Dear Jennifer, dear reviewers,

Thank you very much for your comments – they have improved the manuscript greatly. We have streamlined the text and stated more clearly what the novelty of the paper is. Some figures have been improved too. We have addressed all the comments individually and are looking forward to hearing from you again.

Best Regards, Thomas and Polona

Authors' response to Anonymous Referee #1

In Black: Questions addressed by the reviewers In Red: Our answers In Blue: Changes made to the manuscript

1. Summary

This paper discusses how late winter export/import anomalies lead to low/high ice concentration and thickness in the Laptev Sea. The discussion is very clear, the figures are good, and the English is quite readable. There is some redundant text that could be cut. I recommend for publication with minor revision.

2. Specific Comments

Figure 1: The caption should explain what AL, WNS, NE, and T are. The black and grey lines are quite short and a bit difficult to see against the colors.

Thank you for this comment. We now explain abbreviations in the figure caption.

"The approximate positions of prominent polynyas are indicated: The Western New Siberian polynya (WNS), the Anabar-Lena polynya (AL), the Taymyr polynya and the Northeastern Taymyr (NET) polynya."

Also, perhaps you can change this to a 2-panel presentation, with panel 1 = 2008 model ice thickness + 2008 EM observations, and panel 2 = 2012 model ice thickness + 2012 EM obs?

A direct comparison of model and EM thickness is difficult and previous studies rather compared sea ice volume estimates based on SAR data and EM-measurements with model outputs (see Rabenstein et al. 2012 and answer to your comment on Line 31, Page 3). In this manuscript, the EM data is primarily used to indicate thinning effect of enhanced export on thickness distribution.

Line 14, Page 3: "time lags of 3 days" What does this mean?

With time lag of 3 days we were referring to the temporal resolution of the dataset. The motion information provided by this product is the motion of sea ice obtained from images being 3 days apart. We now use the term "temporal resolution" in the manuscript.

"The motion fields are based on a combination of drift vectors estimated from scatterometer (SeaWinds/QuikSCAT and ASCAT/MetOp) and radiometer (Special Sensor Microwave Imager, SSM/I) data. They are available with a grid size of 62.5 km and have a temporal resolution of 3 days."

Line 31, Page 3: So, the HEM does not provide ice thickness, but snow + ice thickness. Thus it cannot be directly compared to model ice thickness, correct?

That's correct. However, in Rabenstein et al. 2012, EM data was used together with ice age information from SAR data to number sea ice volume production in polynyas. Laptev Sea has very little precipitation in winter and snow cover on new ice in polynya is negligible. So, assuming the snow cover to be small, EM thickness can be compared to model sea ice thickness directly.

Also: You use SMOS ice thickness in this work, so you should discuss SMOS data in your Data section.

We were using SMOS data only to prove the presence of thin ice along the coast of the Laptev Sea. Adding it to the data section would probably make it even longer and not add any additional value to the manuscript. However, we now provide a reference (that was missing) to the applied data in the text and figure caption.

"Color coding corresponds to the sea ice thickness as obtained from Soil Moisture Ocean Salinity (SMOS) satellite on April 20, 2012 (source: University Hamburg, \cite{Tian-Kunze2016})."

I will comment that your data section is very good in describing the data that you use, including error estimates. The model section should probably provide some information here about its validation in the Laptev Sea of the parameters of interest, ie ice concentration (compare to SSM/I), ice thickness (compare to SMOS) and ice motion (compare to CERSAT).

The sea ice concentration, thickness and drift from the model used in this study have been compared to observations by Itkin et al, 2014 (added in references). In section 2.3 we now summarize their findings (see below). However we do not use the model for any absolute estimates, but merely as a tool in a sensitivity study. Therefore we believe that the model is realistic enough to capture the relationships between the processes and give trustable qualitative results.

"\citet{itkin2014} compared sea ice concentration, thickness and drift speed of a similar model setup without landfast ice parametrization to satellite observations. They reported that the model overestimates the summer sea ice concentration in the shelf seas compared to the OSI-SAF sea ice concentration product \citep{osi}. Compared to the ICESat sea ice thickness \citep{zwally2002} the model reproduces the regional sea ice thickness distribution well, but it tends to overestimate the winter sea ice thickness on the Siberian shelf seas. Comparison to the CERSAT and NSIDC sea ice drift products \citep{girard2012,fowler2013} showed that the sea drift speeds in the model fall within the uncertainty of the drift products with the exception of very high drift velocities that are overrepresented by the model. Adding the landfast ice parametrization reduces the sea ice thickness bias on the shelf and partially slows down the drift speeds in the same region \citep{itkin2015}. Despite the biases the model performance is reasonably good and can give trustable results for qualitative studies e.g. sensitivity studies."

New references were added, please see

1) Itkin et al. 2014: Is weaker Arctic sea ice changing the Atlantic water circulation?, JGR

2) OSI 2013: EUMETSAT Ocean and Sea Ice Satelitte Application Facility. Global sea ice concentration reprocessing dataset 1978-2009 (v1.1, 2011), Norwegian and Danish Meteorological Institutes

3) Fowler, 2013: Polar Pathfinder Daily 25 km EASE-Grid Sea Ice Motion Vectors. Version 2. NSIDC

Figure 3: Color scale should use "regular" intervals, eg 120, 140, 160

Yes, that's better. We now use regular intervals.

Line 1, Page 5: "...contributed to the low..." ie eliminate the "a"

Check, thanks.

Line 4, Page 5: zero, or 15%?

Correct, less than 15 %. This was corrected. Thanks.

Figure 4: Is "ice concentration" an average over the domain? Is the domain bounded by the coast, the western islands, and the N and E sections? Also, I suggest you mark the years 2008 and 2012 since these are discussed in the text. Also, I suggest you eliminate the minus signs on the ice concentration, since to me, they seem to suggest a concentration anomaly. Also, in the caption, you should explicitly note the different vertical scales of area ice flux in the 2 panels. Also, in the final sentence of the caption: "...data are..." not "data is" referring to "correlations" which is plural.



The figure and caption are now improved as you suggested.

"Time series of the late winter sea ice transport and summer sea ice concentration for the Laptev Sea (closed box inside the northern and eastern boundaries and coastlines): a) satellite-based estimates; b) model simulations. Trend lines of ice fluxes are represented by dashed lines. Note that the sea ice concentration axis is inverted to facilitate the comparison. Likewise, the scale of fluxes is not the same on both panels. The correlations between the model and satellite data are provided in text of corresponding colors." Line 6, Page 6: "...variability is controlled by wind velocities." Probably (I have not read Krumpen et al. 2013) the sea ice variability was found to be controlled by surface wind which was calculated via sea level pressure and thus geostrophic wind. But of course the ice moves owing to surface wind. So just say "wind" and you are ok.

Correct, wind was calculated via sea level pressure gradients. We now use "wind" only.

Line 7, Page 6: "...is associated to an increasing drift speed due to a thinning ice cover." You should prove this, or refer to Krumpen 2013 if this is shown in that work.

The reasons for the increasing drift speeds are manifold. We make this more clear now and refer to the changing ice cover (thinning/decreasing concentration and multi-year ice).

"The positive trend in observed ice export of 7.19 \times 10 $^3\kms^2$ /year ($\ps = 0.0049$) is however associated to an increasing drift speed, likely being the consequence of a change in the ice cover (thinning and/or decreasing concentration), caused by the rapid loss and thinning of thick multiyear ice (\cite{Haas2008})."

Line 8, Page 6: ": : :statistically not significantly different from no trend at 95% confidence (p = 0.0888)." ie it is significant if you relax your standard to 91% confidence.

Corrected to:

"The trend in simulated export rates is higher $(12.02\\times 10^{3} \ \text{km}^{2}\)$ and statistically significant at $91\$ confidence level ($\$ = 0.0888)."

Lines 9-10, Page 6: ": : :as well as for the summer sea ice concentration." You find that the correlation is exactly 0.73 for both export and concentration? This is hard to believe.

The correlation coefficient was wrong in both cases. The mistake is now corrected:

"The overall agreement between simulations and observations is high, with a correlation coefficient of 0.33 for the late winter sea ice exports and 0.81 for the summer sea ice concentrations."

Lines 13-14, Page 6: It is "more than double" for export, but not for concentration.

Now corrected to:

"Despite the good agreement, the simulated sea ice area export and summertime ice concentration are much higher than the satellite-based estimates."

Figure 5: The symbols are far too small to read. It seems impossible to make them large enough to read but small enough to fit on these busy graphs. Perhaps you should simply not try to distinguish these individual years within the 3 colors. Also: I cannot see the gray symbols and lines at all on a hard copy. Also: what does "above" or "below" mean, if gray means +/- 25%? IE does above mean > + 25% of the mean? Also, what is the "average volume sea ice export?" IE please provide this number here.

Figure has been adjusted and the caption rewritten to:





"Sea ice concentration and volume seasonal cycle (1992-2014) as obtained by the model: a) control run, b) model forced with a climatology between May and December. The mean volume sea ice export is 226 km^3/season and the line colors are used to distinguish between years with average (\pm , of the mean), high (above 25\% of the mean) and low (bellow 25\% of the mean) volume sea ice export."

Line 4, Page 9: Is it particularly surprising that there is no year-to-year memory in the thin ice of the Laptev Sea?

Good point. We have acknowledged that in the manuscript:

"The Siberian shelf seas are lately almost completely ice free in summer, so it is not surprising that the sea ice memory on the Laptev Sea is only preserved from one late winter to the next and not beyond. "

The first 2 paragraphs of the Discussion are somewhat redundant with previous text and could be cut substantially, I think.

We agree. The paragraph was cut substantially:

"The negative correlation of observed and simulated late winter sea ice export from the Laptev Sea and subsequent summer sea ice concentration can be explained by the replacement of the exported ice by new ice formed in polynyas situated along the landfast ice edge. The comparison of the HEM ice thickness measurements obtained in April 2008 and April 2012 over Laptev Sea pack ice visualizes the thinning effect of enhanced offshore ice advection on the sea ice cover, resulting in an earlier onset of ice retreat."

Line 25, Page 9: ": : :may be a consequence: : :" I do not understand this sentence.

The end of the paragraph has been now rewritten to:

"Too high wind speed in some of the atmospheric forcing data for the Laptev Sea region have been pointed out already by \citet{ernsdorf2011} and \citet{fofonova2014}, e.g. NCEP-CFSR atmospheric forcing used in this study is likely overestimating the wind speeds in the early 1990s. PIOMAS simulations with various atmospheric forcing show that the simulation with NCEP-CFSR results with a relatively low winter sea ice volume in the early 1990s that is comparable to the state in the recent years \citep{lindsay2014}."

Page 10, first full paragraph starting, "Our model: : :" Is this paragraph really necessary?

We agree. We have removed the text and merged it with the conclusions.

Page 10, material on fast ice: It seems to me that this material should go into a dedicated section in your results, i.e. before the discussion section.

The material we used here originates from a paper published by Selyuzhenok et al. (2015). To keep data section short, we decided not to include it and limit it to the discussion. However, we agree that the fast ice topic deserves a dedicated chapter. Please see changes in the discussion section (new chapter: Impact on fast ice decay). Also, the "fast ice decay" was added to the title.

Line 26, Page 10: What does "linked" mean? This is not a scientific term. Do you mean that it is correlated (at zero lag?)?

Yes, Selyuzhenok et al. 2015 found a high correlation value here. We corrected this in the manuscript.

Line 27, Page 10: ": : : below a certain extent: : :" What "certain" extent?

"Certain extent" refers to a threshold value Selyuzhenok et al. (2015) was using in order to define beginning and end of different periods, such as onset of formation, break-up or end of fast ice season. We now refer to the threshold value in the manuscript.

"The interannual and seasonal variability and trends of the southeastern Laptev Sea fast ice, an area with the widest fast ice extent in the Arctic located between 77 \$^{\circ}\$N, 125 \$^{\circ}\$E and 72 \$^{\circ}\$N, 140 \$^{\circ}\$E, were recently investigated by \citet{selyuzhenok2015}."

Line 30, Page 10: How is the SE Laptev Sea defined? Please show this on Figure 1.

We agree. The coverage of SE Laptev Sea requires further explanation (between 77N/125E and 72N/140E). However, we decided to include this in the text, rather than in Figure 1.

"The interannual and seasonal variability and trends of the southeastern Laptev Sea fast ice, an area with the widest fast ice extent in the Arctic located between 77 \$^{\circ}\$N, 125 \$^{\circ}\$E and 72 \$^{\circ}\$N, 140 \$^{\circ}\$E, were recently investigated by \citet{selyuzhenok2015}."

Also, change the word "were" to "where"

Thanks, this was changed.

Line 34, Page 10: ": : : and ice export is higher: : : " ie "higher" not "high" 0.63 is not really too high.

Thanks, we are now using "higher", since the sentence refers to the one before (lower r for the onset of fast ice breakup and ice area export).

"The correlation coefficient between onset of fast ice breakup and ice area export is small (\$r\$ = -0.35). This indicates that onset of fast ice breakup is independent of winter ice dynamics and, as suggested by \citet{selyuzhenok2015} and \citet{Bareiss1999} rather attributed to the timing of river breakup. However, the correlation between end of fast ice season and ice export is higher (\$r\$ = -0.63)."

Figure 7 caption: The red line, not the blue line.

Thanks for the hint. However, following the suggestion of reviewer number #2 the figure was removed completely.

Authors' response to Anonymous Referee #2

In Black: Questions addressed by the reviewers

In Red: Our answers

In Blue: Changes made to the manuscript

1. Summary

The manuscript introduces the relationship between winter sea-ice dynamics and ice retreat in summer over the Laptev Sea shelf. A number of relevant processes are discussed in order to explain the linkage between the preceding late winter sea-ice thickness and the following summer sea-ice extent. This manuscript is intended to further results by Krumpen (2013), also using numerical simulations. Data from this region are of general interest and should be published, but the framework for developing ideas by Krumpen (2013) is not entirely appropriate and adds very little value to already published results. As the results highlighted are mainly linked to those already published by Krumpen (2013) I find that the manuscript is not appropriate for publication in its present form.

2. General comments

As I see, the major problem with this manuscript is novelty. In lines 20-23, page 1 the authors pointed out that "...the recent study of Krumpen et al. (2013) showed a high statistical connection of the late winter (Feb-May) sea ice export through the northern and eastern boundary to the summer sea ice concentration. Years of high ice export in late winter have a thinning effect on the ice cover, which in turn preconditions the occurrence of negative sea ice extent anomalies in summer, and vice versa. ". This is exactly the same as the authors represented in abstract in lines 3-4, page 1: "...we show that years of offshore directed sea ice transport have a thinning effect on the late winter sea ice cover, and vice versa.". What is the difference between the results reported by Krumpen et al. (2013) and those presented in this manuscript? I would like the authors to describe how this manuscript develops the findings by Krumpen (2013) and what is really new here comparing to already published results. The sensitivity study using numerical simulation is good and important, but seems to be not sufficient alone to get this manuscript publishable in its present form.

Although the paper builds up upon previous work of Krumpen et al. (2013), it certainly covers new aspects and provide new insights into a mechanism that has not received much attention. The presented results indicate that this mechanism may be the most important one controlling summer ice retreat along the North East passage (NEP). In the following, we highlight the scientific value and new findings that go beyond previous study. However, we agree that this findings should be made clearer in the manuscript.

In Krumpen et al. (2013) the statistical connection between late winter export and summer ice extent was discovered for the first time. However, the preconditioning effect is not a focus of the paper and by that time, the investigation was limited to sea ice motion and concentration data, completely neglecting sea ice thickness as such. In this manuscript, we were able to deepen the understanding of the linkage between winter ice dynamics and summer ice extent and highlight the importance for seasonal forecasts, by means of a sensitivity study using a numerical model and insitu ice thickness observations:

First important question we address is weather numerical models are capable of resolving the described process. A correct representation of the preconditioning effect will enable models to

predict sea ice anomalies along the NEP and beyond. Our results show that the applied regional model captured the preconditioning effect of late winter dynamics on summer ice extent quite well, although existing GCMs have difficulties in predicting sea ice extent in marginal ice zones, in particular the Laptev Sea. This finding is indeed novel and of high interest to the model community. The need for these kind of studies was just discussed on the Sea Ice Prediction Workshop 2017, in Bremerhaven. Our sensitivity study also shows that besides the preconditioning there are other mechanisms that become important after winter and contribute towards the actual summer sea ice situation. Combined with the publication of Polyakov et al. (2017), Steele and Ermold (2015) and Maslanik (2000), our manuscript provides, for the first time, a complete picture of processes controlling summer ice extent on the Laptev Sea shelf: The preconditioning effect of winter ice dynamics (this manuscript), enhanced ocean ventilation (Polyakov 2017), warming winters (Ricker 2017), cyclones bringing anomalous warm air masses to the Laptev Sea during summer months (Maslanik), and winds that force ice floes/edge back into warm waters cause melting (Steele and Ermold).

Apart from complementing the current understanding of ice retreat in summer, our model simulation also provides insight into long-term changes of sea ice volume export that is currently not available from observations or satellite data. The simulated trend of sea ice volume export for the period from 1992 till 2014 is positive, but not significant. This indicates that the observed acceleration of the sea ice drift and associated increase in area export out of the Laptev Sea may not be compensated by the thinning effect of enhanced offshore advection. Hence, we expect that an increased volume export from the Laptev Sea into the Transpolar Drift has far reaching consequences for the entire Arctic sea ice mass balance.

In this manuscript, we can also show that winter ice dynamics not only precondition pack ice extent in summer, but also influence fast ice decay. Up to know, the shortening of the fast ice season was very much associated to changing temperatures, delay in freeze-up and earlier onset of river breakup. Here we discover ice advection as another (so far unknown) mechanism that speeds up fast ice break-up, and as such, contributes to the increasing coastal erosion, warming of permafrost, etc. This aspect is another new finding, adding to the existing knowledge.

Last but not least, the thinning effect of ice advenction on Russian pack ice was never investigated with in-situ data. In this manuscript we present for the first time thickness observations showing the thinning effect of two different winters of different export strength. From our perspective, the in-situ data alone is very unique and worth of publishing.

J. A. Maslanik, A. H. Lynch, M. C. Serreze, and W. Wu (2000): A Case Study of Regional Climate Anomalies in the Arctic: Performance Requirements for a Coupled Model, Journal of Climate, doi: http://dx.doi.org/10.1175/1520-0442(2000)013<0383:ACSORC>2.0.CO;2

Steele, M., and W. Ermold (2015), Loitering of the retreating sea ice edge in the Arctic Seas, J. Geophys. Res. Oceans, 120, 7699-7721, doi:10.1002/2015JC011182.

Polyakov, I., and Pnyushkov, A. and Alkire, M., and Ashik, I. and Baumann, T. and Carmack, E.and Goszczko, I. and Guthrie, J. and Ivanov, V. and Kanzow, T. and Krishfield, R. and Kwok, R. and Sundfjord, A. and Morison, J. and Rember, R. and Yulin, A. (2017), Greater role for Atlantic inflows on sea-ice loss in the Eurasian Basin of the Arctic Ocean, Science, eaai8204, doi:10.1126/science.aai8204.

In the introduction we now review recent studies on ice retreat in the eastern Eurasian Basin and better explain the importance of this study:

«The Laptev Sea became almost completely ice free during summertime in the past years. Similar conditions in the other Siberian Seas (Kara, East Siberian and Chukchi Sea) facilitate ship transports conducted without support of icebreakers through the Northeast Passage from Europe to the Asian Far East. Ice retreat in the Laptev Sea is the consequence of atmospheric and oceanic processes and regional feedback mechanisms acting on the ice cover. During summer, local anomalies in sea ice extent are thought to be controlled by synoptic-scale processes (e.g. cyclones) superimposed on the large-scale atmospheric circulation \citep{Bareiss2005}. The connection between shifts in the atmospheric circulation and the role of cyclonicity for anomalies in summer sea ice concentration were discussed by \cite{Serreze1993, Serreze1995, Maslanik1996} and \cite{Maslanik2000}. In particular cyclones entering the Laptev Sea from the southwest enhance the northward ice transport and are associated with an inflow of anomalous warm air masses of above average air temperatures. If ice retreat happens early enough to allow atmospheric warming of this open water (e.g. during years of high export), winds that force ice floes back into this water cause melting. The interaction between surface winds and warm sea surface temperatures in areas from which the ice has already retreated were recently investigated by \cite{Steele2015}. During winter, anomalous high temperatures reduces sea ice growth of first year ice, resulting in a thinner ice cover at the end of April \citep{ricker2017}. In addition, enhanced winter ventilation of the ocean reduces sea ice formation at a rate now comparable to losses from atmospheric thermodynamic forcing \citep{polyakov2017}. Observations carried out in the eastern Eurasian Basis have shown that weakening of the halocline and shoaling of intermediate-depth Atlantic Water layer results in heat flux equivalent to 40 – 54 cm reductions in ice growth in 2013/2014 and 2014/2015. The winter preconditioning of the summer sea ice cover has been lately used by \citet{kimura2013} to develop a summer sea ice outlook based on the winter sea ice motion. Locally in the Laptev Sea, the major source area of the Transpolar Drift, the recent study of \citet{krumpen2013} showed a high statistical connection of the late winter (Feb-May) sea ice export through the northern and eastern boundary to the summer sea ice concentration. Years of high ice export in late winter have a thinning effect on the ice cover, which in turn preconditions the occurrence of negative sea ice extent anomalies in summer, and vice versa.

A correct representation of the above described processes in numerical models will improve predictions of sea ice anomalies along the Northeast Passage and beyond. To improve understanding of individual mechanisms contributing to sea ice decline, in this study, we further investigate the preconditioning effect of winter ice dynamics on the local summer sea ice cover. To separate the winter from the summer processes that influence the summer sea ice cover in the Laptev Sea, we perform a sensitivity study by means of a numerical model. This allows us to quantify the importance of the local winter preconditioning for the summer sea ice cover. The model is also used to test if the observed increase sea ice area export is reflected in an increase in sea ice volume export out of the Laptev Sea. This would extend the importance of the regional sea ice transports to the larger region of the Transpolar Drift system.»

Also the conclusion was improved, so that it would highlight the key findings of the paper in a better way:

«Our findings highlight the importance of sea ice dynamics in winter for summer sea ice conditions in the Laptev Sea and likewise in the adjacent Siberian Seas, where large polynya systems develop in winter. Here we show for the first time the thinning effect of winter offshore winds that open polynyas at fast ice edge by means of airborne thickness measurements carried out in 2008 and 2012. The new sea ice grown in polynyas relatively late in the season stays rather thin and becomes subject to quick summer melt, which initiates early ice retreat and low summer sea ice concentration in the Laptev Sea. To confirm the preconditioning of the summer sea ice cover with the winter exports we perform a sensitivity study where we force our model with inter-annual atmospheric forcing from January till May and then switch to the climatological forcing till the end

of the year. Our results show a clear distinction between years with high and low sea ice export: Years with high late winter sea ice export are characterized by a thinner ice cover and reduced ice volume. The thinner ice cover melts faster which leads to the development of large open water zones that heat up quickly. In addition, model simulations indicate that the volume export from Laptev Sea is increasing, since the thinning of the ice cover cannot compensate for the enhanced area export. Moreover we could show that ice dynamics in winter not only precondition local summer ice extent, but also accelerate fast ice decay. During years of early ice retreat, coastal waters heat up quickly. This may favor melt of grounded ridges at the fast ice edge serving as anchor point for fast ice in winter.

The mechanism presented in this manuscript complements earlier studies of \cite{Steele2015, polyakov2017, ricker2017} investigating the declining ice cover in the eastern Eurasian Basin. Here we highlight the importance of winter ice dynamics for sea ice anomalies of thickness, volume and extent in addition to atmospheric processes acting on the ice cover in winter and summer. «

Similar changes were made to the abstract:

"Ice retreat in the eastern Eurasian Arctic is the consequence of atmospheric and oceanic processes and regional feedback mechanisms acting on the ice cover, both in winter and summer. A correct representation of these processes in numerical models is important, since it will improve predictions of sea ice anomalies along the Northeast Passage and beyond. In this study, we highlight the importance of winter ice dynamics for local summer sea ice anomalies in thickness, volume and extent. By means of airborne sea ice thickness surveys made over pack ice areas in the southeastern Laptev Sea, we show that years of offshore directed sea ice transport have a thinning effect on the late winter sea ice cover. To confirm the preconditioning effect of enhanced offshore advection in late winter on the summer sea ice cover we perform a sensitivity study using a model. Results verify that the preconditioning effect plays a bigger role for the regional ice extent. Furthermore, they indicate an increase in volume export from Laptev Sea as a consequence of enhanced offshore advection, which has far reaching consequences for the entire Arctic sea ice mass balance. Moreover we show that ice dynamics in winter not only precondition local summer ice extent, but also accelerate fast ice decay. "

3. Specific comments

Page 4, line 15: I suggest to explain term "polynya".

A short sentence was added to the manuscript.

"Flaw polynyas are open water sites between pack ice and fast ice of high net ice production sustained by winds."

Page 4, line 24: Reference to Figure 4 appears before reference to Figure 3.

Thanks. Corrected

Page 4, line 26: There is one more maxima at \sim 0.5m.

Thanks. Corrected

"Flights that were made in 2008 (April 14, 16 and 24) covers much thicker ice with a mean thickness of 2.7 m. The thickness distribution shows two modes: one at 0.5 m and another one at 1.5 m. Following \citet{rabenstein2012}, the ice was originally formed in polynyas in the southeastern part of the Laptev Sea, but got heavily compacted during a longer period of onshore-directed ice drift in late winter. Due to presence of a compact ice cover in near shore areas, ice retreat took place relatively late in the season and large parts of the Laptev Sea remained ice covered during summer (Fig. \ref{fig:retreat}, left panel)."

Page 6, lines 6-7: How do you know that the positive trend in ice export is associated to an increasing drift speed due to a thinning ice cover?

That's right. We don't now for sure and make this more clear now. The investigation of Krumpen et al. (2013) has shown that the increase in drift speed is not associated to changing wind. Hence it is likely related to a change in ice cover itself (thinning/decreasing concentration and multi-year ice).

"Following \citet{krumpen2013}, the variability is primarily controlled by changes in geostrophic wind. The positive trend in observed ice export of 7.19\$\times\$10\$^3\$ km\$^2\$/year (ps = 0.0049) is however associated to an increasing drift speed, likely being the consequence of a change in the ice cover (thinning and/or decreasing concentration), caused by the rapid loss and thinning of thick multiyear ice (\cite{Haas2008})."

Page 7, lines 8-9: I would like to see one more graph showing simulated ice export for 1992-2014.

In this paper we relate summer sea ice concentration with the late winter sea ice export. The averages of the late winter sea ice fluxes are shown in Fig. 4. Although the summer sea ice export probably does play a role for the summer situation in the Laptev Sea (in addition to the on-site melt), this is not the focus of the paper and adding a detailed year to year seasonal cycle of the exports might distract the reader from the main message: preconditioning of the summer situation by the winter conditions and the potential to use this for a better sea ice forecast on the Siberian shelfs. We would therefore prefer to omit such an addition in the manuscript text, but we included it here in the figure for your reference. Here we only show winter sea ice fluxes (October-May). The winter fluxes are identical for both model runs in the sensitivity study.



Caption: Sea ice concentration and volume seasonal cycle (1992-2014) as obtained by the model forced with a climatology between May and December. The mean volume sea ice export is 226 km\$^3\$/season and the line colors are used to distinguish between years with average (\$\pm\$25\% of the mean), high (above 25\% the mean) and low (bellow 25\% the mean) volume sea ice export.

Page 9, line 10: Change "is determined" to "are determined".

Thanks, corrected

Page 10, lines 17-19: This is primarily applicable only to the outflowing Arctic shelves with a strong seaice export like the Laptev Sea where the Transpolar Arctic Drift is originated. Please be more specific here.

We have taken this into account and rewritten the text into:

"This provides evidence that the advection of sea ice out of the Laptev Sea has a stronger preconditioning effect than the thickness of the ice cover itself. Ergo increase in the sea ice drift speed, as observed on all Siberian shelf seas \citep{Spreen2011}, play a bigger role for the regional ice extent in summer than changes in the thickness of the ice cover."

Page 10, lines 26-28: I didn't understand this sentence.

See answer to your comment on Page 11, line 1-3: Processes involved are now better described in the manuscript

Page 10, lines 34-35: I would like to know the physical mechanism behind this statistical relationship.

See answer to your comment on Page 11, line 1-3: Processes involved are now better described in the manuscript

Page 11, lines 1-3: This suggestion is very speculative. During years of high ice export and early melt of thin ice zones, shallow water heats up quickly, but this heat in available to favor bottom melt of fast ice only in a case of the on-shore water transport toward the area covered with landfast ice. In contrast, this area is mainly affected by the off-shore transport of the riverine water.

We appreciate this comment. Indeed it is unlikely that warm water advects on-shore and favours bottom melt of fast ice. A possible explanation is related to the mechanisms that controls maximal fast ice extent in the south-eastern Laptev Sea. At shallow spots located far offshore, ice likely gets grounded early in the year (December) and serves as an anchor point for fast ice. The study of Selyuzhenok et al. (2015) examines mechanisms driving fast ice growth and decay. Since the maximal fast ice extent closely follows the 20-25 m isobaths, it is likely that grounding is the responsible mechanism. The occurrence of ridges thick enough to reach the sea floor and potential grounding spots were now examined by a follow-up paper of Selyuzhenok et al., currently under revision (Polar Research). Using upward looking sonar and EM measurements in combination with high resolution satellite data the authors could show that grounding is a recurrent feature that controls location of the fast ice edge at the end of the winter.

Assuming grounding of ridges at the fast ice edge to be the driving mechanism controlling fast ice extent, warm water may speed up melt of ridges at the fast ice edge and erode anchor points accelerating fast ice retreat.

We adjusted the text accordingly. Again, thanks for this hint.

"New ice zones formed at the end of the winter during offshore advection events rapidly melt once temperature rise above freezing. It stands to reason that the ice albedo feedback not only accelerate retreat of surrounding sea ice, but also leads to an earlier onset of fast ice decay. The Laptev Sea is characterized by an extensive fast ice extent. The interannual and seasonal variability and trends of the southeastern Laptev Sea fast ice, an area with the widest fast ice extent in the Arctic located between 77 \$^{\circ}\$N, 125 \$^{\circ}\$E and 72 \$^{\circ}\$N, 140 \$^{\circ}\$E, were recently investigated by \citet{selyuzhenok2015}. The authors used operational sea ice charts provided by AARI to determine onset of fast ice growth, extent, beginning of breakup, and end of fast ice season between 1999 and 2013. For a detailed description of methods and applied data we refer to \cite{selyuzhenok2015}. The fast ice edge in late spring closely follows the 20-25 m isobaths indicating that grounded ridges serve as an anchor point for fast ice and hence determine, among other factors, maximal fast ice extent. The onset of fast ice breakup starts near the Lena Delta and is closely correlated to the river breakup (compare Figure 5 in \cite{selyuzhenok2015}). Mid of June river runoff overfloes fast which leads to a reduction in surface albedo. In addition, it contributes to a direct input of heat. As the fast ice breaks up along the Delta, it continues to retreat eastward. Following \cite{Barreis1999} further decay is controlled by onset of surface melt which was confirmed by \cite{selyuzhenok2015} who find a strong correlation with the timing of the end of the fast ice season (time when fast ice extent drops below a certain threshold value) and the onset of surface melt derived from passive microwave data. The onset of breakup and end of fast ice season are both showing negativ trends of -0.3 days/year and -1.0 days/year, respectively. Hence, the time it takes for fast ice to decay is shortening by -1.3 days/year.

How dynamics of pack ice in winter influence fast ice decay has not been studied. Therefore we compare the sea ice export with the timing of fast ice breakup and end of fast ice season obtained from satellite data. We limit the comparison to the southeastern Laptev Sea, were mechanisms of growth and decay were studied in detail by \citet{selyuzhenok2015} and accurate information about timing of breakup is available. The correlation coefficient between onset of fast ice breakup and ice area export is small (\$r\$ = -0.35). This indicates that onset of fast ice breakup is independent of winter ice dynamics and, as suggested by \citet{selyuzhenok2015} and \citet{Bareiss1999} rather attributed to the timing of river breakup. However, the correlation between end of fast ice season and ice export is higher ($\hat{s}r\hat{s} = -0.63$). Hence, in addition to the onset of surface melt, years of strong offshore advection precondition earlier end of the fast ice season and shortening of the duration of the breakup period, and vice versa. We argue that during years of high ice export and early melt of thin ice zones, shallow waters heat up quickly and more heat is available to favor bottom melt of grounded ridges at the fast ice edge. Melting away the anchor points controlling fast ice extent in winter may then accelerate its retreat in spring. The tendency towards earlier fast ice retreat may therefore not only be related to rising temperatures in spring and earlier onset of surface melt, but also to the acceleration of pack ice drift and increased offshore advection."

Page 11, lines 7: This conclusion can hardly be extended to the adjacent Siberian shelf seas. It may work only for the areas with coastal polynyas developed during late winter and spring.

Large polynya system develop at the landfast ice edge in winter also in the other Siberian shelf seas (Kara Sea and East Siberian Sea). Preusser et al (2016) recently gave an extensive overview study based on MODIS data. His results confirm that the polynays in Kara Sea and East Siberian Sea are active in late winter/spring, but they show no increasing trend in sea ice export. We have added the reference and adjusted the text:

"Our findings highlight the importance of sea ice dynamics in winter for summer sea ice conditions in the Laptev Sea and likewise in the adjacent Siberian Seas, where large polynya systems develop in winter \citep{preusser2016}."

Page 11, lines 17-18: This conclusion wasn't properly justified.

The negative correlation indicates that ice dynamics in winter influence fast ice decay. We believe that the existence of this statistical relationship provide evidence. However, the physical mechanism behind it can not be properly justified. We changed it accordingly:

"Moreover we could show that ice dynamics in winter not only precondition local summer ice extent, but also accelerate fast ice decay. During years of early ice retreat, coastal waters heat up quickly. This may favor melt of grounded ridges at the fast ice edge serving as anchor point for fast ice in winter."

4. Figures

Page 11, Figure 7: I don't think that this figure is necessary. Moreover, there is no blue line as introduced in figure caption.

The figure has been removed.

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Winter sea ice export from the Laptev Sea preconditions the local summer sea ice cover <u>and fast</u> <u>ice decay</u>

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Abstract. Recent studies based on satellite observations have shown that there is a high statistical connection between the late winter (Feb-May) sea ice export out the Laptev Sea, and Ice retreat in the eastern Eurasian Arctic is the ice coverage in the following summer consequence of atmospheric and oceanic processes and regional feedback mechanisms acting on the ice cover, both in winter and

- 5 summer. A correct representation of these processes in numerical models is important, since it will improve predictions of sea ice anomalies along the Northeast Passage and beyond. In this study, we highlight the importance of winter ice dynamics for local summer sea ice anomalies in thickness, volume and extent. By means of airborne sea ice thickness surveys made over pack ice areas in the southeastern Laptev Sea, we show that years of offshore directed sea ice transport have a thinning ef-
- 10 fect on the late winter sea ice cover, and vice versa. Once temperature rise above freezing, these thin ice zones melt more rapidly and hence, precondition local anomalies in summer sea ice cover. The . To confirm the preconditioning effect of the winter ice dynamics for enhanced offshore advection in late winter on the summer sea ice extent is confirmed with a model sensitivity study where we replace the inter-annual summer atmospheric forcing by a climatology. In the model, years with high
- 15 late winter sea ice export always result in a reduced sea ice cover, and vice versa. We conclude that the observed tendency towards an increased ice export further accelerates ice retreat in summer. The mechanism presented in this study highlights the importance of winter ice dynamics for summer sea ice anomalies in addition to atmospheric processes acting on the ice cover between May and September. Finally, cover we perform a sensitivity study using a numerical model. Results verify that
- 20 the preconditioning effect plays a bigger role for the regional ice extent. Furthermore, they indicate an increase in volume export from Laptev Sea as a consequence of enhanced offshore advection, which has far reaching consequences for the entire Arctic sea ice mass balance. Moreover we show

that ice dynamics in winter not only precondition local summer ice extent, but also accelerate fast ice decay.

25 1 Introduction

The Laptev Sea became almost completely ice free during summertime in the past years. Similar conditions in the other Siberian Seas (Kara, East Siberian and Chukchi Sea) facilitate ship transports conducted without support of icebreakers through the Northeast Passage from Europe to the Asian Far East. Although the summer sea ice melt was the main process leading to the latest sea ice

- 30 minimums in summer 2007 and 2012 when large surfaces of the Siberian Seas were ice free, in both cases the sea ice cover susceptibility to the melt has been preconditioned by Ice retreat in the Laptev Sea is the consequence of atmospheric and oceanic processes and regional feedback mechanisms acting on the ice cover. During summer, local anomalies in sea ice extent are thought to be controlled by synoptic-scale processes (e.g. cyclones) superimposed on the large-scale atmospheric circulation
- 35 (Bareiss and G orgen, 2005). The connection between shifts in the atmospheric circulation and the general thinning of the sea role of cyclonicity for anomalies in summer sea ice concentration were discussed by Serreze et al. (1993); Serreze (1995); Maslanik et al. (1996) and Maslanik et al. (2000). In particular cyclones entering the Laptev Sea from the southwest enhance the northward ice transport and are associated with an inflow of anomalous warm air masses of above average air temperatures. If
- 40 ice retreat happens early enough to allow atmospheric warming of this open water (e.g. during years of high export), winds that force ice floes back into this water cause melting. The interaction between surface winds and warm sea surface temperatures in areas from which the ice cover (Perovich et al., 2008; Parkinson and Comiso, 20 has already retreated were recently investigated by Steele and Ermold (2015). During winter, anomalous high temperatures reduces sea ice growth of first year ice, resulting in a thinner ice cover at the
- 45 end of April (Ricker et al., 2017). In addition, enhanced winter ventilation of the ocean reduces sea ice formation at a rate now comparable to losses from atmospheric thermodynamic forcing (Polyakov et al., 2017). Observations carried out in the eastern Eurasian Basis have shown that weakening of the halocline and shoaling of intermediate-depth Atlantic Water layer results in heat flux equivalent to 40 54 cm reductions in ice growth in 2013/2014 and 2014/2015. The winter
- 50 preconditioning of the summer sea ice cover has been lately used by Kimura et al. (2013) to develop a summer sea ice outlook based on the winter sea ice motion. Locally in the Laptev Sea, the major source area of the Transpolar Drift, the recent study of Krumpen et al. (2013) showed a high statistical connection of the late winter (Feb-May) sea ice export through the northern and eastern boundary to the summer sea ice concentration. Years This suggests that years of high ice export in late winter
- 55 have a thinning effect on the ice cover, which in turn preconditions the occurrence of negative sea ice extent anomalies in summer, and vice versa.



0.0 0.1 0.2 0.3 0.4 > 0.4 SMOS ice thickness (m), 2012/04/20

Figure 1. The Laptev Sea and the northern and eastern boundaries (white lines) on which satellite and model derived sea ice export estimates are based. Color coding corresponds to the sea ice thickness as obtained from Soil Moisture Ocean Salinity (SMOS) satellite on April 20, 2012 (source: University Hamburg, Tian-Kunze et al. (2014) Tian-Kunze et al. (2017)). The black and grey line show the flight path of EM-Bird ice thickness measurements made during the April 2008 (TD XIII) and April 2012 (TD XX) campaign, respectively. The approximate positions of prominent polynyas are indicated: The Western New Siberian polynya (WNS), the Anabar-Lena polynya (AL), the Taymyr (T) polynya, and the Northeastern Taymyr (NET) polynya.

In A correct representation of the above described processes in numerical models will improve predictions of sea ice anomalies along the Northeast Passage and beyond. To improve understanding of individual mechanisms contributing to sea ice decline, in this study, we further investigate the

- 60 <u>hypothesis about the preconditioning effect of winter ice dynamics on the local summer sea ice cover.</u> To separate the winter from the summer processes that influence the summer sea ice cover in the Laptev Sea, we perform a sensitivity study by means of a numerical model. This allows us to quantify the importance of the local winter preconditioning for the summer sea ice cover. The model is also used this effect and to test if the observed increase sea ice area export is reflected in
- 65

an increase in sea ice volume export out of the Laptev Sea. This would extend the importance of the regional sea ice transports to the larger region of the Transpolar Drift system.

The outline of this paper is as follows. In Section 2 we describe the observational and satellite data sources, and the numerical model. In Section 3, we review the preconditioning effect of late winter ice dynamics on the sea ice cover by means of airborne sea ice thickness surveys made at the

ro end of the winter 2008 and 2012. In section 4, we extend the late winter sea ice export of Krumpen

et al. (2013) till 2014 and compare satellite-based estimates with results obtained from the numerical model. Finally, we investigate the importance of the winter preconditioning for the summer sea ice cover in a sensitivity study (section 5). In sections 6 and 7 we discuss and sum up our findings and investigate the impact of winter ice dynamics on fast ice decay.

75 2 Data

Satellite- and model-based sea ice area export out of the Laptev between February and May is calculated using ice drift velocities and ice concentration information obtained at the northern (NB) and eastern boundary (EB) of the study area (Fig. 1). The NB spans a length of 700 km and is positioned at 81°N, between Komsomolets Island and 140°E. The EB with a length of 460 km, connects the
eastern end of the NB with Kotelnyy Island (76.6°N, 140°E). Following Krumpen et al. (2013), the sea ice flux is the sum of the NB and EB flux, which is the integral of the product between the v and u component of the ice drift and ice concentration. The volume flux is calculated in a similar way, but replacing the sea ice concentration with the sea ice thickness. Note that in this study, a positive (negative) flux refers to an export out of (import into) the Laptev Sea.

85 2.1 Satellite-based ice area export

The applied ice drift and concentration data is provided by the European Space Agency (ESA) via the Center for Satellite Exploitation and Research (CERSAT) at the Institut Francais de Recherche pour d'Exploitation de la Mer (IFREMER), France. The motion fields are based on a combination of drift vectors estimated from scatterometer (SeaWinds/QuikSCAT and ASCAT/MetOp) and

- 90 radiometer (Special Sensor Microwave Imager, SSM/I) data. They are available with a grid size of 62.5 km , using time lags and have a temporal resolution of 3 days. The applied concentration product is provided by the same organization and is based on 85 GHz SSM/I brightness temperatures, using the ARTIST Sea Ice (ASI) algorithm. The product is available on a 12.5 km×12.5 km grid (Ezraty et al., 2007). A comparison with ice drift information obtained from Environmen-
- tal Satellite (ENVISAT) Synthetic Aperture Radar (SAR) images and long-term moorings equipped with Acoustic Doppler Current profilers (ADCP) have shown that accuracy of the of IFREMER motion data is high and the uncertainty in ice area export is around $81 \times 10^3 \times 10^3$ km² for the NB and $\times 10^3$ km² for the EB over the entire winter (Oct-May) (Rozman et al., 2011; Krumpen et al., 2013). For more details about the applied ice drift and concentration products we refer to
- 100 Ezraty et al. (2007); ?); Krumpen et al. (2016) Ezraty et al. (2007); Girard-Ardhuin and Ezraty (2012); Krumpen et al. (2016).

2.2 Airborne ice thickness data

Within the framework of the Russian-German research cooperation 'Laptev Sea System' two helicopterbased electromagnetic (HEM) ice thickness surveys were made in the southeastern Laptev Sea at the end of April 2008 (campaign TD XIII) and 2012 (campaign TD XX, Fig. 1). The measurements

- 105 made over pack ice zones north of the landfast ice edge were used to estimate sea ice production in flaw polynyas (?Krumpen et al., 2011) (Rabenstein et al., 2013; Krumpen et al., 2011) and for validation of ESA's SMOS (Soil Moisture Ocean Salinity) satellite derived ice thickness products (Huntemann et al., 2014; Tian-Kunze et al., 2014) (Huntemann et al., 2014; Tian-Kunze et al., 2014, 2017). Flaw polynyas are open water sites between pack ice and fast ice of high net ice production sustained
- 110 by winds. For a detailed description of the HEM principle we refer to (Haas et al., 2009; Krumpen et al., 2016). In short, the instrument that is towed by a helicopter 15 meters above the ice surface utilizes the contrast of electrical conductivity between sea water and sea ice to determine its distance to the ice-water interface. An additional laser altimeter yields the distance to the uppermost snow surface. The difference between the laser and HEM derived distance is the ice plus snow thickness.

115 According to Pfaffling et al. (2007), the accuracy over level sea ice is in the order of \pm 10 cm.

2.3 Model

The numerical model used in this study is a regional coupled sea ice - ocean model based on the Massachusetts Institute of Technology General Circulation Model code - MITgcm (Marshall et al., 1997; MITgcm Group, 2014) with a model domain covering the Arctic Ocean, Nordic Seas and northern

- 120 North Atlantic. The horizontal resolution is 1/4° (~28 km) on a rotated grid with the grid equator passing through the geographical North Pole. The sea ice model is a dynamic-thermodynamic sea-ice model with a viscous-plastic rheology (Losch et al., 2010) and has a landfast ice parametrization as described by Itkin et al. (2015), where more details about the model set-up can be found. The model is forced by the atmospheric reanalysis The Climate Forecast System Reanalysis (Saha, 2010).
- 125 NCEP-CFSR) from 1979 to 2010 and then from 2011 to 2014 with the NCEP Climate Forecast System Version 2 (Saha, 2014, CFSv2). The selection of the NCEP-CFSR atmospheric forcing is based on the low biases compared to other atmospheric reanalysis (Lindsay et al., 2014). Itkin et al. (2014) compared sea ice concentration, thickness and drift speed or of a similar model setup without landfast ice parametrization to satellite observations. They reported that the model overestimates the summer
- 130 sea ice concentration in the shelf seas compared to the OSI-SAF sea ice concentration product eite (?) (OSI-SAF, 2013). Compared to the ICESat sea ice thickness (Zwally et al., 2002) the model reproduces the regional sea ice thickness distribution well, but it tends to overestimate the winter sea ice thickness on the Siberian shelf seas. Comparison to the CERSAT and NSIDC sea ice drift products (Girard-Ardhuin and Ezraty, 2012; ?) (Girard-Ardhuin and Ezraty, 2012; Fowler et al., 2013) showed
- 135 that the sea drift speeds in the model fall within the uncertainty of the drift products with the exception of very high drift velocities that are overrepresented by the model. Adding the landfast ice parametrization reduces the sea ice thickness bias on the shelf and partially slows down the drift speeds in the same region (Itkin et al., 2015). Despite the biases the model performance is reasonably good and can give trustable results for qualitative studies e.g. sensitivity studies.



Figure 2. Ice thickness distributions obtained from HEM measurements made offshore the landfast ice edge during the TD XIII campaign (blue: April 14, 16 and 24, 2008) and TD XX (yellow: April 20, 2012) campaign. The positions of the measurements are indicated in Fig. 1

140 3 Preconditioning of summer ice extent by winter ice dynamics

The preconditioning effect of late winter ice export on local ice cover in the following summer was investigated by Krumpen et al. (2013). A comparison of satellite-based late winter ice flux with summer ice anomalies revealed a negative coupling with a correlation coefficient of r = -0.65. The negative correlation of late winter sea ice export from the Laptev Sea and subsequent summer sea ice

- 145 concentration can be explained by the replacement of the exported ice by new ice formed in polynyas situated along the landfast ice edge. Note that there is a close relationship (r = 0.85) between acrossboundary ice export and estimated polynya area (Krumpen et al., 2013, compare Fig. 12), because offshore wind favors both, ice transport away from the coast and the development of thin ice in flaw polynyas. If new ice zones are formed comparatively late and ice motion is dominated by an
- 150 offshore directed drift component, new ice areas stay rather thin and may melt more rapidly once temperatures rise above freezing. In contrast, new ice zones formed during winters with enhanced onshore advection of sea ice, are subject to a stronger dynamic thickening which in turn delays onset of sea ice retreat.
- Sea-While sea ice thickness observations in the Laptev Sea that could confirm this preconditioning mechanism are scarce, but the existing HEM ice thickness measurements (Fig. 2) were taken during two contrasting years of late winter sea ice export. In our simulation (compare Fig. 4) as well as in the satellite-based data, the sea ice export in winter 2008 was lower than average, while 2012 was characterized by an above average export (see chapter 4). Flights that were made in 2008 (April 14, 16 and 24) cover primarily ice thicker than much thicker ice with a mean thickness of 2.7 m.
- 160 The thickness distribution shows two modes: one at 0.5 m and another one at 1.5 m. Following **?** Rabenstein et al. (2013), the ice was originally formed in polynyas in the southeastern part of the



Figure 3. Timing (day of the year) of sea ice retreat in the Laptev Sea in spring 2008 and 2012. The onset of ice retreat is defined as the first day in a series of at least 7 days with a sea ice concentration of zero (Janout et al., 2016).

Laptev Sea, but got heavily compacted during a longer period of onshore-directed ice drift in late winter. Due to presence of a compact ice cover in near shore areas, ice retreat took place relatively late in the season and large parts of the Laptev Sea remained ice covered during summer (Fig. 3,

- 165 left panel). In contrast, HEM measurements that were made on April 20, 2012 cover a substantially different ice regime: The winter of 2011/2012 was characterized by the second highest northward advection rates observed since 1992 (compare Fig. 4). As a consequence, the continuous ice export away from the landfast ice edge led to the development of an almost 200 km wide thin ice zone of less than 40 cm ice thickness. Ice thickness estimates obtained from the SMOS satellite (Fig. 1, data)
- 170 source Tian-Kunze et al. (2017)) confirm the presence of large thin ice zones all along the landfast ice edge. It stands to reason that the presence of thin ice preconditioned early sea ice retreat (Fig. 3, right panel) and contributed to the a low summer ice extent in the Laptev Sea. Note that the date of sea ice retreat for 2008 and 2012 was estimated using IFREMER ice concentration data at each grid point and defined as the first day in a series of at least 7 days with a sea-ice concentration of zeroless
- 175 $\frac{15\%}{15\%}$. For more details we refer to Janout et al. (2016).

4 Model and satellite data inter-comparison

Before investigating the impact of winter ice dynamics on summer ice conditions with the model, its performance was examined via a comparison of simulated versus satellite-based ice export and extent. Fig. 4 presents observed (panel a) and simulated (panel b) winter sea ice export (Feb -



Figure 4. Time series of the late winter sea ice transport and summer sea ice concentration for the Laptev Sea (closed box inside the northern and eastern boundaries and coastlines): a) satellite-based estimates; b) model simulations. Trend lines of ice fluxes are represented by dashed lines. Note that the sea ice concentration axis is inverted to enhance facilitate the readability comparison. Likewise, the scale of fluxes is not the same on both panels. The correlations between the model and satellite data is are provided in the text of corresponding colors.

- 180 May) and summer ice extent (Aug Sep). Both, model and satellite-based estimates show large interannual variability in export and summer ice coverage. Following Krumpen et al. (2013), the variability is primarily controlled by changes in geostrophic windvelocities. The positive trend in observed ice export of 7.19×10^3 km²/year (p = 0.0049), is however associated to an increasing drift speed<u>due to a thinning ice cover</u>, likely being the consequence of a change in the ice cover
- 185 (thinning and/or decreasing concentration), caused by the rapid loss and thinning of thick multiyear ice (Haas et al., 2008). The trend in simulated export rates is higher $(12.02 \times 10^3 \text{ km}^2/\text{year})$ but statistically not significant and statistically significant at 91% confidence level (p = 0.0888). The overall agreement between simulations and observations is high, with a correlation coefficient of 0.73-0.33 for the late winter sea ice export as well as exports and 0.81 for the summer sea ice
- 190 concentrationconcentrations. Unfortunately, sea ice volume flux estimates covering the entire investigation period are not available from observations due to the lack of the sea ice thickness measurementsfrom space. However, the model simulation shows that the volume export is highly correlated to the area flux (r = 0.98), and has a positive trend of 19.8 km³/year (not significant, p = 0.1729). Despite the good agreement, the simulated sea ice area export and summertime ice concentration are
- 195 more than double of much higher than the satellite-based estimates. The averaged simulated sea ice concentration during summer and ice export during winter amount to 47 % (\pm 16 %) and 388×10³



Figure 5. Sea ice concentration and volume seasonal cycle (1992-2014) as obtained by the model. Years : a) control run, b) model forced with above average a climatology between May and December. The mean volume sea ice export is 226 km³/season and the line colors are depicted in red, below average in blue. Years with exports close used to distinguish between years with average ($\pm 25\%$ of the mean), high (above 25% the mean) and low (+-bellow 25% the mean) are depicted in gray volume sea ice export.

Sea ice concentration and volume seasonal cycle (1992-2014) as obtained by the model forced with a elimatology between May and December. Years with above average volume sea ice export are depicted in red, below average in blue. Years with exports close to the mean (+- 25) are depicted in gray.

km² ($\pm 231 \times 10^3$ km²), while averaged satellite-based estimates are 29 % (± 18 %) and 142×10³ km² ($\pm 90 \times 10^3$ km²).

5 Sensitivity study

- 200 The negative correlation of late winter sea ice export out of the Laptev Sea and the following summer sea ice concentration is confirmed by our simulation. The correlation coefficient between winter export and summer ice cover of the remote sensing products is -0.65, while the correlation of simulated variables is even higher (r = -0.77). This indicates that the winter processes preconditioning summer sea ice cover are well captured by our model. Fig. 22-5 a shows the seasonal cycle of sea
- 205 ice concentration and volume between 1992 and 2014 in the Laptev Sea as obtained by the model. Years of above average ice export are shown in red, while years of below average export are indicated in blue. It is apparent that years of high ice export result in lower summer ice extent and vice versa. The export also impacts sea ice thickness, and consequently sea ice volume of the Laptev Sea. Strong offshore advection of sea ice In the model, sea ice thickness is 30 % lower during years of
- 210 <u>high export which in turns leads to a reduced sea ice volume and the other way around.</u>

To differentiate between the effect of winter and summer processes preconditioning the ice cover in August and September we designed a sensitivity study where the model is forced with the interannual atmospheric reanalysis in winter (Jan - Apr). From May till December a climatology (CLIM) is used instead. At every beginning of the year the simulation is continued from a state taken from

- 215 the control run (CTRL). Figure ?? 5 b shows the sea ice concentration and seasonal sea ice volume cycle from 1992 2013 as obtained by the model forced with a climatology between May and December. Results indicate that there is a clear tendency to the separation of the annual cycles of the sea ice concentration and volume in CTRL, which becomes more pronounced in CLIM. In contrast to CTRL, in CLIM all years with high late winter sea ice exports result in low summer sea ice
- 220 concentration and vice versa. Note that the impact of export strength on sea ice concentration is apparent already in April and May, when years with high sea ice export have typically lower sea ice concentration as compared to years with low sea ice export. This points to the importance of the late winter polynyas for the summer sea ice cover. Likewise the annual cycle of sea ice volume thickness is strongly connected to the export strength. A year that starts with a above average ice thickness
- 225 (high sea ice volume), but has a strong polynya activity in the late winter will have a <u>thinner ice</u> <u>cover (low sea ice volume)</u> in summer. Also the opposite is true. This means The Siberian shelf seas are lately almost completely ice free in summer, so it is not surprising that the sea ice memory on the Laptev Sea shelf is only preserved from one late winter to the next and not beyond.

6 Discussion

- 230 The negative correlation of observed and simulated late winter sea ice export from the Laptev Sea and subsequent summer sea ice concentration can be explained by the replacement of the exported ice by new ice formed in polynyas situated along the landfast ice edge. This 'late polynya ice' has less than 4 month time to grow, as in May the atmospheric temperatures can already be above the freezing temperature of sea water (?), and can be as thin as 10 cm and rarely thicker than 1 m (?).
- 235 The thickness of the late polynya ice and the area that is covered by it is determined by the ratio of onshore and offshore winds. Onshore winds compress the ice against the landfast ice edge, close polynyas and result in a low sea ice export from the Laptev Sea, while offshore winds open polynyas and drive the ice out of the Laptev Sea. In early spring, areas covered by thin ice formed during late polynya events are less resilient to melting processes and will thus be characterized by an earlier
- 240 onset of ice retreat than regions covered by the thick ice that has been growing the entire winter. The comparison of the HEM ice thickness measurements obtained in April 2008 and April 2012 over Laptev Sea pack ice visualizes the thinning effect of enhanced offshore ice advection on the sea ice cover, resulting in an earlier onset of ice retreat.

The presence of extensive thin ice areas in years with a high late winter sea ice export precondition low sea ice extent and volume in the following summer. This connection is confirmed by the model sensitivity study where we replace the inter-annual summer atmospheric forcing by a climatology. Although the model is not perfectly tuned to observations (simulated export and summer ice coverage are double of satellite-based estimates), the use of the model for a sensitivity study is sufficiently rigorous, since we expect to provide a zero-order estimate of the potential contribution of winter ice

- 250 export on summer sea ice cover. In addition, the mismatch between simulated and observed fluxes may be further attributed to an overestimation of wind speed in the reanalysis data. Too high wind speed in some of the atmospheric forcing data for the Laptev Sea region have been pointed out already by Ernsdorf et al. (2011) and Fofonova et al. (2014). The high sea ice fluxes and low sea ice concentrations in our simulation in the e.g. NCEP-CFSR atmospheric forcing used in this study
- 255 is likely overestimating the wind speeds in the early 1990smay be a consequence of another bias in the atmospheric forcing that is specific for the NCEP-CFSR. PIOMAS simulations with various atmospheric forcing show that the simulation with NCEP-CFSR results with a <u>relatively low</u> winter sea ice volume in the early 1990s that is comparable to the state in the recent years (Lindsay et al., 2014).
- In the model, years with high late winter sea ice export result in a reduced sea ice cover. In CLIM the effect is even more pronounced. However, note that summer ice concentration and volume in CLIM are by about 13 % and 32 % larger than in CTRL. In addition, the spread between the years is unrealistically low . The standard deviation in CLIM for summer ice concentration and volume is only \pm 7 % and \pm 0.19×10³ km³ compared to the \pm 16 % and \pm 0.28×10³ km³
- 265 in CTRL. This points to the importance of atmospheric processes acting on the ice cover during summer months. Following Bareiss and G orgen (2005), in addition to the preconditioning effect of winter ice dynamics, local anomalies in summer sea ice extent are thought to be which is the consequence of synoptic-scale processes (e.g. cyclones) superimposed on the large-scale atmospheric circulation during summer. The connection between shifts in the atmospheric circulation and the role
- 270 of cyclonicity for anomalies in summer sea ice concentration were discussed by Serreze et al. (1993); Serreze (1995); Maslanik et al. Maslanik et al. (2000). In particular cyclones entering the Laptev Sea from the southwest enhance the northward ice transport and are associated with an inflow of anomalous warm air masses of above average air temperatures. If ice retreat happens early enough to allow atmospheric warming of this open water (e.g. during years of high export), winds that force ice floes back into this water cause
- 275 melting. The interaction between surface winds and warm sea surface temperatures in areas from which the ice has already retreated were recently investigated by Steele and Ermold (2015) averaged forcing fields in the CLIM.

Our model simulation also provides insight into long-term changes of sea ice volume export that is currently not available from observations or satellite data. The simulated trend of sea ice volume

280 export for the period from 1992 till 2014 is positive, but not significant. This indicates that the observed acceleration of the sea ice drift and associated increase in area export out of the Laptev sea may not be compensated by the thinning effect of enhanced offshore advection. Hence, we expect

that an increased volume export from the Laptev Sea into the Transpolar Drift has far reaching eonsequences for the entire Arctic sea ice mass balance. How winter ice dynamics on the Siberian

shelves interacts with Arctic wide changes is part of an upcoming study. Moreover, it is notable that the simulated sea ice area export from the Laptev Sea has a higher correlation to the summer sea ice concentration than the volume export. This provides evidence that the northward advection of sea ice has a stronger preconditioning effect than the thickness of the ice cover itself. Ergo changes in the sea ice drift speed, as observed in large parts of the Arctic (Spreen et al., 2011), play a bigger role for the ice extent in summer than changes in the thickness of the ice cover.

6.1 Impact on fast ice decay

New ice zones formed at the end of the winter during offshore advection events rapidly melt once temperature rise above freezing. It stands to reason that the ice albedo feedback not only accelerate retreat of surrounding sea ice, but also leads to an earlier onset of fast ice decay. The Laptev

- 295 Sea is characterized by an extensive fast ice extent. The interannual and seasonal variability and trends of the southeastern Laptev Sea fast ice, an area with the widest fast ice extent in the Arctic located between 77 °N, 125 °E and 72 °N, 140 °E, were recently investigated by Selyuzhenok et al. (2015). The authors used operational sea ice charts provided by AARI to determine onset of fast ice growth, extent, beginning of breakup, and end of fast ice season between 1999 and 2013. Following
- 300 Selyuzhenok et al. (2015), the For a detailed description of methods and applied data we refer to Selyuzhenok et al. (2015). The fast ice edge in late spring closely follows the 20-25 m isobaths indicating that grounded ridges serve as an anchor point for fast ice and hence determine, among other factors, maximal fast ice extent. The onset of fast ice breakup is closely linked with Lena River breakup. In contrast, starts near the Lena Delta and is closely correlated to the river breakup
- 305 (compare Figure 5 in Selyuzhenok et al. (2015)). Mid of June river runoff overfloes fast which leads to a reduction in surface albedo. In addition, it contributes to a direct input of heat. As the fast ice breaks up along the Delta, it continues to retreat eastward. Following Bareiss et al. (1999) further decay is controlled by onset of surface melt which was confirmed by Selyuzhenok et al. (2015) who find a strong correlation with the timing of the end of the fast ice season (time when fast ice extent
- 310 drops below a certain extent) is strongly correlated with threshold value) and the onset of surface melt derived from passive microwave data. Both show a negative trend of -2.6 and -8.7 The onset of breakup and end of fast ice season are both showing negativ trends of -0.3 days/decade respectively. year and -1.0 days/year, respectively. Hence, the time it takes for fast ice to decay is shortening by -1.3 days/year.
- 315 How dynamics of pack ice in winter influence fast ice decay has not been studied. Here Therefore we compare the sea ice export with the timing of fast ice breakup and end of fast ice season (Fig. ??) obtained from satellite data. We limit the comparison to the southeastern Laptev Sea, were mechanisms of growth and decay were studied in detail by Selyuzhenok et al. (2015) and accurate infor-

mation about timing of breakup is available. The correlation coefficient between onset of fast ice

- breakup and ice area export is small (r = -0.35). This indicates that onset of fast ice breakup is independent of winter ice dynamics and, as suggested by Selyuzhenok et al. (2015) and Bareiss et al. (1999) rather attributed to the timing of river breakup. However, the correlation between end of fast ice season and ice export is high-higher (r = -0.63). Hence, in addition to the onset of surface melt, years of strong offshore advection precondition earlier end of the fast ice season and shortening of
- 325 the duration of the breakup period, and vice versa. We argue that during years of high ice export and early melt of thin ice zones, shallow waters heat up quickly and more heat is available to favor bottom melt of fast ice and grounded ridges at the fast ice edge. Melting away the anchor points controlling fast ice extent in winter may then accelerate its retreat in spring. The tendency towards earlier fast ice retreat may therefore not only be related to rising temperatures in spring and earlier
- 330 onset of surface melt, but also to the acceleration of pack ice drift and increased offshore advection. Comparison of fast ice decay and ice export between 1999 - 2013: Timing of fast ice breakup and end of fast ice season in the southeastern Laptev is given by grey and black dots respectively. Data was provided by Selyuzhenok et al. (2015). Trend lines are plotted on top. The blue line shows ice area export (km²) out of the Laptev Sea taken from satellite data (see section 2).

335 7 Conclusion

Our findings highlight the importance of the late winter sea ice processes for the sea ice dynamics in winter for summer sea ice conditions in the Laptev Sea and likewise in the adjacent Siberian Seas-The high correlation of late winter export and the summer sea ice concentration together with the HEM measurements taken in 2008 and 2012 in the Laptev Sea point to the importance of the , where

- 340 large polynya systems develop in winter (Preußer et al., 2016). Here we show for the first time the thinning effect of winter offshore winds that open polynyas at fast ice edge and drive the sea ice northwards in the central Arctic. by means of airborne thickness measurements carried out in 2008 and 2012. The new sea ice grown in polynyas is thin and subject to a relatively late in the season stays rather thin and becomes subject to quick summer melt, which leads to initiates early ice retreat
- 345 and low summer sea ice concentration and volume in the Laptev Sea. To confirm the preconditioning of the summer sea ice cover with the winter exports we perform a sensitivity study where we force our model with inter-annual atmospheric forcing from January till May and then switch to the climatological forcing till the end of the year. Our results show a clear distinction between years with high and low sea ice export: Years with high late winter sea ice export are characterized by a thinner
- 350 ice cover and reduced ice volume. The thinner ice cover melts faster which leads to the development of large open water zones that heat up quickly. Following Steele and Ermold (2015), winds that force ice floes back into this water in the subsequent month cause melting and further accelerates ice retreat. In addition, model simulations indicate that the observed increase in sea ice area export from

volume export from Laptev Sea is increasing, since the thinning of the ice cover cannot compensate

- 355 for the enhanced area export. This provides evidence that the advection of sea ice out of the Laptev Sea is accompanied by an has a stronger preconditioning effect than the thickness of the ice cover itself. Ergo increase in the volume exportsea ice drift speed, as observed on all Siberian shelf seas (Spreen et al., 2011), play a bigger role for the regional ice extent in summer than changes in the thickness of the ice cover. Moreover we could show that ice dynamics in winter not only precon-
- 360 dition local summer ice extent, but also accelerate fast ice decay. <u>During years of early ice retreat</u>, coastal waters heat up quickly. This may favor melt of grounded ridges at the fast ice edge serving as anchor point for fast ice in winter.

The mechanism presented in this study highlights manuscript complements earlier studies of Steele and Ermold (2015); Polyakov et al. (2017); Ricker et al. (2017) investigating the declining ice

365 cover in the eastern Eurasian Basin. Here we highlight the importance of winter ice dynamics for summer-sea ice anomalies of thickness, volume and extent in addition to atmospheric processes acting on the ice cover between May and Septemberin winter and summer.

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