The Cryosphere Discuss., doi:10.5194/tc-2017-28, 2017
Manuscript under review for journal The Cryosphere
Discussion started: 15 March 2017

The Cryosphere Discussions

Winter sea ice export from the Laptev Sea preconditions the local summer sea ice cover

Polona Itkin[1] and Thomas Krumpen[2]

[1]Norwegian Polar Institute, Tromsø, Norway
[2]Alfred Wegener Institute, Helmholtz Center for Polar and Marine Research, Bremerhaven, Germany

Correspondence to: Thomas.Krumpen@awi.de

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 the ice coverage in the following summer. 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, 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 preconditioning effect of the winter ice dynamics for 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 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, we show that ice dynamics in winter not only precondition local summer ice extent, but also accelerate fast ice decay.

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 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 the general thinning of the sea ice cover (Perovich et al., 2008; Parkinson and Comiso, 2013). The winter 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 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.

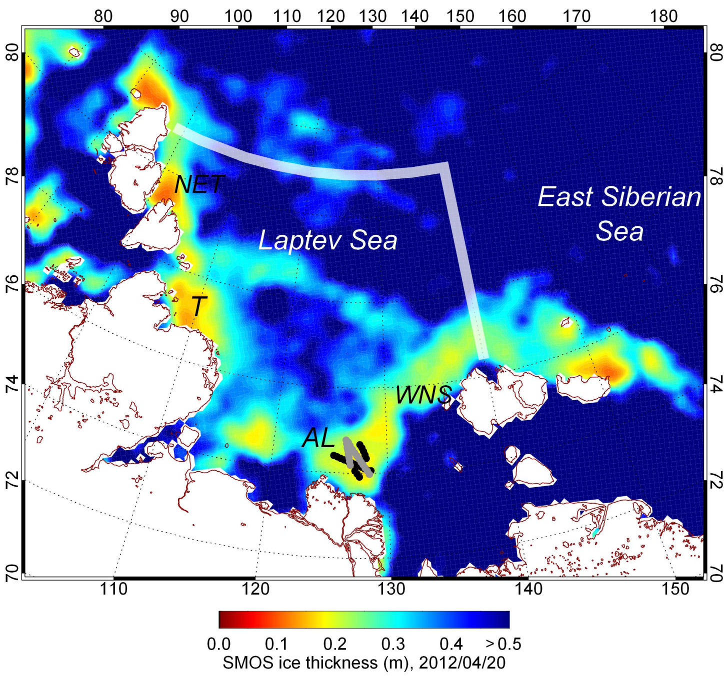

Figure 1. The Laptev Sea and the northern and eastern boundaries (white lines) on which satellite and model derived sea ice export estimates are based. Color coding corresponds to the sea ice thickness as obtained from Soil Moisture Ocean Salinity (SMOS) satellite on April 20, 2012 (source: University Hamburg, Tian-Kunze et al. (2014)). 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.

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.

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 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.

The Cryosphere Discuss., doi:10.5194/tc-2017-28, 2017
Manuscript under review for journal The Cryosphere
Discussion started: 15 March 2017

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.

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 radiometer (Special Sensor Microwave Imager, SSM/I) data. They are available with a grid size of 62.5 km, using time lags 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 Environmental 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 81×10^3 km^2 for the NB and 57×10^3 km^2 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 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 helicopter-based 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 made over pack ice zones north of the landfast ice edge were used to estimate sea ice production in flaw polynyas (Rabenstein et al., 2012; Krumpen et al., 2011b) 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). 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. According to Pfaffling et al. (2007), the accuracy over level sea ice is in the order of ± 10 cm.

The Cryosphere Discuss., doi:10.5194/tc-2017-28, 2017
Manuscript under review for journal The Cryosphere
Discussion started: 15 March 2017

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 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, 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).

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 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 across-boundary 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 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 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. Flights that were made in 2008 (April 14,16 and 24) cover primarily ice thicker than 1.5 m. Following Rabenstein et al. (2012), 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. 3, 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) confirm the presence of large thin ice zones all along the landfast ice edge. It stands

The Cryosphere Discuss., doi:10.5194/tc-2017-28, 2017
Manuscript under review for journal The Cryosphere
Discussion started: 15 March 2017

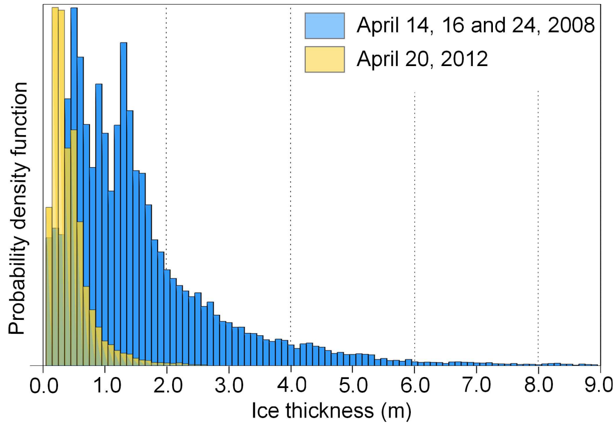

Figure 2. Ice thickness distributions obtained from HEM measurements made offshore the landfast ice edge during the TD XIII campaign (blue: April 14, 16 and 24 , 2008) and TD XX (yellow: April 20, 2012) campaign. The positions of the measurements are indicated in Fig. 1

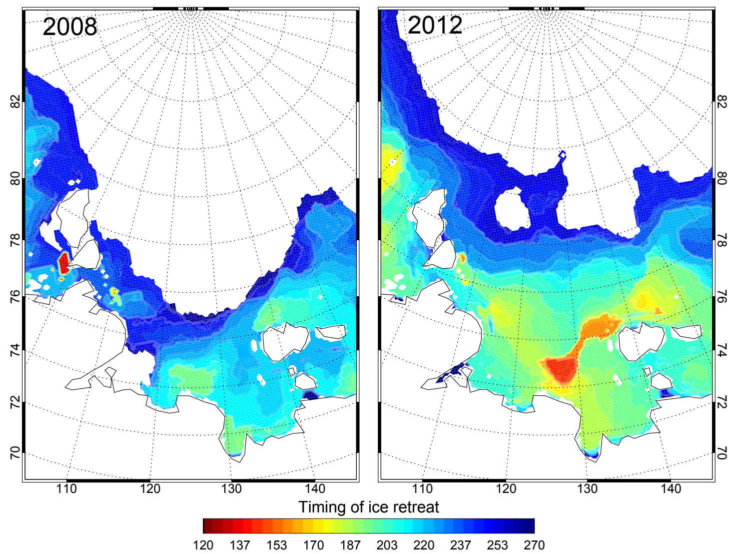

Figure 3. Timing (day of the year) of sea ice retreat in the Laptev Sea in spring 2008 and 2012. The onset of ice retreat is defined as the first day in a series of at least 7 days with a sea ice concentration of zero (Janout et al., 2016).

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 zero. For more details we refer to Janout et al. (2016).

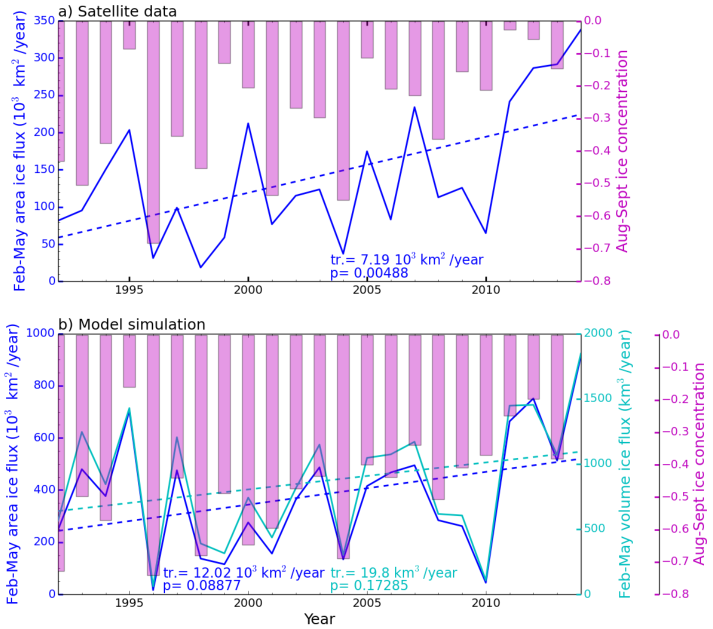

Figure 4. Time series of the late winter sea ice transport and summer sea ice concentration: a) satellite-based estimates; b) model simulations. Trend lines of ice fluxes are represented by dashed lines. Note that the sea ice concentration axis is inverted to enhance the readability. The correlations between the model and satellite data is provided in the text.

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 – 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 wind velocities. The positive trend in observed ice export of 7.19×10^3 km^2/year (p = 0.0049), is however associated to an increasing drift speed due to a thinning ice cover. The trend in simulated export rates is higher (12.02×10^3 km^2/year) but statistically not significant (p = 0.0888). The overall agreement between simulations and observations is high, with a correlation coefficient of 0.73 for the late winter sea ice export as well as for the summer sea ice concentration. 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 measurements from 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 km^3/year (not significant, p = 0.1729). Despite the good agreement, the simulated sea ice area export and summertime ice concentration are more than double of the satellite-based estimates. The averaged simulated sea ice concentration during summer and ice export during

The Cryosphere Discuss., doi:10.5194/tc-2017-28, 2017
Manuscript under review for journal The Cryosphere
Discussion started: 15 March 2017

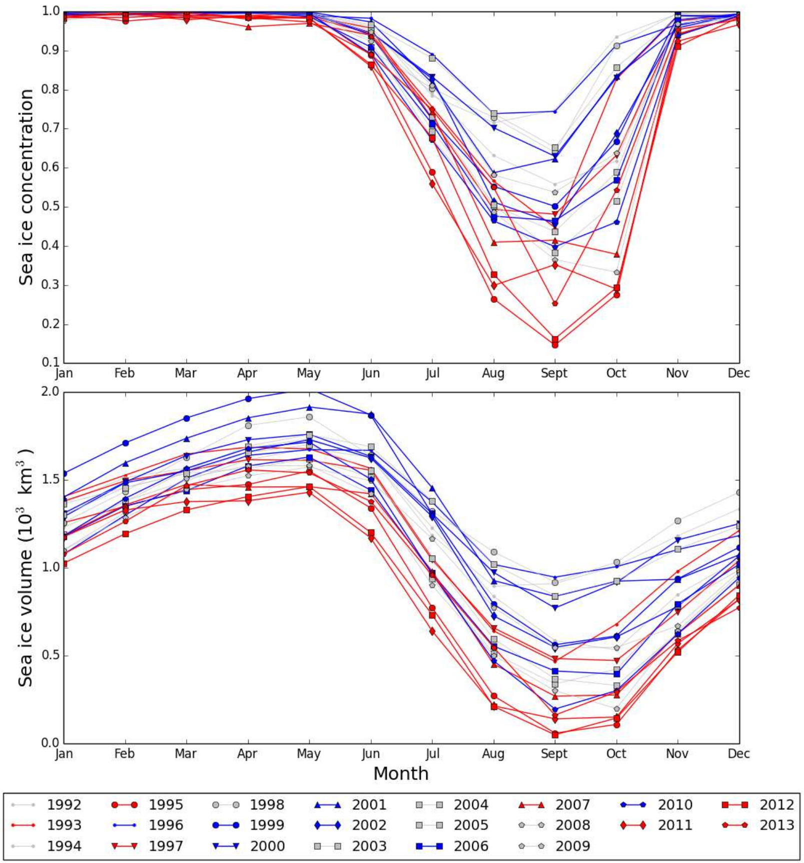

Figure 5. Sea ice concentration and volume seasonal cycle (1992-2014) as obtained by the model. Years with above average volume sea ice export are depicted in red, below average in blue. Years with exports close to the mean (+- 25%) are depicted in gray.

winter amount to 47 % ($\pm$ 16 %) and 388$\times10^3$ km^2 ($\pm$ 231$\times10^3$ km^2), while averaged satellite-based estimates are 29 % ($\pm$ 18 %) and 142$\times10^3$ km^2 ($\pm$ 90$\times10^3$ km^2).

5 Sensitivity study

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. 5 shows the seasonal cycle of sea 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

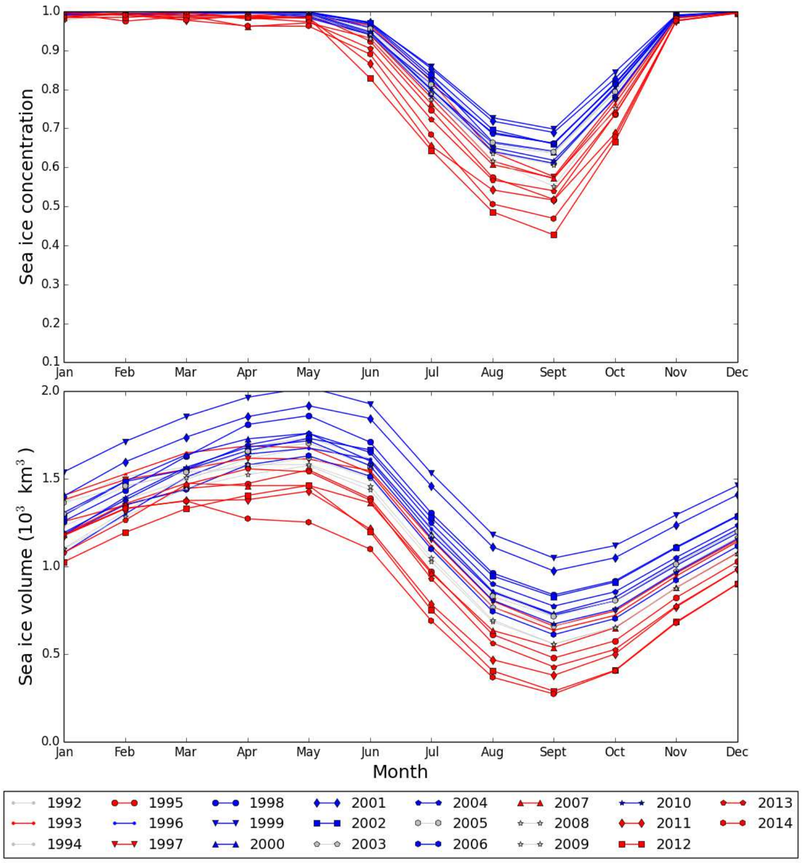

Figure 6. Sea ice concentration and volume seasonal cycle (1992-2014) as obtained by the model forced with a climatology between May and December. Years with above average volume sea ice export are depicted in red, below average in blue. Years with exports close to the mean (+- 25%) are depicted in gray.

summer ice extent and vice versa. The export also impacts sea ice volume of the Laptev Sea. Strong offshore advection of sea ice leads to a reduced sea ice volume and the other way around.

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 inter-annual 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 the control run (CTRL). Figure 6 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 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 is strongly connected to the export strength. A year that starts with a high sea ice volume, but has a strong polynya activity in the late winter will have a low sea ice volume in summer. Also the opposite is true. This means 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

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 (Krumpen et al., 2011a), and can be as thin as 10 cm and rarely thicker than 1 m (Rabenstein et al., 2012). 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 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.

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 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 1990s may 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 winter sea ice volume in 1990s 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$\times$10^3 km^3 compared to the $\pm$ 16 % and $\pm$ 0.28$\times$10^3 km^3 in CTRL. This points to the importance of atmospheric processes acting on the ice cover during summer months. Following Bareiss and Goergen (2005), in addition to the preconditioning effect of winter ice dynamics, local anomalies in summer sea ice extent are thought to be 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 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 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 Steele and Ermold (2015).

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. 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.

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, 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 Selyuzhenok et al. (2015), the onset of fast ice breakup is closely linked with Lena River breakup. In contrast, the end of the fast ice season (time when fast ice drops below a certain extent) is strongly correlated with onset of surface melt derived from passive microwave data. Both show a negative trend of -2.6 and -8.7 days/decade respectively. How dynamics of pack ice in winter influence fast ice decay has not been studied. Here we compare the sea ice export with the timing of fast ice breakup and end of fast ice season (Fig. 7) 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 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 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 (r = -0.63). Hence, in addition to the onset of surface melt, years of strong offshore advection precondition earlier end of the fast

The Cryosphere Discuss., doi:10.5194/tc-2017-28, 2017
Manuscript under review for journal The Cryosphere
Discussion started: 15 March 2017

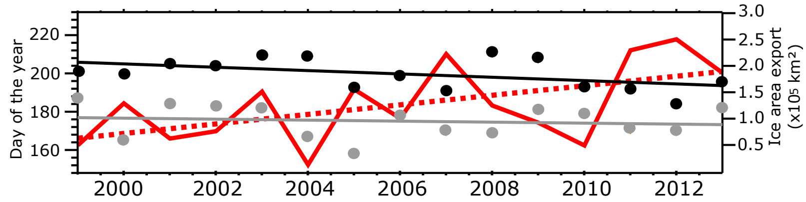

Figure 7. Comparison of fast ice decay and ice export between 1999 - 2013: Timing of fast ice breakup and end of fast ice season in the southeastern Laptev is given by grey and black dots respectively. Data was provided by Selyuzhenok et al. (2015). Trend lines are plotted on top. The blue line shows ice area export (km^2) out of the Laptev Sea taken from satellite data (see section 2).

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 fast ice and accelerate its retreat. 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.

7 Conclusion

Our findings highlight the importance of the late winter sea ice processes for the 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 winter offshore winds that open polynyas at fast ice edge and drive the sea ice northwards in the central Arctic. The new sea ice grown in polynyas is thin and subject to a quick summer melt, which leads to 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 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 the Laptev Sea is accompanied by an increase in the volume export. Moreover we could show that ice dynamics in winter not only precondition local summer ice extent, but also accelerate fast ice decay. 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.

Acknowledgements. We acknowledge Valeria Selyuzhenok (Nansen International Environmental and Remote Sensing Centre, St. Petersburg) for providing us with data on fast ice breakup and Christian Haas (Alfred Wegener Institute) for his valuable comments. This work was carried out as part of the Russian–German cooperation QUARCCS and CATS, funded by the BMBF under grant tbd and 63A0028B, the Alfred Wegener Institute, the Norwegian Ministry of Foreign Affairs, and Norwegian Ministry of Climate and Environment (Arktis 2030).

References

Bareiss, J. and Goergen, K.: Spatial and temporal variability of sea ice in the Laptev Sea: Analysis and review of satellite passiv-microwave data and model results, 1997 to 2002, Global and Planetary Change, 48, 28–54, doi:10.1016/j.gloplacha.2004.12.004, 2005.

Bareiss, J., Eicken, H., Helibig, A., and Martin, T.: Impact of river discharge and regional climatology on the decay of sea ice in the Laptev Sea during spring and early summer, Arctic and Antarctic Alp. Res., 31, 214–229, doi:10.2397/155259, 1999.

Ernsdorf, T., Schröder, D., Heinemann, G., and Danilov, S.: Impact of atmospheric forcing data on simulations of the Laptev Sea polynya dynamics using the sea-ice ocean model FESOM, Journal of Geophysical Research, 116, doi:10.1029/2010JC006725, 2011.

Ezraty, R., Girard-Ardhuin, F., Piollé, J. F., Kaleschke, L., and Heygster, G.: Arctic and Antarctic Sea Ice Concentration and Arctic Sea Ice Drift Estimated from Special Sensor Microwave Data, Département d'Océanographie Physique et Spatiale, IFREMER, Brest, France and University of Bremen, Germany, 2.1 edn., ftp://ftp.ifremer.fr/ifremer/cersat/products/gridded/psi-drift/documentation/ssmi.pdf, 2007.

Fofonova, V., Androsov, A., Danilov, S., Janout, M., Sofina, E., Wiltshire, K. H., and Overduin, P.: Semidiurnal tides in the Laptev Sea Shelf zone in the summer season, Continental Shelf Research, 73, doi:10.1016/j.csr.2013.11.010, 2014.

Girard-Ardhuin, F. and Ezraty, R.: Enhanced Arctic sea ice drift estimation merging radiometer and scatterometer data, IEEE Transaction in Geoscience and Remote Sensing, Recent advances in C-band scatterometry Special Issue, 50, 2639–2648, doi:10.1109/TGRS.2012.2184124, 2012.

Haas, C., Lobach, J., Hendricks, S., Rabenstein, L., and Pfaffling, A.: Helicopter-borne measurements of sea ice thickness, using a small and lightweight, digital EM system, Journal of Applied Geophysics, 67, 234–241, 2009.

Huntemann, M., Heygster, G., Kaleschke, L., Krumpen, T., Mäkynen, M., and Drusch, M.: Empirical sea ice thickness retrieval during the freeze up period from SMOS high incident angle observations, The Cryosphere, 8, 439–451, doi:10.5194/tc-8-439-2014, http://www.the-cryosphere.net/8/439/2014/tc-8-439-2014.html, 2014.

Itkin, P., Losch, M., and Gerdes, R.: Landfast ice affects the stability of the Arctic halocline: evidence from a numerical model, Journal of Geophysical Research, 120, doi:10.1002/2014JC010353, 2015.

Janout, M., Hoelemann, J., Waite, A., Krumpen, T., von Appen, W., and Martynov, F.: Sea-ice retreat controls timing of summer plankton blooms in the Eastern Arctic Ocean, Geophysical Research Letters, 43, doi:10.1002/2016GL071232, 2016.

Kimura, N., Nishimura, A., Tanaka, Y., and Yamaguchi, H.: Influence of winter sea-ice motion on summer ice cover in the Arctic, Polar Research, 32, doi:10.3402/polar.v32i0.20193, 2013.

Krumpen, T., Haas, C., Hendricks, S., Hoelemann, J., Gerdes, R., and Kalmbach, D.: HELIOS, a nadir-looking sea ice monitoring camera, Cold Region Science and Technology, 65, 308–313, doi:10.1016/j.coldregions.2010.11.007, 2011a.

Krumpen, T., Hoelemann, J. A., Willmes, S., Maqueda, M. A. M., Busche, T., Dmitrenko, I. A., Gerdes, R., Haas, C., Hendricks, S., Kirillov, S., Rabenstein, L., and Schroeder, D.: Sea ice production and water mass modification in the eastern Laptev Sea, Journal of Geophysical Research, 116, doi:10.1029/2010JC006545, 2011b.

Krumpen, T., Janout, M., Hodges, K. I., Gerdes, R., Girard-Ardhuin, F., Hölemann, J. A., and Willmes, S.: Variability and trends in Laptev Sea ice outflow between 1992 - 2011, The Cryosphere, 7, 349– 363, doi:10.5194/tc-7-349-2013, 2013.

Krumpen, T., Gerdes, R., Haas, C., Hendricks, S., Herber, A., Selyuzhenok, L., Smedsrud, L. H., and Spreen, G.: Recent summer sea ice thickness surveys in Fram Strait and associated ice volume fluxes, The Cryosphere, 10, 523–534, doi:10.5194/tc-10-523-2016, http://www.the-cryosphere.net/10/523/2016/, 2016.

The Cryosphere Discuss., doi:10.5194/tc-2017-28, 2017
Manuscript under review for journal The Cryosphere
Discussion started: 15 March 2017

Lindsay, R., Wensnahan, M., Schweiger, A., and Zhang, J.: Evaluation of Seven Different Atmospheric Reanalysis Products in the Arctic, Journal of Climate, 27, 2588–2606, doi:10.1175/JCLI-D-13-00014.1, 2014.

Losch, M., Menemenlis, D., Campin, J.-M., Heimbach, P., and Hill, C.: On the formulation of sea-ice models. Part 1: Effects of different solver implementations and parameterizations, Ocean Modelling, 33, 129–144, 2010.

Marshall, J., Adcroft, A., Hill, C., Perelman, L., and Heisey, C.: A finite-volume, incompressible Navier Stokes model for studies of the ocean on parallel computers, Journal of Geophysical Research, 102, 5753–5766, 1997.

Maslanik, J., Serreze, M., and Barry, R.: Recent decreases in Arctic summer ice cover and linkages to atmospheric circulation anomalies, Geophysical Research Letters, 23, 1677– 1680, doi:10.1029/96GL01426, 1996.

Maslanik, J., Lynch, A., Serreze, M., and Wu, W.: A case study of regional climate anomalies in the Arctic: performance requirements for a coupled model, Journal of Climate, 13, ´383–401, doi:10.1175/1520-0442(2000)013<0383:ACSORC>2.0.CO;2, 2000.

MITgcm-Group: MITgcm User Manual, Online documentation, MIT/EAPS, Cambridge, MA 02139, USA, 2014.

Parkinson, C. L. and Comiso, J. C.: On the 2012 record low Arctic sea ice cover: Combined impact of preconditioning and an August storm, Geophysical Research Letters, 40, 1356–1364, doi:10.1002/grl.50349, 2013.

Perovich, D. K., Richter-Menge, J. A., Jones, K. F., and Light, B.: Sunlight, water, and ice: Extreme Arctic sea ice melt during the summer of 2007, Geophysical Research Letters, doi:10.1029/2008GL034007, 2008.

Pfaffling, A., Haas, C., and Reid, J. E.: A direct helicopter EM sea ice thickness inversion, assessed with synthetic and field data, Geophysics, 72, F127–F137, 2007.

Rabenstein, L., Krumpen, T., Hendricks, S., Haas, C., Hoelemann, J., and Koeberle, C.: Thickness distribution and volume production of up to 4 months old polynya sea ice in the Laptev Sea, The Cryosphere Discussion, 7, 441–473, doi:10.5194/tcd-7-441-2013, 2012.

Rozman, P., Hoelemann, J., Krumpen, T., Gerdes, R., Koeberle, C., Lavergne, T., and Adams, S.: Validating satellite derived and modelled sea-ice drift in the Laptev Sea with in situ measurements from the winter of 2007/08, Polar Research, 30, doi:10.3402/polar.v30i0.7218, 2011.

Saha, S.: The NCEP Climate Forecast System Reanalysis, Bulleting of the American Meteorological Society, 2010, 1015–1057, doi:10.1175/2010BAMS3001.1, 2010.

Saha, S.: The NCEP Climate Forecast System Version 2, Journal of Climate, 27, 2158–2208, doi:10.1175/JCLI-D-12-00823.1, 2014.

Selyuzhenok, V., Krumpen, T., Mahoney, A., Janout, M., and Gerdes, R.: Seasonal and interannual variability of fast ice extent in the southeastern Laptev Sea between 1999 and 2013, Journal of Geophysical Research: Oceans, 120, 7791–7806, doi:10.1002/2015JC011135, http://dx.doi.org/10.1002/2015JC011135, 2015.

Serreze, M.: Climatological aspects of cyclone development and decay in the Arctic, Atmosphere and Ocean, 33, 1–23, doi:10.1080/07055900.1995.9649522, 1995.

Serreze, M., Box, J., Barry, R., and Walsh, J.: Characteristics of Arctic synoptic activity, 1952–1989, Meteorology and Atmospheric Physics, 51, 147–164, doi:10.1007/BF01030491, 1993.

Spreen, G., Kwok, R., and Menemenlis, D.: Trends in Arctic sea ice drift and tole of wind forcing: 1992-2009, Geophysical Research Letters, 38, 1–14, doi:10.1029/2011GL048970, 2011.

Steele, M. and Ermold, W.: Loitering of the retreating sea ice edge in the Arctic Seas, Journal of Geophysical Research, 120, 7699–7721, doi:10.1002/2015JC011182, 2015.

Tian-Kunze, X., Kaleschke, L., Maaß, N., Mäkynen, M., Serra, N., Drusch, M., and Krumpen, T.: SMOS derived sea ice thickness: algorithm baseline, product specifications and initial verification, The Cryosphere, 8, 997–1018, doi:10.5194/tc-8-997-2014, http://www.the-cryosphere.net/8/997/2014/tc-8-997-2014.html, 2014.