showed that the winter maximum fast-ice extent (March/April) as well as the shape and location of the fast-ice edge did not vary significantly over the regarded time period, they likewise presented an overall decrease in the fast-ice season (-2.8 d/yr^{-1}) due to a later formation and earlier break-up. These described changes regarding the timing of fast-ice formation in early winter could explain the observed structures of positive / negative trends in proximity of fast-ice areas.***

In order to put these observations into context, we suppose that this characteristic pattern of opposing trends in the western and eastern Arctic as well as the apparently fast-ice related structures in the Laptev Sea and Kara Sea could be connected to an overall later appearing fall freeze-up (Markus et al., 2009; Stroeve et al., 2014) in recent years, which itself is thought to result from a complex mixture/interplay of steadily increasing (2m-) air temperatures, distinct large-scale atmospheric patterns (e.g. Rigor et al., 2002) and the overall downward trend of total sea-ice extent and volume in the Arctic. As being one of the main regions with highly pronounced and significant positive trends in both POLA and IP throughout the complete winter period, the following section will take a closer look on polynya dynamics in the Laptev Sea."

Page 18, line 11: I suggest the authors cite the two other studies at the end of this sentence (i.e. Tamura and Ohshima 2011, and Iwamoto et al. 2014) I further suggest that the authors clarify that by "more accurate" they solely refer to the spatial accuracy and not to an accuracy of the TIT and IP computation approaches. Perhaps this could be done by replacing "and for more accurate" with "and therefore spatially more accurate"?

→Please refer to our response under general comment (1).

Page 18, Figure 9: I have a late comment to the choice of the regions LAP and SZN. I am wondering why these two regions were defined as they are. Why does the western part of region LAP extends well into the Severnaya Zemlja area and with that well beyond the shelf break? Wouldn't it be more consistent to let region LAP and shortly south of the Vilkitsky Strait?

Regarding the definition of our polynya masks, we tried to apply the same or very similar margins as in earlier studies in order to ensure "spatial consistency" wherever possible (LAP, KAR, STO, NOW). In case of the Laptev Sea (LAP), we followed the studies of Willmes et al. (2011) and Bareiss and Goergen (2005), who analyzed the sub-regions of Eastern Severnaya Zemlya (ESZ), North Eastern Taymyr (NET), Taymyr (T), Anabar-Lena (AL) and Western New Siberian (WNS).

The new Severnaya Zemlya North (SZN) mask was defined to close the gap between the Kara Sea and Laptev Sea masks and thereby include the high frequencies of thin ice at the northern tip of Severnaya Zemlya.

Page 19, Figure 10: What is the motivation to interpolate / smooth the POLA in this figure? Wouldn't similar conclusions be reached by simply showing the daily POLA as is?

Compare comment REF#3; new version of Fig.10 below:

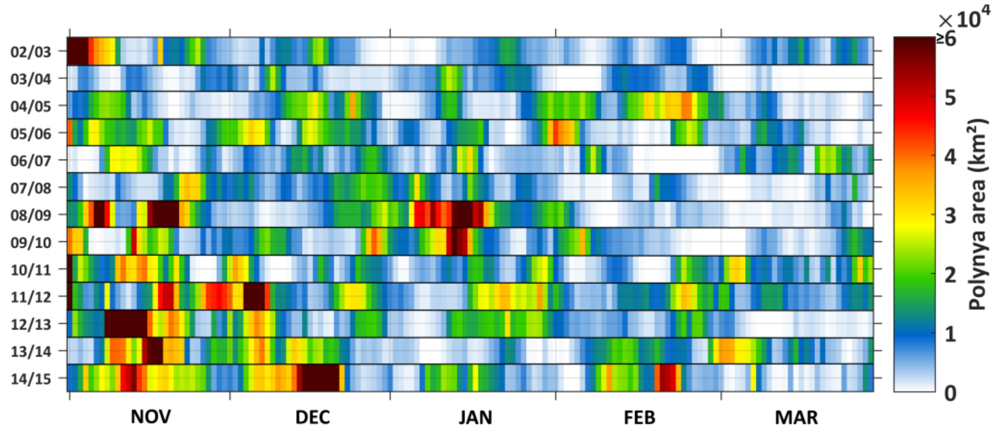


Figure 5 Daily polynya area (TIT ≤ 0.2 m) in the Laptev Sea region between 2002/2003 and 2014/2015. Values are calculated within the margins of the applied polynya mask (Fig. 1) and saturated at a level of 6 x 10^4 km^2 for a better discrimination of lower values.

Lines 9/10: "largest POLA values appear on average in November and ..." Is this perhaps still fall freeze-up?

Rephrased to "**largest areas of thin-ice** appear on average in November and **(…) ".**

In addition, please refer to our response under general comment (4).

Lines 12/13: "polynya activity" Are the authors referring to the sheer occurrence of a polynya or to the POLA? If the authors talk about the former then one could conclude that the activity is as large today as it was in the past. The main difference is that the POLA tends to be larger recently.

We slightly changed the sentence in order to make it less confusing, so that it now reads:

"***A pronounced seasonal variation is visible for the winter seasons 2004/2005, 2005/2006 and from 2010/2011 onwards, while the other years show less polynya activity (more lengthy periods with a closed polynya; white color in Fig.10) and overall smaller polynya extents in February and March***."

Line 18: "position of the fast-ice edge": I suggest the authors include a note that Figure 11 of course integrates over the full winter season from November to March. That is, periods of polynya activity exchange with quiet periods during which the fast ice potentially extends northwards. This is just to avoid a readers' conclusion that the fast ice breaks up; the fact that there can be bands of higher ice production within the area which should be fast-ice covered can also (if not merely) be associated with the episodic nature of fast ice development, particularly during early winter.

We will put more effort on highlighting the period over which the values were integrated/accumulated in the text (as in the caption of Fig.11). Certainly, bands of high ice production are almost exclusively related to the early freezing season (~November/Early December), at least in case of the southern Laptev Sea. Fast-ice areas in eastern proximity of Severnaya Zemlya and the Vilkitsky Strait showed to be more variable even in late winter.

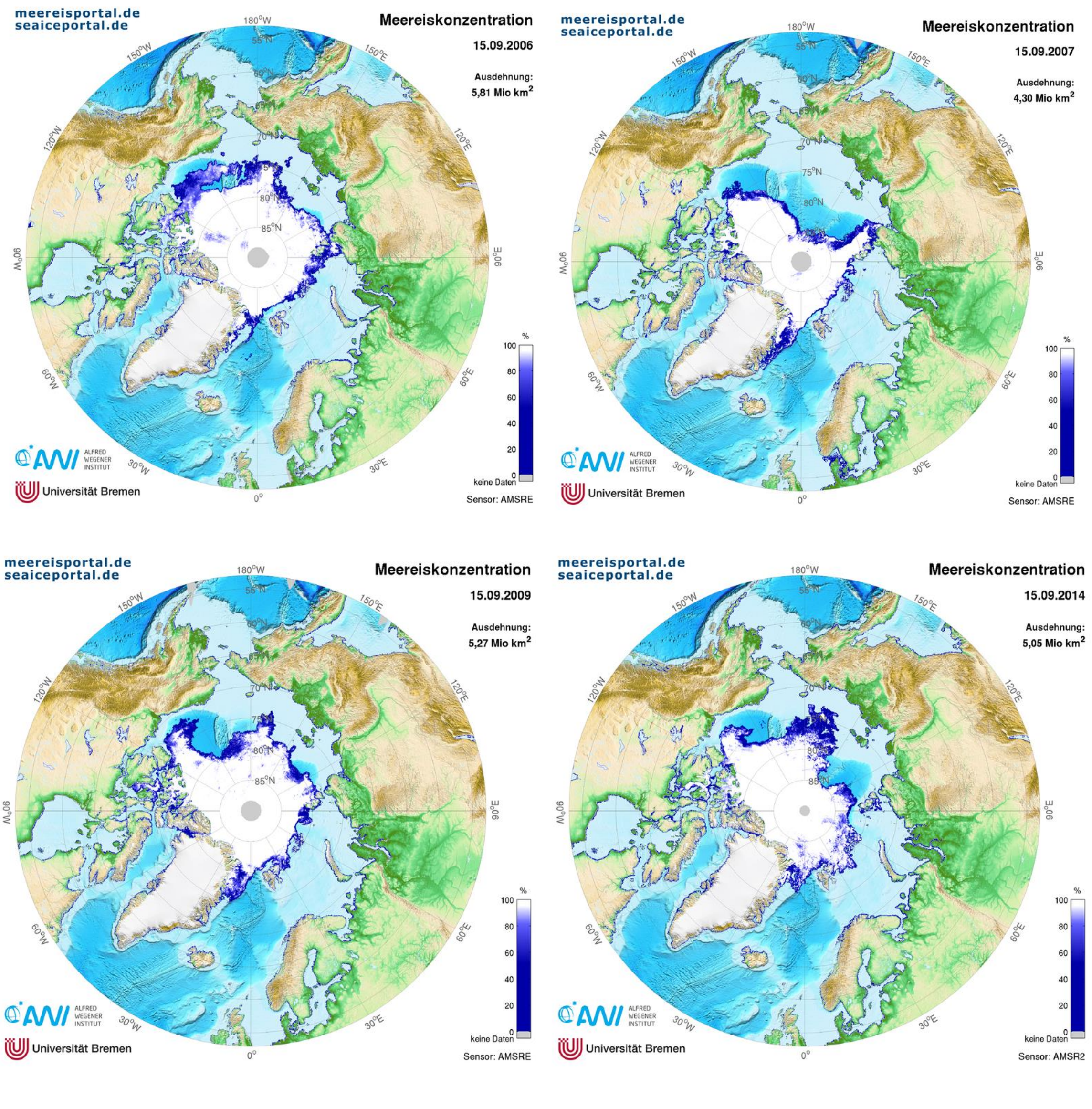
Page 19, line 19 until page 21, line 3: Did the authors check whether winters with a characteristic "ice arc" feature can be related to years where the sea ice did not melt completely in that region of the Kara

Sea? Also: While in the Nares Strait the dominant wind direction and hence formation of the ice arc is clear, how is this in the Vilkitsky Strait?

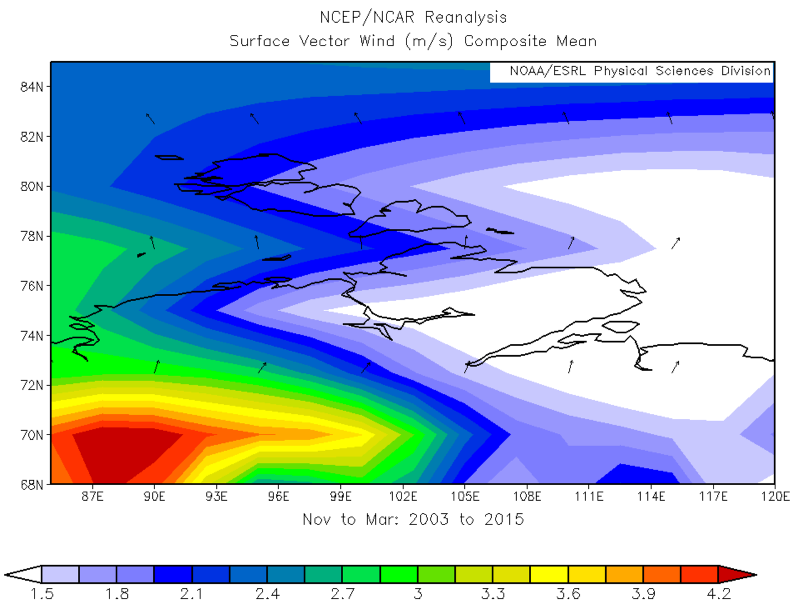
Years with "ice-arch-like" feature (2006/2007, (2007/2008), 2009/2010, 2014/2015) → see SIC maps below: First two years yes (ice seemed to remain in that area), other two years apparently no ice.

The Vilkitsky Strait is generally dominated by low pressure systems centered around eastern Kara Sea, which most commonly results in south-western to southern winds (compare NCEP/NCAR figure below) and thereby high TIT-frequencies surrounding the eastern exit of Vilkitsky Strait / the western Laptev Sea. However, potential channeling effects in Vilkitsky Strait and hence increased wind speeds are presumably not resolved by ERA-Interim.

In the Vilkitsky Strait, the presence of topographically-channeled storms not detected by ERA-I is documented by a high-resolution (5 km) atmospheric model simulations in Janout et al. (2016)[7].



[7] Janout, M., Hölemann, J., Timokhov, L., Gutjahr, O., Heinemann, G., 2016: Circulation in Vilkitsky Trough in the eastern Arctic Ocean: Crossroads between Siberian river water, Atlantic water and polynya-formed dense water. Journal of Geophysical Research, in review.



Page 21, lines 8-12: While one could have a look at the paper by Krumpen et al. (2013) the authors could also, in one of their images in Figure 11, draw a line which marks the gate across which the IAE is computed.

The geographical locations of these two boundaries (NB/EB) on which meridional and zonal ice area flux estimates were based in Krumpen et al. (2013) are now additionally illustrated in Fig.9 (see below, cyan solid lines in the inset) and **some further explanation on the IAE values will be given in the manuscript (see also the comment by Prof. Göran Björk (Ref. #2)).**

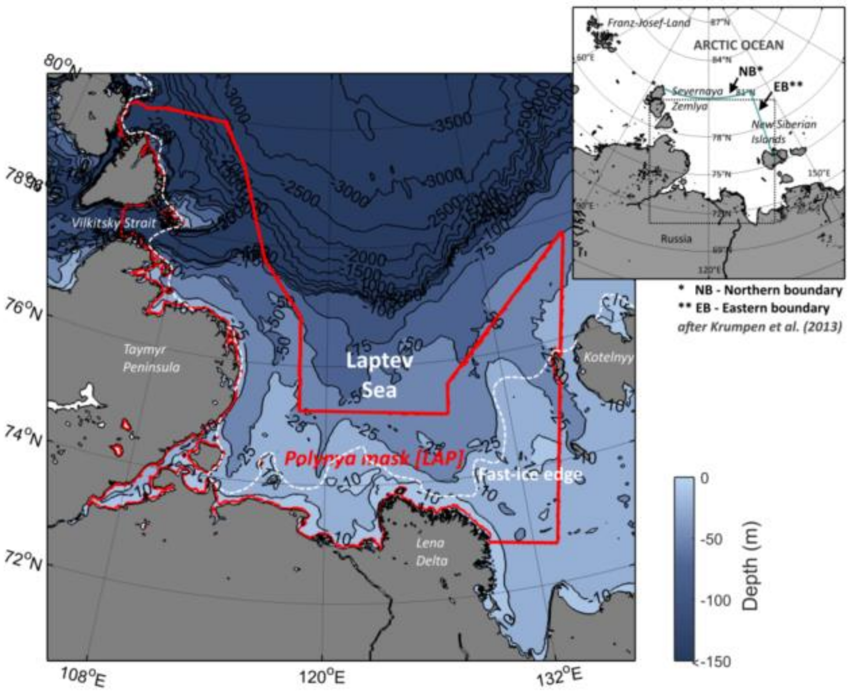


Figure 6 The geographical location of the Laptev Sea in the eastern Arctic. The applied polynya mask is marked in red, enclosing the locations of typical polynya formation along the coast and fast-ice edge (dashed white line; position derived from long-term thin-ice frequencies in March (Fig. 4)). Flux 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).

Line 12: "significant" With which p-value?

In this case, the p-value is 0.009 (depicted in Fig.12). However, to avoid that this information is missed by the reader we will add them at the respective part of the text.

Lines 16-19 and page 22, lines 10-14: While I am not doubting that the IP of the LAP has indeed increased for November-March for 2002/03 through 2014/15 I am wondering whether the authors could also include a critical comment of these numbers and take into account that freeze-up has been commencing later recently over many regions of the Arctic Ocean (Markus et al., Recent changes in Arctic sea ice melt onset, freeze-up, and melt season length, J. Geophys. Res., 2009; Parkinson, C., Spatially mapped reductions in the length of the Arctic sea ice season, Geophys. Res. Lett., 2014) and that this could be the main driver for the increase in IP observed in the present study - in addition to a thinner, more easily to be deformed and pushed away by offshore winds sea ice cover. Yes, the authors mention the "length of the freezing period", among other reasons, but remain not conclusive enough to my taste. In particular, it is not the length of the freezing period but the onset of freeze-up. Unmentioned remains also a potential air-temperature increase particularly during winter which would counterbalance an increase in IP during November-March.

Please refer to our response to your general comment (4) and (regarding air-temperature increase) to your last comment below.

Conclusions:

Page 22, line 24: "and the sea-ice budget in general". I suggest that the authors remain more specific here and write: "and the associated sea-ice budget related to winter-time sea-ice production." Even though the polynyas for sure make a substantial contribution to the Arctic Ocean sea ice budget which is certainly mainly determined via the annual freeze-up and ice thickening underneath existing sea ice due to congelation growth.

We will add this suggestion in order to be more specific in that context.

Page 23, lines 3-4: I suggest to here only mention those negative trends which are significant. Hence one could end the sentence after "... variability."

Fixed accordingly.

Lines 4-6: What the authors write here could be true but certainly deserves more work to be done. Most importantly, however, this is not a result the authors achieved and I recommend that the authors stay with their own results in the conclusion bullets before they eventually give an idea about what they think could be a possible reason for the changes observed in their data set.

We can follow your remark here. However, potential linkages should definitely be highlighted here. Hence, we slightly altered the formulation of this sentence to keep it more in a conjunctive sense.

Lines 13-14: Is the paper by Boisvert and Stroeve, 2015, focusing on the Laptev Sea? I cross-read the paper and had difficulties to find evidence for the link presented here. Yes, air- and skin-temperatures seem to have a positive trend in the LAP - especially in October and November but no further information about the winter is given. Increasing temperatures at first glance point to a decrease in IP, though. It is important that the authors clearly state how the causal links are and not only list a number of potentially relevant papers. The same applies to the "significant lengthening of the melt season". I suggest to be more specific here as well, because the melt-onset is not important here but the commence of freeze-up.

Last part refers again to general comment (4).

As for the paper by Boisvert and Stroeve (2015), the winter period is shown in the supplement, Fig.S2 (column (a) → DJF).

Regarding increasing air temp in winter (see also last comment result section): Interdependencies in our applied model are rather complex as to just conclude that increasing air temp leads to less IP. Besides the (2-meter) air temperature, turbulent fluxes of sensible / latent heat and hence the energy balance in general are strongly influenced by changes in wind speed, ice surface temperature (i.e. the vertical temperature gradient), specific humidity q, etc. In other words - what might seem as a logical consequence at the first glance does not necessarily result in the expected effect. For instance, increased air temperatures often coincide with increased IST, thereby maintaining the vertical temperature gradient or even increasing it, so that the resulting ocean heat loss / IP could be altered in the opposite direction.

At this point of the MS, we meant to highlight currently observed changes in the Laptev Sea with a possible influence on polynya dynamics. Admittedly, we could have done a better job at explaining connected implications. Hence, we reformulated this part of the MS in order to highlight potential linkages more clearly. Maybe even more noticeable, we decided to move this part to the end of Sect. 4 in order to shorten this particular part of the conclusions.

Rephrased and rearranged to read:

End of Sect. 4:

"(…) Other linkages and dependencies with the Arctic sea-ice extent in September (annual minimum), the timing of the freeze-onset and further connections to large-scale atmospheric circulation patterns are very likely and have been proposed by various previous studies (e.g. Alexandrov et al. (2000); Deser et al. (2000); Rigor et al. (2002); Willmes et al. (2011); Krumpen et al. (2013). Especially a significant lengthening of the melt season in recent years and hence a later freeze-up in autumn already seems to imprint on derived POLA (i.e. thin-ice area) and IP estimates in the early winter period (Markus et al., 2009; Parkinson, 2014; Stroeve et al., 2014). In that context, increasing atmosphere- and ocean-temperatures in autumn and winter have recently been reported by Boisvert and Stroeve (2015) that comprise the potential to alter/shift vertical temperature gradients with consequences for the surface energy balance and ultimately IP. Further, a shortened fast-ice duration and enhanced variability of the fast-ice edge in early winter (Yu et al., 2014; Selyuzhenok et al., 2015) presumably influences the location of flaw-leads and consequently high ice production / brine release. Frankly, all these (potential) interconnections are rather complex and would require more detailed investigations that go beyond the scope of the present study. In the context of other reported changes during the spring and summer period (Janout et al., 2016), it may emerge that the overall set-up for atmosphere-ice-ocean interactions in the Laptev Sea is gradually changing towards a new state."

Conclusion, bullet point (4):

"(…) While the interannual variability in terms of location and extent seems to be rather high, the positive trends in both POLA and IP time series fit well to results and observations from other recently published studies in the Laptev Sea. A clear relation between increasing sea-ice area export (Krumpen et al., 2013) and positive trends in IP could be demonstrated, and future comparisons with recently derived volume-flux estimates in the Transpolar Drift (Krumpen et al., 2016) certainly promise further insights on the absolute contribution of polynyas to the volume ice export out of the Laptev Sea and adjacent seas."

RC2: 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 Prof. Göran Björk (referee) on August 23, 2016

General comments

This work gives a comprehensive description of Arctic polynyas based on high resolution surface temperature (MODIS) data. This data set has the advantage of a higher spatial resolution compared with satellite products used in earlier investigations. It gives a 22 % higher total polynya ice production than recent results which shows that the development of satellite products, algorithms and analyses is still an important issue in order to follow the past and future development of the Arctic Ocean ice cover. It reveals significant positive trends of the polynya ice production in the eastern arctic which can be further utilized for analyses of the effect on dense water mass formation on the shelves which likely have influence on shelf circulation, shelf basin interaction and water chemistry. The paper is generally of a high quality in language and analyses and is therefore well suited for publication.

We would like to thank the Prof. Göran Björk (referee #2) for his valuable comments and remarks. We carefully went over the mentioned parts of the manuscript. Specific comments will be addressed in the following.

Specific comments

I'm not perfectly happy with the sentence starting on line 6 page 3 ("A regular monitoring..."). It appears to be somewhat a repetition of the sentence on page 5 line 8 ("Hence an accurate...").

Thank you for this remark, but in our sense the sentence on page 6 refers to the general monitoring of thin-ice areas using remote sensing data, while the section on page 5 refers to the determination of sea-ice production.

Page 9 Table1 text. I miss some more explanation of what the "interannual average coverage" means. Coverage of what? It is hard to understand as it stands now.

The referee is right regarding the somewhat misleading / confusing formulation of the caption here. We changed it accordingly to read:

"Areal extents (i.e. total ocean area) of all applied polynya masks in km². Further, the interannual average amount of MODIS swaths that could be used for calculating daily composites in a given region is indicated, together with the interannual average daily MODIS coverage (decimal cover fraction ranging from 0 to 1 with their respective standard deviations) before (COV2) and after (COV4) application of the Spatial Feature Reconstruction (SFR) for each polynya region from 2002/2003 to 2014/2015 (November to March). (…)"

Page 9 Line 2 and before. It is hard to follow the logic why fixed values for ice and Lf are used. The arguments regarding frazil ice crystals are not clear to me.

The presented thin-ice algorithm does not explicitly discriminate between different ice types. It follows the assumption that a linear temperature profile can be used to calculate the heat conduction through the ice. Hence, we added this information to the manuscript. Regarding the choice of constant values for the ice density and latent heat of fusion (L_f), we followed earlier studies (e.g. Willmes et al. (2011), Tamura and Ohshima (2011), Iwamoto et al. (2014)) to ensure comparability of achieved results. These studies followed an even earlier characterization of sea-ice formation mechanisms by Martin (1981).

Page 12 Line 2. It is interesting to see persistent leads well off the shelf in the Beaufort Sea. These must be related to the large scale ice circulation in the area and it is remarkable that they are so persistent that the show up as well defined bands in this type of data (most notable in Feb-Mar). I wonder if this structure has been described before or if it is a new finding. It is worth some more comment anyhow.

Thank you for this interesting remark. Indeed, these broad lead-structures in the Beaufort Sea (related to the clockwise rotation of the Beaufort Gyre) have been previously described e.g. by Willmes and Heinemann (2015, Remote Sens., doi:10.3390/rs8010004), who also used MODIS TIR data, and also by Röhrs et al. (2012, TC, doi:10.5194/tc-6-343-2012), who used coarser resolution AMSR-E passive microwave data for their analysis.

What is interesting in the present study though, is the relatively high persistence of these leads (so that they are not discarded from our daily thin-ice distributions) together with apparently distinct favorable locations of appearance so that they appear in the these interannual frequencies of TIT ≤ 0.2m. Therefore, we added the following statement *"(…) leads are mainly located in the area of the Beaufort Sea and north of Greenland (shear zones)* ***which can be attributed to their relatively high spatial and temporal persistence. (…)***".

Page 12 Line 3. I can't see the leads along the Transpolar drift in figure 4. The central area around the North Pole appears to be without leads in the figure.

The referee is correct with this remark, as we were aiming to highlight enhanced TIT frequencies in the Atlantic sector of the Transpolar Drift (~Fram Strait region; see above for FEB). However, as frequencies are quite low and mainly located outside our indicated regions of interest (i.e. polynya margins; Fig.1), we decided to remove this sentence to avoid confusion.

Page 15 Line 8. Suggestion: "is especially large " instead of "increases".

Fixed, thank you for this suggestion.

Page 19 Line 13. Sentence starting with "A pronounced seasonal..." is unclear. I can see that the seasonal variation is largest in the late half of the period, but the last part is confusing.

We slightly changed the sentence in order to make it less confusing, so that it now reads:

"***A pronounced seasonal variation is visible for the winter seasons 2004/2005, 2005/2006 and from 2010/2011 onwards, while the other years show less polynya activity (more lengthy periods with a closed polynya; white color in Fig. 10) and overall smaller polynya extents in February and March.***"

Page 19 Line 18. I think the reader needs some more help to identify the fast ice edge in figure 11 and also in earlier figures. It is not clear to me since there are several bands of high ice production from the coast and outward in most of the fields.

The referee is right that characteristics of the fast-ice edge might be difficult to assess for readers who are unfamiliar with the topic. This is especially true when showing plots that integrate over the period from Nov.-Mar., and therefore inhibit different stages of fast-ice development. However, a complete mapping / marking of these areas is a quite challenging task and definitively not feasible for this present study. In order to address your remark, we decided to keep most of the figures as they are (except for Fig.9 where we inserted the approximate average position of the fast-ice edge at the end of March; see below) and put more effort on describing the characteristics.

P21 Line 9. IAE need to be defined better. Is it the export just outside the Laptev Sea or what?

To quote Krumpen et al. (2013), the ice area flux is calculated as the integral of the product between the U and V component of the ice drift velocity and ice concentration at the northern boundary (NB) and eastern boundary (EB) of the Laptev Sea. In their study, a positive flux (given in km^2) is referred to an export out of the Laptev Sea into the Transpolar Drift and East Siberian Sea, while a negative flux denotes to an import into the Laptev Sea. Please refer to the mentioned study for more details on the data sets, calculation procedure and outcomes.

The geographical locations of these two boundaries (NB/EB) on which meridional and zonal ice area flux estimates were based in Krumpen et al. (2013) are now additionally illustrated in Fig.9 (see below, cyan solid lines in the inset) and **some further explanation on the IAE values are now given in the manuscript.**

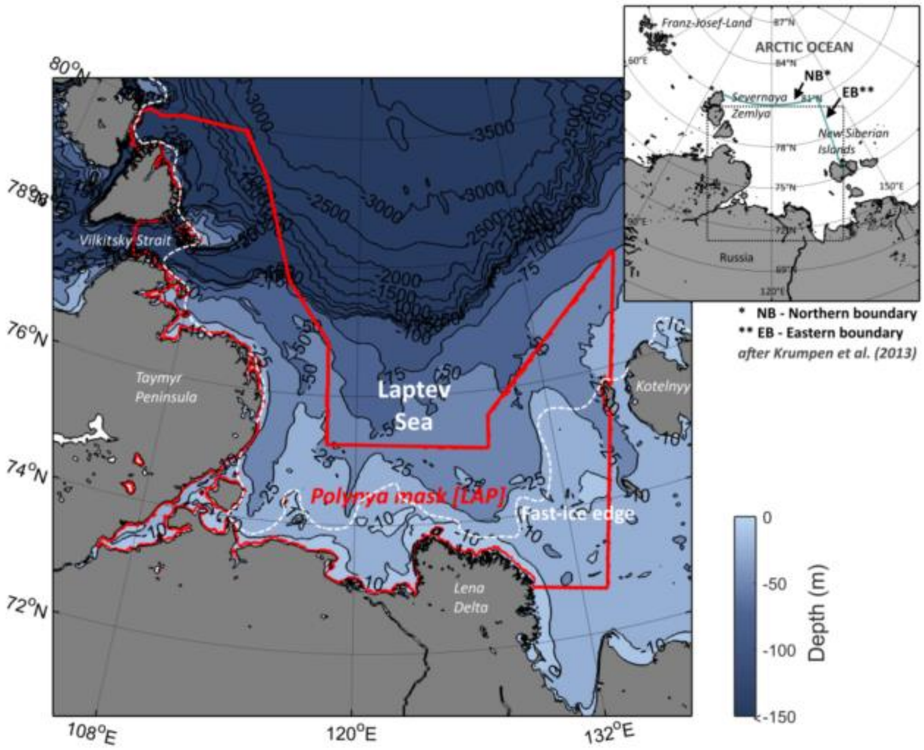


Figure 1 The geographical location of the Laptev Sea in the eastern Arctic. The applied polynya mask is marked in red, enclosing the locations of typical polynya formation along the coast and fast-ice edge (dashed white line; position derived from long-term thin-ice frequencies in March (Fig. 4)). Flux 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).

Technical corrections

None

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↓). For typical L↓ 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↓ 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.

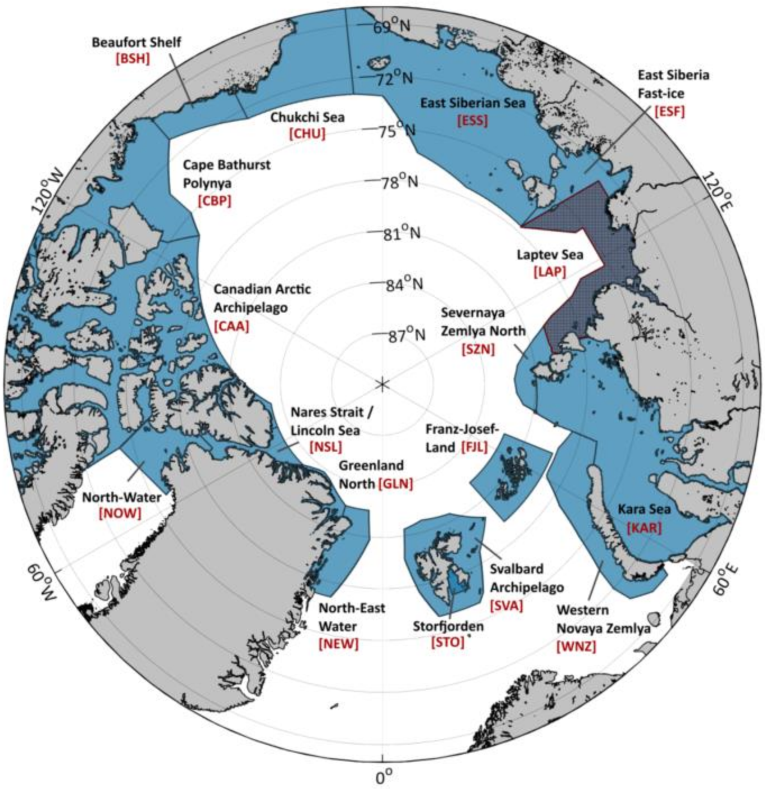


Figure 1 Map of all investigated areas of interest located in the Arctic, north of 68 ◦ N. Except for the Laptev Sea (red frame), all other applied polynya masks are marked in blue and enclose the typical location of each polynya in wintertime.

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.

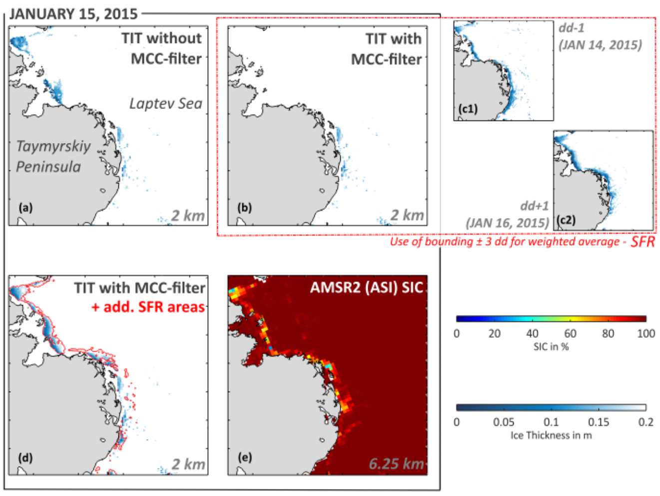


Figure 2Different stages in the MODIS thin-ice thickness (TIT up to 0.2 m) processing chain for a single exemplary day (January 15, 2015). Sub-panels (a), (b), (c1/c2) and (d) all feature a subset (north-western Laptev Sea) from daily pan-Arctic TIT composites, with (a) showing the daily TIT without 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)**.

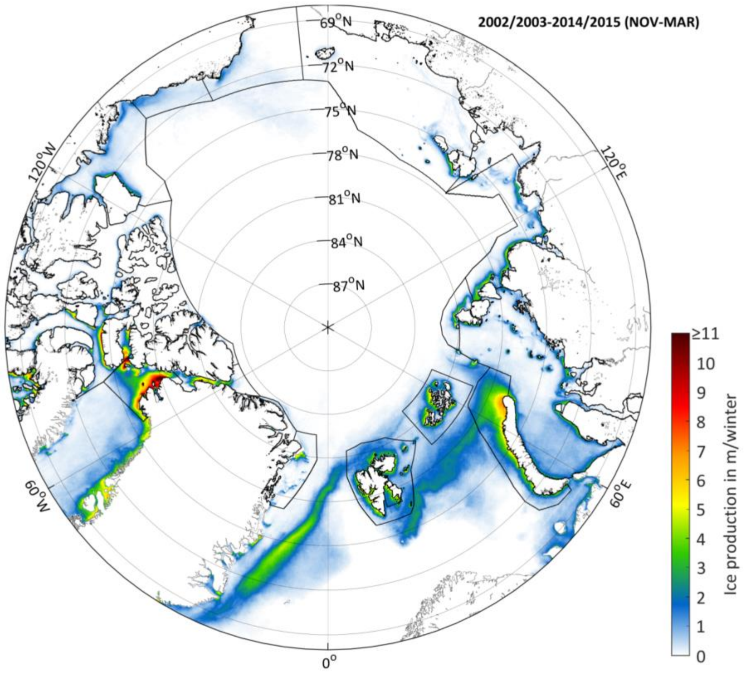


Figure 3 Average (2002/2003 to 2014/2015) accumulated ice production (m per winter) during winter (November to March) in the Arctic, north of 68°N. The margins of applied polynya masks (Fig. 1) are shown in black dashed lines.

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.

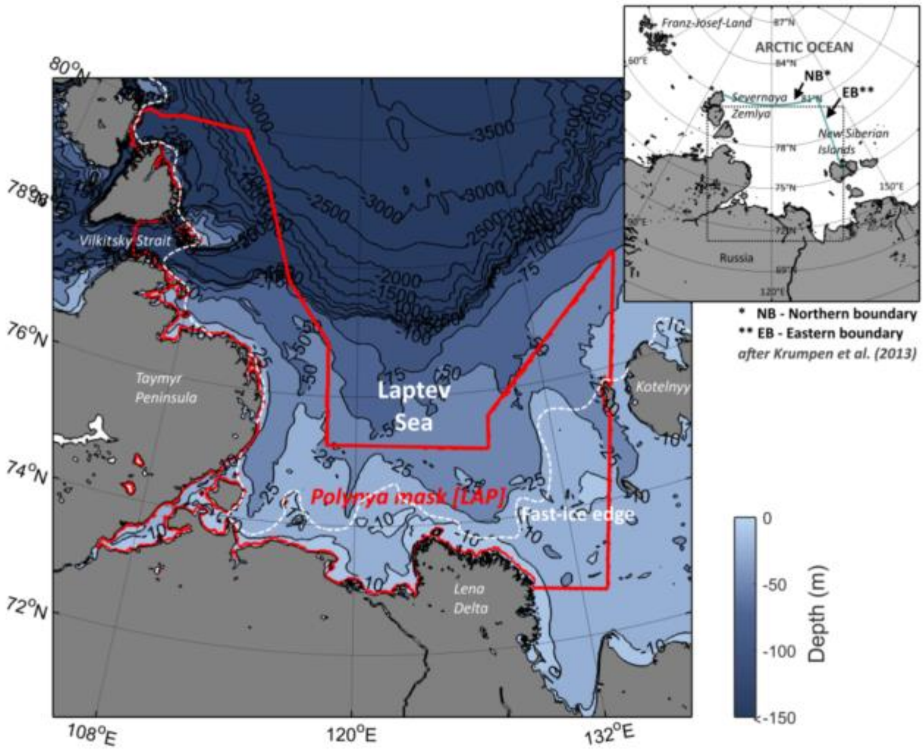


Figure 4 The geographical location of the Laptev Sea in the eastern Arctic. The applied polynya mask is marked in red, enclosing the locations of typical polynya formation along the coast and fast-ice edge (dashed white line; position derived from long-term thin-ice frequencies in March (Fig. 4)). Flux 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.

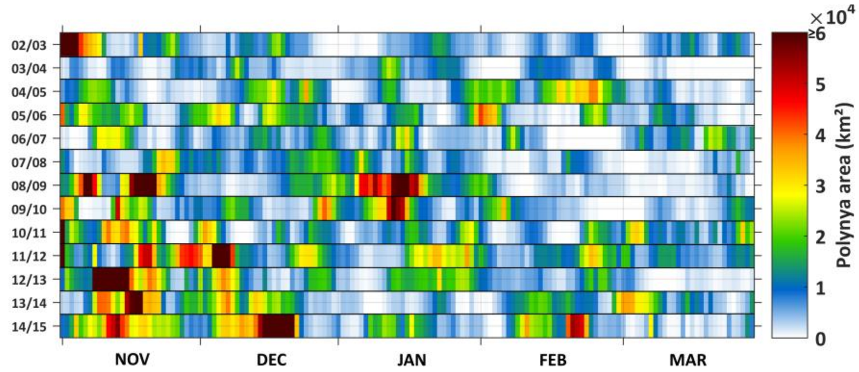


Figure 5 Daily polynya area (TIT ≤ 0.2 m) in the Laptev Sea region between 2002/2003 and 2014/2015. Values are calculated within the margins of the applied polynya mask (Fig. 1) and saturated at a level of 6 x 10^4 km^2 for a better discrimination of lower values.

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

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Abstract. High-resolution MODIS thermal infrared satellite data are used to infer spatial and temporal characteristics of ~~16~~ 17 prominent coastal polynya regions over the entire Arctic basin. Thin-ice thickness distributions (≤ 20 cm) are calculated from MODIS ice-surface temperatures, combined with ECMWF ERA-Interim atmospheric reanalysis data in an energy balance model for 13 winter-seasons (2002/2003 to 2014/2015; November to March). From all available MODIS swath-data, (quasi-) daily thin-ice thickness composites are computed in order to derive quantities such as polynya area and total thermodynamic (i.e. potential) ice production. A gap-filling approach is applied to account for cloud and data gaps in the MODIS composites. All polynya regions combined cover an average thin-ice area ~~(POLA) of 184.3~~ of 226.6 $\pm$ ~~35.6~~ 36.1 x10^3km^2 in winter. This allows for an average total wintertime accumulated ice production of about ~~1444~~ 1811 $\pm$ ~~258~~ 293 km^3, whereby the Kara Sea region and the North Water polynya (both ~~19%)~~15%), polynyas at the western side of Novaya Zemlya (20%) as well as scattered smaller polynyas in the Canadian Arctic Archipelago (all combined ~~15~~12%) are the main contributors. Other well-known sites of polynya formation (Laptev Sea, Chukchi Sea) show smaller contributions and range between 2 and ~~7%. Compared to an earlier study~~ 5%. We notice distinct differences to earlier studies on pan-Arctic polynya characteristics~~that utilized lower resolution passive microwave remote sensing data, our estimates are about 22% larger on average. This partly originates~~ , originating to some part from the use of high-resolution MODIS data, ~~which increases~~ as the capability to resolve small scale (> 2km) ~~thin-ice features such as large leads~~ polynyas and also large leads is increased. Despite the short record of 13 winter-seasons, positive trends in ice production are detected for several regions of the eastern Arctic (most significant in the Laptev Sea region with an increase of 6.8 km^3/yr) and the North Water polynya, while other polynyas in the western Arctic show a more pronounced variability with varying trends. We emphasize the role of the Laptev Sea polynyas as being a major influence on Transpolar Drift characteristics through a distinct relation between increasing ice production and ice area export. Overall, our study ~~contains the most~~ presents a spatially highly accurate characterization of circumpolar polynya dynamics and ice production ~~to date~~ which should be valuable for future modeling efforts on atmosphere- sea ice - ocean interactions in the Arctic.

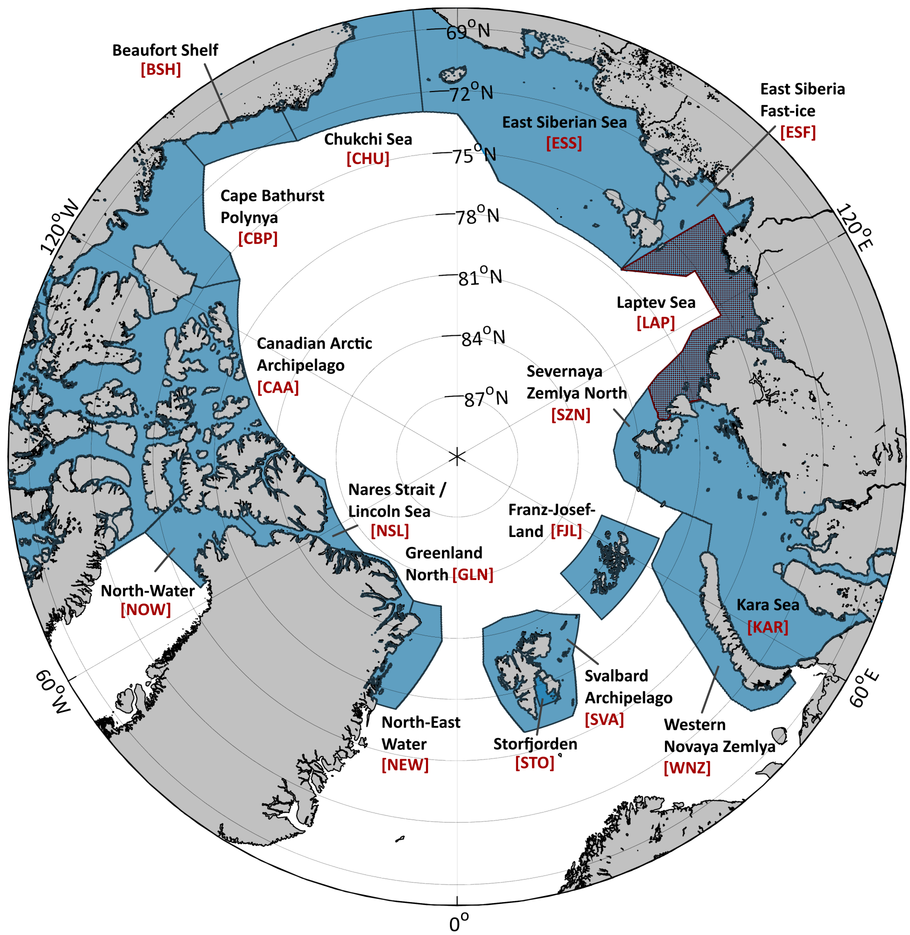

Figure 1. Map of all investigated areas of interest located in the Arctic, north of 68° N. ~~The~~ Except for the Laptev Sea (red frame), all other applied polynya masks are marked in blue ~~, enclosing~~ and enclose the typical location of each polynya in wintertime.

1 Introduction

The sea ice cover in the Arctic is subject to continuous changes through a variety of thermodynamic and dynamic processes, which are driven by atmosphere and ocean dynamics. ~~Large areas~~ Areas of open water and thin ice~~(~~, i.e. polynyas and leads~~)~~ , are characteristic features in this ice scape with a huge influence on local physical, biological and chemical processes at the interface between the atmosphere and the ocean (Barber and Massom, 2007).

Especially during wintertime, the presence of open water and thin ice leads to increased ocean to atmosphere heat fluxes, thereby allowing for new ice production and brine release as well as generally strong modifications of both the atmospheric boundary layer and upper ocean layers (Ebner et al., 2011; Gutjahr et al., 2016). Hence, an accurate assessment of wintertime sea-ice production in the Arctic is of vital interest for the understanding of Arctic sea-ice dynamics, the annual sea ice mass balance and, in general, for the verification of climate and ocean models. In case of the Arctic, it is widely considered that the main mechanism for polynya and lead openings are divergent ice motions caused by wind-induced stress (Smith et al., 1990). Therefore, most Arctic polynyas can be found adjacent to or in proximity of a fixed obstacle such as the coastline, attached land-fast ice or ice bridges under offshore-wind conditions (Williams et al., 2007). While the time of formation, the duration and the spatial extent of a polynya can be highly variable from year to year, their location of formation is generally rather stable (Morales-Maqueda et al., 2004). Leads are, in contrast, by far more variable both in space and time (Willmes and Heinemann, 2016). A regular monitoring of these open water and thin-ice areas with a high spatial accuracy is therefore a crucial step to be able to detect long-term changes, potential linkages and feedbacks to other environmental compartments as well as spatial and temporal patterns.

Based on the inventory of Barber and Massom (2007), we here define a total of ~~16~~ 17 individual polynya regions in the Arctic north of 68° N (Fig.1). Some of these areas are designed to match reference areas in previous studies (e.g. Kern, 2008). The areal extent, i.e. the total ocean area, of each sub-region is depicted in ~~Table 1.~~ Tab. 1. The vast majority of polynyas of our study is located around the Arctic shelf areas, with the largest fraction in the Siberian shelf region (East Siberian Sea (ESS), Laptev Sea (LAP), Severnaya Zemlya North (SZN), Kara Sea (KAR), Western Novaya Zemlya (WNZ)). Other well-known sites of polynya formation are the North Water (NOW) Polynya in northern Baffin Bay, several other frequently appearing thin-ice zones around northern Greenland (Nares Strait / Lincoln Sea (NSL), Greenland North (GLN), North-East Water (NEW) polynya), the Storfjorden (STO) polynya in the Svalbard Archipelago (SVA) and a number of smaller polynya locations around Franz-Josef Land (FJL), the Canadian Arctic Archipelago (CAA) as well as the Beaufort (BSH and CBP) and Chukchi (CHU) Seas. The marginal ice zone (MIZ) in Fram Strait and ~~west of Novaya Zemlya~~ northern Barents Sea is excluded in our investigations due to a variety of potential ambiguities originating from ocean heat fluxes and a high interannual variability of the MIZ in terms of location and extent.

Pan-Arctic estimations of daily thin-ice thicknesses and ice production in polynyas were previously published by Tamura and Ohshima (2011) and Iwamoto et al. (2014), who both presented newly developed empirical thin-ice algorithms. Therein, commonly used passive microwave remote sensing data from the Special Sensor Microwave / Imager (SSM/I) and Advanced Microwave Scanning Radiometer - EOS (AMSR-E) satellite sensors is related to reference thin-ice thicknesses from Advanced Very High Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS) thermal infrared data, based on a characteristic inverse relationship between the surface brine volume fraction and the thickness of sea ice (Iwamoto et al., 2014). In both studies, the advantages of passive microwave systems (complete daily coverage in the Arctic, almost no influence of clouds) come at the cost of quite coarse spatial resolutions (6.25 - 25 km) which strongly limit the ability to resolve small and/or narrow thin-ice areas in close proximity to coastlines or along fast-ice edges (Preußer et al., 2015a).

According to Willmes et al. (2011), a retrieval of long-term ice production is challenging for several reasons. ~~First, the~~ The derivation of polynya area needs to be addressed with spatial and temporal resolutions ~~,~~ that are sufficient to capture the seasonal and regional dynamics of polynya events (Winsor and Björk, 2000; Morales-Maqueda et al., 2004; Tamura et al., 2008; Willmes et al., 2010). ~~Second~~Further, the heat loss over the polynya has to be calculated, which requires detailed information about the fraction of open water, the ice thickness and its distribution within the polynya. The distribution of thin-ice largely affects the heat loss by providing feedback on the ice surface temperature, thereby altering the vertical temperature gradients both through the ice as well as towards the lower atmospheric boundary layer. Not less important, an accurate calculation of heat loss requires a state-of-the-art approach regarding the parametrization of the surface energy balance, turbulent fluxes of latent and sensible heat and the conductive heat flux through the ice. Thus, detailed (i.e. region-specific and ideally highly resolved) information on meteorological quantities and correct formulations for the turbulent exchange coefficient for heat (C_H) are of particular importance (Gutjahr et al., 2016).

In order to address those challenges, the prime focus of this study is aimed towards the derivation of (quasi-) daily spatial thin-ice thickness distributions, which allows for a pan-Arctic retrieval of associated quantities like polynya area and thermodynamic ice production. We make use of a high-resolution and long-term record of thermal-infrared data from MODIS, as measured ice-surface temperatures can be combined with atmospheric reanalysis data in a 1-D energy balance model (Adams et al., 2013) to obtain ice thicknesses up to 50 cm (Sect. 3.1). Based on these daily distributions and taking into account a necessary compensation for inherent cloud- and data gaps (Sect. 3.2), the amount of new sea-ice formation can be determined (Sect. 3.3). In Sect. 4, our achieved results will be presented and discussed, before closing this paper with final conclusions and prospects for further investigations. In recent studies using the same methodology based on MODIS data, we focused on the ~~NOW polynya (Preußer et al., 2015a) and the~~ Storfjorden polynya (Preußer et al., 2015b) ~~. In the present study we have~~ and NOW polynya (Preußer et al., 2015a). The present study has a strong focus on the Laptev Sea region ~~, which is~~ due to significant changes over the last decade (Sect. 4.2) as well as its role as a central component of the ~~transpolar drift system and showed significant changes in the last decade~~Transpolar Drift, a large-scale drift system where ice from the Siberian coastal regions is advected across the Arctic Ocean and through Fram Strait.

2 Data

2.1 MODIS ice-surface temperatures

The MOD/MYD29 Collection 5 sea-ice product (Hall et al., 2004; Riggs et al., 2006) is used to derive thin-ice thickness (TIT) from MODIS satellite data. It features swath data of ice-surface temperatures (ISTs) from both MODIS instruments on board the Terra and Aqua polar-orbiting satellite platforms. All swath data offer a spatial resolution of 1x1 km^2 at nadir and include a basic cloud-screening procedure using the MODIS cloud mask (~~MOD35~~MOD/MYD35; Ackerman et al. (2010)). In general, the accuracy of the MOD/MYD29 ISTs is given with 1–3 K (Hall et al., 2004). All IST swaths covering the Arctic Ocean and adjacent seas were extracted using meta data information for each MODIS swath. Subsequently, single swaths are mapped onto a common equirectangular (reference-) grid covering all areas north of 68° N , with the output resolution set at 2 km in order to account for the decreasing spatial resolution of the MODIS sensor off-nadir. For our analysis between 2002/2003 and 2014/2015 (November to March), we used a total of 143,000 MODIS swaths for the complete Arctic domain, averaging at 73 scenes per day. The average amount of MODIS scenes per day and polynya region is additionally listed in Tab. 1.

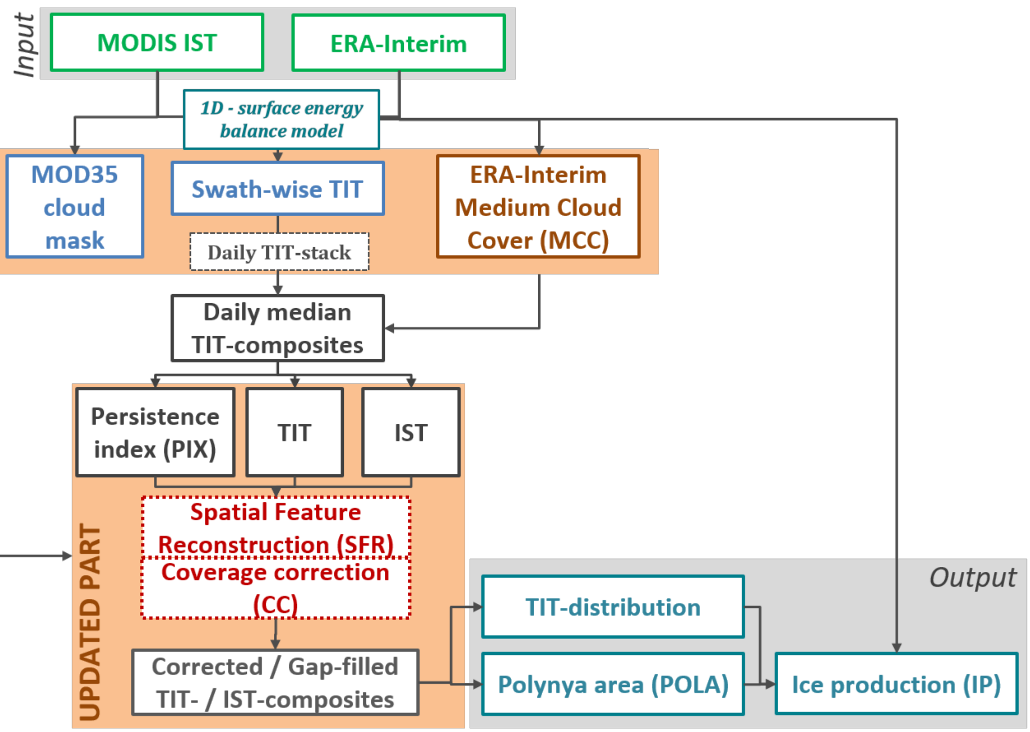

Figure 2. Schematic overview on the current version of the MODIS thin-ice thickness (TIT) retrieval scheme, based on Paul et al. (2015b) and Preußer et al. (2015a). The most recent updates are highlighted in orange and are mainly aimed towards an additional cloud-cover treatment. Besides indicated abbreviations, 'IST' denotes to ice surface temperature.

2.2 ERA-Interim atmospheric reanalysis data

In order to provide the necessary atmospheric input for the applied surface energy balance model, the following variables from the European Center for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis product (Dee et al., 2011) are used: 2m-temperature, 2m-dew point temperature, 10m-wind speed and mean sea-level pressure. As the use of the MOD35 cloud mask during nighttime often inhibits misclassifications and ambiguities from undetected clouds and sea smoke, we additionally utilize ERA-Interim medium cloud cover (MCC) information. The study of Liu and Key (2014) demonstrated that the ERA-Interim MCC fields correspond closely to the MODIS derived cloud patterns throughout the seasons and can therefore be used as an additional quality control during the TIT retrieval. The temporal resolution of all variables is 6 h, so that each single MODIS swath can be linked to the closest time step of the atmospheric fields from ERA-Interim for the calculation of thin-ice thickness~~.~~, with the overall average time difference being 90 ± 52 minutes (max. 180 minutes). The data set is provided by ECMWF at a spatial resolution of 0.75° (approx. 80 km). All ERA-Interim data fields are linearly interpolated and projected on the common reference grid in order to match the higher spatial resolution of MODIS data.

3 Methodology

3.1 MODIS thin-ice thickness retrieval using a surface energy balance model

We derive daily TIT distributions up to 50 cm by using an approach that follows the work of Yu and Rothrock (1996), Yu and Lindsay (2003) and Drucker et al. (2003). The core of this approach is an one-dimensional energy balance model, in which ice surface temperature (IST) and the thin-ice thickness are related to atmospheric radiation fluxes and turbulent heat fluxes. The original method of Yu and Rothrock (1996) was first improved and modified by Willmes et al. (2010) and Adams et al. (2013)~~,~~ ~~while~~. More recently, the latest modifications of the algorithm are described in detail in Preußer et al. (2015b, a) and Paul et al. (2015b), together with comprehensive information on applied parametrization schemes that are used to calculate atmospheric radiation fluxes and turbulent heat fluxes. A complete overview on the currently used data-processing chain is given in Fig. 2.

There are certain limitations and simplifications attached to this procedure to derive TIT. First, it is only applicable to clear sky conditions, as clouds and sea smoke would strongly alter the recorded IST (Riggs et al., 2006). Second, we only use nighttime scenes to avoid potential ambiguities from incident short-wave radiation (Yu and Lindsay, 2003; Adams et al., 2013). Furthermore, newly formed ice is assumed to be free of snow and the temperature profile between the surface (IST) and the lower boundary of the ice (constant; freezing point of sea water) is linear. Consequently and following this assumption, the approach does not explicitly discriminate between different ice types within a polynya, as TIT are solely derived from calculating the heat conduction in/through the ice (aside from subsequent gap-filling; see Sect. 3.2).

The study of Adams et al. (2013) presented a sensitivity analysis of the TIT retrieval, which revealed average uncertainties of $\pm$ 1.0 cm, $\pm$ 2.1 cm and $\pm$ 5.3 cm for TIT classes 0–5 cm, 5–10 cm and 10–20 cm, respectively. Between 20–50 cm, the uncertainty increases considerably. Therefore, we constrain our analysis accordingly as a thickness range of TIT ≤ 0.2 m is widely regarded as a threshold for polynya areas and for estimates of thermodynamic ice production in polynyas (Yu and Rothrock, 1996; Adams et al., 2013; Haid et al., 2015).

3.2 Calculation of daily TIT composites and correction of cloud- and data gaps

Because of the restriction to nighttime scenes, a less frequent ~~IST~~ MODIS coverage is present in the beginning (November) and at the end (March) of each winter-season. In order to increase the ~~IST~~ MODIS coverage for all considered areas (Fig. 1), we derive daily composites of IST and TIT from the total number of available MODIS swaths covering the Arctic domain on a given day (compare Sect. 2.1). Following the procedure described in Sect. 3.1, the TIT is first calculated from each single swath on its own. Subsequently, the daily median TIT per pixel is calculated and stored alongside its corresponding IST value and daily averaged energy-balance components.

As described in Sect. 2.2, we additionally make use of ERA-Interim MCC fields as an indicator for potential cloud-coverage during the generation of daily TIT composites. Previous studies showed that a threshold of 75 % cloud-cover in the MCC-fields is quite effective in identifying and filtering/removing potentially cloud-affected areas (Paul et al., 2015b; Preußer et al., 2015a). The combined MODIS and ERA-Interim cloud information allows for the assignment of four different quality-classes for each pixel in the daily composites: (1) confident clear-sky pixels ('ccs'; clear-sky MODIS and ERA-Interim), (2) mixed-covered

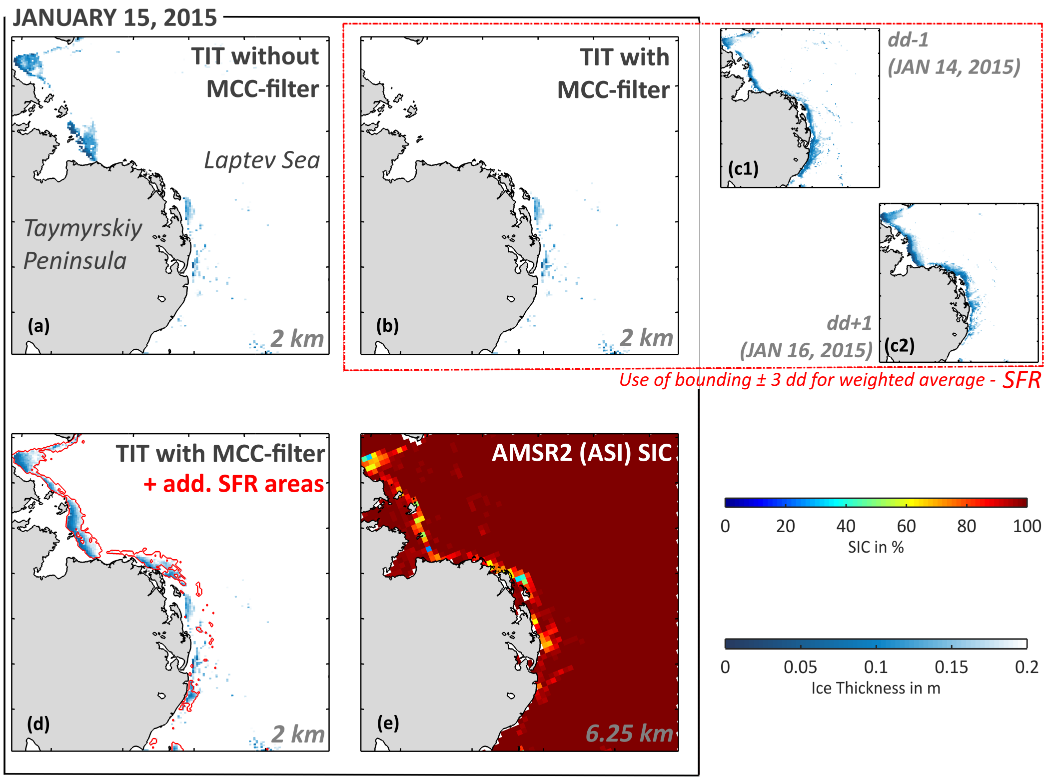

Figure 3. Different stages in the MODIS thin-ice thickness (TIT up to 0.2 m) processing chain for a single exemplary day (January 15, 2015). Sub-panels (a), (b), (c1/c2) and (d) all feature a subset (north-western Laptev Sea) from daily pan-Arctic TIT composites, with (a) showing the daily TIT without 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)~~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.

pixels ('mcp'; ratio between clear-sky input swaths and the total number of input swaths per pixel), (3) definitive cloud-covered pixels ('dcc'; both in MODIS and ERA-Interim) and (4) completely uncovered pixels ('ucp').

Paul et al. (2015b) introduced an additional cloud-cover check based on the daily persistence of each pixel that is classified as thin ice (TIT ≤ 0.2 m). Misclassified thin-ice detections (i.e. clouds) are generally associated with low persistence-values due to their more mobile nature and displacements on sub-daily time scales. In contrast, polynyas show a higher spatial and temporal persistence due to their distinct formation mechanisms (Sect. 1). Leads, however, may be discarded by this criteria, since they generally have a low persistence due to their short lifetime and sea-ice drift caused by wind, ocean currents and tides. Based on these simple but distinct relations, we use a pixel-wise persistence index (PIX), defined as 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.

All derived quality attributes (MCC-filter, cloud-cover information, PIX) are utilized in the Spatial Feature Reconstruction (SFR) algorithm (Paul et al., 2015a), which was recently successfully applied on a regional scale in both the Antarctic and Arctic to increase the information about otherwise cloud-covered areas (Paul et al., 2015b; Preußer et al., 2015a). The basic principle is that cloud-induced gaps in the daily TIT composites are compared with the TIT of the surrounding six days. In doing so, a probability of thin-ice occurrence is derived using a weighted composite of the ~~surrounding days . The~~ days surrounding an initial day of interest (DOI). As in previous studies, we applied the following set of weights: $w_3 = 0.02$ (DOI $\pm$ 3), $w_2 = 0.16$ (DOI $\pm$ 2) and $w_1 = 0.32$ (DOI $\pm$ 1). The probability threshold remains fixed at *th* = 0.34 and needs to be surpassed in order to assign 'new' probable polynya pixels. Paul et al. (2015a) showed that this combination is less restrictive in terms of missing MODIS coverage in close proximity of the initial DOI. The procedure is applied on all areas with identified low-quality data (low persistence, cloud-covered), so that indicated gaps can be filled with new information on potential thin-ice occurrences. For these areas, new TIT and IST values are pixel-wise allocated using a weighted average of the surrounding six days (Paul et al., 2015b; Preußer et al., 2015a). Table ~~1~~ 1 gives an overview on the achieved ~~IST and TIT~~ MODIS coverage before and after application of the SFR algorithm. On a pan-Arctic level, the average (2002/2003 to 2014/2015) MODIS coverage is increased from around ~~0.76 (ccs~~ 0.75 (confident clear-sky and high-quality ~~mcp) to 0.94~~ mixed-cover pixels featuring clear-sky conditions in more than 50% of all daily input swaths) to 0.93 (including SFR areas), with certain regions performing better (e.g. CBP, LAP, NEW, SZN) and some other regions noticeably worse (CHU, GLN, WNZ).

~~Case~~ A total of 66 case studies in the Brunt Ice Shelf region of Antarctica demonstrated the generally good performance of the algorithm ~~by~~ in comparison to more intelligible approaches by realistically reproducing artificially cloud covered thin-ice areas with an average spatial correlation of 0.83 ~~(Paul et al., 2015a).~~ and a RMSE of 1904 km^2 (Paul et al., 2015a). When compared to reference runs based on equally-weighted and in some cases shorter time intervals, the SFR procedure featuring above listed weights w_3 to w_1 (DOI $\pm$ 3 days) yielded superior results both in spatial correlation and reconstructed POLA-values, regardless of the temporal polynya evolution (e.g. opening/closing events). As an additional example from the Arctic (north-western Laptev Sea), Fig. 3 visualizes the basic principle of the SFR algorithm, together with a qualitative comparison of Advanced Microwave Scanning Radiometer 2 (AMSR2) sea-ice concentration (SIC) data ~~(Spreen et al., 2008)~~(Spreen et al., 2008; Beitsch et al., 2014). As a first step, the MCC-filter eliminates potentially cloud-influenced areas which are in this case located north of the Taymyr

Table 1. Areal extents (i.e. total ocean area) of all applied polynya masks in km^2. Further, the interannual average amount of MODIS swaths that could be used for calculating daily composites in a given region is indicated, together with the interannual average daily MODIS coverage (decimal cover fraction ranging from 0 to 1 with their respective standard deviations) before (COV2) and after (COV4) application of the Spatial Feature Reconstruction (SFR) for each polynya region from 2002/2003 to 2014/2015 (November to March). The abbreviation 'ccs' denotes to confident clear-sky coverage, while 'HQ mcp' are high-quality mixed-cover pixels where either MODIS or ERA-Interim medium cloud cover feature cloud signals in the daily composites. In addition, the average thin-ice thickness (TIT, in cm) inside each polynya region (for all TIT $\leq$ 0.2 m) is given together with its standard deviation. An overview on all applied predefined polynya masks is given in Fig. 1.

Region	*Total ocean area* (10^3km^2)	*Avg. number of MODIS swaths* (d^{-1})	*COV2* (ccs, HQ mcp)	*COV4* (ccs, HQ mcp, SFR)	*Avg. TIT* (cm)
Beaufort Shelf (BSH)	91.6	6	0.76 ± 0.03	0.97 ± 0.02	14.0 ± 0.5
Canadian Arctic Archipelago (CAA)	719.6	14	0.82 ± 0.03	0.96 ± 0.01	13.7 ± 0.2
Cape Bathurst (CBP)	311.6	10	0.81 ± 0.03	0.98 ± 0.01	14.1 ± 0.4
Chukchi Sea (CHU)	286.0	5	0.55 ± 0.04	0.79 ± 0.03	12.8 ± 0.4
East Siberian Fast-Ice (ESF)	110.1	8	0.77 ± 0.04	0.96 ± 0.01	14.3 ± 0.3
East Siberian Sea (ESS)	904.1	9	0.70 ± 0.03	0.92 ± 0.01	14.0 ± 0.3
Franz-Josef-Land (FJL)	140.1	13	0.79 ± 0.04	0.97 ± 0.02	11.7 ± 0.8
Greenland North (GLN)	33.8	13	0.67 ± 0.04	0.81 ± 0.04	16.3 ± 0.4
Kara Sea (KAR)	725.5	14	0.75 ± 0.04	0.95 ± 0.02	11.7 ± 1.1
Laptev Sea (LAP)	281.1	12	0.80 ± 0.03	0.98 ± 0.01	13.5 ± 0.5
North East Water (NEW)	112.0	13	0.81 ± 0.03	0.98 ± 0.01	13.7 ± 0.5
North Water (NOW)	110.1	13	0.85 ± 0.04	0.97 ± 0.01	11.5 ± 0.5
Nares Strait / Lincoln Sea (NSL)	55.5	14	0.83 ± 0.03	0.96 ± 0.01	13.6 ± 1.0
Storfjorden (STO)	11.7	9	0.75 ± 0.04	0.95 ± 0.03	9.2 ± 1.7
Svalbard Archipelago (SVA+STO)	204.3	13	0.68 ± 0.06	0.90 ± 0.04	7.2 ± 1.0
Severnaya Zemlya North (SZN)	65.3	12	0.80 ± 0.04	0.98 ± 0.01	13.5 ± 0.6
Western Novaya Zemlya (WNZ)	211.6	12	0.60 ± 0.07	0.83 ± 0.04	6.8 ± 1.6
Total	~~4159.6~~ 436.2	~~0.76~~ 73[a]	0.75 ± 0.04	~~0.94~~ 0.93 ± 0.02	~~13.1~~ 12.7 ± 0.6

a Not the sum of all regions, as single MODIS swaths may cover multiple regions at the same time.

Peninsula (Laptev Sea, Russia). One could argue that this filtering is a bit harsh, but we choose a more conservative threshold to minimize the risk of 'false' thin-ice pixels. Afterwards, the SFR algorithm is applied and a new gap-filled TIT composite (Fig. 3 (d)) is produced. In this particular example from January 15, 2015, the reconstructed TIT distribution compares well with locations of lower SIC from AMSR2 (Fig. 3 (e)) while maintaining the increased spatial detail at the same time. ~~We~~ Based on this example and successful applications in previous works by the authors (Paul et al., 2015a, b; Preußer et al., 2015a), we conclude that the applied schemes to compensate and correct cloud-effects work reasonably well on a pan-Arctic scale and allow for a fair comparison to other commonly used remote sensing approaches to infer polynya characteristics, with limitations regarding the reconstruction of leads.

3.3 Derivation of ice production and polynya area

Ice production rates are derived by assuming that the entire heat loss at the ice surface to the overlying atmosphere contributes to new ice formation (Tamura et al., 2007, 2008; Willmes et al., 2011). Components for the following equation (Eq. 1) can be taken from calculated and gap-filled daily MODIS composites.

$$\frac{\partial h}{\partial t} = \frac{-\bar{Q}_{ice}}{\rho_{ice} * L_f} \tag{1}$$

Therein, $\frac{\partial h}{\partial t}$ denotes to the ice production rate, $\bar{Q}_{ice}$ is the daily mean conductive heat flux through the ice, ρ_{ice} is the density of the ice (ρ_{ice} = 910 $\mathrm{kg/m^3}$; Timco and Frederking (1996)) and L_f is the latent heat of fusion of sea ice (L_f = 0.334 $\mathrm{MJ/kg}$; Tamura and Ohshima (2011)). Concerning L_f, Tamura and Ohshima (2011) noted that an accurate value for areas of high ice production is not known so far. Following the work of Martin (1981), Tamura and Ohshima (2011) argued that frazil ice consists of freshwater ice crystals enclosed with a thin saline layer and that frazil ice production rates are of similar magnitudes as freshwater ice production rates. Consequently, we also use fixed values for ρ_{ice} and L_f in order to ensure comparability with earlier studies focusing on sea-ice production in (Arctic) polynyas (e.g. Willmes et al., 2011; Tamura and Ohshima, 2011; Iwamoto et al., 2014). However, this simplification may introduce an additional error source in our estimates due to spatially and temporally varying conditions for ice formation. Note that the negative sign in Eq. 1 implies that the atmospheric heat flux is positive when the surface gains energy, and at the same time it assures that ice production only takes place when there is a net energy loss from the surface. According to the surface energy balance, the heat flux $\bar{Q}_{ice}$ is equal to the total atmospheric heat loss (sum of net radiation, turbulent latent and sensible heat flux). We do not consider an ocean heat flux, although it might potentially reduce thermodynamic ice growth in certain areas of the Chukchi Sea (Hirano et al., 2016), the Canadian Arctic Archipelago ~~(Hannah et al., 2009)~~ (Hannah et al., 2009; Melling et al., 2015) and northern Baffin Bay ~~(Steffen, 1985)~~(e.g. Steffen, 1985; Yao and Tang, 2003) by as much as 23-27% in case of the NOW polynya (Tamura and Ohshima, 2011; Iwamoto et al., 2014). The volume ice production rate $\frac{\partial V}{\partial t}$ (*IP*) is calculated by multiplying $\frac{\partial h}{\partial t}$ with the areal extent of each pixel in the regarded region. Ice production rates are calculated for each pixel with a TIT ≤ 0.2 m and afterwards extrapolated to daily rates. However, it has to be noted that daily IP rates ~~may~~ inhibit a positive bias due to the exclusive use of both nighttime and clear-sky MODIS scenes. The former is mainly of concern during the late autumn / early spring period when polar night conditions are absent, while the latter circumstance is unavoidable throughout each winter when relying on optical and infrared remote sensing data. Since low-level clouds reduce the net radiative loss by about 50 $\mathrm{W/m^2}$ 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. 1) 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 $\mathrm{W/m^2}$, which corresponds to less than 0.4 m IP per winter.

The daily polynya area (POLA, in $\mathrm{km^2}$) in each polynya mask (Fig. 1) is defined as the accumulated total area of all thin-ice pixels with a TIT ≤ 0.2 m. Remaining MODIS coverage gaps after the application of the SFR approach (e.g. prolonged periods of stable cloud cover, i.e. no coverage on more than 3 consecutive days) are handled by additionally applying an extrapolation approach (coverage-correction; CC) on calculated POLA and IP estimates, which yields daily values with an error-margin of 5 to 6% ~~(Preußer et al., 2015b, a). If the daily coverage including the additional SFR areas (~~(Preußer et al., 2015b). In case of very persistent cloud cover inside the respective reference areas and a resulting daily MODIS coverage below 50% (i.e. COV4 ~~) falls below~~ $<$ 0.5), both daily POLA and IP ~~inside the respective reference areas~~ are linearly interpolated from bounding days. The complete period from November to March each winter is considered for the calculation of POLA / IP, which implies that the here derived values are potentially influenced by shifts in the timing of freeze onset during the early freezing season (November / December).

For topographically complex regions like Greenland and Arctic fjords, recent studies revealed shortcomings of the coarse-resolution ERA-Interim data regarding the representation of mesoscale spatial features in the wind field, such as tip-jets, channeling effects or other topography-induced phenomena related to locally increased wind speeds (e.g. Moore et al., 2016). Thus, ERA-Interim shows a tendency to underestimate peak wind speeds (Moore et al., 2016) which might in some cases induce a negative bias (lower heat fluxes/ smaller POLA / less IP) in regions where polynya formation is strongly influenced by the local topography (e.g. CAA, NOW, NEW, SZN). In our study, the usage of ERA-Interim is motivated by ensuring comparability to similar studies (e.g. Iwamoto et al., 2014) as well as the constraint that higher-resolution atmospheric data sets such as the Arctic System Reanalysis (ASRv1 – 30km; Bromwich et al., 2015) are currently not available for the complete time period from 2002 to 2015.

4 Results and Discussion

4.1 Thin-ice dynamics, polynya area and thermodynamic ice production in the Arctic for 2002/2003–2014/2015

Interannual average values for TIT ≤ 0.2 m are listed in ~~Table 1~~ Tab. 1 for each polynya region. They range between ~~7.2~~ 6.8 cm (~~SVA~~WNZ) and 16.3 cm (GLN), with an overall average of about ~~13.1~~ 12.7 $\pm$ 0.6 cm. The underlying long-term time series of average wintertime TIT within each polynya (not shown) reveal a tendency towards decreasing thin-ice thicknesses in almost every region (e.g. up to 2.5 cm per decade in the ~~Kara Sea~~Storfjorden polynya), with the only exceptions being the CAA, GLN and NEW.

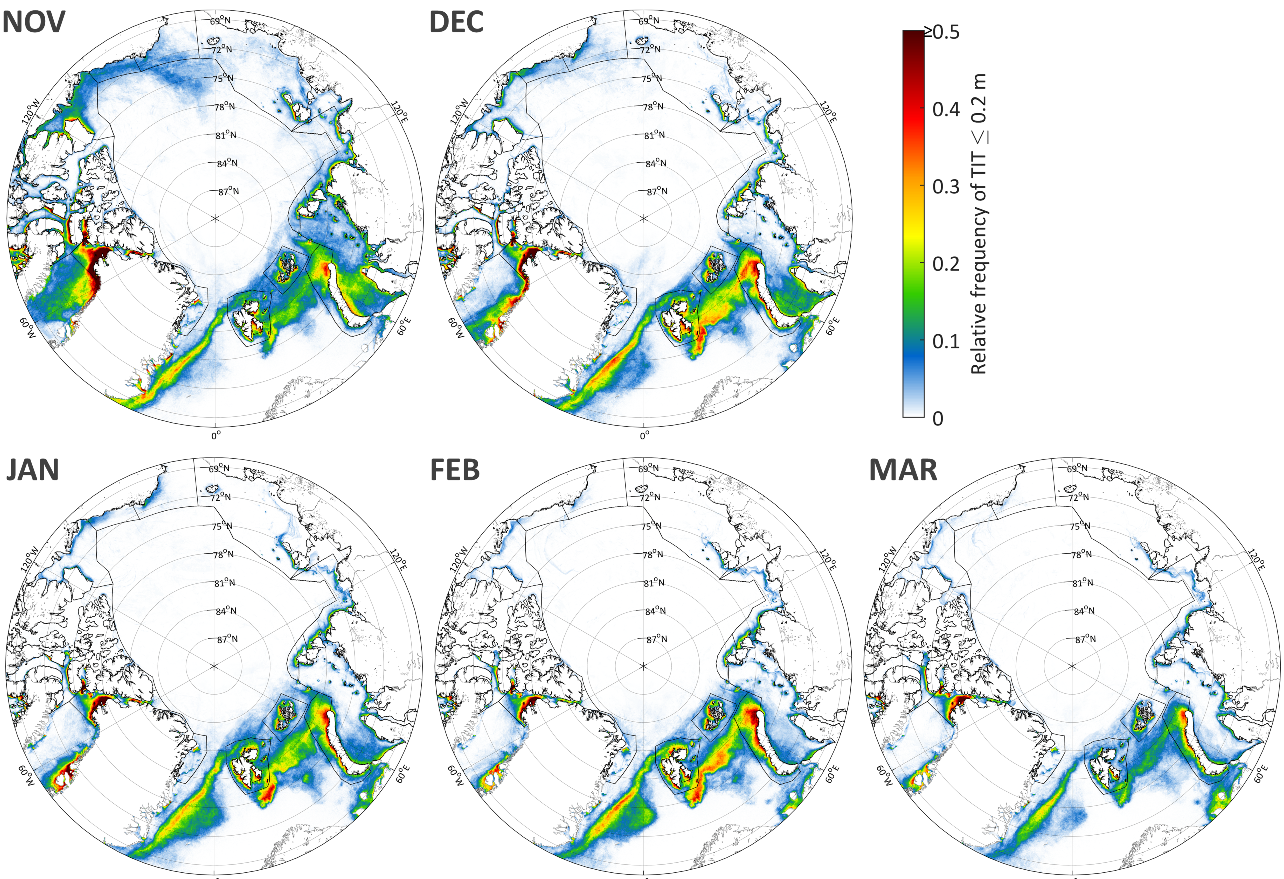

Figure 4. Average wintertime (November to March) frequencies of TIT ≤ 0.2 m in the Arctic between winters 2002/2003 and 2014/2015. Note that only thin-ice areas within the margins of a given polynya mask (dashed black lines; compare Fig. 1) are used for further analysis, while all other areas are discarded. Hence, areas with high TIT frequencies in the marginal ice zone (MIZ) around Fram Strait and northern Barents Sea are excluded from further analysis due to potential ambiguities originating from ocean heat fluxes and a high interannual variability of the MIZ in terms of location and extent.

Thin-ice frequencies of larger than 0.5 are primarily found around the Canadian Arctic, first and foremost in the ~~NOW-polynya~~ North Water (NOW) polynya and the eastern CAA (Fig. 4). More specifically, coastal areas around Devon Island and south-eastern Ellesmere Island (Hells Gate / Cardigan Strait) and larger areas at the eastern exits of Lancaster Sound and Jones Sound are well visible and have previously been related to tidal currents and slightly increased ocean heat fluxes (Hannah et al., 2009; Melling et al., 2015). Other areas with similar magnitudes include the Storfjorden polynya and coastal areas (north-)west of Novaya Zemlya. Besides, elongated thin-ice areas along the Siberian shelf (Laptev and Kara Sea; frequencies around 0.05 to 0.35 each month) are well delineated. Locations of frequent thin-ice occurrences in the Kara Sea are in accordance with results from the study of Kern (2008). The northern Barents Sea, Franz-Josef-Land and the Svalbard archipelago ~~/ Storfjorden~~ also feature quite high appearance rates of around 0.1 to 0.3. Contrary to earlier reports (Barber and Massom, 2007), the North-East Water (NEW) polynya in north-eastern Greenland (approx. 81° N, 13° W) neither shows any sign of disappearance, nor is it limited to the spring to late autumn period. With average frequencies of around 0.1 to 0.25 each month in winter, it has more likely to be categorized as a regularly forming polynya. Comparatively low frequencies below 0.15 (especially from January to March) are primarily found in the Beaufort and Chukchi Sea as well as in the East Siberian Sea. Vast fast-ice areas, e.g. along the Siberian coast, can be detected from monthly TIT frequencies, as these areas usually appear at fixed locations attached to the shore and TIT frequencies tend towards zero as the ice quickly thickens by congelation ice growth. Hence, our 13-year record of monthly TIT-occurrence rates offers the potential to further develop ~~and optimize~~ optimized automatic methods for a regular Arctic-wide mapping of monthly fast-ice extents and could thereby compliment currently existing approaches from earlier studies (e.g. Yu et al., 2014; Mahoney et al., 2014; Selyuzhenok et al., 2015).

Compared to the study of Willmes and Heinemann (2016), leads are only weakly visible in this long-term averages (frequencies below 0.05–0.1). In Fig. 4, leads are mainly located in the area of the Beaufort Sea and north of Greenland (shear zones) ~~. Further, they appear along the Transpolar Drift, a large-scale drift system where ice from the Siberian coastal regions is advected across the Arctic Ocean and through Fram Strait.~~ which can be mainly attributed to their relatively high spatial and temporal persistence. Frequent lead occurrences in e.g. the East-Siberian Sea found by Willmes and Heinemann (2016) are not reflected in our study. In some regions, however, the influence of (shelf-) bathymetry and associated ocean currents on the spatial distribution of polynya and lead occurrences is also visible in our here derived TIT frequencies (e.g. eastern exit ~~Vilkitzky~~ Vilkitsky Strait, Hanna Shoal / northern Chukchi Shelf, northern ESS).

In Fig. 5 and Fig. 6, the interannual variability of the average POLA (in km^2) and accumulated IP (in km^3) are presented for all examined polynya regions, respectively. In both figures, the difference between the beginning (November to December) and end (January to March) of the freezing (winter) period is additionally highlighted. Concerning POLA, it shows that the largest average wintertime extents are found in the NOW, WNZ and KAR areas. The study of Preußer et al. (2015a) demonstrated that ~~these~~ the large POLA values in the NOW-region are part of a (non-significant) long-term increase of average polynya extents between 1978 and 2015. ~~As mentioned above~~In case of polynyas in proximity of Novaya Zemlya, the here derived average wintertime value for POLA of around 42 x 10^3 km^2 is fairly close to the respective value by Iwamoto et al. (2014) (49 x 10^3 km^2), despite the circumstances that their study covers an extended winter period from September to May and features a different mask area, which stretches over some part of the western Kara Sea. As mentioned earlier, Kern (2008) presented

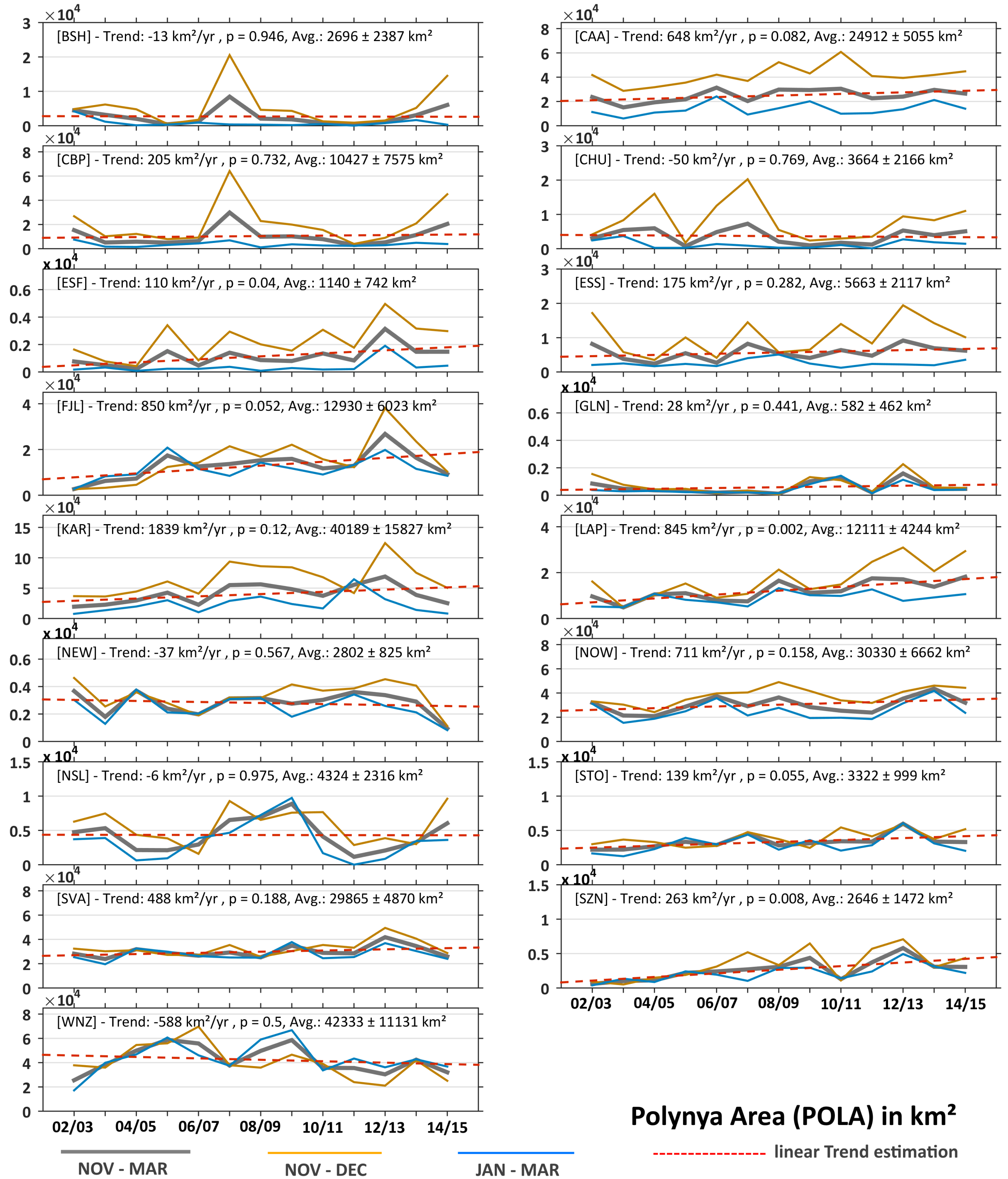

Figure 5. Regional time series of the annual average polynya area (POLA; TIT ≤ 0.2 m) in km^2 for 2002/2003 to 2014/2015, together with a seasonal comparison (November to December vs. January to March) and a linear trend estimation. The estimated linear trend (in km^2/yr), its p-value and the interannual average POLA (in km^2) are additionally listed in each sub-panel. Please note the varying scale on each y-axis.

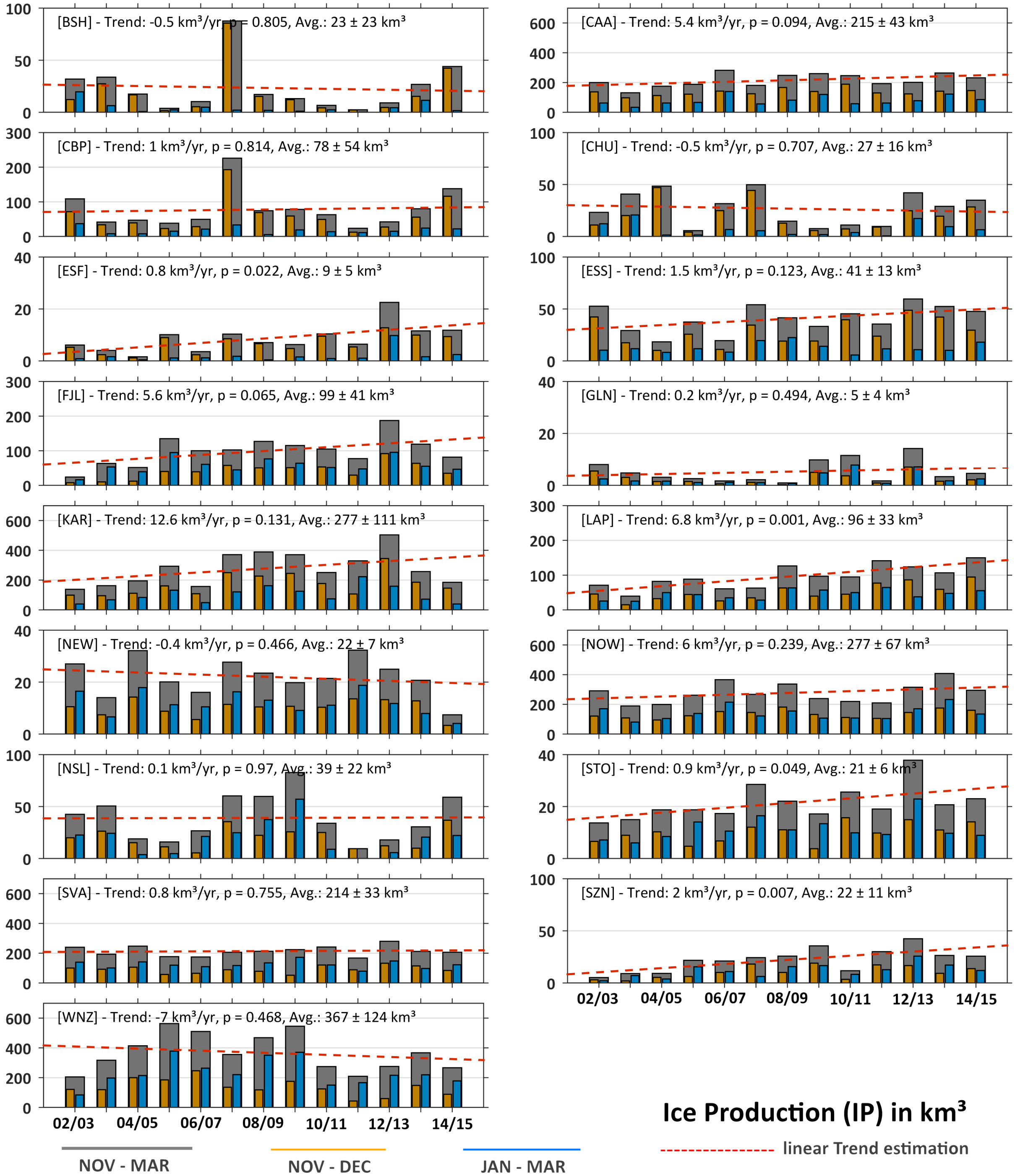

Figure 6. Regional time series of the annually accumulated ice production (IP) in km^3 for 2002/2003 to 2014/2015, together with a seasonal comparison (November to December vs. January to March) and a linear trend estimation. The estimated linear trend (in km^3/yr), its p-value and the interannual average IP (in km^3) are additionally listed in each sub-panel. Please note the varying scale on each y-axis.

Table 2. Average ~~accumulated ice production in per winter and average~~ polynya area (POLA) in km^2 ~~) for~~ in each polynya region ~~from~~ between 2002/2003 ~~to~~ and 2014/2015 (SFR cloud-cover correction applied). Besides being based on the available winter period from November to March, ~~with SFR cloud-cover correction~~it is further separated between the early freezing season (November to December) and the late freezing season (January to March). All values are derived from daily MODIS TIT composites after application of the predefined polynya masks (Fig. 1). Trends ~~of IP and $POLA$~~ are additionally given, where underlined, bold and bold italic numbers denote statistical significance (two-sided t-test) at the 90, 95 and 99 % level, respectively.

	November to March		November to December		January to March	
Region	*Avg. POLA* ($10^3\mathrm{km}^2$)	*Trend POLA* ($\mathrm{km}^2/\mathrm{yr}$)	*Avg. POLA* ($10^3\mathrm{km}^2$)	*Trend POLA* ($\mathrm{km}^2/\mathrm{yr}$)	*Avg. POLA* ($10^3\mathrm{km}^2$)	*Trend POLA* ($\mathrm{km}^2/\mathrm{yr}$)
Beaufort Shelf (BSH)	2.7 ± 2.4	-13	5.5 ± 5.8	132	0.8 ± 1.1	-111
Canadian Arctic Archipelago (CAA)	24.9 ± 5.1	648	41.5 ± 8.3	958	13.7 ± 5.2	438
Cape Bathurst (CBP)	10.4 ± 7.6	205	20.6 ± 16.9	581	3.6 ± 2.0	-49
Chukchi Sea (CHU)	3.7 ± 2.2	-50	8.2 ± 5.7	-95	1.3 ± 1.1	-37
East Siberian Fast-Ice (ESF)	1.1 ± 0.7	**110**	2.3 ± 1.3	**200**	0.4 ± 0.5	48
East Siberian Sea (ESS)	5.7 ± 2.1	175	10.3 ± 5.2	385	2.5 ± 1.1	33
Franz-Josef-Land (FJL)	12.9 ± 6.0	850	15.2 ± 9.7	**1565**	11.5 ± 4.9	380
Greenland North (GLN)	0.6 ± 0.5	28	0.8 ± 0.6	14	0.5 ± 0.4	37
Kara Sea (KAR)	40.2 ± 15.8	1839	64.9 ± 26.8	3209	23.5 ± 15.5	904
Laptev Sea (LAP)	12.1 ± 4.2	***845***	17.0 ± 8.0	***1559***	8.8 ± 2.7	362
North East Water (NEW)	2.8 ± 0.8	-37	3.3 ± 1.0	-10	2.4 ± 0.9	-55
North Water (NOW)	30.3 ± 6.7	711	37.7 ± 7.1	**1072**	25.4 ± 7.8	464
Nares Strait / Lincoln Sea (NSL)	4.3 ± 2.3	-6	5.7 ± 2.6	18	3.4 ± 2.8	-22
Storfjorden (STO)	3.3 ± 1.0	139	3.9 ± 1.1	**175**	2.9 ± 1.3	115
Svalbard Archipelago (SVA+STO)	29.9 ± 4.9	488	32.8 ± 6.5	732	27.9 ± 5.3	327
Severnaya Zemlya North (SZN)	2.6 ± 1.5	***263***	3.4 ± 2.2	**353**	2.1 ± 1.2	***203***
Western Novaya Zemlya (WNZ)	42.3 ± 11.1	-588	40.4 ± 13.8	-1806	43.6 ± 13.0	230
Total	226.6 ± 36.1	**5468**	309.4 ± 62.6	8864	171.3 ± 32.6	3151

POLA values for the Kara Sea. His retrievals are based on approximately the same reference area (Fig. 1), which in this case allows for a fair comparison to the here presented numbers. It shows that the average POLA in the late freezing season reveals similar magnitudes in recent years. During the period from 1979 and 2004, the average POLA (in Kern (2008): January to April) ranged between 1 to 5 x 10^4 km^2 (except for 1995: around 6 x 10^4 km^2), which is close to the range of our here presented results for January to March (Fig.5; Tab. 2). Although the estimated positive trend in POLA remains non-significant for the Kara Sea as in Kern (2008), the magnitude of the trend in the late freezing period (January to March; around 9000 km^2/decade) seems to have increased from 2400 km^2/decade (Kern, 2008) to around 9000 km^2/decade over the last 13 years. The interannual POLA variability in all regions is generally pronounced, but ~~increases~~ is especially large for smaller polynyas / thin-ice regions such as the NSL, NEW and ESS. Concerning seasonal differences, it appears that some regions (e.g. NEW, GLN, LAP, SZN) have the tendency towards larger thin-ice areas during the freeze-up period since approximately 2006/2007 to 2007/2008. About 8 to 10 polynya regions show distinct positive trends of up to 18,390 km^2 per decade (KAR), with only the

Table 3. Average accumulated ice production (IP) in km^3 in each polynya region between 2002/2003 and 2014/2015 (SFR cloud-cover correction applied). Besides being based on the available winter period from November to March, it is further separated between the early freezing season (November to December) and the late freezing season (January to March). All values are derived from daily MODIS TIT composites after application of the predefined polynya masks (Fig. 1). Trends are additionally given, where underlined, bold and bold italic numbers denote statistical significance (two-sided t-test) at the 90, 95 and 99 % level, respectively.

	November to March			November to December			January to March	
Region	Acc. IP (km^3)	Trend IP ($\mathrm{km}^3/\mathrm{yr}$)	~~$POLA$~~	Acc. IP (km^3)	Trend ~~$POLA$~~ IP ($\mathrm{km}^3/\mathrm{yr}$)		Acc. IP (km^3)	Trend IP (~~/yr~~ $\mathrm{km}^3/\mathrm{yr}$)
Beaufort Shelf (BSH)	23 ± 23	-0.5	~~2.7~~	19 ± ~~2.4~~ 23	~~-12.8~~ 0.0		5 ± 5	-0.4
Canadian Arctic Archipelago (CAA)	215 ± 43	5.4	~~24.9~~	136 ± ~~5.1~~ 23	~~648.5~~ 2.5		79 ± 31	2.9
Cape Bathurst (CBP)	78 ± 54	1.0	~~10.4~~	60 ± ~~7.6~~ 48	~~204.9~~ 1.1		18 ± 10	-0.1
Chukchi Sea (CHU)	27 ± 16	-0.5	~~3.7~~	20 ± ~~2.2~~ 14	~~-50.2~~ -0.3		7 ± 6	-0.2
East Siberian Fast-Ice (ESF)	9 ± 5	**0.8**	~~1.1~~	7 ± ~~0.74~~ 3	~~**109.5**~~ **0.6**		2 ± 2	0.3
East Siberian Sea (ESS)	41 ± 13	1.5	~~5.7~~	28 ± ~~2.1~~ 13	~~175.4~~ 1.3		13 ± 5	0.2
Franz-Josef-Land (FJL)	99 ± 41	5.6	~~12.9~~	42 ± ~~6.0~~ 24	~~850.4~~ **4.1**		57 ± 22	1.5
Greenland North (GLN)	5 ± 4	0.2	~~0.6~~	3 ± ~~0.5~~ 2	~~27.8~~ 0.0		3 ± 2	0.2
Kara Sea (KAR)	277 ± 111	12.6	~~40.2~~	174 ± ~~15.8~~ 76	~~1839.2~~ 9.0		104 ± 56	3.6
Laptev Sea (LAP)	96 ± 33	***6.8***	~~12.1~~	51 ± ~~4.2~~ 24	~~***844.8***~~ ***4.8***		45 ± 14	**2.0**
North East Water (NEW)	22 ± 7	-0.4	~~2.8~~	10 ± ~~0.8~~ 3	~~-37.1~~ 0.0		12 ± 4	-0.4
North Water (NOW)	277 ± 67	6.0	~~30.3~~	135 ± ~~6.7~~ 27	~~710.7~~ 3.4		145 ± 45	2.6
Nares Strait / Lincoln Sea (NSL)	39 ± 22	0.1		20 ± 10	0.2	~~4.4~~	20 ± ~~2.3~~ 16	~~4.0~~ -0.1
Storfjorden (STO)	21 ± 6	**0.9**	~~3.3~~	10 ± ~~1.0~~ 4	~~139.4~~ **0.5**		11 ± 4	0.4
Svalbard Archipelago (SVA+STO)	214 ± 33	0.8	~~29.9~~	91 ± ~~4.9~~ 24	~~487.5~~ 1.6		123 ± 24	-0.8
Severnaya Zemlya North (SZN)	22 ± 11	***2.0***	~~2.6~~	10 ± ~~1.5~~ 6	~~***263.0***~~ **0.9**		12 ± 6	**1.1**
Western Novaya Zemlya (WNZ)	367 ± 124	-7.0		136 ± 56	-6.8		231 ± 88	-0.2
Total	~~1444~~ 1811 ± ~~258~~ 293	~~**41.5**~~ 34.5	~~184.3~~	940 ± ~~35.6~~ 178	~~**6055.8**~~ 22.4		871 ± 175	12.1

LAP, ESF and SZN regions being significant (two-sided t-test) with $p \leq 0.05$. Interestingly, sub-regions located in proximity of the Beaufort Gyre (BSH and CBP) indicate very large thin-ice areas between November and December 2007, shortly after the 2nd lowest September sea-ice extent since 1979 (approx. 4.7 million km^2; Parkinson and Comiso (2013)). This did not appear in a similar way in 2012 (record low of approx. 3.4 million km^2). A detailed investigation shows that the freeze-up in the Beaufort Sea area was much slower in 2007 and extended until mid-December, while in 2012 the same area was ice-covered by November 10. The study of Timmermans (2015) linked this significant delay in ice growth to upward mixing processes of ocean heat in the Canada Basin, originating from the release of stored solar heat input following summer 2007. This resulted in large areas with very thin ice (around 170,000 km^2) in November to December and consequently allowed for huge amounts of latent and sensible heat to be released from the ocean, leading to extraordinary high IP values in these areas (Fig. 6).

Regarding IP, many of the above described features are also visible in the regional time series of Fig. 6. Contrary to Tamura and Ohshima (2011), the majority of polynya regions shows overall positive (up to 126 km^3 per decade (KAR)) or no trends in wintertime ice production, and only ~~three~~ four regions indicate a slight, yet insignificant decrease over the last 13 years (BSH, CHU, NEW~~). A complete overview~~ , WNZ). Complete overviews on calculated average POLA and IP values per region, together with their respective trends, ~~is given in Table 2.~~ are given in Tab. 2 and Tab. 3, respectively. These overviews highlight that seasonal differences (November to December vs. January to March) have a huge effect on calculated average values and trends for the complete winter period from November to March. Consequently, the here discussed numbers should be regarded as winter integrals with potentially inherent effects originating from the timing of freeze-up onset. In case of e.g. the Kara Sea, Franz-Josef-Land, the Chukchi Sea, the Canadian Arctic Archipelago and the Storfjorden polynya, large thin-ice areas during the early freezing period in November and December imprint on the total winter averages as well as derived trends of POLA and IP, especially from 2007/2008 onwards. While the majority of polynyas also feature positive trends in the late freezing season from January to March, these trends are for the most part not significant.

~~Average (2002/2003 to 2014/2015) accumulated ice production (per winter) during winter (November to March) in the Arctic, north of 68° N.~~

The average total ice production in Arctic polynyas sums up to ~~1444~~ 1811 $\pm$ ~~258~~ 293 km^3 per winter. Thus, it lies in between previously determined average values of 2940 $\pm$ 373 km^3 (Tamura and Ohshima, 2011; 1992/1993 - 2007/2008) and 1178 $\pm$ 65 km^3 (Iwamoto et al., 2014; 2002/2003 - 2010/2011) per winter. We expect that the MODIS-derived quantities offer a valuable increase in both spatial and quantitative accuracy due to the use of high-resolution and gap-filled daily fields of thin-ice thicknesses. A shortening of the averaging interval to the period 2002/2003 - 2010/2011 (as in Iwamoto et al. (2014), but not accounting for differences in covered winter period) reduces the here derived average total ice production marginally by about 1-2%. In order to assess apparent differences between our here derived data-set and the passive microwave ~~data-set~~ data set by Iwamoto et al. (2014), a more direct comparison based on identical reference areas and ~~periods~~ the same winter period would be necessary.

A spatial overview of the average (2002/2003 to 2014/2015) accumulated ice production per winter (November to March) is presented in Fig. 7. Likewise to Fig. 4, the ~~North Water (NOW)~~ NOW polynya stands out at first glance due to its high average ice production of up to 14 m per winter. However, smaller polynyas in the Canadian Arctic (around Devon Island) feature comparatively high values for ice production. Most other areas in the Arctic produce on average between 1-3 m of ice per winter, with a few noticeable exceptions like Franz Josef Land (about 4-5 m per winter)~~and some~~ , the northern tip of Novaya Zemlya (5-7 m per winter) and some coastal areas in the Kara Sea (1-4 m per winter). While the core areas of high ice production show a high resemblance to Iwamoto et al. (2014) with marginal differences in absolute numbers, MODIS is capable to provide enhanced spatial detail. This is especially valuable concerning the narrow thin-ice areas along the coast and fast-ice edges in the eastern part of the Arctic (Kara Sea, Laptev Sea, East Siberian Sea), as these areas are not resolved by the coarse-resolution passive microwave data (6.25 km; Iwamoto et al., 2014). This striking advantage is also reflected in the comparatively narrow fjords and bays/sounds around Greenland and the Canadian Archipelago, where a high ice production of up to 3 meters per winter is found. While these observations, mostly related to differences in spatial resolution, could explain the above described discrepancy in average accumulated numbers to some extent (compare Preußer et al. (2015a)), the net effect of a lower grid size cannot be quantified here.

Spatial trends between the winter seasons 2002/2003 and 2014/2015 (November to March) can be calculated by applying a linear regression on the annual accumulated IP per pixel. The resulting map is shown in Fig. 8 (a). Besides many inter-

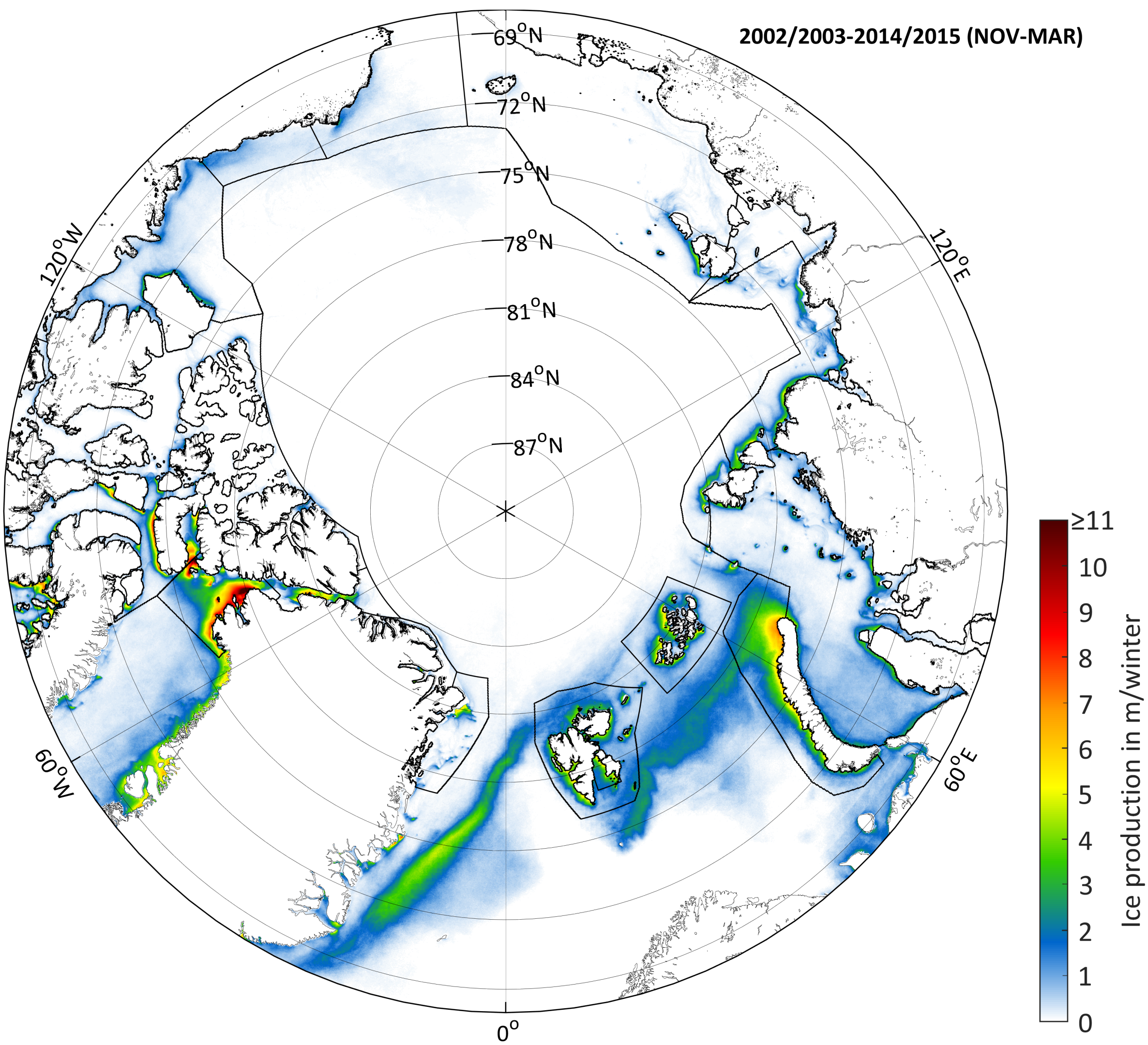

Figure 7. Average (2002/2003 to 2014/2015) accumulated ice production (m per winter) during winter (November to March) in the Arctic, north of 68° N. The margins of applied polynya masks (Fig. 1) are shown in black dashed lines.

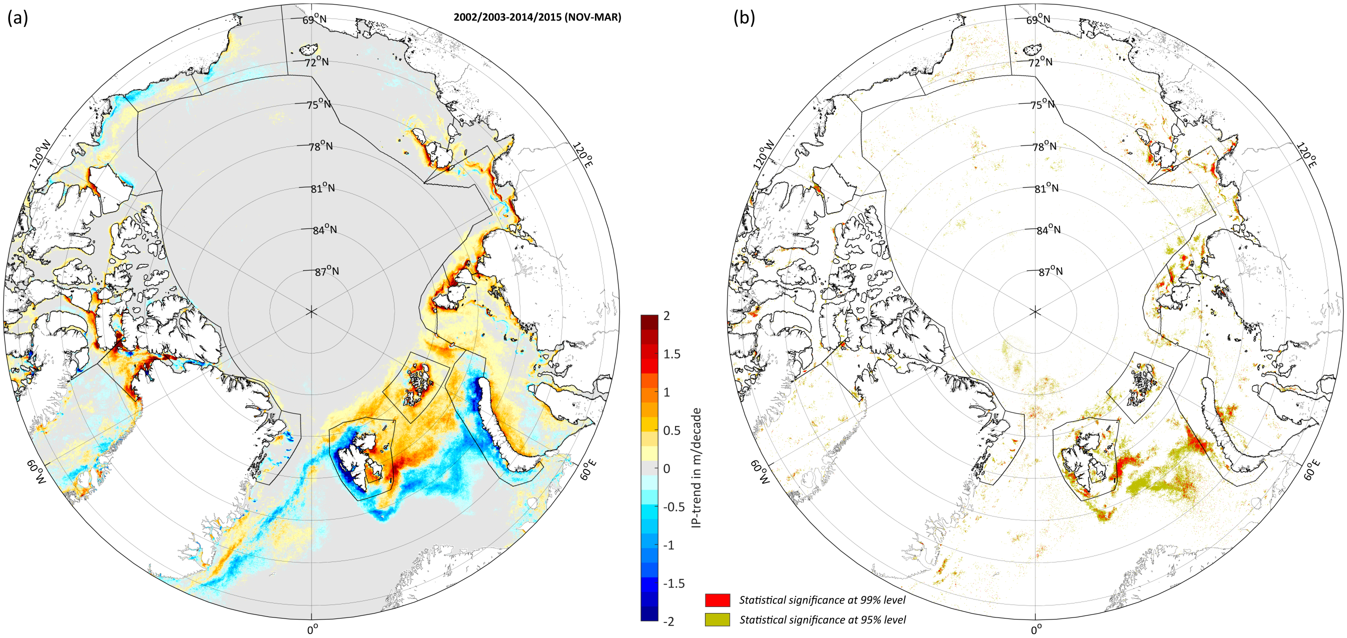

Figure 8. (a) Decadal trends (m per decade) of wintertime (November to March) ice production in the Arctic, north of 68° N. Trends are calculated by applying a linear regression on the annual accumulated IP per pixel for the period 2002/2003 to 2014/2015. Areas with statistical significance (based on a two-sided t-test) at the 95% ~~(dark yellow)~~ and 99% ~~(red)~~ level are depicted in ~~sub-panel~~ (b). The margins of applied polynya masks (Fig. 1) are shown in black dashed lines.

esting small-scale patterns, two main conclusions can be drawn from this spatial overview: (1) While the trends identified in the western Arctic show no consistent pattern, large areas of the eastern Arctic are characterized by significant (~~compare~~ two-sided t-test; significance levels indicated in Fig. 8 (b)) positive trends that can exceed 2 meters per decade and (2) the ~~structure of~~ spatial structure of opposing negative / positive ~~spatial trends along the Siberian coast suggests a tendency towards a diminishing~~ IP-trends along the coasts of the Laptev Sea and Kara Sea suggests a southward shift of the fast-ice edge with potential implications for the fast-ice extent over the recent 13 years. ~~We~~ Decreasing fast-ice extents and durations in the eastern Arctic between 1976 and 2007 were recently described by Yu et al. (2014). In addition, Selyuzhenok et al. (2015) analyzed the fast ice in the south-eastern Laptev Sea in more detail (1999 to 2013). While their study showed that the winter maximum fast-ice extent (March/April) as well as the shape and location of the fast-ice edge did not vary significantly over the regarded time period, they likewise presented an overall decrease in the fast-ice season (-2.8 $\mathrm{d/yr^{-1}}$) due to a later formation and earlier break-up. These described changes regarding the timing of fast-ice formation in early winter could explain the observed structures of positive / negative trends in proximity of fast-ice areas.

In order to put these observations into context, we suppose that this characteristic pattern of opposing trends ~~and the 'retreating-behavior' of fast ice~~ in the western and eastern Arctic as well as the apparently fast-ice related structures in the Laptev Sea and Kara Sea could be connected to ~~a shortened freezing period~~ an overall later appearing fall freeze-up (Markus et al., 2009; Stroeve et al., 2014) in recent years, ~~resulting~~ which itself is thought to result from a complex mixture/interplay of steadily increasing (2m-) air temperatures, distinct large-scale atmospheric patterns (e.g. Rigor et al., 2002) and the overall downward trend of total sea-ice extent and volume in the Arctic. As being one of the main regions with highly pronounced and significant positive trends in both POLA and IP throughout the complete winter period, the following section will take a closer look on polynya dynamics in the Laptev Sea.

4.2 Regional focus - Laptev Sea

One main advantage of the high-resolution MODIS data is the ability to perform detailed investigations on a regional scale across the Arctic. The grid spacing of 2 km allows for the detection of relatively fine and delineated polynya structures and for more accurate statements about areas of high ice production, as it was previously possible.

The Laptev Sea was previously described as a key region to investigate climatic changes in the Arctic shelf seas (ACIA, 2005), as it is one of the major source area for sea ice export into the Transpolar Drift system (Dethleff et al., 1998). As can be seen in Fig. 9, the Laptev Sea is located between the Severnaya Zemlya at the western boundary, the Lena Delta at the southern edge and the New Siberian Islands, which serve as the boundary in the East (approximately 70-80°N, 100-140°E). The water-mass composition in the Laptev Sea is temporarily quite variable, as there is a huge freshwater inflow during the summer and autumn period (around 750 km^3 per year; Rigor and Colony (1997)) and strong ice-formation accompanied with brine rejection in polynyas during winter (Bauch et al., 2012). These processes significantly alter the stratification of the upper ocean layers as well as the salinity levels in the annual cycle. These and other recurring features of the sea ice and ocean environments have recently been illustrated and updated by Janout et al. (2016).

During the freezing period (roughly October to June), fast ice forms along the coastlines of the Laptev Sea, which usually reaches its maximum areal extent by April. The approximate location of the fast-ice edge at the end of March is depicted in Fig. 9. For drifting sea ice, the ~~fast ice~~ fast-ice edge forms an advanced coast line ~~,~~ with heavy ridging occurring along this edge during onshore wind events (Rigor and Colony, 1997). The combination of this fast-ice edge and off-shore components of the mean wind-patterns enable the formation of several flaw-lead polynyas across the Laptev Sea which can reach widths of up to 200 km (Bareiss and Görgen, 2005; Martin and Cavalieri, 1989; Ernsdorf et al., 2011; Adams et al., 2013).

When comparing previous studies dealing with ice production rates in the Laptev Sea (Dethleff et al., 1998; Winsor and Björk, 2000; Dmitrenko et al., 2009; Willmes et al., 2011; Tamura and Ohshima, 2011; Bauer et al., 2013; Iwamoto et al., 2014; Gutjahr et al., 2016), it gets clear that there are large differences depending on the applied methods and various different data-sets. In these studies, values for the accumulated ice production during an average winter season ('extended' winter-period from November to April) are ranging between 55 km^3 (Willmes et al., 2011) for an approach using microwave and thermal infrared remote sensing data in combination with atmospheric reanalysis data, and 258 km^3 (Dethleff et al., 1998), who used a simple relationship between wind direction/speed and polynya area. Estimated average values (September to May) from Tamura and Ohshima (2011) (152 km^3) and Iwamoto et al. (2014) (77 km^3) range in between. Although derived for different time periods and slightly varying reference areas, these large discrepancies highlight the relevance of applying improved and high-resolution approaches to quantify sea-ice production.

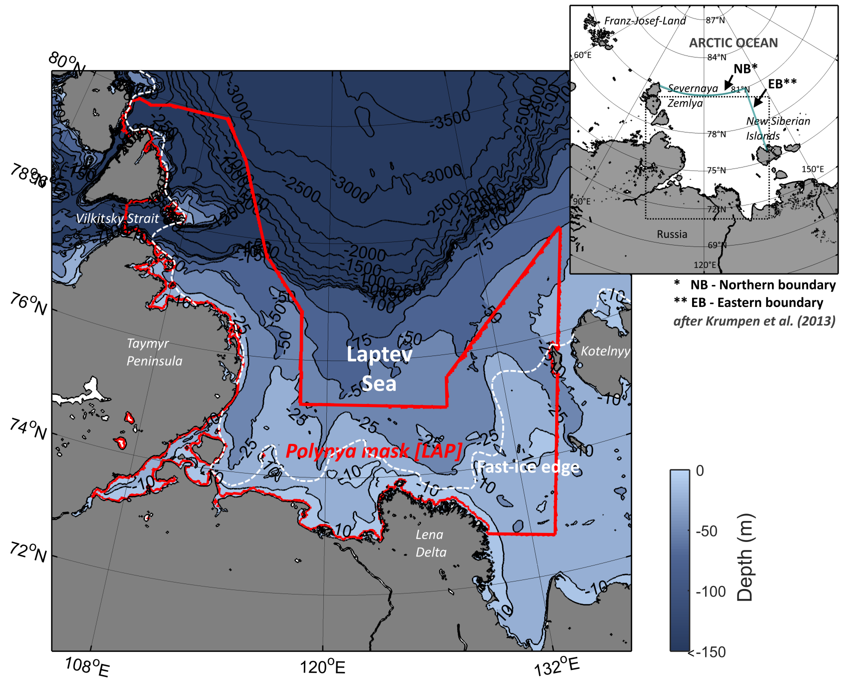

Figure 9. The geographical location of the Laptev Sea in the eastern Arctic. The applied polynya mask is marked in red, enclosing the locations of typical polynya formation along the coast and fast-ice ~~edges~~edge (dashed white line; position derived from long-term thin-ice frequencies in March (Fig. 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 (cyan solid lines). Bathymetric data by Jakobsson et al. (2012) (IBCAO v3.0).

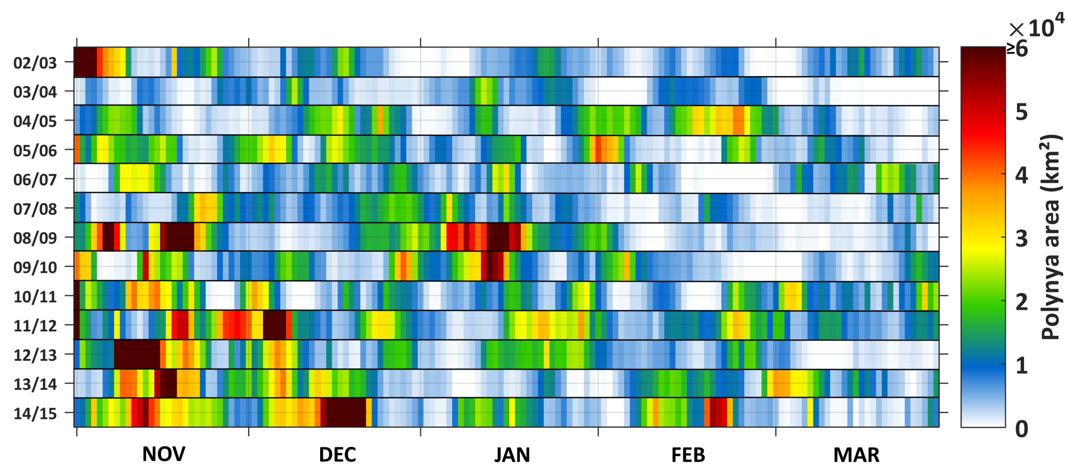

Figure 10. ~~Hovmoeller plot of the~~ The daily polynya area (TIT $\leq$ 0.2 m) in the Laptev Sea region ~~.~~ for the winter seasons 2002/2003 to 2014/2015. Values are calculated within the margins of the applied polynya mask (Fig. 1) and saturated at a level of ~~5~~6 x 10^4 km^2 for a better discrimination of lower values.

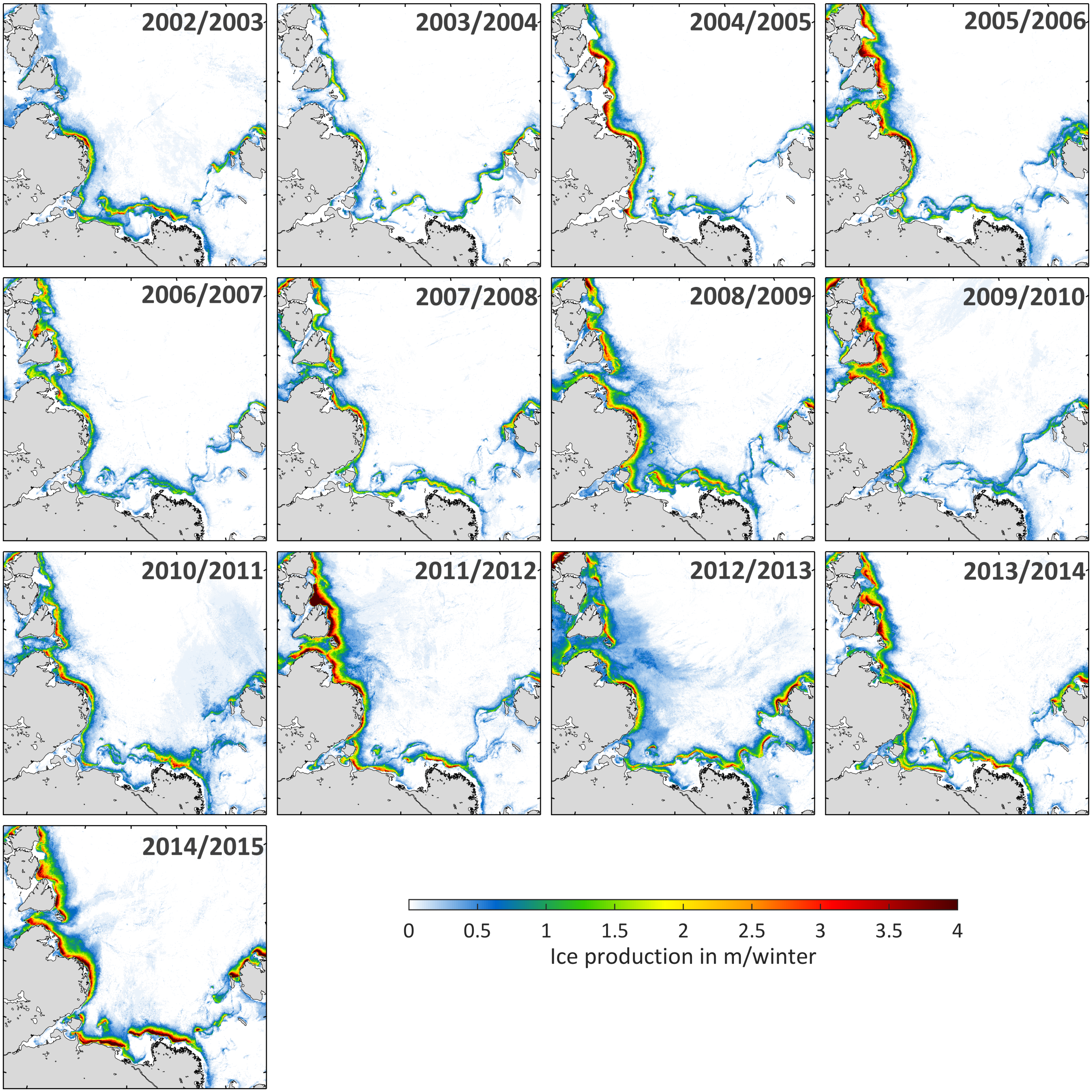

Figure 11. Overview of wintertime (November to March) accumulated ice production (m per winter) in the Laptev Sea region between 2002/2003 and 2014/2015.

In order to give an overview on the long-term development of thin-ice areas (TIT ≤ 0.2 m) in the Laptev Sea, the daily POLA is presented in Fig. 10. It is evident that the largest ~~POLA values~~ areas of thin-ice appear on average in November and more recently also in December ~~.~~ (compare Tab. 2). A tendency towards an increased duration of these polynya-events can be observed. In the winter-seasons 2008/2009 and 2009/2010, large POLA exceeding 50000 km^2 are also observed in January and another major polynya event can be noted for mid-February 2015. A pronounced seasonal variation is visible for ~~about half of the 13-year record, while some other years (prior to~~ the winter seasons 2004/2005, 2005/2006 and from 2010/2011 ~~)~~ ~~show only weak polynya activity in~~ onwards, while the other years show less polynya activity (more lengthy periods with a closed polynya; white color in Fig. 10) and overall smaller polynya extents in February and March.

Fig. 11 shows an annual comparison (2002/2003 to 2014/2015) of accumulated (November to March) ice production (in m per winter) for the Laptev Sea. The highest ice-production rates of sometimes more than 4 m per winter occur predominantly in proximity of the Taymyr Peninsula and Severnaya Zemlya (western Laptev Sea), as well as along the southern fast-ice edge (mainly coastwards of the regions with high ice production). However, ice production in the eastern Laptev Sea (west and north of the New Siberian Islands) shows a greater ~~inter-annual~~ interannual variability. Furthermore, it is striking that the position of the fast-ice edge in Fig. 11 is highly variable over the 13-yr record (as ~~noted~~ in Sect. ~~3.1~~4.1, Fig. 8 (a)). However, it has to noted that certain bands of higher ice production, especially in the south-eastern Laptev Sea, reflect the wintertime evolution of fast ice (compare Selyuzhenok et al., 2015) and are hence primarily related to the early winter period from November to December. Another interesting observation can be made in the ~~Vilkitzky~~ Vilkitsky Strait, which is located in the western Laptev Sea south of Severnaya Zemlya (Fig. 9). The distribution of thin-ice areas contributing significantly to the total sea-ice production in that area seems to shift westwards towards the Kara Sea in several years (2005/2006 to 2012/2013 and 2014/2015). In some cases, the shape of these areas resembles an arch-type/ice-bridge pattern/mechanism, a feature that is commonly appearing e.g. in Nares Strait between Ellesmere Island and Greenland (Williams et al., 2007).

Krumpen et al. (2013) discovered that most of the ice being incorporated in the Transpolar Drift originates from the western and central part of the Laptev Sea. Further, it was indicated that the contribution from polynyas, while being generally small, is limited to events in proximity of the Laptev Sea boundaries. As noted before, the north-western Laptev Sea shows by far the largest contribution to the total wintertime ice production in the Laptev Sea polynyas, which implies a potential significant influence on the interannual variability of the ice export during winter. In order to check this hypothesis, we compare annual accumulated IP values to independently derived ice-area export (IAE) values (both presented as anomalies and normalized with their standard deviation) in Fig. 12 for 2002/2003 to 2014/2015. IAE values are taken from the updated time series of Krumpen et al. (2013), where they were calculated as the integral of the product between the eastward and northward component of the ice drift velocity and ice concentration at the northern boundary (NB) and eastern boundary (EB) of the Laptev Sea, respectively. Likewise to a high agreement between polynya area and across-boundary ice export (Krumpen et al., 2013), there is also a significant correlation between calculated ice production and the areal ice export ($r = 0.69$ with $p = 0.009$).

The spatial overview of annual ice production (Fig. 11) is supplemented by the previously shown time series of the average wintertime POLA and accumulated IP per winter (Fig. 5 and Fig. 6, respectively). Both time series of POLA and IP in the Laptev Sea show an overall positive trend (significant with $p \leq 0.01$), which can for the most part be traced back to larger

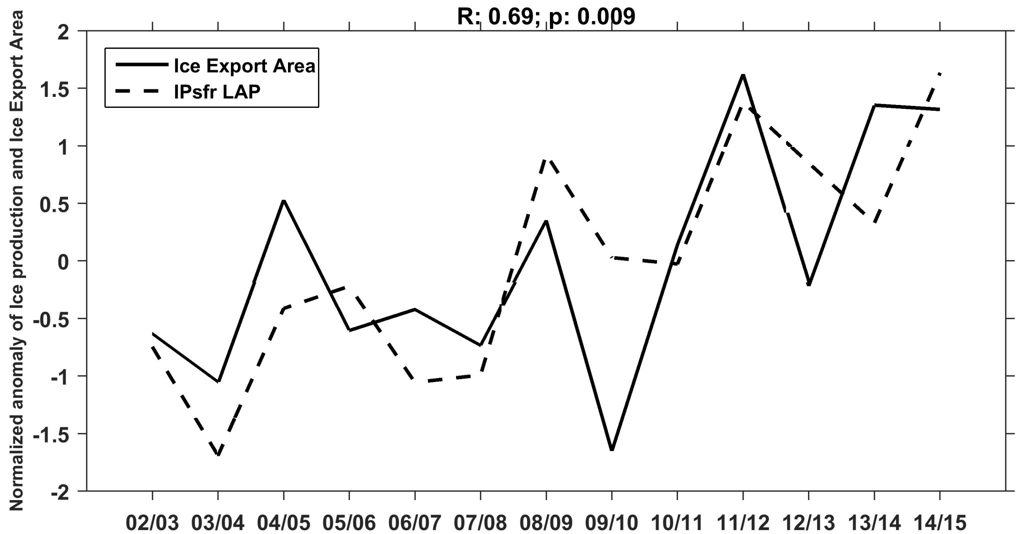

Figure 12. Normalized anomalies of accumulated wintertime ice production (IP of the present study; dashed line) and accumulated Ice Area Export (IAE; solid line) for winter seasons 2002/2003 to 2014/2015. IAE data is based on an updated time series by Krumpen et al. (2013).

thin-ice areas during the freeze-up period in November and December (as decribed above; Fig. 10). This is underlined by Tab. 2 and 3, which both reveal largest average values of POLA / IP and most significant trends during that period of winter. The average ice production from November to March in the Laptev Sea is estimated with about 96 $\pm$ 33 km^3 (2002/2003 - 2014/2015), with a positive trend of 6.8 km^3 per year. Compared to other Arctic polynyas (compare Tab. ~~2~~3), this corresponds to a share of about ~~7~~5% of the total ice production in polynya regions.

As the relative strength of the Transpolar Drift is dependent on atmospheric dynamics, it has previously been linked to atmospheric indices like the Arctic Oscillation (AO) Index (Rigor and Wallace, 2004). For the period from 1982 to 2009, the study by Kwok et al. (2013) presented indicators for a net-strengthening of both the Transpolar Drift and the Beaufort Gyre as well as a general increase of the Arctic ice drift-speed. The latter is presumably connected to a decreasing fraction of multi-year (MY) ice and a more fragile, thus mobile, sea-ice cover with potential implications for polynya and lead dynamics not only in the eastern Arctic. According to Rigor et al. (2002), a positive winter AO promotes both an increased ice transport out of the Arctic Ocean through Fram Strait and an increased ice transport away from the Siberian coastal areas, thereby leaving open water and thin ice that foster new ice formation. Hence, positive trends in both POLA and IP not only fit well to the previously estimated positive trend in IP from Iwamoto et al. (2014) but also to the positive trend of 0.85 x 10^5 km^2 per decade in the Laptev Sea ice area flux (Krumpen et al., 2013). Other linkages and dependencies with the Arctic sea-ice extent in September (annual minimum), the ~~length of the freezing period~~ timing of the freeze-onset and further connections to large-scale atmospheric circulation patterns are very likely and have been proposed by various previous studies ~~(e.g. Alexandrov et al. (2000); Deser et al. (2000); Rigor et al. (2002); Willmes et al. (2011); Krumpen et al. (2013), but do~~ (e.g. Alexandrov et al., 2000; Deser et al., 2000; Rigor et al., 2002; Willmes et al., 2011; Krumpen et al., 2013). Particularly a significant lengthening of the melt season in recent years and hence a later freeze-up in autumn already seems to imprint on the derived POLA (i.e. thin-ice area) and IP estimates in the early winter period (Markus et al., 2009; Parkinson, 2014; Stroeve et al., 2014). In that context, increasing atmosphere- and ocean-temperatures in autumn and winter have recently been reported by Boisvert and Stroeve (2 comprise the potential to alter/shift vertical temperature gradients with consequences for the surface energy balance and ultimately IP. Further, a shortened fast-ice duration and enhanced variability of the fast-ice edge in early winter (Yu et al., 2014; Selyuzhenok influences the location of flaw leads and consequently high ice production / brine release. Frankly, all these (potential) interconnections are rather complex and would require more detailed investigations that go beyond the scope of ~~this paper.~~ the present study. In the context of other reported changes during the spring and summer period (Janout et al., 2016), it may emerge that the overall set-up for atmosphere-ice-ocean interactions in the Laptev Sea is gradually changing towards a new state.

5 Conclusions

In the present study we analyzed circumpolar polynya dynamics and ice production in the Arctic based on high-resolution MODIS thermal infrared imagery and atmospheric reanalysis from the ERA-Interim data set. Pan-Arctic and (quasi-) daily thin-ice thickness distributions were calculated using a 1D-energy balance model for the period from 2002/2003 to 2014/2015 (November to March). After applying a necessary and well-working gap-filling approach to compensate for cloud and data gaps, the thermodynamic ice production was derived by assuming that all heat loss at the ice surface contributes to the growth of sea ice. We presented results for ~~16~~ 17 prominent polynya regions, whereby the a strong focus was set on the Laptev Sea region in the eastern Arctic. Despite existing limitations originating from the use of thermal infrared remote sensing data during winter, we think that this new data set of 13 consecutive winter seasons is a huge step forward for ~~an~~ a spatially accurate characterization of Arctic polynya dynamics and the ~~seasonal~~ associated sea-ice budget ~~in general~~related to winter-time sea-ice production. Our main findings and conclusions are the following:

(1) The use of high-resolution MODIS data increases the capability to resolve small scale (> 2km) thin-ice features such as narrow polynyas and leads, which therefore contribute to our ice production estimates. This represents an advantage compared to other (passive microwave) data sets.

(2) The average wintertime accumulated ice production in all 16 polynya regions is estimated with about ~~1444~~ 1811 ± ~~258~~ 293 km^3. The largest contributions originate from the western proximity of Novaya Zemlya (20%), the Kara Sea region and the North Water polynya (both ~~19~~15%) as well as scattered smaller polynyas in the (eastern) Canadian Arctic Archipelago (all combined around ~~15~~12%). Compared to the most recent study on ice production in Arctic polynyas by Iwamoto et al. (2014), our estimate on the average total ice production is about ~~22~~52-54% larger, although differences in the regarded time frame, reference areas~~and applied satellite sensors~~ , sensor-specifics as well as a potential bias due to cloud cover and/or the exclusive assumption of clear-sky conditions certainly contribute to this discrepancy.

(3) Positive trends in ice production can be detected for several regions of the eastern Arctic (most significant in the Laptev Sea region with an increase of 6.8 km^3/yr and the North Water polynya, while other polynyas in the western Arctic show

a more pronounced interannual variability~~with even slightly negative trends in the Beaufort and Chukchi Sea as well as the North-East Water polynya~~. These regionally different trends ~~are considered to be caused by~~ could potentially originate from changes in the overall sea-ice mobility (i.e. sea-ice drift), ~~temporal shifts in the length of the ice growth-/melt-seasons and~~ a temporal shift of the freeze onset in autumn (leading to larger thin-ice areas in November and December) or distinct large-scale atmospheric set-ups that ~~promoted~~ promote an increased ice export and enhanced ice production in the Siberian shelf regions during winter.

(4) The Laptev Sea region was chosen as a special focus in our study as it is one of the core areas for ice production in the Arctic with a distinct connection to Transpolar Drift characteristics and showing a strong positive trend. Ice production in the Laptev Sea was mapped with enhanced spatial detail, which is especially valuable in this region with narrow and elongated flaw leads close to the fast-ice edge. Our results showed that polynyas in the Laptev Sea contribute with at least ~~7~~5% to the total potential sea-ice production in Arctic polynyas. While the interannual variability in terms of location and extent seems to be rather high, the positive trends in both POLA and IP time series fit well to results ~~from previous~~ and observations from other recently published studies in the Laptev Sea~~, which described increasing atmosphere- and ocean-temperatures (Boisvert and Stroeve, 2015), a significant lengthening of the melt season (Stroeve et al., 2014), a shortened fast-ice duration (Selyuzhenok et al., 2015) and increasing~~. A clear relation between increasing sea-ice area export (Krumpen et al., 2013) ~~, among other changes during the spring and summer period (Janout et al., 2016). Future comparisons with newly~~ and positive trends in IP could be demonstrated, and future comparisons with recently derived volume-flux estimates in the Transpolar Drift (Krumpen et al., 2016) certainly promise further insights on the absolute contribution of polynyas to the volume ice export out of the Laptev Sea and adjacent seas.

(5) ~~The qualitative comparison~~ Compared to the MODIS-derived lead product by Willmes and Heinemann (2016)~~reveals a shortcoming of the here applied~~ , the SFR-algorithm ~~, as it is not entirely possible~~ used in the present study is not able to adequately reconstruct leads with a low spatial and temporal persistence. A thoughtful combination of both concepts is therefore a goal worth to achieve for future ~~/continuing~~ investigations on thin-ice regions in the polar regions using thermal infrared data from MODIS or other comparable satellite sensors, allowing for estimates of IP by leads also for the central Arctic ocean.

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