Referee #1

Dear referee, thank you very much for your thorough review. It has helped us to substantially improve the manuscript. Please find detailed responses to each of your comments below.

General comments:

General Comment 1: Four questions/comments I have after reading the introduction, which I suggest you to comment on in the paper:

1) Do fresh water export (through Fram Strait) variations influence sea-ice production on and off the Greenland shelf?

2) How much of the sea ice drifting south along the Greenland coast on the shelf is advected into the open Greenland Sea, i.e. off the shelf, and how is this related to the wind?

3) What are the water masses encountered in the Greenland Sea on and off the shelf?

4) PIOMAS is your work horse. Even though PIOMAS seems to have an excellent performance it should be kept in mind that this is a model with some inherent difficulties to describe the actual physical properties. Therefore it could add excellence to your paper by stating that you are aware of potential biases (as you will show below) in the model parameters, and by making the point that you are less interested in absolute values but rather in long-term variations and trends (and there is no reason why the model should have any drift over time, i.e. one could expect a bias in the sea-ice thickness of 1 m in 1979 to be of the same magnitude in 2009 under the same environmental conditions).

Response:

1) In our study we consider only the area off the Greenland shelf. In this region, according to Fig. 5 (c,d), water salinity increases by 0.1-0.25 in the upper 50-m mixed layer over all the “MIZ” zone used. This is in spite of a larger ice transport through Fram, and we explain this in the paper by a larger concurrent Atlantic water transport into the Greenland Sea. The salinity increase by 0.2, leads to a drop of the water freezing temperature by 0.1. Using Cp=3900 J/(kg ^{o}C), water density=1030 kg/m^3 and the MIZ area =2.3*10^{11} m^2, we find the additional heat needed to be applied due to the salinity drop to be about 1*10^{17} J. This is 3 order of magnitude less than the additional heat released by the ocean (2*10^{20} J) and the salinity variations can be neglected.

2) The advection of sea ice drifting south along the eastern Greenland coast indeed has an influence on interannual sea ice variability of the interior Greenland Sea. We have not found any quantitative estimate in the literature. However, a qualitative linkage between wind pattern and sea ice advection from the eastern Greenland coast is described in Germe et al. (2011). According to Germe et al. (2011), in the region the wind varies with the NAO phase. During the negative NAO phase, a reduction of the northerly wind, permits a more intensive westward Ekman drift of sea ice into the Greenland Sea interior. This information is now included in Introduction (page 3 lines 4 — 6). These may slightly increase the ice volume off shelf due to transport form the shelf. These variations in ice advection are incorporated into PIOMAS through dependence of ice concentration of wind and ocean current drag. Thus, they are included in our mass balance estimates.

3) The paragraph below, describing the water masses in the sea, is added to the Introduction (page 2, lines 6— 17):

“The upper 500 m in the western Greenland Sea is formed by mixing the Polar Water (PW) with temperature, close to freezing and salinity from 33 to 34 and the Atlantic Water (AW) with temperature over 3 ◦ C and salinity around 34.9 recirculating in the southern part of the Fram Strait (Moretskij and Popov, 1989; Langehaug and Falck, 2012; Jeansson et al., 2017). The maximum PW content quickly decreasing in the off shelf direction is found in the upper 200 m of the Greenland shelf (Håvik et al., 2017). The AW is found below the PW. Its core is observed in the seawards branch of the EGC, trapped by the continental slope. The centrals parts of the Greenland Sea represents a mixture of the AW and the PW with the Greenland Intermediate Water (with temperature -0.4 – -0.8 ◦ C and salinity ∼34.9). The core of the Greenland Intermediate Water is found at 500-1000 m. The Greenland Sea Deep Water (with temperature -0.8 – -1.2◦C and salinity ∼34.9) is found below 1000 m. The latter two water masses are formed by advection of the intermediate and deep water, coming from the Arctic Eurasian basin through the Fram Strait, mixed with the recirculating Atlantic Water by winter convection (Moretskij and Popov, 1989; Alekseev et al., 1989; Langehaug and Falck, 2012). The convection depth in the Greenland Sea often exceeds 2000 m (Latarius and Quadfasel, 2016; Bashmachnikov et al., 2019).”

4) We agree that the missing information on PIOMAS potential biases is important for understanding the results. There are indications of sea ice thinning since 1980s (e.g. Lindsay and Zhang 2005). A reduction of the sea-ice thickness in the Fram Strait was observed in 2003–2012 (Renner et al. 2014). As the PIOMAS bias depends on the ice thickness, the error sign and magnitude will differ in different parts of the region and with time. This issue was addressed in the Discussion (Sec. 5.1). Taking into account you comment, we also changed the data description (page 4, lines 5-8):

“The spatial patterns of PIOMAS ice thickness agrees well with those, derived from in situ and satellite data. The model overestimates the thickness of thin ice and underestimates the thickness of thick ice. Such systematic differences might affects long-term trends in thickness and volume (Schweiger et al., 2011). There is an indication that the PIOMAS shows a conservative sea ice volume trend (1979-2010).”

General Comment 2: The CS-2 data set is taken as if it is the truth. There are two concerns which need to be mentioned in the data-set description and again mentioned in the context of your inter-comparison between PIOMAS and CS-2 sea-ice thickness. 1) The CS-2 sea-ice thickness retrieval requires snow depth information which is taken from a climatology. Hence any inter-annual variation in sea-ice thickness might not be due to an actual variation in sea-ice thickness but due to a variation in the match between the snow-depth climatology and the actual snow depth. 2) By the same token: The snow-depth climatology used is not valid outside the Arctic Ocean. Snow depths outside the Arctic Ocean are based on an extrapolation which, e.g. in the Hudson Bay provide negative snow depths.

Response: We fully agree that the uncertainties of the CryoSat-2 sea ice thickness retrieval need to be discussed in more detail. Indeed, the modified Warren Climatology, which is used to convert freeboard into sea ice thickness, is not applicable in the Fram Strait. Therefore the snow depth used for the thickness retrieval in Fram Strait is based on an extrapolation of the climatology. On the other hand, ice flows that pass the Fram Strait, comming from the Central Arctic, are advected very fast within one month (up to 500 km/month) . Therefore, we would not expect a significant difference in snow depth between 82°N and 78°N. Nevertheless, the fact that a climatology is used here, means that interannual variations in snow depth are not captured, and can therefore cause interannual biases in the sea ice thickness retrieval. We have added a paragraph in section 2.2 for clarification (page 4 lines 25-31):

“Uncertainties of CS2 ice thickness increase below 78 ◦ N due to sparse orbit coverage (Ricker et al., 2014). The CS2 retrieval is based on sea ice freeboard measurements that are converted into sea ice thickness assuming hydrostatic equilibrium. Estimates of snow depth, required for the conversion, are based on the modified Warren climatology (Warren et al., 1999; Ricker et al., 2014). This climatology is not defined in the Fram Strait or Greenland Sea, therefore, snow depth estimates are extrapolated. Moreover, interannual variability in snow depth is not captured by the climatology, which can potentially cause biases in the final sea ice thickness retrieval. In addition, high drift speeds can also cause biases in the ice thickness retrieval due to the timeliness of the satellite passes within one month. The typical uncertainty is in the range of 0.3 - 0.5 m, but may potentially reach higher values.”

General Comment 3: This concern goes to Section 3.2. I have a few comments / questions here which I ask the authors to explain better and/or comment in their paper.

1) I would strongly recommend to assign an ice mass balance GAIN to a POSITIVE value of "MB" and an ice mass balance LOSS to a NEGATIVE value of "MB" and not the way done currently. It is confusing the way written.
2) Did you take into account how long sea ice stays in your region of interest? Or in other words: How long does a group of ice floes entering the Greenland Sea at Fram Strait need to travel the distance to Denmark Strait? Could this impact your estimates?
3) How did you compute the regional sea-ice volume? What is the region over which you compute the sea-ice volume?
4) Please carry out a unit check. Which physical units do V, QF and MB have? Do these fit together?

5) You combine the difference in the regional sea-ice volume of two consecutive months, e.g. January and February, with the sea-ice volume flux difference at the northern (QF) and southern (QD) end of your region of interest for February. I assume that the time for which the sea-ice volume data are "valid" are Jan 15 and Feb 15, i.e. the middle of the respective month, integrating over Jan 1 to 31 and Feb. 1 to 28. For which time period is the sea-ice volume flux estimate valid? To me February implies that it is also derived for February and is hence valid for Feb 1 to Feb 28. Please describe what you combined in more detail because to me the balance seems not closed the way it is computed / written. It seems to me that you are combining different time periods.

Response:
1) The notation and corresponding formula were change according your recommendation.

2) On average it take 3-4 month for sea ice to travel from the Fram Strait to the Denmark Strait (Mironov, 2004). Once the sea ice entered the region, the its volume added for in the regional volume balance (V(m+1)-Vm). For the interannual variations discussed, the travel time from the Fram Strait to the Denmark Strait does not impact the estimates.

3): Thank you, this information was missing. We added the following sentence to the text (page 7, lines 2-5):
“The regional sea ice volume was calculated for the area limited by 82 ◦ N and 66 ◦ N latitudes and boarder on the east shown in Figure 11a (green box). We slightly extended the eastern boundary of the Greenland Sea to the south-east, compared to its classical definition in order to include the entire area of the Odden ice tongue formation.”

4): Thank you, there was a time variable missing in the equation (5). It is now corrected: V, MB are in km^3, QF is in km^3 $month^{-1}$.

5): The regional sea ice volume and the sea ice fluxes in the computations are estimated using the same sea ice thickness data, averaged over the same month. The balance is then correctly obtained for the integral ice volume over the Greenland Sea. Here we neglect higher frequency (intra-monthly) variations. The point of this comment might be that after ice enters the northern part of the region, it might take time for it to travel to the central areas of the Greenland Sea, where it efficiently melts. However, the results of our study are obtained for interannual (cold-season-mean) variations. Averaged over the cold season and taking into account the ice travel time of 3-4 months (see above), we may consider the process of ice inflow and that of ice melt to be simultaneous on these time scales.

General Comment 4: A lot of the interpretation of the data is / needs to be based on the ARMOR data set period which begins in 1993 and ends in 2016. On the other hand, the main results obtained with PIOMAS with respect to sea-ice volume and sea-ice volume fluxes and sea-ice mass balances are for the period 1978/79 through 2017, hence a substantially longer period. The paper would benefit from adding a careful consideration and discussion of the considerably different trends in the sea-ice volume related variables for the shorter ARMOR period in comparison to the longer period. Conclusions might change.

Response: Thank you, good point. We have calculated the trend in sea-ice variables since 1995 in order to exclude an anomalous sea ice volume flux thorough the Fram Strait in 1994, which would affect the linear trend. For this shorter period the trends SIV and SIF lose their statistically significance, as the lengths of the time series, used for the computations, are now much shorter. Nevertheless, the magnitudes of the trends remain close to those derived for 1979-2015 (see table below), which indicates that the two results are comparable. As the long-term trends (1979-2015) represents the changes in sea-ice parameters with a higher formal statistical accuracy, we keep this result in the paper. However, the linkage between ocean and sea ice is analyzed based on a shorter time series (1993-2015), limited by the ocean data-base.

Trends (1995-2015) in monthly mean characteristics in the Greenland Sea calculated over annual (September-August), winter (October-April) and summer (March-September) periods: sea ice volume (SIV, km^3/year), sea ice volume loss (SIV loss, km^3/year), sea ice flux though the Fram Strait (SIF Fram, km^3/year), water temperature in MIZ (Tw, °C/year) and in the West Spitsbergen Current (TWSC, °C/year), heat flux across the Svinoy section (Q_{Svinoy}, TW/year).

parameter	season	trend	r^2	STD	p-value
SIV, km^3/year	annual	-8.80 (-0.89%)	0.26	2.31	0.03
	winter	-8.12 (-1.25%)	0.27	3.19	0.02
	summer	-6.82 (-1.05%)	0.15	3.75	0.09
SIV loss, km^3/year	annual	0.57 (0.53%)	0.02	0.92	0.54
	winter	1.01 (0.94%)	0.03	1.46	0.50
	summer	-0.36 (-0.33%)	0.01	1.07	0.74
SIF Fram, km^3/year	annual	0.89 (1.11%)	0.05	0.91	0.34
	winter	0.81 (1.02%)	0.02	1.37	0.56
	summer	0.85 (1.05%)	0.08	0.67	0.22

General Comment 5:

1) The period considered starts in winter 1978/79 and hence at a time when Is-Odden events occurred quite regularly. The paper lacks a discussion of the results with respect to the Is-Odden variability and, in particular, about the practical absense of the Is-Odden since about 2004 (?).

2) In addition, the paper lacks a discussion about the validity of the usage of an average MIZ area in a highly dynamic region where, thanks to the Is-Odden, sea-ice edges can be located substantially further off-shelf than suggested by the MIZ area chosen. Particularly in the context of Equation 7 usage of an actually varying MIZ might change the picture.

3) Finally, the period also covers the so-called ice-surge years 1989-1991 when a lot of the really thick and old ice exited the Arctic Ocean through the Fram Strait. A discussion of whether this is visible in the results or not (and why not) would also nicely complement this paper - perhaps even more than the relatively hypthetical considerations about NAO-Index links with water mass properties, circulation changes, and mixed layer depth variations.

Response:

1) The interannual variation in Odden occurrence is linked to the local surface temperature, local wind and on the large scale - to variations in NAO phase (e.g. Germe et al. 2011, Rogers and Hung 2008, Comiso 2001, Shuchman et al. 1998). The idea that the ocean may be important in modulating the formation of Odden tongue was proposed by Visber et al. (1995). Germe et al. (2011) showed that the occurrence of the Odden feature is not linked neither to the regional sea-ice variability, nor to the Fram Strait sea-ice areal flux. We also did not find any link between the sea-ice variables and the time series Odden occurrence from literature. On the other hand, the increase in the ocean heat content between 1993-2016 are visible in the area of Odden formation. At this stage, we only provide an addition argument in favor of further quantification and understanding of the oceanic influence on the Odden formation. We added few sentences to the discussion (page 13 lines 11-14):

"The interannual variations in sea ice area were previously linked to variations in air temperature (Comiso et al., 2001). The results of our paper permitted to speculate, that ocean temperature may be important in controlling Odden formation (see also Shuchman et al. (1998); Germe et al. (2011)). E.g. the reduction of Odden tongue occurrence in 2000s (Latarius and Quadfasel, 2010) might be partially driven by the increase in upper ocean heat content (Fig.5b)."

and (page 10 lines 27-34):

"With a stronger melting of sea ice at the seawards part of the MIZ, together with the ice volume loss, we should observe a sea ice area loss. This is consistent with Germe et al. (2011). In particular, positive water temperature trends over the eastern part of the Odden region suggest an overall decrease of the Odden formation by the end of the study period. The mean temperature trends over the Odden region (the area within the dotted line in Fig.15b) is 0.08 $\circ$ C per year, i.e. there is an area-mean increase by 1.8 $\circ$ C from 1993 to 2016. This exceeds the mean ocean temperature increase, averaged in the MIZ area (Eq.7), which includes the northern shelf break regions with negative temperature trends. Therefore, the estimates of the heat available for the ice melt, based on the values presented in Eq.(7), should be considered as the lower limit of the heat release within the Odden region."

2): In order to justify the validity of average MIZ, we added the following information to the text (page 7 lines 21 -34):

"The position of the real MIZ strongly varies in time and along the EGC, being a function of local direction and intensity of sea ice transport by wind and current, variation in the characteristics of ice transport from the Arctic and interaction of ice floes, local ice thermodynamics, etc. Presence of melting sea ice, in turn, affects the upper ocean and air temperatures. A warmer winter ocean warms up the air, which can further be advected over the sea ice causing its melt away from the sea ice edge. Furthermore, an anomalously warmer ocean may prevent (or delay) formation of a new ice. All these distant factors certainly affect the MIZ position. However, if we estimate ocean temperature variations only along the actual MIZ, we do not account for these effects. The considerations above show that defining the oceanic region directly and indirectly affecting the ice volume in the sea is not straightforward. In this study we define interannual variations of ocean temperature in a fixed region, which is defined as an area enclosed between the 500-m isobath, marking the Greenland shelf break, and the mean winter location of the sea ice edge (Fig. 11). Using the fixed region also assures compatibility of interannual temperature variations. For the computations, the sea ice edge was defined as the 15% mean winter NSIDC sea ice concentration for 1979-2016. For brevity we further, somewhat deliberately, call this region the MIZ area. We further will see that temperature trends remain positive and of the same order of magnitude all over the western Greenland Sea, except for a few limited areas along the shelf break. This assure robustness of the results to the choice of the study region."

As the trends in Figure 5b are all positive and of the same order of magnitude, some reasonably sizable variations in the position of the eastern boundary of the study region makes no difference to the result. The following discussion is added (page 10 lines 10-34):

"Figure 5a shows interannual variations of November 2 ◦ C sea water isotherm (averaged over the upper 200-m layer). Water temperature in November reflects the heat fluxes accumulated during the warm period. It shows the background conditions formed by the beginning of winter cooling, when sea ice start forming localy. However, the performed tests show that the tendency of the isotherm to approach the shelf break is consistent for different isotherms (from 1 to 3 ◦ C), for different layer thickness (50 to 200 m) and for different months. The difference is only observed for winter months, when the whole upper 200-m mixed layer effectively releases heat and the interannual trends become insignificant. From 1990s to 2000s the 2 ◦ C isotherm approached the shelf break. The largest westwards propagation is observed in the WSC recirculation area (76-78 ◦ N) and northwest of Jan Mayen (70-73 ◦ N), in the southern Odden tongue region. The linear temperature trend (Fig. 5b) shows warming in the whole area of the eastern MIZ. The strongest warming follows the pathway of the recirculating AW in the northern Greenland Sea (Glessmer et al., 2014; Håvik et al., 2017) which is known to strongly affect the central regions of the sea (Rudels et al., 2002; Jeansson et al., 2008). The warming in the northern Greenland Sea is linked to a strong warming of the WSC and of the Norwegian Atlantic Front Current (NwAFC), while that in the southernmost part of the sea – with the NIIC. Two exceptions can be noted: the northwestern part of the coastally trapped EGC (where negative trends are obtained in the area dominated by a colder PW outflow from the Arctic) and the area of the EGC recirculation into the Greenland Sea at 72-74 ◦ N extended from the continental shelf break to 8-9 ◦ W (here the tendencies in the upper ocean temperature are close to zero). The latter is the area, where the Odden ice tongue starts spreading into the Greenland Sea interior (Germe et al., 2011). The decrease of warming in these areas is consistent with a stronger sea ice/PW transport from the Arctic (Sec. 4.2).

With a stronger melting of sea ice at the seawards part of the MIZ, together with the ice volume loss, we should observe a sea ice area loss. This is consistent with Germe et al. (2011). In particular, positive water temperature trends over the eastern part of the Odden region suggest an overall decrease of the Odden formation by the end of the study period. The mean temperature trends over the Odden region (the area within the dotted line in Fig.5b) is 0.08 ◦ C per year, i.e. there is an area-mean increase by 1.8 ◦ C from 1993 to 2016. This exceeds the mean ocean temperature increase, averaged in the MIZ area (Eq.7), which includes the northern shelf break regions with negative temperature trends. Therefore, the estimates of the heat available for the ice melt, based on the values presented in Eq.(7), should be considered as the lower limit of the heat release within the Odden region."

3) Thank you, it is an interesting point. We added the following text to the discussion (page 12 lines 19 – 28:

“The PIOMAS Fram Strait sea ice volume flux can be also affected by these systematic errors. The model studies show three major positive peaks in the Fram Strait sea ice volume flux since 1979: 1981-1983, 1989-1990, 1994-1995 (Arfeuille et al., 2000; Lindsay and Zhang, 2005). The anomaly in 1989-1990 was caused by an increase in the thickness of the transported sea ice, while the anomaly in 1994-1995 was due to an intensification of southward sea ice drift (Arfeuille et al., 2000). The reduction of Arctic myltiyear ice fraction during late 1980s – early 1990s (Comiso, 2002; Rigor and Wallace, 2004; Yu et al., 2004; Maslanik et al., 2007) are in line with this finding. The sea ice volume flux through the Fram Strait derived from PIOMAS shows the peaks in 1981-1985 and 1994-1995, but does not capture the anomaly of 1989-1990 (Fig.14c). During this period there is no significant shift in the PIOMAS effective sea ice thicknesses in the Fram Strait which is likely caused by the PIOMAS systematic errors which smoothed the differences in thickness between thick and thin ice.”

and (page 16 lines 4 – 6):

“However, those PIOMAS-based trends should be treated cautiously. The absence of positive anomaly in PIOMAS-based SIF in 1989-1990 indicate that the PIOMAS underestimate thickness of thick in the Fram Strait and the Greenland Sea. The biases might lead to the actual long-term SIF trend to be weaker, while the SIV trend to be stronger.”

Specific comments:

Comment: Page 1 - Line 18: From where is "oceanic buoyancy advected to the sea"? Which sea?

Response: The sentence is re-phrased: “as well as oceanic buoyancy advection into the region.”

Comment: Page 2 - Line 2: "by solid ice transport" –> do you refer to sea-ice transport? Then I suggest to name it like this and then add something like "melting outside the Arctic Ocean"

Response: The sentence is re-phrased.

Comment: - Line 10: Did Ricker et al. (2018) also exclude extreme negative NAO events? If not then please re-formulate the sentence accordingly.

Response: Thank you. Ricker et al. (2019) did not exclude extreme negative NAO events. The sentences are re-phrased:
“There is a moderate correlation (0.62) between between NAO index (excluding extreme negative NAO events) and winter sea-ice area flux through the Fram Strait over 24 years of satellite observations (1978-2002) (Kwok et al. 2004). A higher correlation (0.70) between NAO index and winter sea-ice volume flux based CS2 data (2010-2017) is reported by Ricker et al. (2018).”

Comment: - Lines 13-15: Please make sure you write sea-ice volume flux where you refer to volume flux and sea-ice area flux where you refer to area flux. Here it remains unclear what "sea ice flux" is.

Response: Thank you, corrected

Comment: - Line 16/17: I am not sure the statement about the sea-ice production holds the way written, because "sea-ice production" is not just about sea-ice area but also about sea-ice thickness and/or volume. I did not find any hint about sea-ice volume in Germe et al. (2011). It is a tricky region. Perhaps you could split this statement into two parts: one related to the sea-ice on the shelf which particularly in the northern part (i.e. between Fram Strait and 75 degN) experiences a lot of fractioning and lead openings in which sea-ice forms quickly and to considerable thicknesses while the other one related to the off-shelf new ice formation in the Is-Odden tongue area, which is mostly thin, grease and pancake ice, sea ice. I agree with you that the largest variability is observed in the Is-Odden region but, to my knowledge, we also simply don't know anything about the variability of sea-ice production on the Greenland Sea shelf.

Response: Thank you, the sentence is re-phrased:

"The sea ice production in the Greenland Sea takes place east of the shelf between 71-75ºN and north of 75ºN withing the highly dynamic pack ice transported southwards along the Greenland coast. The latter fills in cracks and leads and can reach considerable thickness. While the sea ice forming east of the shelf is mostly thin newly-formed ice."

Comment: - Lines 32/33: "Shorter time series" <–> Figure 3c in Spreen et al. (2009) does not go along well. I suggest to rewrite this statement.

Response: Thank you, clarified this in the text:

"A combined time series of of sea-ice volume flux through the Fram Strait (1990-1996 (Vinje et al. 1998; 1991-1999 (Kwok et al., 2004) and 2003-2008 (Spreen et al., 2009)) shows a shift towards lower fluxes in the early 2000s compared to 1990s. However, the later study of Ricker et al. (2018) reveals that the sea-ice volume flux in 2010-2017 is similar to that in 1990s. Due to different uncertainties in the data used by the cited authors and to different methodologies used in those studies, it not possible to merge their results to get uninterrupted data-set for the entire period from 1990 to 2017. Although individual studies do not present significant trends in the volume flux, the overall tendency remains unknown."

Comment: Page 3 - Section 2.1 general: Please provide information such as grid resolution and type, time step (6-hourly?, daily?), etc. with which you used the PIOMAS data.

Response: We added this information:
"The original monthly PIOMAS sea ice thickness data were re-gridded to 25 km EASE-2."

Comment: - Lines 7-10: Please be more specific with the data sets assimilated into PIOMAS, e.g. which algorithm the sea-ice concentrations are based upon, what the origin of the sea-surface temperature data set used and what kind of NCEP/NCAR data is used? Is the latter from re-analysis?

Response: We have slightly changed the sentences, the detailed information can be found in the referred literature:

"It assimilates NSIDC (National Snow and Ice Data Center) near-real time sea daily ice concentration, daily surface atmospheric forcing and the sea-surface temperature in the ice-free areas from NCEP (National Centers for Environmental Prediction)/NCAR (National Center for Atmospheric Research) reanalysis (Zhang et al., 2003, Schweiger et al., 2011)."

Comment: - Line 17/18: I suggest to use "inter-comparison" instead of "cross-validation". What you carry out is not a validation - mainly because you don't have the true sea-ice thickness at hand. The same applies to later usage of this term.

Response: We agree that "inter-comparison" is a better term. Corrected.

Comment: - Line 19: While you describe the CS-2 data in Section 2.2 you don't describe the ULS data (which you state here to be used for the "cross-validation" of the sea-ice volume)

Response: Thank you, the presence of ULS data in the text is confusing. It was used for sea ice volume flux estimation in Kwok et al., 2004. To avoid confusion we removed "ULS" from the text and refer to the data set as "observation-based".

Comment: - Line 25/26: What kind of a grid is this? "spatial resolution" –> "grid resolution".

Response: Changed:
"The CS2 data-set provide monthly average sea ice thickness on EASE-2 grid with 25x25 km spatial resolution from 2010 to 2017."

Comment: - Line 29: I find your variable notation quite confusing and not to the point (here and again later in your paper). Suggestion: SIC –> C, HI –> I, HIE –> I_eff , i.e. with "eff" as a subscript. You could drop the "i" in the subscript and simply write in the text that you carry out this computation for every grid cell.

Response: Corrected.

Comment: Page 4 - Lines 12/13: How are the vertical density profiles computed? Are these part of the ARMOR data set or did you compute them on your own? Are the mentiond current velocities relevant for your paper? Are these available with the same grid resolution?

Response: The routine computations of water density is done using UNESCO 1981 equation of state of the seawater. We use current velocities for computation of oceanic heat advection through selected sections. The currents are gridded into the same spatial grid as the T-S data. To avoid ambiguity we re-phrased the sentence as:

"The oceanic heat fluxes are estimated using currents from the ARMOR data-set with the same spatial and temporal resolution. The current velocities at various depth levels are obtained by extrapolating the sea-surface current from the satellite altimetry, downwards using the thermal wind relations. The vertical density profiles, used for the computations, are assessed from the previously obtained temperature and salinity profiles (Mulet et al., 2012)."

Comment: - Lines 18-20: It is not entirely clear to me from how many profiles (?) with which average inter-profile distance (?) data contribute to the time series used. What is meant by "the core"?

Response: The entire paragraph is re-written:

"Long-term series of monthly gridded water temperature is obtained from "The Climatological Atlas of the Nordic Seas and Northern North Atlantic" (Korablev 2007}. The data-base merges together data from ICES (International Counsel for Exploration of the Sea), from IMR (Institute of the Marine Research), from a number of international projects (ESOP, VEINS, TRACTOR, CONVECTION, etc.), as well as from Soviet Union cruises in the study region. However, there are too few observations in the EGC before the 2000s. In this paper we use long-term temperature time series in the much better sampled upper WSC at 78°N, west of East-Fjord (Fig. 1). The depth averaged water temperature at 100-200 m is used, as this layer is dominated by the Atlantic Water and it is not directly affected by heat exchange with the atmosphere all year round. This results in the highest temperature at these depths during cold season. Even this region was sampled in a quite irregular manner, with a lower sampling frequency in winter. Since 1979, the average number of samples was 161 per year, varying from, on average, 2-5 per year from November to May to 20-35 per year from June to October. The data-gaps in the time series were filled in by kriging with the 30-km window. The interannual variations presented in this study were averaged over the months the most densely covered with data (June to September)."

Comment: - Line 21: Would it do any harm on the data set to also include data from May? That way you would comply with your earlier definition of summer: May through September.

Response: The data in May are too scares and were not included in the mean values. This certainly does not affect the observed interannual trends.

Comment: - Lines 24-29: Which sea-ice drift data set is used? Is this quantity provided by PIOMAS? You have introduced the effective sea-ice thickness already before and can delete the second sentence here, changing "sea-ice thickness" to "effective sea-ice thickness" in the first sentence. Did Sumata et al. (2014/2015) also include PIOMAS and/or the sea-ice drift data set you used in their inter-comparison studies?

Response: We use NSIDC Pathfinder v 3 data It is now mentioned in the text. Sumata et al. (2014, 2015) used the version 2 of the NSIDC data-set. The redundant sentences about the effective ice thickness is removed.

Comment: Page 5: - Equations 2 to 4 and related text: Following up with my comment to Equation 1 I suggest that you also here change the notation. It seems that you need to use super-scripts to indicate the source of the data, i.e. I^CS2_eff for the effective sea-ice thickness from CS-2 (see Eq. 1) and I^PIOMAS_eff for the effective sea-ice thickness from PIOMAS. On which grid is this computation carried out? If l = 25 km = constant distance between grid cells (or grid cell centers?), then it needs to be a grid such as the EASE-grid? Please be more specific here. Furthermore, usage of D_x and D_y suggests that your drift data set indeed only contains drift components relative to the grid (which?) on which the data set is provided and does NOT contain the true u (West-East positive) and v (South-North positive) motion components? May I nevertheless suggest that you change "D" to something like "v" for velocity or, even better, "u" and "v" (of course keeping the sub-scripts x and y)? If you then also replace "l" by "d" for distance then equations 2 and 3 might be more understandable at first glance.

Response: We agree that in this form the understanding of equations requires some time. Nevertheless, we decided to leave the equations like they are in order to keep it consistent with Ricker et al. 2018. The calculations are performed at the EASE-2 grid. As it mentioned in the data description, the CS2 is originally on EASE-2 grid and the PIOMAS data was converted to EASE-2 grid.

Comment: - Lines 9-11: I suggest to term this sea-ice volume flux component QD. I suggest to refer to Figure 1 for illustration of the location of this gate. Is QD defined positive when leaving the Greenland Sea?

Response: The gates are now illustrated in Figure 1. We also introduced QD in the text:

“ A similar methodology was used to assess the sea-ice volume flux through the Denmark Strait (QD) along the meridional section (66ºN and 35ºW – 20ºE). The positive sign of QD corresponds to the sea ice volume outflow from the Greenland Sea.”

Comment: - Lines 11-15: It might make sense to put these lines into a new paragraph, starting with "In order ...". I don’t understand what you did here. Did you read the figures of the sea-ice volume fluxes from the papers or did you carry out the entire computations again on your own or did you copy the figures? Please be more specific in what you did. Please also stress that in case of Spreen et al. (2009) you only used the ICESat data part.

Response: Thank you, it is supposed to be a new paragraph. The monthly fluxes from Kwok et al. (2004) and Spreen et al. (2009) are presented as tables in the corresponding papers. The flux from Ricker et al. (2018) was provided by the author. From Spreen et al. (2009) we use monthly-mean flux derived using weighted ICESat thickness data. The interested reader can refer to the cited literature for details.

Comment: - Line 17: "formed due to thermodynamically" ?? please re-phrase

Response: Thank you, corrected:
“ lost or gained due to due to freezing or melt..”

Comment: - Lines 28-30: Did you use density or potential density? You text is confusing here.

Response: For computation of the vertical density gradients we use potential density. We made the corresponding changes in the text of this paragraph:

“The method is similar to that used by Pickart et al. (2002), but is applied to the vertical profiles of the potential density gradients. Before processing, the potential density profiles were filtered to remove the small-scale noise. The gravitationally unstable segments were artificially mixed to neutral stratification. The MLD is defined as the depth where the vertical density gradient exceeds its two local standard deviations within a 50-m window, centered at the tested depth.”

Comment: Page 6 - Line 2: "tested point" –> perhaps better: "tested depth"?

Response: Thank you, corrected.

Comment: - Lines 4-7: Please motivate your choice of defining the MIZ. I am asking because the inter-annual variation of the MIZ certainly results in actually much larger or much smaller areas to be considered. Particularly for winters before 2004, when the Is Odden was observed more often than after 2003, this definition would mean that the MIZ is defined for a much smaller region than actually occupied.

Response: This comment virtually repeats the **General Comment 5 2)**. We added the required information to the text (please see the answer to the **General Comment 2)** above).

Comment: - Lines 11-15: Please write where this transect Q is located. If Q is located along a latitude, isn’t d_x constant? I understood that the ARMOR data set as 1/4 degree resolution, so that neighboring data points are separated by the distance corresponding to 1/4 of a degree at the latitude of Q. If not - how is d_x computed? In Equation 6, I suggest to use a small "v" for the current speed and instead of the subscript "w" use "water" to avoid confusion with the vertical velocity component which is usually termed "w". Are density and specific heat of water constants or do these vary with temperature? Is 1030 kg/mˆ3 a valid value for the Greenland Sea? d_z denotes the "processed depth level" but the index "i" in Q_i and T_i denotes the i-th grid cell? Perhaps it makes sense to re-write Equation 6 with two integral signs, one over dx and one of dz? Please write the motivation to use T_ref = -1.8degC (because you want to estimate the role of this heat flux in melting sea ice).

Response: The computed total oceanic heat flux is indeed an integral over the section, where d_x=1/4° and d_z varies from 10 m with depth (as presented in the original ARMOR data-set we corrected the equation 6 to:
"

$$Q = \iint [\rho c_p (T - T_{ref}) v] dxdz \quad (6)$$

where ρ=1030 kg m^{-3} is the mean sea water density; c_p = 3900 J kg^{-1} $^oC^{-1}$ is specific heat of sea water; T is sea water temperature, T_{ref} =-1.8 ^{o}C is the "reference temperature", v is current velocity perpendicular to the transect. The choice of the reference temperature is conditioned by study of the role of heat fluxes on melting sea ice."

Comment: - Line 26/27: This tail grows over time and is most pronounced in April. Are you able to assign a particular area in your region of interest to this tail?

Response: The referred tail grows from October to April with an increase of the fraction of thick ice in the region. The 'tail' values mainly fall in the dark blue area in Figure 1b.

Comment: Figure 1: - Why do you show data for the period September-April? You defined winter further above as October-April. This is confusing. - Which sea-ice concentration data set is used in Fig. 1 a? NSIDC offers a multitude of different data sets. - Did you interpolate the PIOMAS data onto the CS-2 grid or vice versa? - The color bar used as legend in Figure 1 b is empty. Please correct. - If possible I would enlarge the figure. -Caption: "isobash" –> "isobath"; state the time period (months, years) for which Fig. 1b) is computed.

Response:
- Thank you, it is a typo. We show the October-April trend in SIC.
- We used NSIDC Bootstrap Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS, Version 2. The reference is added to the Figure 1 caption.
- The PIOMAS was interpolated to the CS2 grid. A clarifying sentence was added to the data description: "The original monthly PIOMAS sea ice thickness data were re-gridded to 25 km EASE-2."
- Thank you, the figure is updated.
- Unfortunately the figure can not be enlarged since we used the journal standard two-column figure in the Latex template. Probably typesetting solves this.
- Thank you, the typo is corrected and the time period is added to Figure 1 b.

Comment: Figure 2: - Again the question one which grid this comparison is carried out - I don't understand how the data points in Figure 2 h) are computed. It says area-mean ... but I find several points per month, as if several sub-areas were used. - While the color coding of Figure 2 a) to g) and its usage in Figure 2 h) is nice, the scatterplots in a) to g) would benefit from color-coding the probability of a respective SIT data pair to occur. That way one cannot not use the color anymore in Fig 2 h) but there you could use different symbols and only provide ONE region mean value and express the variability of the area-mean monthly SIT by error bars denoting plus/minus one standard deviation for both data sets. - Caption: I note that image i) is not existent. That part of the caption should be deleted. - Please note the unit of the RMSE given in the scatterplots.

Response: The data comparison is performed om 25 km EASE-2 grid. It is now clear from the description of the data. Figure 2 h shows all monthly “snapshots” from November 2010 to December 2016. Therefore, there are several values for each calendar months.
Following the reviewer suggestion, we change the color-code in the Figure. However, we did not use month-average values and error bars for panel h. In our opinion, the current plot is more informative.

Comment: Page 7 - Line 6: "start decreasing" –> well, you might not want to exaggerate this finding, it is just for 2016 and 2017.

Response: - Thank you, we removed this line.

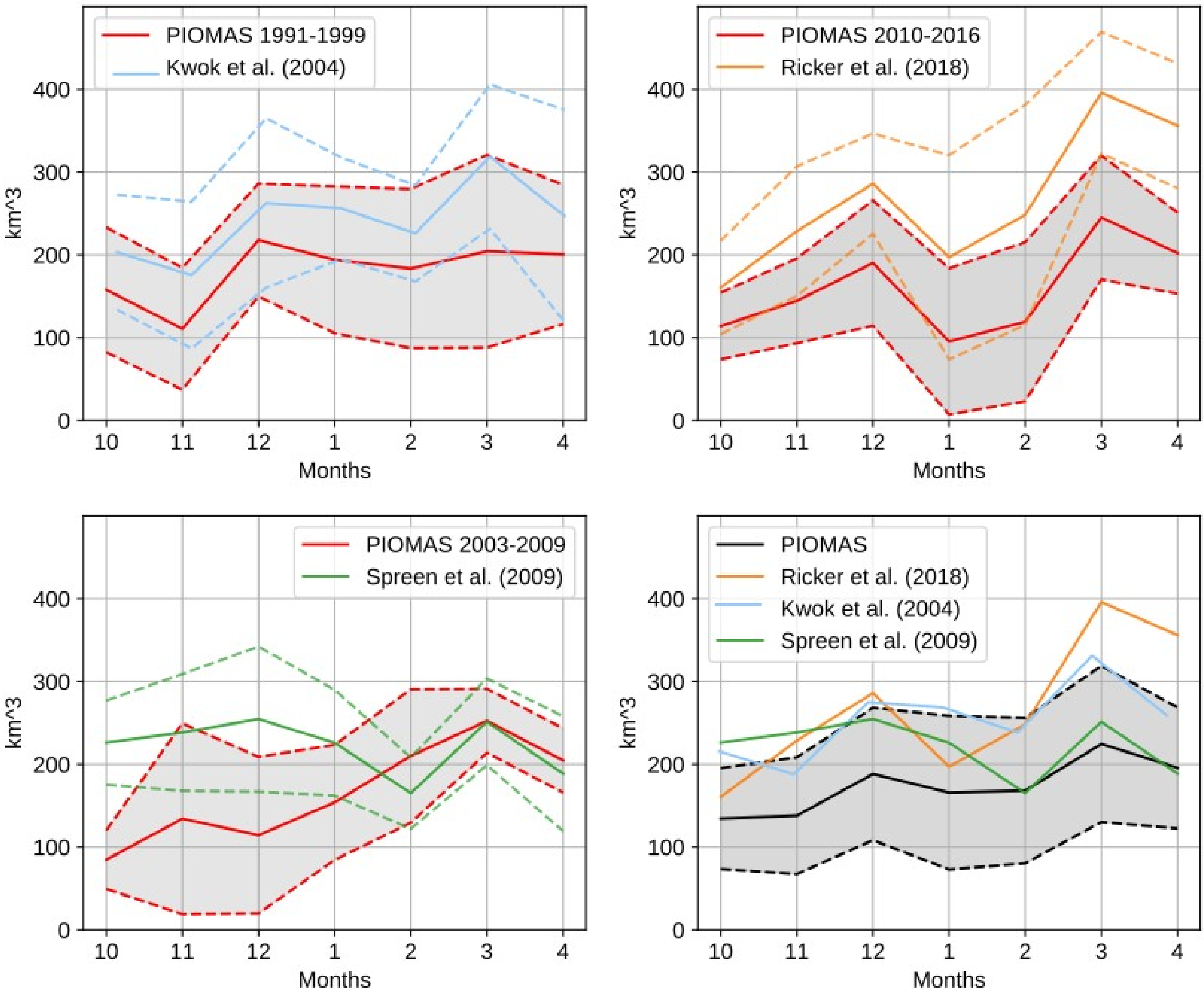
Comment: - Lines 10-12: I guess your statements about the inter-annual and intra-annual variations in sea-ice volume flux hold - particularly in the light that PIOMAS is known to under-estimate thickness for thick sea ice and therefore not unexpectedly show a slight negative bias in the Fram Strait sea-ice volume flux compared to the other data sets. <–> But I am much less confident with the results about the sea-ice volume for the reasons laid out in GC2 and because Fig. 1 b) has very small areas where the difference PIOMAS minus CS-2 SIT is acceptably low. Positive and negative sea-ice thickness differences along your gate in the Fram Strait tend to cancel each other out and therefore the sea-ice volume flux agreement is good (By the way: There the CS-2 SIT dataset is potentially much more credible than, e.g. at 78deg N). The large bias at the Denmark Strait possibly is not to relevant because of the small flux value anyways. But the majority of the Greenland Sea shows a substantial bias between PIOMAS and CS-2 and you need to discuss whether this bias (if it is real) is relevant for your findings or not.

Response: We agree that there is a substantial bias between PIOMAS and CS2 in the region. As the reviewer has mentioned CS2 data has also rather high uncertainties at these latitudes. Nevertheless, Figure 2 shows that there is a high correlation between the two data-sets on month-to-month (Fig. 2A-g), as well as on year-to-year (Fig. 2h) time scales. Therefore, we believe that the relative interannual sea-ice volume changes are captured by PIOMAS and the data allows estimation of a conservative SIV trend. This is in agreement with conclusions of Schweiger et al. (2011) who performed a detailed investigation of PIOMAS uncertainties. The systematic PIOMAS error and its influence in the trends is discussed in Section 5.1

Comment: Figure 3: - I believe it is sufficient to show the mean monthly values for the three satellite / ULS data sets. One can see whether they are within the error margin of PIOMAS or not. If you want to provide the standard deviations of the three other data sets then you could do this in a Table, don’t you think so. In any case Fig. 3 b) would become more readable without the dotted lines. - I am a bit confused about the different time scales. In Fig. 3 a) you show PIOMAS for 1991 to 2017 but in Fig. 3 b) your computations are based in one year less (2016)? - I have to admit that I don’t like that the grey shaded area denotes the standard deviation over the entire period. Did you by chance play around with the data to see how this shaded area looks like when using exactly the same periods as used for the observations? Only in that case a check whether the observations fall into the shaded area or not makes sense. - The legend under Fig. 3 b) says Ricker et al. 2017 instead of 2018. - Fig. 3 c), y-axis: check unit. - Please enlarge the entire figure.

Response:
-Figure 3a shows PIOMAS time series up to 2016. The typo in caption is corrected.
- In Figure 3 b we removed the standard deviation curves for the observation-based data set. The PIOMAS standard deviation remains. We agree that the PIOMAS seasonal cycle computed for the entire period between 1991-2016 and its standard deviation is not directly comparable to the seasonal cycle of observation-based data. However, following Spreen et al. (2009) and Ricker et al.

(2018), we present this figure to give an impression of how well the different seasonal cycles fit to each other. Below we plotted the PIOMAS seasonal cycles for the same time periods as the observation-based data-sets. There is some general similarity with Figure 3 b: Kwok et (2004) fits fairly well to the PIOMAS curves, Spreen et al. (2009) results fit better during the second half of the year, the results by Ricker et al. (2018) show the same seasonal cycle, but are above the PIOMAS estimates.
The typo in the legend is corrected.



Comment: Lines 14-28 and Figure 4 and Table 3: - Please describe whether the seasonal (i.e. summer and winter) values shown in Figure 4 are total values, i.e. May+June+July+August+September, or mean monthly values for these months). I assume the latter. Possibly I overlooked something of this description in the text?

Response: The values are monthly means averaged over winter, summer and the whole season. We clarified it in the text and in the caption for Figure 4.

Comment: - Please explain why in Figure 4 (see caption) you re-define winter to Dec.-Apr and summer to May-Nov. while earlier in the paper you use Oct.-Apr. for winter and May-Sep. For summer; also for Table 3 you seem to have used the latter two periods.

Response: Thank you, this is a typo migrated from an earlier version of the manuscript. It is now corrected.

Comment: - Why do you refer the winter and summer trends to the annual mean sea-ice volume (lines 15-17)? Wouldn’t it have been more straightforward to relate the seasonal trends to the respective seasonal mean values?

Response: We relate winter and summer trends to the long-term annual mean value in order to show their relative importance in comparison to the overall sea-ice volume in the region.

Comment: - I suggest to enlarge Figure 4 as a whole. That way you would be able to replace the "a", "w" and "s" in the annotation of the different colored lines by "annual", "winter" and "summer" and make the Figure as a whole more readable - because in this case you can also resolve the ambiguity in the annotation with "a" which so far means "AOI" in image a) but "annual" in image d).

Response: The figure size is set to the journal standard of a two-column figure. We replaced ‘w’, ‘s’ and ‘a’ by ‘winter’, ‘summer’ and ‘annual’ in all panels.

Comment: - You forgot to describe what is shown in Figure 4 c). I assume these are the mean seasonal monthly mean sea-ice volume fluxes through Fram Strait?

Response: Thank you, we added the missing description for panel c) .

Comment: In general the caption of Figure 4 needs a revision since it should contain information about what "a", "w", and "s" mean. The unit of TWSC should possibly be just ◦C. For the ocean heat flux you might want to add "Q_Svinoy" in the caption as well as at the right y-axis annotation and use the currently present "TW" as the unit.

Response: Thank you, it is now corrected.

Comment: - I note that you display annual values in Table 3 but refer to decadal values in the text. It might be good to harmonize this and change the values in Table 3 to decadal values as well. - "unexpectedly goes along with an increase in the monthly ice volume flux through" –> "coincides with an increased sea-ice volume import through"

Response: Thank you, the sentence is re-phrased. We leave the annual trends in the Table 3 since the conversion to the decadal scale is straightforward.

Comment:- Since in Line 20 you state a significance level it might be good to do this for the trends in the total Greenland Sea sea-ice volume as well; these are even more significant it seems.
Response: The level of significance was added to the text.

Comment:- Table 3, caption: "summer (March-September)"–> "summer (May-September)"

Response: Thank you, corrected.

Comment:- Line 21: I don’t understand where the 112.8 kmˆ3 /decade come from. If I add up 12 times the monthly sea-ice import per decade (of 9.6 kmˆ3) then I end up with 115.2 kmˆ3 / decade - in case this is what you wanted to do.

Response: Thank you, your estimate is correct. The wrong value migrated from an older version of the manuscript.

Comment:- Line 22: "Fig 2" –> I guess this needs to be Fig. 3 a)

Response: Thank you, corrected.

Comment:- Lines 23-28: Please spend a bit more time and effort to describe what we see in Figure b) and relate it to Equation 5. I also suggest to exchange images b) and c). You could write that for quite a number of years the sea-ice volume loss is larger in summer than winter - which is not surprizing as summer is the main melting season. Fig. 4 c) kind of shows the left difference of Equation 5. Would it make sense to show an additional image in which you show the the right difference, i.e. the mean difference of the sea-ice volume of consecutive months? Such an additional image could aid in the interpretation of Fig. 4 b).

Response: We extended the description for Figure 4 b:

“For about a half of the years during the study period, sea ice volume loss in summer is higher than that in winter. However, there are a few years (1992, 1994, 2004-2007) when winter sea ice volume loss significantly exceeds the summer one. During these years an increased sea ice volume flux thought the Fram Strait is detected (Fig. 4c).”

Concerning the right part of Equation 5, it would not show much more additional information. It is clear from Fig. 4 b and c, that variations in SIV are defined by the Fram Strait sea ice volume flux component.

Comment: Table 3: - What is rˆ2? - What is the unit of the STD and for which period / over which data is it computed?

Response: Now this information is provided in the Table heading:
r^2 - coefficient of determination, STD - standard deviation (m), p-value - probability value.

Comment: Page 8 - Line 2: "downwards" –> "with depth"?
Response: Thank you, corrected.

Comment: - You use the upper 50-m layer and the upper 200-m layer when showing and explaining your results. Why two different thick water layers? Please motivate / explain in the text or change.

Response: The obtained results are the same, whether we use the upper 50-m layer or the upper 200-m layer. We added the following text to make the choice of the layers clearer for a reader :

“The sea ice is affected by the heat in the upper mixed layer, the depth of which varies on synoptic, seasonal and interannual time scales. Our analysis shows that the obtained tendencies are largely independent from the choice of the water layer, at least within the upper 200 m of the water column. In further analysis we present results for the upper 50 m layer (the typical summer mixed layer in the MIZ) and the upper 200 m layer (the typical winter mixed layer in the MIZ).”

For consistency, we further added lines on characteristics of both, 50 m and 200 m layers in Figure 6. There is no principal difference between the results.

Comment: - Line 8: "over the 200-m layer" –> "over the upper 200-m layer"
Response: Thank you, corrected.

Comment: - What is the reason to show the November 2◦C isotherms? Why not December or February?

Response: We clarified this in the text. The following text is added:

“Water temperature in November reflects the heat fluxes accumulated during the warm period. It shows the background conditions formed by the beginning of winter cooling, when sea ice start forming localy. However, the performed tests show that the tendency of the isotherm to approach the shelf break is consistent for different isotherms (from 1 to 3 ºC), for different layer thickness (50 to 200 m) and for different months. The difference is only observed for winter months, when the whole upper 200-m mixed layer effectively releases heat and the interannual trends become insignificant.”

Comment: - Line 10 and Figure 5 b): Please be consistent with what you show. In the text you speak about "linear temperature trends". In the caption of Figure 5 you write "linear change in temperature" and the title of Figure 5 b) says dT2016-1993 which could be interpreted as a plain difference between 2016 and 1993. Please correct and/or modify accordingly. If Fig. 5b) indeed shows a trend then you need to change the unit.

Response: Thank you, this was a typo in the captions, now corrected. The correct captions for Fig. 5 (b,d) are is "linear temperature trends (^{o}C year^{-1})" and "linear salinity trends (year^{-1})".

Comment: - Figure 5 in general: I suggest to remove all Figure titles and put the respective information in the annotation of the legend and the caption.

Response: We removed the titles above the panels to avoid confusion.

Comment: - Line 11: You refer to the MIZ only and therefore "western" needs to be "eastern". - How realistic is the cooling in the northern part of the MIZ?

Response: Thank you, this is corrected.
The cooling in the northern part of the MIZ is consistent with the stronger sea ice and Polar Water transport. The upper ocean cooling in the western Fram Strait is also derived from the model study (Chatterjee et al., 2018)

Comment: - Line 12&14 and Figure 5 d): Same comment as for Line 10 and Figure 5 b)
Response: Figure 5 in updated.

Comment: - Line 12: "Fig. 4d" –> "Fig. 5D"
Response: The sentence is removed.

Comment: - Lines 13 and 16: Add "layer" behind "200-m"
Response: Thank you, this is corrected.s

Comment: - Line 16: "and over the MIZ area"? Would "in the MIZ area" be better? As far as I understood you, you concentrate on the MIZ, don’t youd?
Response: Thank you, this is corrected.

Comment: - Lines 17/18: "From ..." –> this is one way to interpret this figure. Another way would be to interpret the early years’ small temperature decreases from Sep. to Mar. as a negative anomaly; it is unfortunate that you don’t have data before 1993. You could refer in this context to Figure 5b and Figure 4d, right?

Response: Thank you, we added the references to the Figures 5 and 4.

“The temperature increases during all seasons, but the strongest increase is detected in autumn (by 0.5 and 0.6°C over the 24 years). The winter convection efficiently uplifts heat to the sea surface. The heat accumulated in summer is mostly released during winter. Figure 4d suggests the results can be extrapolated back to, at least, 1980, as the slope of the trend lines in temperature of advected Atlantic Water for 1980-1992 is practically the same as for the period discussed above.”

Comment: - Lines 19-22: "The heat ..." –> I am not sure I understand what you want to state here. First of all, isn’t it normal that the heat stored during summer & fall is released during winter? Secondly, an increasing (as you postulated) cooling from September to March (Fig. 6 a) can indeed by caused by an intensification of the vertical mixing and hence a more efficient ocean-atmosphere heat exchange. Also, it could be caused by a higher autumn water temperature but also by a lower March water temperature. What I am missing here is an attempt to relate the observed differences to the extent of the Is-Odden. Its formation and presence has a profound impact on the upper layer water mass properties. I would delete the Line 19/20 sentence part "decreasing the ...". This is a hypothesis.

Response: We agree that this is a standard situation. However, we talk about temperature trends in the upper 200-m layer, and it is not obvious that all additional advected heat in the layer will be release through the sea-surface. In the end of this paragraph, we wanted to highlight this result. The heat naturally goes to the atmosphere or to the ice melt. However, we do not have in-situ measurements to prove this with computations. We changed the end of the paragraph to:

“We observe a growing difference between September and March temperatures (Fig. 6a) together with a decrease of temperature interannual trends to insignificant in winter. The growing difference in temperature is observed in spite of the equal winter and summer trends in the heat inflow with the NwAC (see T_w and Q_{Svinoy} in Tab.3). Therefore, in the MIZ region, all additional heat, accumulated in the upper 200-m layer during summer, is uplifted to the sea surface by winter convection, preventing ice formation in the ice-free areas or melting the ice in the ice-covered ones. ”

Comment: - Line 24: add "(not shown)" behind "in winter". For Figure 6 b) one could also postulate a step change between 1993-2006 and 2007-2015.

Response: Thank you, corrected. The step change is characteristic for this particular case, which reflects mostly winter situation. For summer or autumn, the trends do not show a step, but are rather monotonous. In Figure 6, we now have both, the results for the upper 50m and for the upper 200m layers.

Comment: - Lines 25/26: For the discussion of Fig. 6 b) you refer to Fig. 6 d); I’d see a much better association between Fig. 5 a) and 5 d) in the sense that the dip / peak around 1997/98 could be an anomaly.

Response: The reviewer possibly means that the peak in 1996-1998 forms the trend. However, the negative trend will persist if we remove this peak, which is easily seen from Figure 6d. However, to show the configuration of the isotherms during different years we also refer to Fig. 5a:

“This goes together with a decrease of the annual mean distance of the 2 or 3°C isotherm to the shelf break (Fig. 6d): from 120 km in 1993 to 50 km in 2016 (see also Fig.5a).”

Comment: - Line 28: add "are" before "observed"
Response: Thank you, corrected.

Comment: - Lines 30-32: What explains the peaks in winters 2008/09 and 2010/11 in Fig. 6 c)? These are possibly the main reasons for the observed increase in MLD.

Response: If these years are removed, the trend remains, but the difference along the trend between mean MLD in 1993 and 2016 will be 30 m, instead of 50 m. This corresponds to an overall increase in winter vertical mixing in the Greenland Sea, where the intensity of deep convection increases from around 1000 m in the beginning of the 1990s to over 1500-2000 after the mid-2000s (Bashmachnikov et al., 2019).
The question by the referee is very difficult to answer, as the intensity of vertical mixing depends on a number different factors. This requires a full separate study. We may note that 2009 and 2011 were the years with an anomalously high density in the Greenland Sea north of Jan Mayen. We also note a low oceanic advection of heat during 2008 (the third highest MLD) and 2011 and anomalously high heat fluxes to the atmosphere due to a small extent of ice-cover during winter 2009. All these factors are favourable for the detected deeper mixing in MIZ during the mentioned years.

Comment: Page 9 - Line 1: These September temperature values are not shown somewhere, are they?

The time series of mean September water temperature in the 200-m layer is added to Fig. 4b.

Comment: Equations 7 and 8: - Please spend a subscript "water" to the density in Equation 7 and replace the subscript "L" in Equation 8 by "ice". - Replace "dq" by "dQ" in Equation 8.
- In the text you write 1.8◦C for 2016, in Equation 7 you used 2.0◦C. Please correct.
Response: Thank you, corrected.

Comment: - Lines 12/13: I don't agree with the way you estimate the sea-ice volume loss for the 24-year period. That trend you use (possibly from Table 3) is computed over the entire period, starting in winter 1978/79 and not for the period 1993-2015. Fig. 4 b) clearly shows that if one would compute a trend for the 1992/93 through 2014/15 winter time period it might be negative. Also, you use 12 months while in Equation 7 you insert the winter MLD change. It seems hence doubtful to use the entire year. It might therefore make sense to revise this estimate.

Response: Thank you, for the comparison of SIV loss and an increase in oceanic heat release, only winter months has to be taken into account. We corrected the estimates. We agree that out calculations would have had more weight if all trends were computed for the same period. If we shorten the period for sea-ice variable analysis to 1993-2015, the trend in SIV loss becomes negative, but not statistically significant (e.g. trend in winter SIV loss equals -1.19 km^3 /year, p-value equals 0.47). Note, that if we exclude the season of extreme SIV loss in 1994 and compute trends from 1995 (see the answer to General Comment 4), the magnitude of the trends becomes very close to the long-term ones. Although we do not have the data on MIZ temperature and MLD before 1993, the indications of changes in ocean state since 1979 can be seen from temperature of West Spitzbergen Current.

Comment: - Line 13: "of ice needed to fuse" ? –> delete?
Response: Thank you, corrected.

Comment: - Lines 13-15: Would it make sense to also mention that a large fraction of your MIZ area is potentially not covered by sea ice anyways? Would it also make sense to mention that new ice formation in the Is-Odden area but also otherwise in your MIZ area counter-acts this heat release? Would it make sense to also mention that the heat not necessarily needs to reach the surface but stays aways from the sea ice at some depth? My feeling is that one should not overlook the assumptions made.

Response: Some of the suggestion by the reviewer follows directly the discussion of Eq. 8 on page 12 lines 5-8 (some heat is directly released to the atmosphere and do not interact with ice, or goes to ice melt). Also during ice formation the upper ocean becomes more saline, which enhances the convection and increases heat release towards the sea-surface. However, sea ice melt may inhibit the heat release by increasing the haline stratification near the sea-surface. These issues are added to the discussion:

“Certainly, not all heat released by the upper ocean in the MIZ area goes to the ice melt. An unknown fraction of heat is directly transferred to the atmosphere through open water, ice leads or is advected away from the MIZ area by ocean currents and eddies. Melting the ice may additionally increase haline stratification at the lower boundary of the ice, preventing ocean heat contacting with the ice cover. However, the estimates above suggest that, the autumn warming of the upper MIZ region, limited from below by the winter mixed layer, is able to release the amount heat far exceeding the amount, sufficient for the observed reduction of SIV in the region.”

Comment: - Line 22: "multiyear" –> Do you refer to multiyear ice here? In that case write it accordingly.
Response: Thank you, corrected.

Comment: - Line 23: Whom do you mean with "The authors"?
Response: Re-phrased.

Comment: - Lines 23/24: This is a global statement, perhaps too global. PIOMAS under-estimates thicker ice thickness and over-estimates thinner ice thickness. Please discuss this in more detail because, yes, the thick ice in the Greenland Sea has become thinner but at the same time the Is-Odden feature with a lot of thin ice has vanished.
Response: We added the text regarding PIOMAS uncertainties in response to you General Comment 5 3)

Comment: - Lines 25/26: "compared to know from literature fluxes" –> "compared to flux values known from literature"
Response: Thank you, corrected.

Comment: - Lines 29/30: Fig. 2 i) does not exist. I guess this needs to be Fig. 1 b). "is lower compared to" –> I’d say this applies to 2/3 of the meridional gate. Don’t forget the zonal part of the gate where the differences are opposite. Don’t forget also GC2 in this context. "the NSIDC sea ice drift" –> needs to be introduced in the data section. Version 2 is quite old, by the way. State of the art is Version 4.

Response: Thank you, the reference to the figure is corrected. We also clarified in the text that the meridional gates are the main gated for sea ice import to the region. For flux calculation we used the NSIDC Pathfinder Version 3 (product, which is now introduced in the method description.

Comment: Page 10 - Lines 2-7: As an outlook you could add that it might make sense to separately, in PIOMAS, look at the changes in sea-ice formation in the true MIZ, i.e. the actually ice covered area and not just the average MIZ as defined by you, and in the consolidated ice covered part on the shelf. There are many leads created in the wider Fram Strait area in which thin ice grows quickly and which is advected southward on the shelf, continuing to grow.

Response: We agree that formation of sea ice in crack and leads might have a large contribution to the energy balance. However such study requires a data of higher resolution than the PIOMAS has.

Comment: - Line 7: "intensification of in sea ice melt" ?
Response: Thank you, corrected.

Comment: - Line 24: "through to be mostly driven" ?
Response: Thank you, corrected.

Comment: - Lines 25-27: Please rewrite this sentence. It is confusing. Which "inconsistency"? Which "peculiarities"? "delution"? Does Polar Water have an influence on your area?
Response: The phrase is re-written as:
"The interannual variations in the vertical mixing intensity between the Atlantic water, the Polar water and the modified Atlantic water, returning from the Arctic in the southern Fram Strait, as well as variations in ocean-atmosphere exchange in that area leads to interannual variability of the Atlantic water advected by the EGC into the Greenland Sea (Langehaug & Falck, 2012)."

Comment: Page 11 - Line 5: "NAO phase increases of the intensity" ?
Response: Thank you, corrected.

Comment: - Line 17: Fig. 4 f) needs to be Fig. 4 d).
Response: Thank you, corrected.

Comment: - Line 33: "Governed by ..." This sentence is difficult to read; please re-formulate.
Response: The sentence is re-formulated:
A more intense convection, governed by thermohaline characteristics of the upper Greenland Sea, the ice extent and the intensity of ocean-atmosphere heat and freshwater exchange (Marshall and Schott, 1999; Moore et al., 2015), lowers the sea-level in the Greenland Sea (Gelderloos et al., 2013; Bashmachnikov et al., 2019). This in turn increases the cyclonic circulation in the region.

Comment: Figure 7: Here different winter and summer periods than in the rest of the paper are used. Why? Please motivate, change, or delete.
Response: The figure is changed in accordance with recommendations.

Comment: Page 12 - Line 19: Why "Therefore"?
Response: Changed to "This siggests that.."

Editoral stuff:

Comment:- I found "northern winds" and "northerly winds". Please use one term.
Response: Thank you, corrected.

Comment:- Check for "Oddin"
Response: Thank you, corrected.

Comment:- I found "accessed" in case where "assessed" should be used, e.g. Page 3, Line 17 or Page 5, Line 10.
Response: Thank you, corrected.

Comment:- It might enhance the flow of your paper if you always use the same term for the same parameter. Example: use "effective sea-ice thickness" all the time and not "effective ice thickness"
Response: Thank you, corrected.

Comment:- You have an issue with using "though" instead of "through". Please check.
Response: Thank you, corrected.

Comment: Page 1 - Line 16: "The 2/3 of" –> "Two third of …"
Response: Corrected.

Comment: Page 2 - Lines 11-13: there are some issues with blanks and parentheses. Please check.
Response: Thank you, checked and corrected.

Comment: Page 4 - Line 19: WSC needs to be explained. "quire" –> "quite"?
Response: Thank you, corrected.

Comment: Page 5 - Line 9: "months" –> "month" - Line 13: "while in other" –> "while in the other"
Response: Thank you, corrected.

Comment: Page 6 - Line 3: Check references mentioned here - Line 25: Put "Schweiger et al., 2011" in ()
Response: Thank you, corrected.

Comment: Page 7 - Line 23: "significantly" –> "significant" "sea ice balance of the sea" –> "sea-ice mass balance of the Greenland Sea"
Response: Thank you, corrected.

References:
(see also references in the updated version of the manuscript)

Renner, A.H., Gerland, S., Haas, C., Spreen, G., Beckers, J.F., Hansen, E., Nicolaus, M. and Goodwin, H., 2014. Evidence of Arctic sea ice thinning from direct observations. *Geophysical Research Letters*, *41*(14), pp.5029-5036.

Mironov, E.U., 2004. Ice conditions in the Greenland and Barents seas and their long-term forecast.

Referee #2

Dear referee,
Thank you for reviewing our manuscript. The provided references and comments has helped us to improve the text. We addressed all you comments below.

General comments:
Comment: The development of the sea ice volume in the Greenland Sea is investigated, but how is the Greenland Sea defined? The red box in Fig. 1 marks the entire Nordic Seas,which consists of the Norwegian Sea in the east and the Greenland + Iceland Seas aswell as the east Greenland shelf in the west. I would rather say that you study the seaice volume in the Nordic Seas or western Nordic Seas with a focus on the marginalice zone. The inconsistent use of “the Greenland Sea”, “the Nordic Seas”, and “the Greenland-Norwegian region” etc. makes the paper a bit confusing to read and it is notclear to me over which region you actually computed the sea ice volume.

Response: According to classification of the International Hydrographic Organization (IHO) the Greenland Sea extends from the Fram Strait to the Denmark Strait. Its eastern boundary goes along the western coast of Spitsbergen, from the south-eastern point of Spitsbergen to Jan Mayen and further south to the north-eastern extreme of Island. The term Island Sea, presently often used to define the southern part of the Greenland Sea from Jan Mayen to Island, is not a part of the standard oceanographic classification of ocean basins. We do not use this term in this paper.
In the previous version of Figure 1 the Norwegian Sea was included in the study region. In the new version the eastern boundary is corrected (see green boundary in the new version of Fig. 1). We slightly extend the eastern boundary of the Greenland Sea south-eastwards, compared to its classical definition in IHO in order to include the in the study region the entire area of the Odden ice tongue.
We also agree that “the Greenland-Norwegian region” is stylistically bad and replaced it with “The Nordic Seas”.

Comment: The authors start by introducing the Greenland Sea as an important area for deep convection and that the intensity of convection is controlled by buoyancy fluxes, in particular the input of freshwater (and sea ice). However, little is said about the observed changes in local sea ice formation, the retreat of the ice edge, winter-time heat loss, and their combined effect on convection in the Greenland Sea which has varied substantially over the past four decades. See e.g. Visbeck et al. (1995); Marshall andSchott (1999); Moore et al. (2015); Brakstad et al. (2019).

Response: We have added the proposed references to the text.. Further, the possible effect of deep convection on the advective process are briefly addressed in the Discussion. However, our study only marginally touches these questionable issues.

Comment: Some statements about the amount of available data in the MIZ (in the ARMOR dataset) are required. How does the generally sparse data coverage along the east Greenland shelf affect your results?

Response: The number of vertical profiles in the Greenland Sea between 1993 and 2016 vary from 50 to 300 per year, on average 150 casts per year. ARMOR dataset also favors from additional use of satellite sea-surface data, particularly relevant for our study. It is, however, difficult to assess the accuracy of the data, as ARMOR assimilates all available in-situ casts.

Comment: It would also be good to compare your mixed-layer properties with observations (i.e. Nilsson et al., 2008; Pawlowicz, 1995; Brakstad etal., 2019). All of these papers show ocean surface temperatures well below 0°C during winter (in the MIZ and in the center of the Greenland Sea). This contradicts what you describe on Page 8 – Line 6-7, that the temperature is always above 0◦C leading to sea ice melt. Furthermore, you have used the mean 15% sea ice concentration contour from 1979 to 2016 to define the MIZ. The position of the ice edge has varied substantially during this period (i.e. Moore et al, 2015). How does that affect your results?

Response: In order to justify the validity of average MIZ, we added the following information in the text (page 7 lines 21-34):

"The position of the real MIZ strongly varies in time and along the EGC, being a function of local direction and intensity of sea ice transport by wind and current, variation in the characteristics of ice transport from the Arctic and interaction of ice floes, local ice thermodynamics, etc. Presence of melting sea ice, in turn, affects the upper ocean and air temperatures. A warmer winter ocean warms up the air, which can further be advected over the sea ice causing its melt away from the sea ice edge. Furthermore, an anomalously warmer ocean may prevent (or delay) formation of a new ice. All these distant factors certainly affect the MIZ position. However, if we estimate ocean temperature variations only along the actual MIZ, we do not account for these effects. The considerations above show that defining the oceanic region directly and indirectly affecting the ice volume in the sea is not straightforward. In this study we define interannual variations of ocean temperature in a fixed region, which is defined as an area enclosed between the 500-m isobath, marking the Greenland shelf break, and the mean winter location of the sea ice edge (Fig. 11). Using the fixed region also assures compatibility of interannual temperature variations. For the computations, the sea ice edge was defined as the 15% mean winter NSIDC sea ice concentration for 1979-2016. For brevity we further, somewhat deliberately, call this region the MIZ area. We further will see that temperature trends remain positive and of the same order of magnitude all over the western Greenland Sea, except for a few limited areas along the shelf break. This assure robustness of the results to the choice of the study region."

Comment: It is interesting that the warming of the Greenland Sea and the MIZ can account for the sea ice volume loss in the area plus the increased sea ice export through FramStrait. However, as noted also in the specific comments, information about the role of the atmosphere is missing. This is crucial in order to obtain a more complete picture of the drivers for the observed development of the sea ice volume. As it stands, you assume that the atmosphere plays a minor role (Page 9 – Line 15 & Page 10 – Line 9).It is possible to quantify the fraction of heat released to the atmosphere, and the role of increased atmospheric temperature, using an atmospheric reanalysis product. I think that considering the atmosphere as well would make your conclusions more solid.

Response: We fully agree that solid conclusion about the oceanic input to the sea ice volume loss in the region can not be drawn without a proper analysis of the atmospheric data. However, the scope of this study, as stated in the last paragraph of the introduction, is to explore the linkage between sea ice and ocean. A consideration of the atmosphere requires a separate investigation, as the atmospheric heat content at the sea surface highly depends on the oceanic one (the sum of sensible and latent heat fluxes in the region is one of the main components of the lower atmosphere heat balance and is directed from the ocean to the atmosphere all year round). In this paper, we find an indication that the estimated increase in ocean heat content can solely be responsible for the additional sea ice volume loss. However, we do not state in the conclusions, that ocean is the only contributor to the sea ice loss.

Comment: I find the link between long-term variations in sea ice volume and the NAO a bit speculative. On page 11 – line 2 you write that several studies have shown that during positive NAO phase, the intensity of ocean heat flux to the Nordic Seas increases by 50%. However, neither of the studies referred to (i.e. Skagseth et al., 2004 and Raj etal., 2018) examines the oceanic heat flux/ heat transport into the Nordic Seas (rather velocity and volume transport). When Raj et al. (2018) discuss the increase of 50% they are talking about an increase in volume transport. What about variations in temperature of the inflowing Atlantic Water? Based on the studies you refer to, I find the link between NAO and temperature/heat content in the MIZ exaggerated. Either focus less on the NAO link, or refer to literature that show the link more clearly, or investigate the link more thoroughly in this paper.

Response: This partly repeats the comments by reviewer 1. In fact, the increase of the volume flux leads to an increase of the heat flux in this region. We re-worked section 5.2, elaborating on the linkage between SIV and NAO and added a number of references. Please, see page 14 lines 12-35 -page 15 lines 1-11) in the new version of the manuscript.

Specific comments:

Comment: Page 1 - Line 16: What do you mean by “this region”? The Greenland Sea, the NordicSeas, or the North Atlantic? I do not think any of these papers state that 2/3 of thedeep AMOC originates from the Greenland Sea.

Response: We change the phrase to: “More than half of the deep AMOC water originated from the Greenalnd Sea (Yashayaev et al., 2007; Rhein et al., 2015).”

Comment: Page 2 - Line 1: Approximately 50% of the freshwater anomaly at the surface or of theentire water column? Also, what do you mean by “the Norwegian-Greenland region”.The Nordic Seas? Changes in salinity of the northward flowing Atlantic Water are alsoimportant (ie. Lauvset et al., 2018; Mork et al., 2019).

Response: In the cited works authors talk about the entire water column (Petterson et al. (2006) also adds ice FW flux). We agree that the Atlantic inflow is also important and indirectly is accounted for in the studies cited in the manuscript. We changed the phrase to:

“The freshwater anomaly in the upper Greenland Sea primarily originates from variations in the freshwater flux from the southern Fram Strait, which is formed by mixing of the Atlantic and the Polar water, as well as by solid ice transport (Serreze et al., 2006; Peterson et al., 2006; Glessmer et al., 2014; Lauvset et al., 2018).”

Comment: Page 2 – Line 6: Another very relevant reference for sea ice flux through Fram Strait, and for comparison with your results, is Smedsrud et al. (2017).
Response: Thank you, we are aware of this study. It is cited in the introduction page 3 lines 18

Comment: Page 2 – Line 14: Please clarify what you mean by “even stronger linked to the ArcticDipole pattern”. In addition, you should briefly introduce the Arctic Dipole pattern, as itmay not be clear to all readers what this is.
Response: We added the phrase, explaining the pattern. For furthert detailes the readers can consult the cited study:
“It is also argued that the interannual variations of the sea ice flux through the Fram Strait is even stronger linked to the Arctic Dipole pattern, that explains a higher fraction of the observed interannual variations in the sea ice area flux than either the AO or the NAO (Wu et al., 2006). The Arctic Dipole pattern is derived as the second sea-level pressure EOF over the Arctic, which has two centers of action: over the Laptev-Kara seas and over the Canadian Archipelago. The pattern represents an important mechanism regulating the ice export through Fram Strait (Wu et al., 2006).”

Comment: Page 2- Line 17: The Odden sea ice tongue has not been formed in the GreenlandSea since the early 2000s (ie. Moore et al., 2015). Since then, sea ice has been close to absent in the center of the Greenland Sea.

Response: Thank you, we added this information to the text.

Comment: Page 3 – Line 4: The detected variations of what?
Response: Thank you, corrected to : «the detected variabtions of sea ice mass balance»

Comment: Page 3 – Line 25: How is monthly sea ice thickness from the Cryosat-2 satellite data-set obtained?
Response: The Cryosat-2 satellite data-set contains monthly average sea ice thinkness informaition sonce Novemner 2010. We now provide references to the data description (Hendricks et al. (2016) and production Ricker et al. (2014). We also added a sentense to the data description (page 4, line 24-25):
"The CS2 retrieval is based on sea ice freeboard measurements that are converted into sea ice thickness assuming hydrostatic equilibrium".

Comment: Page 4 – Line 9: What do you mean by different weights? Please elaborate.

Response: Gridding is done using the standard Gaussian function, there the weight of each measurement decreases with the distance form the measurement point. However, for the equal distances the in-situ measurements are taken with a higher weights. The procedure is a multi-step complex algorithm, as for any gridded data-set. The details of the method for forming the data set an interested reader can find in the cited study.

We changed the phrase to: "The final monthly mean 3D temperature/salinity distributions are obtained through optimal interpolation of all observed in situ for this month together with the derived "synthetic" profiles, where in-situ profiles, in the vicinity of the point of the observations, are taken with a higher weights (Guinehut et al., 2012)."

Comment: Page 4 – Line 11: Include reference to the method used in the World Ocean Atlas data-set.
Response: The reference is added: "(as, for example, it is done in the World Ocean Atlas database, https://www.nodc.noaa.gov/OC5/WOD/pr_wod.html)."

Comment: Page 4 – Line 20-21: Interannual variations of what? In addition, replace " - the months the most densely covered with data" with "which are the months with densest data coverage".
Response: Thank you, corrected.

Comment: Page 5 – Line 10-11: Denmark Strait is between Greenland and Iceland, not all theway to 36E! Please use a different term for your meridional section (a section along the Greenland Scotland Ridge?), or separate it into several sections (ie. one west and oneeast of Iceland).
Response: There was a typo in the coordinates used to calulate flux thought he Denmark Strait. The gates are now illistrated in Figure 1 a.

Comment: Page 5 –Line 17: What do you mean by "due to thermodynamically within the Greenland Sea"? Please clarify.
Response: The sentence is corrected:
"In order to analyse the sea ice volume lost or gained due to local melt or freezing, we calculated the sea ice mass balance (MB) in the Greenland Sea."

Comment: Page 5 – Line 29: How were the density profiles filtered?
Response: The phase is changed to: "Before processing, the small-scale noise in the potential density profiles were filtered out with 10-m sliding means."

Comment: Page 6 – Line 3: How were you able to compare your MLDs with Kara et al. (2003)? None of their figures show MLDs in the Nordic Seas. de Boyer Montégut et al. (2004) are also looking at global mixed layers. I think it would be better to compare with observed MLDs from the Greenland and Iceland seas (Brakstad et al., 2019 and Vågeet al., 2015, respectively).

Response: In the text we refered to the methods suggested in Kara et al. (2003) and de Boyer Montégut et al. (2004). Instead of using figures we programmed the algorithms, described in paper and compared the results. We added the phrase:
"The obtained mean distribution of the MLD, seasonal and interannual variations of the MLD in the central Greenland Sea are consistent with observations (Vage et al., 2015; Latarius & Quadfase, 2016; Brakstad et al., 2019)"

Comment: Page 7 – Line 15-16: How does the negative trend in sea ice volume compare to those found in Moore et al. (2015) and Onarheim et al. (2018)?

Response: The studies Moore et al. (2015) and Onarheim et al. (2018) show the reduction of sea ice extent. In our study we look at the trends in sea ice volume. In general, the sea ice volume loss can be related to the loss of sea ice extent. The reduction in sea ice extent, including Odden tongue formation are partly described in the introduction and discussed in section 5.3. Now we added the references to Moore et al. (2015) and Onarheim et al. (2018) to the text.

Comment: Page 7 – Line 33: Unclear. Please expand. Atlantic-origin water in the EGC is capped by fresh/cold Polar Water and sea ice during winter, which will inhibit ventilation of theAtlantic Water. Våge et al. (2018) show that due to the retreat of the ice edge the last decades, Atlantic Water has been and is more likely to be ventilated in the EGC. However, we do not know if this takes place "regularly".

Response: Our estimates of the winter MLD shows this should happen quite regularly. The ice retreat is presumably one of the reasons. The phrases are changed to:
"A relatively warm AW is observed in the East Greenland Current (EGC), off the Greenland shelf break, below a thin upper mixed layer dominated by the cold PW. Our estimates of winter MLD shows that the AW should be regularly brought to the ocean surface by vertical winter mixing, which is consistent with observations (Håvik et al., 2017; Våge et al., 2018)."

Comment: Page 8 – Line 1-2: The temperature (and salinity) of the Atlantic Water in the EGC is not increasing downstream. Please clarify what you mean by "increasing southeastwards".

Response: We changed the phrase to: "The presence of the AW is observed in climatology as water temperature (and salinity) in the EGC increasing with depth from about 0 ^{o}C at the sea-surface to 2-4^{o}C at 500 m."

Comment: Page 8 – Line 4: "West Islandic Current" is not typically used. Rather use "North Icelandic Irminger Current". A better ref. here would be Jónsson and Valdimarsson(2005) or Hansen et al. (2008).
Response: Thank you, we added the reference to Hansen et al. (2008) and replaced the West Islandic Current by North Icelandic Irminger Current.

Comment: Page 8 – Line 6-7: As stated in the general comments, you need to compare your data with observations and discuss the temperature uncertainty due to limited data in the MIZ. Temperatures of 0.1-0.2◦C in winter seems unrealistically high.

Response: As reviewer correctly mentioned the data are limited in the region. The ARMOR data are based on in-situ data (where available) and interpolated data elsewhere. The temperature uncertainty is close to zero where the casts or the satellite data were obtained. The uncertainty is unknown in the areas where there are no data. However, temperatures above zero are often observed in winter in the region (Latarius & Quadfase, 2016; Brakstad et al., 2019). Here we remind that, for the reasons presented above, we use the fixed region to derive temperature variations, so the near-surface temperature mentioned here is not always in contact with ice, thus can be close to zero.

Comment: Page 8 – Line 14: Perhaps you should show the mixed-layer depth for comparison with previous work (ie. Brakstad et al., 2019 and Våge et al., 2015)
Response: In fact we do show it in Figure 6c, to which we refer now:
"Averaged over the upper 200-m, the typical depth of the winter mixed layer (Fig. 6c), the patterns of the mean distribution and of (a somewhat weaker) tendencies in temperature and salinity closely repeat those in Figure 5."
This value is consistent with Brakstad et al., 2019 and Våge et al., 2015, as now stated earlier in the manuscript.

Comment: Page 8 – Line 17: Clarify what you mean by "overall year mean increase of temperature".
Response: Changed to : "overall increase of annual mean temperature"

Comment: Page 8 – Line 19-22: These lines are confusing and hard to read. What do you meanby "decreasing the interannual trends to insignificant"? Please be more specific.
Response: Changed to: "We observe a growing difference between September and March temperatures (Fig. 5a) together with a decrease of temperature interannual trends to insignificant in winter, in spite of equal winter and summer trends in the heat inflow with the NwAC (see T_w and Q_Svinoy in Tab.3).

Comment: Page 8 – Line 28-29: Bondevik (2011) is gray literature (no peer review). I would encourage you to refer to peer reviewed literature. In addition, add "are" before "ob-served".
Response: Thank you, the typo is corrected. There is only one reference to grey literature and since it is relevant, we decided to keep it.

Comment: Page 8 – Line 28-30: Explain how this increases ice melt.
Response: We added a clarifing sentence:
" The eddies sweep sea ice and PW off and advect warm AW closer to the ice edge, resulting in increase in bottom and lateral sea ice melt"

Comment: Page 8 – Line 30-32: As stated in the general comments: How does your definition ofthe MIZ and the data coverage in the MIZ affect the results?
Response: The choice of the fixed region for defining interannual temperature variations is now justified in page 7 . Please, see the response to the related general comment.

Comment: Page 8 – Line 34-35: This corroborates the results of Lauvset et al. (2018) who exam-ined the relationship between hydrography (and MLD) in the Greenland Sea and thetemperature/salinity of the northward flowing Atlantic Water.
Response: Thank you, we make a link to these study (page 11, lines 23-25):
"Since the winter mixing does not reach the lower limit of the warm Atlantic water at 500-700 m, the deeper the mixing, the more heat is uplifted towards the sea-surface, melting the ice in the MIZ, which is consistent with the findings of Lauvset et al. (2018)."

Comment: Page 9 – Line 6-7: The 20% depend on how you define the Greenland Sea.
Response: To avoid ambiguity,we replaced “Greenladn Sea” with the “study area”

Comment: Page 9 – Line 7: “additional heat release”: In addition to what?
Response: Here we mean the heat released due to an increse in 200-m layer temperature by 2ºC between 1993 and 2016. This should be clear from the equation and text above.

Comment: Page 9 – Line 13-14: It would be interesting to quantify the fraction of heat released to the atmosphere. This should be possible using atmospheric reanalyses.
Response: We agree, but this is not straightforward, as heat is consumed also by different processes (ice melting, mixing in vertical and horizontal). This will require a separate study. Please, also see the response to the related general comment.

Comment: Page 9 – Line 15-16: What about increasing atmospheric temperature?
Response: This repeats one of the general comments. Please, see the respond above. Here we do not state that the atmosphere does not play a role in the ice volume loss. We only compare the amount of oceanic heat to the lost volume of sea ice.

Comment: Page 9 – Line 28: Clarify what you mean by “the discussed above general PIOMAS tendency”
Response: We are not sure that we understand this comment. IN the text we mean “to the discussed above general PIOMAS tendency to underestimate sea ice thickness”, which is discussed few lines above in the same paragraph.

Comment: Page 9 – Line 29: Figure 2i does not exist.
Response: Thank you, corrected.

Comment: Page 10 – Line 6: This sentence is not in agreement with Page 8 – Line 6-7 where youstate that no sea ice formation occur and that the surface temperature is always >0.Here you write that sea ice is formed locally and that the atm. play a role.

Response: There is no contradiction. On p.8 we talk about the climatic seasonal means over the upper 50-m of the whole MIZ, including the warmer south-eastern part of the study region. Here we talk about the sea-surface and episodic formation of the ice tongue over a colder sea-surface (sometimes for a week or two). However, we agree with the reviewer that ice advection should also be important, although in the cited papers this factor was considered less significant.

Comment: Page 10 – Line 11-12: “almost twice of” what? Please clarify.
Response: The sentence was re-phrased:
“The surplus of the amount of the heat, released by the ocean at end of the study period, is more than twice of that necessary for bringing up the observed sea ice volume loss...”

Comment: Page 10 – Line 25-27: These two sentences are very confusing. Which inconsistency? What local peculiarities? Do you need these sentences at all? If so, please re-phraseand be more specific.
Response: The sentence was re-phrased: “The interannual variations in the vertical mixing intensity between the AW, the PW and the modified AW, returning from the Arctic through the southern Fram Strait, as well as variations in ocean-atmosphere exchange in that area leads to interannual variability of the AW advected by the EGC into the Greenland Sea (Langehaug and Falck, 2012).”

Comment: Page 10 – Line 30: Where did you obtain data (heat fluxes) from the Svinøy section? Please include reference.

Response: We computed the heat fluxes through the Svinoy section, using ARMOR dataset.

Comment: Page 11 – Line 2: Raj et al. (2018) show a 50% increase in volume transport not oceanic heat flux. (See general comment).
Response: We substantialy changed the section and added a number of references. Please see the new version of the manuscript, page 14.

Comment: Page 11 – Line 12: You have not really discussed any eastward advection of Polar Water to the southwestern Norwegian Sea. How does this relate to your results? Please elaborate.
Response: This region is out of the scope of our main line. We refer here to previous studies.

Comment: Page 11 – Line 23-24: This sentence contradicts line 19, where you state that the summer NAO is not important?
Response: We state that only winter NAO index should be taken into account for accessing the interannual variations, including those in the intensity of the AW advection. Summer NAO is of little relevance. Many studies in the region take into account only winter NAO index.

Comment: Page 11 – Line 25: What do you mean by "main currents in the Greenland Sea"? Be more specific.
Response: "In spite of the stronger ice melt, the upper ocean salinity in MIZ, as well as along the EGC, as well as along the NwAC, increases during recent decades (Fig. 5d)."

Comment: Page 12 – Line 5-7: Maybe better to refer to Brakstad et al. (2019), Lauvset et al.(2018), and Latarius and Quadfasel (2016) that all look at interannual changes in MLDin the Greenland Sea during your period. Lauvset et al. (2018) and Brakstad et al.(2019) both discuss the role of increased salinity on the mixed-layer depth.
Response: Thank you, know we refer to the suggested studies: "The on-going increase in salinity of the upper Greenland Sea (Fig. 5d) during the recent decades favors the deeper convection (see also Lauvset et al., 2018; Brakstad et al.,2019)."

Comment: Page 12 – Line 9: Smeed et al. (2014) show a weakened AMOC.
Response: Smeed et al. (2014) talks about a relatively small AMOC decline after 2004, on the top of the overall AMOC intensification since the 1970s-1980s (shown also in Smeed et al., 2014). We added a phrase:
"However, during the latest decade, a stagnation or a possible reversal of the tendency is observed (Smeed et al., 2014)"

Comment: Page 12 – Line 20: "govern" is too strong. Line 23-24: "Atlantic Water advection into the MIZ largely contributes to the SIV loss" is more appropriate.
Response: Thank you, corrected.

Comment: Page 12 – Line 28: In the last paragraph: The link to NAO is speculative, and you havenot shown this link in this paper.
Response: We agree with the reviewer. We now put this as a plausible hypothesis:
"This suggest that the simultaneous tendencies in the long-term increase of SIF and of the Atlantic water transport are both linked to a higher intensity of atmospheric circulation during the positive NAO phase, and, possibly, to the positive AMO phase, often linked to the intensification of the AMOC since the 1980s."

Technical corrections:

Comment: Page1 - Line 16: Replace "The 2/3" with "Two thirds"

Response: Replaced

Comment: Page 1 - Line 18: What do you mean by “to the sea”? Into the Greenland Sea?
Response: Re-phrased

Comment: Page 2 – Line 1: Replace “through the Fram Strait” with “through Fram Strait”. (Also the case for Page 2 - Line 6, 9 and 10 etc.)
Response: Replaced

Comment: Page 2 – Line 9: Should be “drive” not “drives”
Response: ‘divers’ is the correct form as it is related to the conditions of wind intensification.

Comment: Page 2- Line 11: The entire reference here should be within parenthesis. “(Kwok et al., 2004)” not “Kwok et al. (2004)”. Also the case for “Schweiger et al. (2011)” on Page 6 - line 25 in example. Please go through all references and make sure they are consistent.
Response: Thank you, corrected

Comment: Page 2 – Line 34: Replace “Oddin” with “Odden”.
Response: Thank you, replaced

Comment: Page 3 – Line 15: Singular vs plurals: Use either “the spatial pattern of PIOMAS icethickness agrees” or “the spatial patterns of PIOMAS ice thickness agree”.
Response: Thank you, corrected

Comment: Page 3 – Line 15: Remove comma after “those”.
Response: Thank you, corrected

Comment: Page 3 – Line 25: Should be “provides” not “provide”
Response: Thank you, corrected

Comment: Page 3- Line 26: Insert “the” before “CS2 data-set”.
Response: The sentence was re-phrased

Comment: Page 4- Line 3: Insert “the” before “ARMOR data-set”.
Response: Thank you, corrected

Comment: Page 4 – Line 7: Insert “depth” before “levels”.
Response: Thank you, corrected

Comment: Page 4- Line 9: Replace “all observed in situ” with “all in situ observations”.
Response: Thank you, replaced

Comment: Page 4 – Line 18: Remove comma before “used” and after “paper”.
Response: Thank you, corrected

Comment: Page 4 – Line 19: Replace “quire” with “quite”
Response: Thank you, replaced

Comment: Page 4 – Line 21: Use “a” instead of “the” in “kriging with the 30-km window”.
Response: Thank you, corrected

Comment: Page 4 – Line 25: Remove comma after “Note”.Page 5 – Line 9: Remove “s” in “months”.
Response: Thank you, corrected

Comment: Page 5 – Line 10: Denmark Strait should be with capital S.
Response: Thank you, corrected

Comment: Page 5 – Line 11: Replace “access” with “assess”.
Response: Thank you, replaced

Comment: Page 5 – Line 13: Should be “were adopted” not “was adopted”.
Response: Thank you, corrected

Comment: Page 5 – Line 13: Add “the” before “other”.
Response: Thank you, corrected

Comment: Page 5 – Line 14: Replace “also is” with “is also”.
Response: Thank you, corrected

Comment: Page 5 – Line 15: Should be “data-sets” not “data-set”.
Response: Thank you, corrected

Comment: Page 5 – Line 27: Add “the” before “ARMOR data-set”.
Response: Thank you, corrected

Comment: Page 6 – Line 3: Remove “de Boyer”. It is written twice.
Response: Thank you, removed

Comment: Page 6 – Line 19: Should be “underestimates” instead of “underestimate”.
Response: Thank you, corrected

Comment: Page 6 – Line 20: Remove “the” before CS2. Also the case on line 21.
Response: Thank you, removed

Comment: Page 6- Line 20: Remove “s” in “values”.
Response: Thank you, removed

Comment: Page 6 – Line 21: Remove “the” before “Spitsbergen”. Also the case on line 23.
Response: Thank you, removed

Comment: Page 6 – Line 23-24: Either use “PIOMAS tend to overestimate” or “PIOMAS overestimates”.
Response: Thank you, corrected

Comment: Page 6 – Line 24: Remove “thickness”.
Response: We believe that “thickness” is used correctly.

Comment: Page 6 – Line 26: “discrepancies” should be singular => “discrepancy”.
Response: Thank you, corrected

Comment: Page 6 – Line 30: Remove “the” before “PIOMAS”.
Response: Changed

Comment: Page 6 – Line 31: Replace “all are” with “are all”.
Response: Thank you, replaced

Comment: Page 6 – Line 31: Add “of” after “correlation”.
Response: Changed

Comment: Page 6 – Line 31: Add “the” before “Ricker et al. (2018) data”
Response: Changed

Comment: Page 7 – Line 16: Replace “comprises” with a more appropriate term (“was”?).
Response: Thank you, replaced

Comment: Page 7 – Line 22: Remove “for” before “about”.
Response: Thank you, corrected

Comment: Page 7 – Line 23: Should be “significant effect” rather than “significantly effect”. Alsoreplace “the sea” with “the Greenland Sea”.
Response: Thank you, corrected

Comment: Page 8 – Line 1: Add “the” before “climatology”.Page 8 – Line 9: “approaches” is an odd choice of tense when you talk about some-thing that happened from 1990s to 2000s. Replace with “approached” or “propagatedtowards”.
Response: Thank you, corrected

Comment: Page 8 – Line 10: It should be “Jan Mayen” not “Yan Mayen”.
Response: Thank you, corrected

Comment: Page 8 – Line 11: Replace “western” with “eastern”. In addition, do you mean “Frontal Current” instead of “Front Current” (same for Page 10 – Line 23)?

Comment: Page 8 – Line 12: The “tendencies” are shown in figure 5d. Replace “Fig. 4d” with “Fig.5d”.
Response: Thank you, corrected

Comment: Page 8 – Line 23: nearly doubles from 1993 to ?
Response: Changed to “from1993 to 2016”

Comment: Page 9 – Line 12: Remove “the” after exceeds. It is written twice.
Response: Thank you, removed

Comment: Page 9 – Line 22: Remove “thickness” after “thick ice”.
Response: We left the sentence unchanged as this wording is used in the cited study.

Comment: Page 9 – Line 25: Should be “appears” not “appear”. Also, replace “lower compared to know from literature fluxes” with “lower than those estimated by previous studies” orsomething similar.
Response: The entire paragraph is changed in response to another comment.

Comment: Page 9 – Line 27: Remove “the” before “data”.
Response: Thank you, corrected

Comment: Page 10 - Line 1: Remove “the” before “sea ice volume”.
Response: Corrected

Comment: Page 10 – Line 13: Replace “uptake” with “take up”.
Response: Corrected

Comment: Page 10 – Line 17: “brining” should be “bringing”.
Response: Thank you, corrected

Comment: Page 10 – Line 18: “later” should be “layer”.
Response: Thank you, corrected

Comment: Page 10 – Line 19: Write “Nansen Basin” with capital B.
Response: Thank you, corrected

Comment: Page 10 – Line 29: Replace “Further” with “Farther”.
Response: Thank you, replaced

Comment: Page 10 – Line 30: “Svinoy” should be “Svinøy”. Also the case on Page 10 - line 34 and Page 11 – line 16 and 17 etc.Page 10 – Line 31: Remove comma after “Barents Sea”.
Response: Thank you, corrected

Comment: Page 10 – Line 34: Remove “in” after “confirmed by”.
Response: Thank you, corrected

Comment: Page 11 – Line 1: Use capital S in “Nordic Seas”. Also the case for line 10 and 20.
Response: Thank you, corrected

Comment: Page 11 – Line 5: Remove “of” after “NAO phase increases”.
Response: Thank you, corrected

Comment: Page 11 – Line 10: “Fram Strat” should be “Fram Strait”.
Response: Thank you, corrected

Comment: Page 11 – Line 11: Replace “through” by “across” and use capital R in “Faroe-Shetland Ridge”.
Response: Thank you, corrected

Comment: Page 11 – Line 12: Inconsistent capitalization of “water”. Here you write “Polar Water”,while in line 6 you use “Atlantic water”. Please be consistent throughout the paper.
Response: Thank you, corrected

Comment: Page 11 – Line 28: Replace “is” with “was” after “more ice”.
Response: Thank you, corrected

Comment: Page 11 – Line 29: Add “the” before “Odden ice tongue”.
Response: Thank you, corrected

Comment: Page 12 – Line 7: Remove “the” after “favours”.
Response: Thank you, corrected

Comment: Page 12 – Line 22: “MID” should be “MLD”.

Response: Thank you, corrected

Comment: Page 12 – Line 23: Add “heat” before “necessary”.
Response: Thank you, corrected

Comment: Page 12 – Line 25: “Froe-Shetland ridge” should be “Faroe-Shetland Ridge”. This sentence is also incomplete. Please re-phrase.
Response: The paragraph was removed

Comment: Figure 1: The color in the right color bar is missing.
Response: Thank you, the figure was updated.

Comment: Figure 2: In the figure caption you describe panel (i) – “difference between mean PI-OMAS and CS2 effective ice thickness”, but panel “i” is not included in the figure (only panels a-h).
Response: Thank you, the caption for panel (I) is removed.

Comment: Figure 4: Please write out what the legends “w”, “s”, and “a” mean.
Response: The letters are replaced by full words

Comment: Figure 5: The color bar in panel “d” has the wrong units. The panel shows change in salinity, but have units of◦C.
Response: Thank you, corrected

Comment: Figure 6: In the figure caption: Remove parenthesis after “cold season”.
Response: Thank you, corrected

Comment: Figure 7: Is there missing a second y-axis for the normalized maximum MLD? If not,I do not understand what the values -1 to 1.5 in normalized maximum MLD mean.Please explain.

Response: MLD was notmalized in the standard way:
MLD(normalized)=(MLD-mean(MLD))/std(MLD))
To avoid confusions, the right y-axis now shows the non-normalized MLD (m).

Comment: Table 3: Explain all columns. (i.e. what is correlated in the column r2?)
Response: Now all columns are explained. R^2 is the coefficient of determintaion. It is a squared coefficient of correlation between the observed values and the ones modeld with the linear trend.

References:

please see the references in the updated version of the manuscript.

Sea ice volume variability and water temperature in the Greenland Sea

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Abstract. This study explores a link between the long-term variations in the integral sea ice volume (SIV) in the Greenland Sea and oceanic processes. Using Pan-Arctic Ice Ocean Modelling and Assimilation System (PIOMAS, 1979-2016), we show that ~~the negative tendencies in SIVgo~~ loss of sea ice volume (SIV) in the region goes in parallel with the increasing ~~ice~~ sea ice volume flux through the Fram Strait. The overall SIV loss in the Greenland Sea comprises 113 km^3 per decade, while the total SIV import through the Fram ~~strait is increasing~~ Strait increases by 115 km^3 per decade. An analysis of the ocean temperature and the mixed layer depth (MLD) in the marginal sea ice zone (MIZ), based on ARMOR data-set (1993-2016), revealed doubling of the amount of the upper ocean heat content available for the sea ice melt in the MIZ. This increase in the upper ocean heat content over the 24-year period can solely explain the SIV loss in the Greenland Sea, even when accounting for the increasing SIV flux from the Arctic. The increase in the ocean heat content is found to be linked to an increase in the temperature of the Atlantic ~~water~~ Water in the Nordic ~~seas~~Seas, following an increase of ocean heat flux form the subtropical North Atlantic. We argue that the predominantly positive North Atlantic Oscillation (NAO) index during the four recent decades, together with the intensification of the deep convection in the Greenland Sea, are responsible for the overall intensification of the circulation in the Nordic ~~seas~~Seas, which explains the observed long-term variations of the SIV.

1 Introduction

The Greenland Sea is one of the key regions of deep ocean convection (Visbeck et al., 1995; Marshall and Schott, 1999; Brakstad et al., 201 an inherent part of the Atlantic Meridional Overturning Circulation (AMOC). ~~The 2/3~~ More than half of the deep AMOC water ~~is formed in this region (Rhein et al., 2011; Buckley and Marshall, 2016)~~originated from the Greenalnd Sea (Yashayaev, 2007; Rhein et al., In turn, the intensity of convection is governed by buoyancy (heat and freshwater) fluxes at the ocean-atmosphere boundary, as well as oceanic buoyancy advection ~~to the sea~~into the region. The freshwater is thought to play the principal role in long-term buoyancy balance of the upper Greenland Sea (Meincke et al., 1992; Alekseev et al., 2001a). The positive local precipitation-evaporation exchange accounts for only 15% of the freshwater balance in the Nordic Seas. Approximately half of the fresh water anomaly in the ~~Norwegian-Greenland region~~ Nordic Seas originates from the freshwater flux through the Fram Strait, which ~~is formed~~ forms by freshening of the upper ocean due to ~~sea-ice~~ sea ice melt in the Arctic ~~basin~~ Ocean and by solid ~~ice transport~~ sea ice transport melting outside the Arctic Ocean (Serreze et al., 2006; Peterson et al., 2006; Glessmer et al., 2014).

A general surface circulation in the region is shown in Fig.1a. The upper 500 m in the western Greenland Sea is formed by mixing the Polar Water (PW) with temperature, close to freezing and salinity from 33 to 34 and the Atlantic Water (AW) with temperature over 3 °C and salinity around 34.9 recirculating in the southern part of the Fram Strait (Moretskij and Popov, 1989; Langehaug The maximum PW content quickly decreasing in the off shelf direction is found in the upper 200 m of the Greenland shelf (Håvik et al., 2017). The AW is found below the PW. Its core is observed in the seawards branch of the EGC, trapped by the continental slope. The centrals parts of the Greenland Sea represents a mixture of the AW and the PW with the Greenland Intermediate Water (with temperature -0.4 – -0.8 °C and salinity ∼34.9). The core of the Greenland Intermediate Water is found at 500-1000 m. The Greenland Sea Deep Water (with temperature -0.8 – -1.2 °C and salinity ∼34.9) is found below 1000 m. The latter two water masses are formed by advection of the intermediate and deep water, coming from the Arctic Eurasian basin through the Fram Strait, mixed with the recirculating Atlantic Water by winter convection (Moretskij and Popov, 1989; Alekseev et al., 1989; Langehaug and Falck, 2012). The convection depth in the Greenland Sea often exceeds 2000 m (Latarius and Quadfasel, 2016; Bashmachnikov et al., 2019).

The sea ice conditions in the Greenland Sea are defined by ~~sea-ice~~ sea ice import through the Fram Strait and by local ice formation and melt. The Fram Strait sea ice ~~flux~~ area (Vinje and Finnekåsa, 1986; Kwok et al., 2004) and volume flux (Kwok et al., 2004; Ricker et al., 2018) is primarily controlled by variations in the sea ice drift, which, in turn, are driven by the large-atmospheric circulation patterns~~(Vinje and Finnekåsa, 1986; Kwok et al., 2004; Ricker et al., 2018)~~. Most of the variability of the atmospheric circulation and drift patterns is captured by the phase of the Arctic Oscillation (AO) or of its regional counterpart – the North Atlantic Oscillation (NAO) (Marshall et al., 2001). The positive AO (or NAO) phase intensifies ~~northern~~ northerly winds that drives more intensive ice transport through the Fram Strait (Kwok et al., 2004). ~~When~~ There is a moderate correlation (0.62) between between NAO index (excluding extreme negative NAO events~~, the correlation coefficient between NAO and~~) and winter sea ice area flux through the Fram Strait ~~(~~over 24 years of satellite observations ~~) reaches 0.6 Kwok et al. (2004), while that with the~~ (1978-2002) (Kwok et al., 2004). A higher correlation (0.70) between NAO index and winter sea ice volume flux ~~vary from 0.4 (over 9 years of mooring observations, 1991-1998; Kwok et al. (2004)) to 0.7 (over 7 years of CryoSat-2 satellite observations,~~ (2010-2017~~; Ricker et al. (2018))~~) is reported by Ricker et al. (2018). It is also argued that the interannual variations of the sea ice area flux through the Fram Strait is even stronger linked to the Arctic Dipole pattern, that explains a higher fraction of the observed interannual variations in the ~~sea-ice~~ sea ice area flux than either the AO or the NAO ~~(Wu et al., 2006)~~(Wu et al., 2006). The Arctic Dipole pattern is derived as the second sea-level pressure EOF over the Arctic, which has two centers of action: over the Laptev-Kara seas and over the Canadian Archipelago. The pattern represents an important mechanism regulating the ice export through Fram Strait (Wu et al., 2006).

The sea ice production in the Greenland Sea ~~primarily takes place~~ takes place east of the shelf between 71-75 °N ~~, where the~~ and north of 75 °N within the highly dynamic pack ice transported southwards along the Greenland coast. The latter fills in cracks and leads and can reach considerable thickness. While the sea ice forming east of the shelf is mainly thin newly-formed ice. The highest interannual variations of sea ice area is observed between 71-75 °N (Germe et al., 2011). In the region ~~,~~ the Odden sea ice tongue is occasionally formed, ~~an~~ a sea ice pattern extending ~~westwards~~ eastwards from the east Greenland shelf and northwest of Jan Mayen (Wadhams et al., 1996; Comiso et al., 2001). The regression of the first empirical orthogonal function (EOF) of the sea ice extent to sea-level pressure shows a weak inverse relation with the NAO-like pattern with correlation coefficient -0.4. ~~Further regression analysis suggests that decrease of the intensity~~ During the negative NAO phase, a reduction of the northerly ~~winds favours a larger area of the Odden sea ice~~ wind, permits a more intensive westward Ekman drift of sea ice into the Greenland Sea interior which favours formation of large Odden tongue (Shuchman et al., 1998; Germe et al., 2011). The Odden tongue area ~~also strongly negatively correlates~~ shows a strong negative correlation with the air temperature (-0.7) over Jan Mayen and with the local sea surface temperature (-0.9) (Comiso et al., 2001). Having stronger correlations with water temperature, the negative correlation of the sea ice area with the air temperature might be an artifact, as both are oppositely affected by the oceanic heat release to the atmosphere (Germe et al., 2011).

The ocean clearly plays an important role in the sea ice formation and melt in the region. In particular, it is speculated that the oceanic convection in the region favours a more intensive warm water flux from the south, affecting the air temperature and the sea ice extent (Visbeck et al., 1995). However, presently there is a lack of investigation linking oceanic processes with the sea ice variability in the Greenland Sea (Comiso et al., 2001; Kern et al., 2010).

Both sea ice area flux through the Fram Strait and local sea ice processes in the Greenland Sea ~~reveal~~ show changes over the recent decades. ~~An~~ The overall reduction in sea ice extent is observed in the region since 1979 (Moore et al., 2015; Onarheim et al., 2018). Since 2000s, a reduction in winter sea ice area is observed in the region of Odden ice tongue formation (Rogers and Hung, 2008; Kern et al., Concurrently, an increase of the sea ice area flux through the Fram Strait since 1979 was reported by Kwok et al. (2004); Smedsrud et al. (2017). ~~Shorter~~ A combined time series of of sea ice volume flux through the Fram Strait ~~showed no significant changes (Kwok et al., 2004; Spreen et al., 2009; Ricker et al., 2018). At the same time, since 2000s, a reduction in winter sea ice area has been detected in the Greenland Sea (in particular in the Oddin ice tongue) from passive microwave observations (Rogers and Hung, 2008; Kern et al., 2010; Germe et al., 2011)~~(1990-1996 (Vinje et al., 1998), 1991-1999 (Kwok et al., 2004) and 2003-2008 (Spreen et al., 2009)) shows a shift towards lower fluxes in early 2000s compared to 1990s (Spreen et al., 2009). However, the later study of Ricker et al. (2018) revealed that the sea ice volume flux in 2010-2017 is similar to that in 1990s. Due to different uncertainties in the data and different methodologies used in those studies, it not possible to merge the results to get an uninterrupted data-set for the entire period from 1990 to 2017. Although individual studies do not reveal significant trends in the sea ice volume flux through the Fram Strait, the overall tendency remains unknown.

In this paper we further explore a link between sea ice volume variability in the Greenland Sea and oceanic processes. The first objective is to estimate the sea ice mass balance in the Greenland Sea from local sea ice formation/melt and from sea ice advection in/out of the sea. We extend this analysis back to 1979 using the PIOMAS sea ice volume data. Further, we link the detected variations of sea ice mass balance to heat flux of the ~~Atlantic water into the region~~ AW with the West Spitsbergen current (WSC) into the region.

2 Data

2.1 PIOMAS sea ice volume

PIOMAS (Pan-Arctic Ice Ocean Modeling and Assimilation System) is a coupled sea ice-ocean model developed to simulate Arctic sea ice volume. It assimilates NSIDC (National Snow and Ice Data Center) near-real time sea daily ice concentration, daily surface atmospheric forcing and the sea-surface temperature in the ice-free areas from NCEP (National Centers for Environmental Prediction)/NCAR (National Center for Atmospheric Research) ~~atmospheric parameters and the sea-surface temperature in the ice-free areas (Zhang and Rothrock, 2003)~~reanalysis (Zhang and Rothrock, 2003; Schweiger et al., 2011). The PIOMAS provides monthly effective sea ice thickness (mean sea ice thickness over a grid cell) on a curvilinear model grid from 1978. A comparison of PIOMAS effective sea ice thickness with in situ, submarine and ICESat ~~satellite~~ (Ice, Cloud, and land Elevation Satellite) data, mainly covering the western Arctic, showed that the PIOMAS uncertainty for monthly mean effective sea ice thickness does not exceed 0.78 m (Schweiger et al., 2011). ~~Although, the model tends to overestimate the thickness of the thin ice and underestimate the thickness of the thick ice, the spatial patterns~~ The spatial pattern of PIOMAS ice thickness agrees well with those ~~,~~ derived from in situ and satellite data. The model overestimates the thickness of thin ice and underestimates the thickness of thick ice. Such systematic differences might affects long-term trends in thickness and volume. There is an indication that the PIOMAS shows a conservative sea ice volume trend (1979-2010) (Schweiger et al., 2011).

Since PIOMAS performance has not been ~~accessed~~ assessed south of the Fram Strait, the first part of this study is devoted to ~~cross-validation~~ inter-comparison of the PIOMAS sea ice thickness in the Greenland Sea with satellite data, as well as of the PIOMAS sea ice volume flux through the Fram Strait with ~~satellite and upward-looking sonar (ULS) observations~~ observation-based flux values know from literature (Sect. 4.1 and 4.2). ~~PIOMAS data was~~ The original monthly PIOMAS sea ice thickness data were gridded to 25 km EASE-2 grid. The PIOMAS data were further used to derive time series of montly mean annual (September-August), mean winter (October-April) and mean summer (May-September) sea ice volume in the Greenland Sea for 1979 – 2016. The grid cell sea ice volume was computed as a product of PIOMAS effective sea ice thickness and the grid cell area.

2.2 AWI Cryosat-2 sea ice thickness

In the Greenland Sea The PIOMAS effective sea ice thickness was ~~cross-validated~~ inter-compared against sea ice thickness from Cryosat-2 satellite data-set (CS2, version 1.2, ~~Grosfeld et al. (2016)~~Ricker et al. (2014); Hendricks et al. (2016)) for the Greenland Sea region (see green box in Fig. 1). The CS2 data-set ~~provide~~ provides monthly average sea ice thickness on EASE-2 grid with 25x25 km spatial resolution from 2010 to 2017. Due to limitations of ice thickness retrieval from satellite altimetry, CS2 data-set used was limited only to the cold season (October-April). The sea ice concentration data, provided along with CS2 thicknesses, was used to derive the effective sea ice thickness (H_{eff}) for the comparison with the PIOMAS data. The conversion was performed for each grid cell:

$$\cancel{HIE_i}H_{eff} = \cancel{HI_i * SIC_i}HC \qquad (1)$$

where ~~HI~~ H – CS2 sea ice thickness~~in the i-th grid cell, SIC~~, C - sea ice concentration~~in the same cell~~.

Uncertainties of CS2 ice thickness increase below 78°N due to sparse orbit coverage (Ricker et al., 2014). The CS2 retrieval is based on sea ice freeboard measurements that are converted into sea ice thickness assuming hydrostatic equilibrium. Estimates of snow depth, required for the conversion, are based on the modified Warren climatology (Warren et al., 1999; Ricker et al., 2014 This climatology is not defined in the Fram Strait or Greenland Sea, therefore, snow depth estimates are extrapolated. Moreover, interannual variability in snow depth is not captured by the climatology, which can potentially cause biases in the final sea ice thickness retrieval. In addition, high drift speeds can also cause biases in the ice thickness retrieval due to the timeliness of the satellite passes within one month. The typical uncertainty is in the range of 0.3 - 0.5 m, but may potentially reach higher values.

2.3 ARMOR data-set

The long-term time series of water temperature at different depth levels and the mixed layer depth (MLD) were derived from the ARMOR data-set (http://marine.copernicus.eu/, 1993-2015). The data-set combines in situ temperature and salinity profiles with satellite observations and is constructed as the following. First, based on a joint analysis of the variations of satellite-derived anomalies (sea-surface temperature and sea-level from satellite altimetry) and of in situ thermohaline characteristics at different depth, linear multiple regressions are obtained. The regressions allow extrapolating satellite data from the sea-surface to standard oceanographic depth levels in a regular mesh of 1/4° x 1/4 °, constructing the so-called "synthetic" vertical temperature and salinity profiles. The final monthly mean 3D temperature/salinity distributions are obtained through optimal interpolation of all ~~observed in situ~~ in situ observations for this month together with the derived “synthetic” profiles, taken with different weights (Guinehut et al., 2012). Use of satellite information provides a more precise and detailed picture of spatial and temporal variability of the thermohaline characteristics than from interpolation of in situ profiles alone (as, for example, it is done in the World Ocean Atlas data-set, $https://www.nodc.noaa.gov/OC5/WOD/pr_wod.html$). The ~~computed vertical density profiles and the altimetry sea-surface currents were further used in~~ oceanic heat fluxes are estimated using currents from the ARMOR data-set ~~for deriving~~ with the same spatial and temporal resolution. The current velocities at various depth levels are obtained by extrapolating the sea-surface current from the satellite altimetry, downwards using the thermal wind relations. The vertical density profiles, used for the computations, are assessed from the previously obtained temperature and salinity profiles (Mulet et al., 2012).

2.4 ~~Water~~ Long timeseries of water temperature of the West Spitsbergen ~~current~~Current

~~Water temperatures were collected from the~~ Long-term monthly gridded water temperatures were obtained from "The Climatological Atlas of the Nordic Seas and Northern North Atlantic" (Korablev et al., 2007). The data-base merges together data from ICES (International Counsel for Exploration of the Sea)~~and~~ , from IMR (Institute of the Marine Research)~~data, data~~ , from a number of international projects (ESOP, VEINS, TRACTOR, CONVECTION, etc.), as well as from Soviet Union cruises in the study region. ~~The temperature time series, used in this paper, were obtained in the core of the WSC~~ However, there are too few observations in the EGC before the 2000s. In this paper we use long-term temperature time series in the much better sampled upper WSC (West Spitsbergen current) at 78°N~~(west of East-Fjord~~, west of East Fjord (Fig. 1b). The ~~data were~~ depth averaged water temperature at 100-200 m is used, as this layer is dominated by the AW and it is not directly affected by heat exchange with the atmosphere all year round. This results in the highest temperature at these depths during cold season. Even this region was sampled in a ~~quire~~ quite irregular manner, with a ~~particular low~~ lower sampling frequency in winter. Since 1979, the average number of samples was 161 per year, varying from, on average, 2-5 per year from November to May to 20-35 per year from June to October. The data-gaps ~~were filled~~ in the time series were filled in by kriging with the 30-km window. The interannual variations ~~used~~ presented in this study were averaged ~~from June to September -~~ over the months the most densely covered with data (June to September).

3 Methods

3.1 Fram Strait and Denmark Strait sea ice volume flux from PIOMAS

The sea ice volume flux through the Fram Strait was calculated as a product of monthly average PIOMAS effective sea ice thickness, area of the grid cell and the sea ice drift velocity (Ricker et al., 2018). ~~Note, that the PIOMAS sea ice thickness represents the mean thickness over a grid cell, called effective sea ice thickness (with zero sea ice thickness for the open water)~~ The sea ice drift data was taken from the Polar Pathfinder Sea Ice Motion Vectors data set (version 3), distributed by the National Snow and Ice Data Center (NSIDC) (Tschudi and Maslanik., 2016). The data is provided on EASE-2 grid with 25x25 km spatial resolution. The gate was selected as a combination of a meridional section (82°N and 12°W - 20°E) and a zonal section (20°E and 80.5°N - 82°N), as suggested by Krumpen et al. 2016. (Fig. 1a). The location of the meridional gate at 82°N was chosen to reduce biases and errors in sea ice drift that become larger with increasing velocities south of the gate (Sumata et al., 2014, 2015). The meridional and zonal sea ice volume flux, Q_v and Q_u correspondingly, were computed as:

$$Q_v = l/cos(\lambda)\cancel{*H*}H(D_x sin(\lambda) - D_y cos(\lambda)) \quad (2)$$

$$Q_u = l/cos(\lambda)\cancel{*H*}H(D_x cos(\lambda) - D_y sin(\lambda)) \quad (3)$$

where l = 25 km is the distance between 2 data-points, H is the PIOMAS effective sea ice thickness and D_x, D_y represents sea ice drift velocity in *x* and *y* directions of the grid, respectively, and λ is the longitude of the respective grid cell. ~~The total~~

The total sea ice volume flux through the Fram Strait (QF, positive – into the Greenland Sea) was obtained as a sum of the meridional and zonal fluxes along the gate:

$$QF = Q_u + Q_v \tag{4}$$

The total sea ice volume flux through the Fram Strait was derived for the period from 1979 to ~~2017 for each months~~2016 for each month. A similar methodology was used to assess the sea ice volume flux ~~though the Denmark strait~~ through the Denmark Strait (QD) along the meridional section (66°N and ~~25~~35°W – ~~36~~20°E). The positive sign of QD corresponds to the sea ice volume outflow from the Greenland Sea.

In order to access the data quality, the resultant sea ice volume fluxes ~~though~~ through the Fram Strait gate at 82°N were ~~cross-validated against available satellite-based~~ inter-compared against available observation-based estimates in the Fram Strait ~~from Kwok et al. (2004); Spreen et al. (2009); Ricker et al. (2018)~~(Kwok et al., 2004; Spreen et al., 2009; Ricker et al., 2018). The gate and the methodology used here ~~was~~ were adopted from Ricker et al. (2018), while in the other two studies somewhat different methodologies and gates locations (Fig. 1a) were used. Each of the studies ~~also is~~ is also based on different ~~data-set~~ data-sets of sea ice concentration (SIC), thickness (SIT) and drift (SID) (Table 1).

3.2 Greenland Sea sea ice mass balance

In order to analyse the sea ice volume lost or ~~formed due to thermodynamically within the Greenland Sea~~gained due to local melt or freezing, we calculated the sea ice mass balance (MB) in the Greenland Sea. It was derived for each month from 1979 to 2016 as:

$$MB = (\cancel{QF_m - QD}V_m - V_{(m-1)})t - (\cancel{V}QF_m - QD_m \cancel{- V_{(m-1)}})t \tag{5}$$

where V_m and ~~$V(m-1)$~~ $V_{(m-1)}$ are regional sea ice volume of the current *m*-th and previous *(m-1)*-th months, QF_m and QD_m are Fram Strait and Denmark Strait sea ice volume flux of the current *m*-th month~~. Therefore, positive MB values correspond to sea ice melt and negative values correspond to sea ice formation within~~ , t - time period equal to 1 month. The regional sea ice volume was calculated for the area limited by 82°N and 66°N latitudes and boarder on the east shown in Figure 1a (green box). We slightly extended the eastern boundary of the Greenland Sea to the south-east, compared to its classical definition in order to include the entire area of the Odden ice tongue formation. The mass balance shows month-to-month increase or loss in sea ice volume within the Greenland Sea due to sea ice formation or melt. Positive MB values correspond to sea ice formation and negative values correspond to sea ice melt within the region. The monthly MB values were averaged over annual, winter and summer periods. Note ~~,~~ that due to averaging ~~positive~~ negative annual values corresponding to sea ice volume loss (Fig.4) can occur due to both an increase in sea ice melt and a decrease in sea ice formation.

3.3 Mixed layer depth (MLD) and marginal ice zone (MIZ) ocean temperature

The MLD was derived using vertical profiles from the ARMOR data-set by the method of Dukhovskoy (Bashmachnikov et al., 2018, 2019). The method is similar to that used by Pickart et al. (2002), but is applied to the vertical profiles of the potential density gradients. Before processing, the small-scale noise in the potential density profiles were filtered ~~to remove the small-scale noise~~out with 10-m sliding means. The gravitationally unstable segments were artificially mixed to neutral stratification. The MLD is defined as the depth where the vertical density gradient exceeds its two local standard deviations within a 50-m window, ~~centred~~ centered at the tested ~~point~~depth (see Bashmachnikov et al. (2018)). The visual control shows that the results are mostly similar to the widely used methods by ~~de Boyer~~ de Boyer Montégut et al. (2004) and Kara et al. (2003), except for the weakly stratified areas, where the Dukhovskoy's method defines the MLD with higher accuracy. The ~~marginal ice zone was~~ obtained mean distribution of the MLD, seasonal and interannual variations of the MLD in the central Greenland Sea are consistent with observations (Våge et al., 2015; Latarius and Quadfasel, 2016; Brakstad et al., 2019).

The position of the real MIZ strongly varies in time and along the EGC, being a function of local direction and intensity of sea ice transport by wind and current, variation in the characteristics of ice transport from the Arctic and interaction of ice floes, local ice thermodynamics, etc. Presence of melting sea ice, in turn, affects the upper ocean and air temperatures. A warmer winter ocean warms up the air, which can further be advected over the sea ice causing its melt away from the sea ice edge. Furthermore, an anomalously warmer ocean may prevent (or delay) formation of a new ice. All these distant factors certainly affect the MIZ position. However, if we estimate ocean temperature variations only along the actual MIZ, we do not account for these effects. The considerations above show that defining the oceanic region directly and indirectly affecting the ice volume in the sea is not straightforward. In this study we define interannual variations of ocean temperature in a fixed region, which is defined as an area enclosed between the 500-m isobath~~(marking the shelf break)~~ , marking the Greenland shelf break, and the mean winter location of the sea ice edge (Fig. 1). ~~The~~ Using the fixed region also assures compatibility of interannual temperature variations. For the computations, the sea ice edge was defined as the 15% mean winter NSIDC sea ice concentration for 1979-2016. For brevity we further, somewhat deliberately, call this region the MIZ area. We further will see that temperature trends remain positive and of the same order of magnitude all over the western Greenland Sea, except for a few limited areas along the shelf break. This assure robustness of the results to the choice of the study region.

3.4 Oceanic horizontal heat flux

The ARMOR data was used to derive a time series of oceanic heat flux into the Nordic Seas. Total oceanic heat flux through the ~~transect (Q~~Svinøy transect (Q_{Svinoy}) is calculated by integrating the heat flux values in the grid points:

$$Q_{\cancel{i}Svinoy} = \int\int[\rho\cancel{*}c_p\cancel{*}(\cancel{T_i - T}T - T_{ref})\cancel{V_w}v]d_xd_z \tag{6}$$

where ρ =1030 kg m^{-3} is the mean sea water density; c_p = ~~4200~~ 3900 J kg^{-1} $^\circ$ C^{-1} is specific heat of sea water; ~~T_i~~ T is sea water temperature~~in an i-th grid cell~~, T_{ref} =-1.8°C is the "reference temperature", ~~V is current speed~~ v is current velocity perpendicular to the transect~~, d_x is the distance between the vertical profiles along the transect, d_z is the thickness of the water~~

~~layer for the processed depth level~~. The choice of the reference temperature is conditioned by study of the role of heat fluxes on melting sea ice.

4 Results

4.1 Assessment of PIOMAS-derived ice volume flux through the Fram Strait and sea ice volume in the Greenland Sea

In order to assess the quality of the PIOMAS data in ~~the~~ region, PIOMAS monthly effective sea ice thickness in the Greenland Sea was compared to those derived using the CS2 data-set (Fig. 2 ~~, 2~~). In general, PIOMAS ~~underestimate~~ underestimates effective sea ice thickness compared to ~~the~~ CS2 (Fig. 1b). The mean difference between PIOMAS and CS2 ~~of a grid cell values~~ grid cell value is - 0.70 m. There are only two locations where PIOMAS shows thicker ice compared to ~~the~~ CS2 – north of ~~the~~ Spitsbergen and along the sea ice edge. On the other hand, CS2 also tends to overestimate sea ice thickness in the marginal ice zone (Ricker et al., 2017). The highest absolute differences between the data sets are attributed to the areas along the Greenland coast (dark blue) and north of ~~the~~ Spitsbergen (dark red) (Fig. 1b). The monthly scatter plots (Fig. 2a-g) show that PIOMAS ~~tend to overestimates~~ tends to overestimate thin sea ice and underestimate thick sea ice thickness, which is in agreement with the tendency reported for the central Arctic ~~Schweiger et al. (2011)~~(Schweiger et al., 2011). This results in moderate correlations between the two data sets (0.63 < r < 0.77) for all winter months. The major discrepancies correspond to sea ice of 3 m and higher thickness, which form "tails" to the lower right corner of the scatter plots (Fig. 2 a-g).

PIOMAS sea ice volume flux through the Fram Strait (October to April) was cross-compared with the ~~satellite-derived and ULS-based~~ fluxes derived using observation-based sea ice thickness data (see Tab.1). The analysis shows that ~~ice volume fluxes in PIOMAS are~~ PIOMAS-based sea ice volume flux is in good agreement with the estimates from other data sets (Fig. 3, Tab. 2). The correlation coefficients between the three data sets and ~~the PIOMAS all~~ PIOMAS are over 0.6. The highest correlation off over 0.8 with the Ricker et al. (2018) data can be explained by using identical gates and methodology for estimating ice volume fluxes (Fig. 1a). However, other statistical criteria (bias, relative percentage difference (RPD), root mean square error (RMSE), Table 2) indicate somewhat stronger mismatch between the PIOMAS and Ricker et al. (2018) ~~ice volume fluxes~~ estimates compared to those between PIOMAS and Kwok et al. (2004) or Spreen et al. (2009). The possible sources of ~~these discrepancies~~ this discrepancy are discussed in Sec. 5. Overall, PIOMAS shows lower sea ice volume fluxes compared to the ~~satellite- and the ULS-based~~ observation-based estimates (Fig. 3c). The interannual variations in the PIOMAS monthly and total winter sea ice volume flux agree well with other data-sets (Fig. 3a; Tab. 2) ~~until 2014, after which PIOMAS fluxes start decreasing, contrary to the results by Ricker et al. (2018)~~. At intra-annual time scales all three data-sets show similar patterns with the minimum flux in October and maximum flux in March (Fig. 3b). Overall, moderate to high correlation between the data-sets, low relative variance and low bias (Tab. 2) suggest that PIOMAS provides a realistic estimate of seasonal and interannual variations of the winter sea ice volume flux through the Fram Strait. Figures 2h and 3c suggest that PIOMAS correctly captures year-to-year variations of the mean effective sea ice thickness in the Greenland Sea and Fram Strait sea ice volume flux. This justifies using PIOMAS for analysing interannual variations of the integral sea ice volume over the Greenland Sea.

4.2 Interannual variations of sea ice flux through the Fram Strait and sea ice volume in the Greenland Sea

The sea ice ~~volumes~~ volume in the Greenland Sea ~~,~~ derived from PIOMAS ~~,~~ revealed statistically significant (at 99% confidence level) negative trends in monthly winter, summer and annual values (Fig. 4a, Tab. 3). The strongest negative trend of 84.8 km^3 per decade or 13.5% of long-term monthly annual mean volume is observed in winter, while for summer months, the trend ~~comprises~~ was 58.2 km^3 per decade or 9.3% of long-term annual mean volume. The sea ice volume in the Greenland Sea shows an overall reduction by 72.4 km^3 or 11.5% of its long-term mean per decade.

The reduction of the sea ice volume in the Greenland Sea ~~unexpectedly goes along with an increase in the monthly ice volume flux~~ coincides with an increased sea ice volume import through the Fram Strait by 9.6 km^3 per decade or 8.8% of its long-term mean (significant at 90% confidence level). Thus, the total increase in the sea ice volume imported to the Greenland Sea ~~though~~ through the Fram Strait ~~comprises 112.8~~ is 115.2 km^3 per decade, which accounts for ~~17.8~~18.2% of the Greenland Sea annual mean sea ice volume. The sea ice volume flux through the Denmark Strait comprises ~~for~~ about 2% (Fig. ~~2~~ 13) of that through the Fram Strait and shows no significant tendency. This flux has no ~~significantly~~ considerable effect on the sea ice mass balance of the ~~sea.~~ Greenland Sea.

A balance between ~~SIV~~ sea ice volume import/export to the Greenland Sea ~~though~~ through the straits and regional changes in ~~SIV~~ the sea ice volume shows the volume of sea ice formed or lost due to thermodynamic processes within the region (Sec. 3.2). The sea ice mass balance in the Greenland Sea expressed in ~~SIV~~ sea ice volume loss is shown in Fig. 4b. ~~The SIV loss shows~~ For about a half of the years during the study period, sea ice volume loss in summer is higher than that in winter. However, there are a few years (1992, 1994, 2004-2007) when winter sea ice volume loss significantly exceeds the summer one. During these years an increased sea ice volume flux thought the Fram Strait is detected (Fig. 4c). There is a positive statistically significant trends in annual and summer ~~values~~monthly mean sea ice volume loss, while winter trend shows low statistical significance (Tab. 3). Overall, the monthly Greenland Sea ~~SIV~~ sea ice volume loss increases by 9.4 km^3 per decade (Fig. 4, Tab. 3).

4.3 Interannual variations of water temperature and MLD in the MIZ of the Greenland Sea

In order to find the reason for the opposite trends of ~~SIV in the Greenland Sea and~~ Greenland Sea sea ice volume in and sea ice volume flux ~~though~~ through the Fram Strait, we investigate water temperature in the study region (Sec. 2.3, 3.3, 3.4). A relatively warm ~~Atlantic water~~ AW is observed in the East Greenland Current (EGC), off the Greenland shelf break, below a thin upper mixed layer dominated by the cold ~~Polar water. The Atlantic water is~~ PW. Our estimates of winter MLD shows that the AW should be regularly brought to the ocean surface by vertical winter mixing, which ~~intensifies in winter (Håvik et al., 2017)~~is consistent with observations (Håvik et al., 2017; Våge et al., 2018). The presence of the ~~Atlantic water~~ AW is observed in the climatology as water temperature (and salinity) in the EGC increasing ~~southeastwards and downwards~~ with depth from about 0 °C ~~at~~ near the sea-surface to 2-4°C at 500 m. In the 24-year means, the northern temperature maximum (Fig. 5a) results from recirculation of ~~Atlantic water~~ AW of the WSC in the southern Fram Strait, while the southern maximum is due to the northwards heat flux with the ~~West Islandic Current (WIC~~North Icelandic Irminger Current (NIIC) through the Denmark Strait

~~(Ypma et al., 2019)~~(Hansen et al., 2008; Ypma et al., 2019). The latter is a northern branch of the Irminger Current. The sea ice is affected by the heat in the upper mixed layer, the depth of which varies on synoptic, seasonal and interannual time scales. Our analysis shows that the obtained tendencies are largely independent from the choice of the water layer, at least within the upper 200 m of the water column. In further analysis we present results for the upper 50 m layer (the typical summer mixed layer in the MIZ) and the upper 200 m layer (the typical winter mixed layer in the MIZ, (Fig. 6c)). In the annual means, the water temperature, averaged over upper 50-m layer of the MIZ, has maximum of 2°C in September and decreases to 0.1-0.2°C in March-April. Averaged over the upper 200-m the patterns of the mean distribution and of (a somewhat weaker) tendencies in temperature and salinity closely repeat those in Figure 5. Always above the seawater freezing temperatures, the ocean melts the sea ice in the MIZ all the year-round.

Figure 5a shows interannual variations of November 2 °C sea water isotherm (averaged over the upper 200-m layer). Water temperature in November reflects the heat fluxes accumulated during the warm period. It shows the background conditions formed by the beginning of winter cooling, when sea ice start forming localy. However, the performed tests show that the tendency of the isotherm to approach the shelf break is consistent for different isotherms (from 1 to 3°C), for different layer thickness (50 to 200 m) and for different months. The difference is only observed for winter months, when the whole upper 200-m mixed layer effectively releases heat and the interannual trends become insignificant. From 1990s to 2000s the ~~isotherm approaches~~ 2°C isotherm approached the shelf break. The largest westwards propagation is observed in the WSC recirculation area (76-78°N) and northwest of ~~Yan~~ Jan Mayen (70-73°N), in the southern Odden tongue region. The linear temperature ~~trends~~ trend (Fig. 5b) ~~confirm the overall~~ shows warming in the ~~western and southern parts of the MIZ,~~ whole area of the eastern MIZ. The strongest warming follows the pathway of the recirculating AW in the northern Greenland Sea (Glessmer et al., 2014; Håvik et al., 2017) which is known to strongly affect the central regions of the sea (Rudels et al., 2002; Jeansson et a The warming in the northern Greenland Sea is linked to a ~~stronger~~ strong warming of the WSC and of the Norwegian Atlantic Front Current (NwAFC), ~~of its extension~~ while that in the southernmost part of the sea – with the NIIC. Two exceptions can be noted: the northwestern part of the coastally trapped EGC (where negative trends are obtained in the area dominated by a colder PW outflow from the Arctic) and the ~~WSC, as well as of the WIC. The mean upper ocean salinity (Fig. 5c) and its tendencies (Fig. 4d) confirm the increasing presence of the Atlantic water in the upper 50-m layer in the MIZ. Averaged over the upper 200-m, the typical depth of the winter mixed layer (not shown), the patterns of the mean distribution and of (a somewhat weaker) tendencies in temperature and salinity closely repeat those in Figure 5~~ area of the EGC recirculation into the Greenland Sea at 72-74°N extended from the continental shelf break to 8-9°W (here the tendencies in the upper ocean temperature are close to zero). The latter is the area, where the Odden ice tongue starts spreading into the Greenland Sea interior (Germe et al., 2011). The decrease of warming in these areas is consistent with a stronger sea ice/PW transport from the Arctic (Sec. 4.2).

With a stronger melting of sea ice at the seawards part of the MIZ, together with the ice volume loss, we should observe a sea ice area loss. This is consistent with Germe et al. (2011). In particular, positive water temperature trends over the eastern part of the Odden region suggest an overall decrease of the Odden formation by the end of the study period. The mean temperature trends over the Odden region (the area within the dotted line in Fig.5b) is 0.08 °C per year, i.e. there is an area-mean increase by 1.8°C from 1993 to 2016. This exceeds the mean ocean temperature increase, averaged in the MIZ area (Eq.7), which includes the northern shelf break regions with negative temperature trends. Therefore, the estimates of the heat available for the ice melt, based on the values presented in Eq.(7), should be considered as the lower limit of the heat release within the Odden region.

Interannual variations of water characteristics, averaged over the upper 200-m and ~~over~~ in the MIZ area, are shown in Figure 6. From 1993 ~~, an overall year mean increase of~~ an overall increase of annual mean temperature in the MIZ is observed, suggesting an increasing intensity of the sea ice melt. The temperature increases during all seasons, but the strongest increase is detected in autumn (by 0.5 and 0.6°C over the 24 years). The winter convection efficiently uplifts heat to the sea surface. The heat ~~is released to the atmosphere and goes tothe sea ice melt, decreasing the interannual trends to insignificant (see Table 3). Therefore, from 1993, we also observe an increase of the water temperature difference from September to March~~ accumulated in summer is mostly released during winter. Figure 4d suggests that the results can be extrapolated back to, at least, 1980, as the slope of the trend lines in temperature of the advected AW for 1980-1992 is practically the same as for the period discussed above. We observe a growing difference between September and March temperatures (Fig. 6a) ~~, e. g.~~ together with a decrease of temperature interannual trends to insignificant in winter. The growing difference in temperature is observed in spite of the equal winter and summer trends in the heat inflow with the NwAC (see T_w and Q_{Svinoy} in Tab.3). Therefore, in the ~~upper~~ MIZ region, all additional heat, accumulated in the upper 200-m ~~layer the heataccumulated in summer is mostly released during winter~~ layer during summer, is uplifted to the sea surface by winter convection, preventing ice formation in the ice-free areas or melting the ice in the ice-covered ones.

Not only the autumn temperature increases in the MIZ, but also the zonal thermal gradient across the MIZ ~~nearly doubles~~ increases 1.7 times from 1993 in ~~annual mean~~ the annual means (Fig. 6 b), and ~~even stronger (2.5 times) increases~~ nearly 4 times in winter. This goes ~~together~~ along with a decrease ~~by half~~ of the annual mean distance ~~of the~~ between the 2°C or 3°C isotherm ~~to~~ and the shelf break (Fig. 6 ~~(d)~~d): from 120 km in 1993 to 50 km in 2016 (see also Fig.5 ~~(a)~~a). The direct result of this effect is a faster melt of the sea ice episodically advected from the MIZ eastwards by EGC filaments and mesoscale eddies (Kwok, 2000; von Appen et al., 2018). These processes can transport sea ice dozens of kilometers eastward (von Appen et al., 2018). The most favourable conditions for the eddy formation are observed for the ~~northern winds~~northely winds. The eddies sweep sea ice and PW off and advect warm AW closer to the ice edge, resulting in increase in bottom and lateral sea ice melt (Bondevik, 2011). ~~This increases the ice melt, however~~However, a few episodic observations of the ice dynamics in the MIZ do not presently allow quantifying the importance of this effect.

The 24-year mean winter mixed layer depth (MLD) in the MIZ off the Greenland shelf vary from 120 m to 250 m with the mean value around 150 m, as derived from ARMOR data-set. Averaged over the MIZ, MLD increases from the mean value of 130 m in 1993 to around 180 m in 2016 (Fig. 6c). Since the winter mixing does not reach the lower limit of the warm Atlantic water at 500-700 m, the deeper the mixing, the more heat is uplifted towards the sea-surface, melting the ice in the MIZ, which is consistent with the findings of Lauvset et al. (2018). The increase of MLD results from a higher upper ocean density due to increasing salinity of the ~~Atlantic water~~AW, tempered by the increasing temperature (Fig. 5b,d). Given the increase in ocean temperature in the upper 200-m layer in the MIZ from 1.3°C in September 1993 to 1.8°C in September 2016 together with an increase in the mean winter MLD from 130 m in 1993 to 180 m in 2016, we can make a rough estimate of the increase (over the 24 years) in the heat released by winter MLD in the MIZ:

$$dQ = dQ_{2016} - dQ_{1993} = c_p * \rho_{water} * (\cancel{2.0}1.8 * 180 - 1.3 * 130) * MIZarea \tag{7}$$

where c_p = ~~4200~~ 3900 J °C^{-1} kg^{-1}, ~~ρ~~ ρ_{water} = 1030 kg m^{-3} , the MIZ area is estimated as 2.3 10^{11} m^2~~, which is about 20% of the area of the Greenland Sea~~. The computations show an additional heat release of ~~2~~ 1.5 10^{20} J, ~~if,~~ following the observed water temperature seasonal cycle, we assume that all the heat from the growing winter MLD is released at the sea-surface. If all this heat would go to melt ice in the MIZ, we get an increase in the ~~SIV~~ sea ice volume loss during winter by:

$$dV = \cancel{dq}dQ/(L * \rho_{\cancel{L}ice})\cancel{\sim 600}\approx 500 km^3 \tag{8}$$

where the specific heat of ice fusion L=3.3 10^5 J kg^{-1} and the ice density of ~~ρ_L~~ ρ_{ice} = 920 kg m^{-3} (Petrich and Eicken, 2010). This far exceeds the ~~the~~ observed sea ice volume loss in the region (SIV loss monthly winter trend * 12 month * 24 years ~~= 340~~ $\approx$ 200 km^{-3})~~of ice needed to fuse~~. Certainly, not all heat ~~,~~ released by the upper ocean in the MIZ area goes to the ice melt~~, a~~. An unknown fraction of heat is directly transferred to the atmosphere through open water~~and leads or~~, ice leads or is advected away from the MIZ area by ocean currents and eddies. The sea ice melt may additionally increase haline stratification at the lower boundary of the ice, preventing ocean heat contacting with the ice cover. However, the estimates above suggest that~~solely the on-going~~, the autumn warming of the ~~Greenland Sea water can result in the reduction of SIV in the Greenland Sea~~upper MIZ region, limited from below by the winter mixed layer, is able to release the amount heat far exceeding the amount, sufficient for the observed reduction of sea ice volume in the region.

5 Discussion

5.1 PIOMAS-derived trends

The revealed regional trends in sea ice volume rely on the PIOMAS model data. A comparison of interannual variations of PIOMAS regional sea ice thickness and the sea ice volume flux through the Fram Strait showed that PIOMAS estimates are in agreement with the ~~satellite-based data~~ observation-based estimates during the recent decades. However, the PIOMAS systematic overestimation of thin ice and underestimation of thick ice thickness, reported for the central Arctic, affects the ~~multiyear volume trend (Schweiger et al. 2011). The authors~~ long-term volume trend (Schweiger et al., 2011). Schweiger et al. (2011) conclude that the PIOMAS-based volume trend is lower that the actual one. Given that similar systematic errors in effective sea ice thickness are found for the Greenland Sea (Fig. 2), it is likely that the derived Greenland Sea sea ice volume trend is underestimated. The PIOMAS Fram Strait sea ice volume flux ~~appear to be lower compared to know from literature~~ can be also affected by these systematic errors. The model studies show three major positive peaks in the Fram Strait sea ice volume flux since 1979: 1981-1983, 1989-1990, 1994-1995 (Arfeuille et al., 2000; Lindsay and Zhang, 2005). The anomaly in 1989-1990 was caused by an increase in the thickness of the transported sea ice, while the anomaly in 1994-1995 was due to an intensification of southward sea ice drift (Arfeuille et al., 2000). The reduction of Arctic myltiyear ice fraction during late 1980s – early 1990s (Comiso, 2002; Rigor and Wallace, 2004; Yu et al., 2004; Maslanik et al., 2007) are in line with this finding. The sea ice volume flux through the Fram Strait derived from PIOMAS shows the peaks in 1981-1985 and 1994-1995, but does not capture the anomaly of 1989-1990 (Fig.14c). During this period there is no significant shift in the PIOMAS effective sea ice thicknesses in the Fram Strait which is likely caused by the PIOMAS systematic errors which smoothed the differences in thickness between thick and thin ice. Since 1993, the PIOMAS Fram Strait sea ice volume flux correlates well with the observation-based fluxes (Fig. 3). The main sources of relative errors between the Fram Strait volume flux estimates can be related to the different choice of methodologies, ~~sets of the data~~ data-sets and gates used to derive sea ice volume fluxes (Table 1, Fig.1). Lower PIOMAS-based sea ice volume flux can be attributed to the discussed above general PIOMAS tendency to underestimate sea ice thickness. Fig. ~~2i~~ 1b shows that for the entire meridional 82°N gate, which are the main gates for sea ice import to the Greenland Sea, the PIOMAS effective sea ice thickness is lower compared to the ~~CS-2~~CS2 effective thickness. In addition, the NSIDC sea ice drift shows lower speed compared to the OSI SAF drift used in Ricker et al. (2018). A combination of lower drift speed with thinner ice thickness might be the reason of the largest offset (Table 2, Fig. 3) between the PIOMAS-based Fram Strait sea ice volume fluxes and those derived in Ricker et al. (2018).

5.2 Link to the variability of ocean temperature and atmospheric forcing

The revealed decrease in the sea ice volume in ~~the~~ Greenland Sea goes in parallel with an increase in the ice volume inflow through the Fram Strait. As the sea ice volume flux through the Denmark Strait does not show any significant change, this indicates a simultaneous intensification of the processes of ice melt and reduction in sea ice formation in the sea. The latter is supported by the highest negative trends in the sea ice area ~~(SIA) (~~Fig. 1, expressed in SIC trend) in the area of the Odden tongue between 73 and 77°N ~~, which is mostly formed locally thermodynamically, at cold air temperatures (Shuchman et al., 1998; Comiso et al., 2001; Rogers and Hung, 2008). The intensification of in the sea ice melt is discussed in the following section. The interannual variations SIA were previously related with the corresponding variations in the~~

The interannual variations in sea ice area were previously linked to variations in air temperature (Comiso et al., 2001). The results of our paper permitted to speculate, that ocean temperature may be important in controlling Odden formation (see also Shuchman et al. (1998); Germe et al. (2011)). E.g. the reduction of Odden tongue occurrence in 2000s (Latarius and Quadfasel, 2010) migh be partially driven by the increase in upper ocean heat content (Fig.5b). In this study we argue that at least the overall ~~SIV~~ sea ice volume loss from 1993 to 2016 is governed by the ocean.

5.3 ~~Link to the variability of ocean temperature and atmospheric forcing~~

The surplus of the amount of the heat, released by the ocean at end of the study period, is ~~almost twice of~~ more than twice of that necessary for bringing up the observed ~~SIV~~ sea ice volume loss, even when accounting for the detected increase in the ~~SIV transport~~ sea ice volume import through the Fram Strait. Heat loss to the atmosphere and the ~~neighbouring~~ neighboring ocean areas should ~~uptake~~ take up the rest of the heat. In particular, the observed increase of ocean temperature over the Greenland Sea (Fig. 5b) may be a reason for a corresponding increase in the air temperature, used for explaining negative trends in the ~~SIA~~ sea ice area (Comiso et al., 2001).

The observed trends are due to both, the increase in temperature of the ~~Atlantic water~~ AW in the MIZ, as well as an increase in winter MLD in the area, ~~brining more Atlantic water~~ bringing more AW to the surface. A significant vertical extent of the warm subsurface ~~Atlantic water later~~AW layer, going down to 500-700 m depth (Håvik et al., 2017), results in a higher ocean heat release for a stronger mixing for the observed MLD in the MIZ. A similar mechanism was suggested for in the Nansen ~~basin~~ Basin of the Arctic Ocean, where an enhanced vertical mixing through the pycnocline is thought to decrease the ~~SIA~~ sea ice area in the basin (Ivanov and Repina, 2018).

In turn, the subsurface ~~Atlantic water~~ AW in the EGC is fed by the recirculation of the surface water of the ~~West Spitsbergen Current~~WSC, an extension of the Norwegian Atlantic Front Current (NwAFC) and the Norwegian Atlantic Slope Current (NwASC). The recirculation is ~~through to be~~ mostly driven by eddies (Boyd and D'Asaro, 1994; Nilsen et al., 2006; Hattermann et al., 2016). The ~~detected inconsistency is due to local peculiarities in~~ interannual variations in the vertical mixing intensity ~~, in local~~ between the AW, the PW and the modified AW, returning from the Arctic through the southern Fram Strait, as well as variations in ocean-atmosphere exchange ~~and a the degree of delution of the advected Atlantic water with the Polar water with its own interannual variability~~in that area leads to interannual variability of the AW advected by the EGC into the Greenland Sea (Langehaug and Falck, 2012). All the processes intensify during highly dynamic winter conditions. Nevertheless, interannual correlation of the summer upper ocean water temperature (0-200 m), spatially averaged over the MIZ area, with that in the upper WSC is 0.8-0.9. Further south, correlation of interannual variations of the MIZ temperature with that of the NwAFC (NwASC) or with the heat flux across the ~~Svinoy~~ Svinøy section are low. Besides differences in local forcing, regional atmospheric forcing over the northwestern Barents Sea ~~,~~ regulates the interannual variations of the heat re-distribution between the WSC and the Barents Sea (Lien et al., 2013), further decreasing the correlations.

Nevertheless, in a long run (during four recent decades), temperature at the WSC, the NwAFC, ~~NwSFC~~ NwASC and the heat flux across ~~Svinoy~~ Svinøy section all show positive trends (Fig. 4, 5). This is confirmed by ~~in~~ a number of studies (Alekseev et al., 2001c; Piechura and Walczowski, 2009; Beszczynska-Möller et al., 2012).

Several studies show that during the positive NAO phase ~~,~~ the intensity of oceanic heat flux to the Nordic ~~seas~~ Seas increases by 50%, and the NwASC intensifies along the Scandinavian coast (Skagseth et al., 2004; Raj et al., 2018). On the other hand, the positive NAO phase drives a higher ice drift through the Fram Strait, proved to be the main driver for interannual variations of SIF to the Greenland Sea (Ricker et al., 2018). It is also noted that the positive NAO phase increases ~~of~~ the intensity of the EGC (Blindheim et al., 2000; Kwok, 2000). Finally, the link between the ~~Atlantic water~~ AW transport by the WSC and the cyclonic circulation in the Greenland Sea, related to NAO phase, is obtained from observations and numerical models (Walczowski, 2010; Chatterjee et al., 2018).

~~Summing up the results above, the positive phase of NAO intensifies the whole current system of~~ During positive NAO phase, the cyclonic atmospheric circulation over the Nordic Seas intensifies (Skagseth et al., 2008; Germe et al., 2011). This leads to stronger northerly winds along the Greenland shelf, as well as stronger southerly winds along the Norwegian coast, leading to a more intensive cyclonic oceanic circulation in the Nordic Seas (Schlichtholz and Houssais, 2011). Several regional studies, based on in situ data, demonstrate a higher intensity of oceanic transport of volume and heat along the AW path towards the Fram Strait during the positive NAO phase. Thus, the NwASC volume inflow to the Nordic Seas ~~, simultaneously~~

~~intensifying sea ice flux~~ increases by 50%, as well as the oceanic heat flux (Skagseth et al., 2004, 2008; Raj et al., 2018). The link between the AW transport by the WSC, as well as of the cyclonic circulation in the Greenland Sea, and the NAO phase is also obtained from observations and numerical models (Walczowski, 2010; Chatterjee et al., 2018). Observations additionally demonstrate that the positive NAO phase drives a stronger ice drift through the Fram ~~Strat and Atlantic water~~ Strait (Vinje and Finnekåsa, 1986; Koenigk et al., 2007; Giles et al., 2011; Köhl and Serra, 2014), a stronger EGC (Blindheim et al., 2000; Kwok and a typically lager extension of Odden ice tongue (Shuchman et al., 1998; Germe et al., 2011). NAO phase is showed to be the main driver for interannual variations of sea ice volume flux to the ~~Nordic seas~~Greenland Sea (Germe et al., 2011; Ricker et al., 2018). The simultaneous long-term (1974-1997) intensification of the ~~Atlantic water~~ AW inflow in the Nordic Seas ~~through~~ across the Faroe-Shetland ~~ridge~~Ridge, and of eastwards advection ~~Polar Water~~ PW to the southwestern Norwegian Sea, as a response to NAO forcing has been noted in ~~(Blindheim et al., 2000). This supports our conclusions.~~several studies (see, for example, (Blindheim et al., 2000; Yashayaev and Seidov, 2015). The long-term variations in the NAO index go in parallel with those in the Atlantic Multidecadal Oscillation (AMO), at least during the latest 70 years (Yashayaev and Seidov, 2015). This suggests that the positive phase of NAO corresponds, in the long-term tendency, to the positive phase of AMO, i.e. the higher water temperature in the North Atlantic. Both tendencies lead to a higher heat fluxes into the Nordic Seas.

From the beginning of 1970s the winter NAO index is growing. From 1979 to 2016 it is mostly positive (Fig. 7), although an overall winter trend can be separated into an increase from 1979 to 1994, a rapid drop from 1995 to 1996 and an increase from 1996 to 2016. The NAO index drop in 1995-1996 ~~is observed as~~ coincides with a drop in ~~SIV loss and~~ regional sea ice volume loss and a decrease in the WSC water temperature (Fig.4 ~~(b,e)), and~~ b,d). This can be related to the minimum heat flux through the ~~Svinoy~~ Svinøy section in 1994 (Fig. 4 ~~(f)~~,d). The time needed for water properties to propagate from ~~Svinoy~~ Svinøy to the Fram Strait with the NwAC is of order of 1.5-2 years (Walczowski, 2010).

Summer NAO index does not govern the interannual variations of the atmospheric system, as well as in the oceanic ones (circulation in the Nordic ~~seas~~ Seas intensifies in winter and is thought to bring more ~~Atlantic Water~~ AW to the recirculation region compared to ~~than~~ that in summer). Consistent with other studies of seasonal interannual variations of current intensity in the region, our results suggest that these are winter variations of the ~~Atlantic water~~ AW transport that bring up the interannual variations of the subsurface water temperature in the MIZ of the Greenland Sea. The decreasing summer NAO index from 1979, may be responsible for a somewhat stronger tendency in the SIV ~~decrease~~ loss in winter, compared to summer (Fig. 4 ~~(~~a,b)~~)~~.

Summing up, the positive phase of NAO intensifies the whole current system of the Nordic Seas, simultaneously intensifying sea ice flux through the Fram Strait and the northward heat flux with the AW to the Nordic Seas. In this paper we demonstrated that the intensification of the AW heat inflow contributes to variations of the sea ice volume in the Greenland Sea. This supplements previous results, showing that the AW inflow dominates the oceanographic conditions over the upper Greenland Sea, except of the shelf area (e.g. (Alekseev et al., 2001b; Marnela et al., 2013).

In spite of the stronger ice melt, the upper ocean salinity in MIZ, as well as along the ~~main currents in the Greenland Sea~~EGC, as well as along the NwAC, increases during recent decades (Fig. 5(d)). We relate salinification in the MIZ area of the upper Greenland Sea to a stronger flux of the ~~Atlantic water~~ AW and more intensive winter mixing. These effects override the additional freshwater input from the ice melt. Oppositely, during freshening of the upper Greenland Sea, the Great salinity anomaly 1966-1972, more ice ~~is~~ was observed in the MIZ region – the Odden ice tongue was pronounced (Rogers and Hung, 2008). This confirms the reverse relation between the sea ice ~~content~~ extent and the MIZ salinity in the Greenland Sea and their dependence on interannual variations of the intensity of the ~~Atlantic Water~~ AW advection.

Another ~~,~~ possibly not independent mechanism is linked to the intensity of the deep convection in the Greenland Sea (Fig. 17). ~~Governed~~ A more intense convection, governed by thermohaline characteristics of the upper Greenland Sea, the sea ice extent and the intensity of ocean-atmosphere heat and freshwater exchange (Marshall and Schott, 1999; Moore et al., 2015), ~~the more intense convection~~ lowers the sea-level in the Greenland Sea (Gelderloos et al., 2013; Bashmachnikov et al., 2019)~~,~~ ~~thus increasing~~ . This in turn increases the cyclonic circulation in the region. This effect works together with NAO forcing. Deep convection in the Greenland Sea shows a consistent increase from about 1000 m in the beginning of 1990s to about 1500-2000 m during 2008-2010, after which a certain tendency to decrease is noted (Bashmachnikov et al., 2019). The on-going increase in salinity of the upper Greenland Sea (Fig. 5(d)) during the recent decades favours ~~the deeper convection~~ deeper convection (see also Lauvset et al. (2018); Brakstad et al. (2019)). Satellite altimetry data show that, during the same period, the area-mean cyclonic vorticity over the Nordic Seas has grown by about 10%. The circulation increase is also consistent with the detected intensification of the AMOC after its minimum in 1980s (Rahmstorf et al., 2015). However, during the latest decade a stagnation or a possible reversal of the tendency is observed (Smeed et al., 2014).

6 Conclusions

Using PIOMAS sea ice volume data we derived trends in the mean annual, winter and summer sea ice volume (SIV) in the Greenland Sea and the sea ice volume flux (SIF) through the Fram Strait for 1979 to 2016. Taking into account the SIV inflow and outflow ~~though~~ through the Fram and Denmark Straits, the thermodynamic SIV loss within the Greenland Sea was derived. It shows an increase in monthly SIV loss by 9.4 km^3 per decade. From 1979 to 2016 the overall SIV loss comprises ~ 270 km^3, in spite of an increase ice SIF by ~ 280 km^3 during the same time period. However, those PIOMAS-based trends should be treated cautiously. The absence of positive anomaly in PIOMAS-based SIF in 1989-1990 indicate that the PIOMAS underestimate thickness of thick in the Fram Strait and the Greenland Sea. The biases might lead to the actual long-term SIF trend to be weaker, while the SIV trend to be stronger.

Our analysis of the upper ocean water properties in the marginal sea ice (MIZ) zone of the EGC, shows a notable increase of the Atlantic Water (AW) temperature below the pycnocline, as well as of winter mixed layer depth from 1993 to 2016. These changes result in a higher sea-surface heat release, providing twice the value of additional heat needed for bringing up the observed SIV loss. ~~Therefore~~This suggests that, the long-term variations of the heat flux entering the Nordic Seas, advected northwards with the NwAC as the ~~Atlantic Water~~ AW and, further on, with the WSC into the MIZ ~~, are found to govern~~ largely contribute the corresponding long-term SIV variations in the Greenland Sea. The analysis of marginal sea ice zone (MIZ) ocean parameters showed an increase in mixed layer depth (~~MID~~MLD) and its temperature from 1993 to 2016. The estimated amount of additional oceanic heat released from 1993 to 2016 surplus the amount of heat necessary for bringing up the observed SIV loss. Therefore, we state that the ~~Atlantic Water~~ AW advection into the MIZ largely contributes to the SIV loss.

~~The long-term variations of the Atlantic water transport all the way through the Froe-Shetland ridge, with the WSC and to the MIZ zone. Interannual variations between the parameters, though, do not have high correlations, governed by variations in the local forcing.~~

~~We also showed~~ We suggest that the simultaneous tendencies in the long-term increase of SIF and of the ~~Atlantic water~~ AW transport are both linked to a higher intensity of atmospheric circulation during the positive NAO phase, and, possibly, to the ~~intensity of deep convection~~positive AMO phase, often linked to the intensification of the AMOC since the 1980s. Not being independent, both mechanisms finally lead to a decrease of SIV in the western Greenland Sea.

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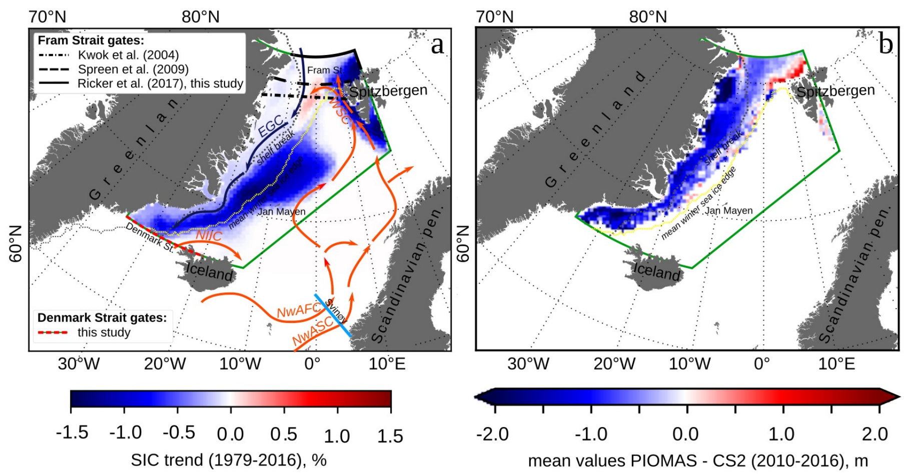

Figure 1. The study region is marked with the ~~red~~ green box: a - linear trends in the mean ~~September-April~~ October-April NSIDC sea ice concentration (SIC) over the period 1979-2016 (Comiso, 2015). The black lines show gates used for estimation of the sea ice volume flux through the Fram Strait. Mean winter sea ice edge is shown in dash yellow, the shelfbreak (500-m ~~isobash~~isobath) is shown in dash grey. EGC is the East Greenland Current, ~~WIC~~ NIIC – the ~~West Islandic~~ North Icelandic Irminger Current, NwAFC – the Norwegian Atlantic Front Current, NwASC – the Norwegian Atlantic Slope Current, WSC – the West Spitsbergen Current; b - mean difference between mean PIOMAS and CS2 effective sea ice thickness (m) for October- April, 2010-2016.

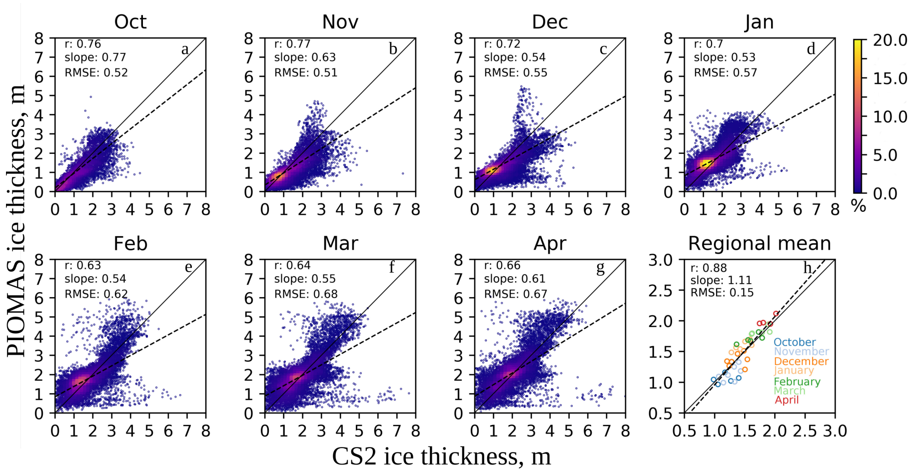

Figure 2. ~~Scatter~~ Density scatter plots of PIOMAS and CS2 monthly effective sea ice thickness (m) in the Greenland Sea, October-April 2010-2016: (a-g) - each point corresponds to one grid-cell sea ice thickness; (h) ~~area-mean~~ mean monthly sea ice thickness over the ice covered area of the Greenland Sea ~~; (i) – difference between mean PIOMAS and CS2 effective ice thickness (m)~~for all inter-compared snapshots. The color of the points in panel h corresponds to ~~the color of the months from October to April (2010-2016) at panels a-g~~a month. The dashed lines show the linear regression fit and the solid lines are 45° angles. The correlation coefficients (r)~~and~~ , the slope of the linear regressions and the root-mean-square error (RMSE) are given in the upper left corner.

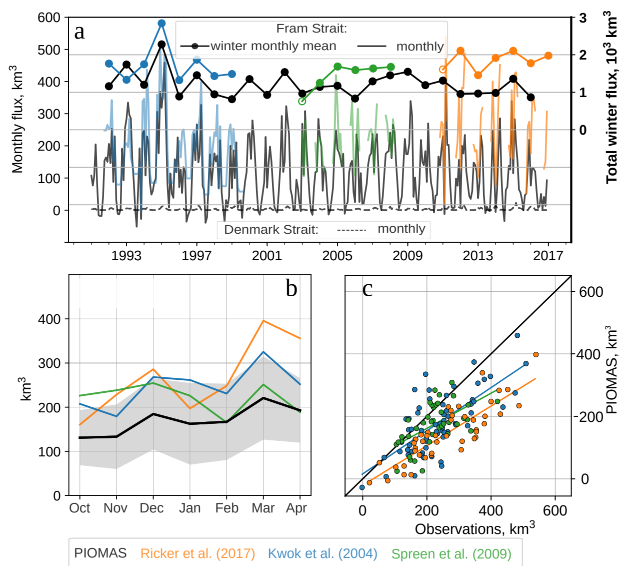

Figure 3. Sea ice volume fluxes (km^3): a - time series of PIOMAS and ~~satellite-based~~ observation-based monthly sea ice volume fluxes ~~(km3)~~ through the Fram and the Denmark Straits, ~~1991-2017~~ 1991-2016 (note that the ~~mean~~ total winter fluxes are referenced to the right scale). Empty circles indicate seasons with an incomplete winter cycle: b - winter intra-annual cycle sea ice volume flux through the Fram Strait, averaged over the period of the observations and over 1991-2016 for PIOMAS data-set. The ~~dash lines (satellite estimates) and the~~ gray background color ~~(PIOMAS)~~ correspond to one standard deviation interval from the PIOMAS mean; c - scatter diagram of monthly mean PIOMAS sea ice volume fluxes through the Fram Strait versus monthly mean observations.

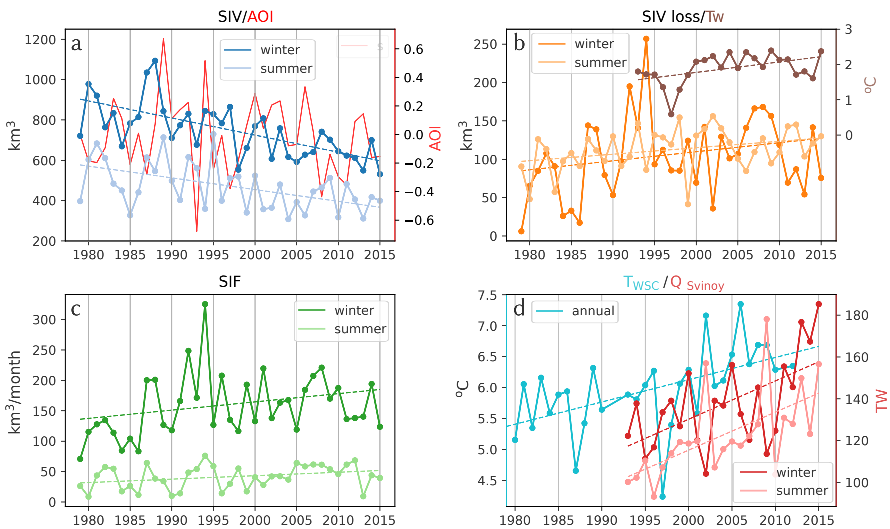

Figure 4. Time series of winter ~~means~~ (December-April) and summer ~~means~~ (May-November) and annual ice-ocean-atmosphere characteristics in the Greenland Sea: (a) monthly mean PIOMAS sea ice volume (SIV, km^3) and monthly summer AO index (AOI), (b) monthly mean PIOMAS sea ice volume loss (SIV loss, km^3) and mean September water temperature in MIZ (Tw,°C), (c) monthly mean sea ice volume flux through the Fram Strait (SIF, km^3/month) (d) annual ~~means of~~ mean water temperature in the West Spitsbergen Current (~~TWSC~~T_{WSC}, $^\circ$C~~/year~~) and monthly mean ocean heat flux (Q_{Svinoy}, TW) through ~~Svinoy~~ Svinøy section (see Fig. 1).

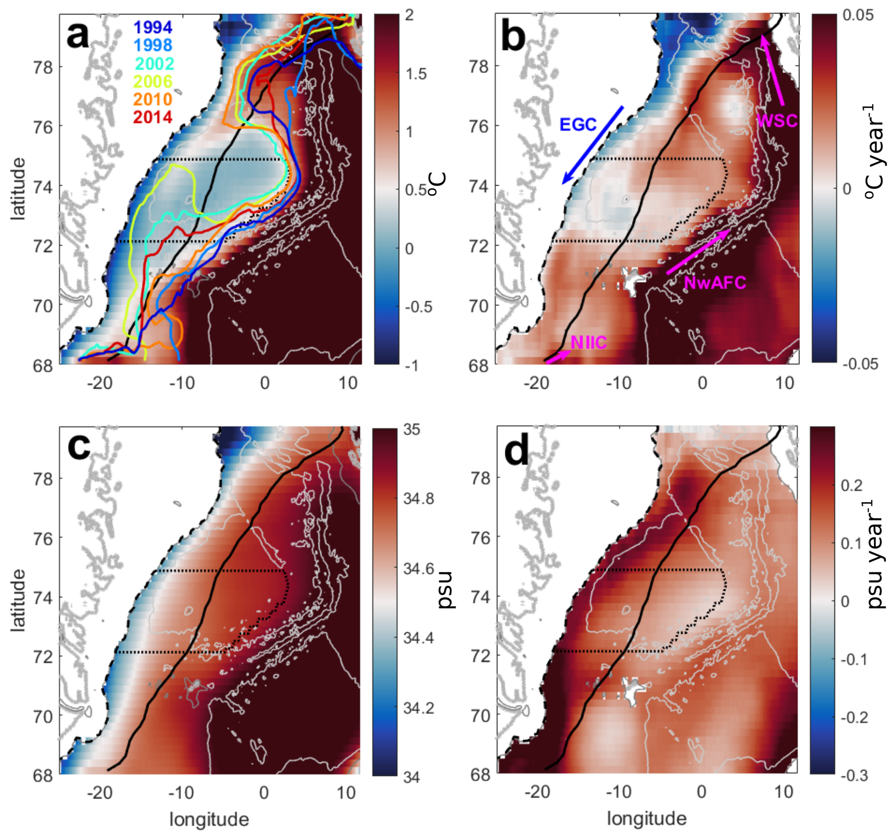

Figure 5. Marginal sea ice zone (enclosed in black lines) and themohaline water properties averaged in the upper 50-m layer during cold season (October-April). a - time-mean (1993-2016) temperature (°C) in MIZ and location of 2°C isotherm in November for selected years; b - linear ~~change in~~ temperature trend (°C year^{-1}) in the upper 50 m-layer from 1993 to 2016; c - time-mean (1993-2016) salinity in MIZ; d) linear ~~change in~~ salinity trend in the upper 50-m layer from 1993 to 2016. In plate (b) EGC is the East Greenland Current, ~~WIC~~ NwAFC – the ~~West Islandic~~ Norwegian Atlantic Front Current, ~~NwAFC~~ NIIC – the ~~Norwegian Atlantic Front~~ North Icelandic Irminger Current, WSC – the West Spitsbergen Current. Dotted lines in panels (b) and (d) mark the region, where Odden tongue is observed.

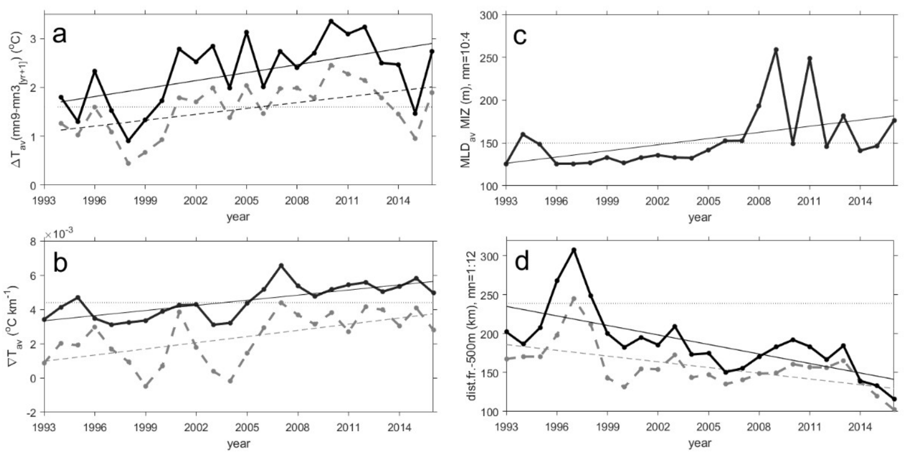

Figure 6. Interannual variations of water properties, averaged over the ~~200-m layer and the~~ MIZ area. (a) Temperature drop (°C) from maximum in September to minimum in ~~March~~ April next year; (b) annual mean temperature gradient across the MIZ (°C km^{-}1); (c) the mixed layer depth (m), averaged over the cold season~~)~~; (d) annual mean distance of the 3°C isotherm from the shelf break (km). In panels (a), (b) and (d) solid black line – data averaged over the upper 50-m layer, dashed gray line – over the upper 200-m layer. In panel (d) 3°C isotherm is shown for the 50-m means and 2°C – for the 200-m means.

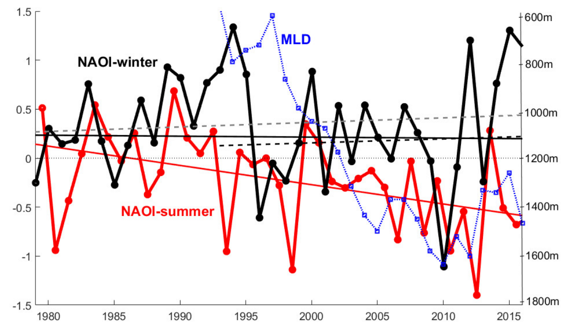

Figure 7. Cold season ~~NAOI~~ NAO index (black, November-April) and warm season ~~NAOI~~ NAO index (red, May-October) with linear trends~~; normalized~~. Additionally plotted are the trends of cold season NAO index since 1993 (black dashed line, October-April) and for winter season (gray dashed line, January-April). The blue line shows maximum MLD in the Greenland Sea derived from ARMOR data-set (see Bashmachnikov et al. (2019) for details).

Table 11. The list of data sources used for estimates of sea ice volume flux through the Fram Strait: sea ice concentrations (SIC), sea ice thicknesses (SIT), sea ice drift velocities (SID) and the time periods of the estimates.

Study	SIC	SIT	SID	Period
Kwok et al. (2004)	ULS moorings	ULS moorings	Kwok and Rothrock (1999)	1991-2002
Spreen et al. (2009)	ASI AMSR-E	ICESat	IFREMER	2003-2008
Ricker et al. (2018)	OSI SAF SIC + sea ice type product	AWI Cryosat-2	OSI SAF	2010-2017
this study	-	PIOMAS	NSIDC Pathfinder ~~v2~~ v3	1979-2017

Table 12. Statistics of monthly PIOMAS versus satellite-based estimates of the sea ice volume fluxes through the Fram Strait: Pearson correlation coefficient (cor. coef), variance relative to PIOMAS (var. rel.), bias, relative percentage difference (RPD), root mean square error (RMSE).

Study	cor.coef.	mean slope	var. rel.,%	bias	RPD,%	RMSE,km^3
Kwok et al. (2004)	0.70	0.71	98	47	66	75
Spreen et al. (2009)	0.60	0.61	97	33	45	56
Ricker et al. (2018)	0.84	0.66	162	107	88	108

var. rel.,% = $(100\% * var_{obs})/var_{PIOMAS}$
bias = $obs. - PIOMAS$

Table 13. Trends in monthly mean characteristics in the Greenland Sea calculated over annual (September-August), winter (October-April) and summer (~~March-September~~May-September) periods: sea ice volume (SIV, km^3 ~~/~~year^{-1}), sea ice volume loss (SIV loss, km^3 ~~/~~year^{-1}), sea ice flux ~~though~~ through the Fram Strait (SIF Fram, km^3 ~~/~~year^{-1}), water temperature in MIZ (Tw, °C ~~/~~year^{-1}) and in the West Spitsbergen Current (TWSC, °C ~~/~~year^{-1}), heat flux across the ~~Svinoy~~ Svinøy section (Q_{Svinoy}, TW ~~/~~year^{-1}). r^2 - coefficient of determination, STD - standard deviation (m), p-value - probability value.

parameter	season	trend	r^2	STD	p-value
SIV, km^3 year^{-1}	annual	-7.24 (-1.15%)	0.42	1.48	<0.01
	winter	-8.48 (-1.35%)	0.44	1.66	<0.01
	summer	-5.82 (-0.93%)	0.26	1.72	<0.01
SIV loss, km^3 year^{-1}	annual	0.94 (0.88%)	0.09	0.52	0.08
	winter	1.18 (1.10%)	0.06	0.83	0.17
	summer	0.84 (0.79%)	0.10	0.45	0.07
SIF Fram, km^3 month^{-1} year^{-1}	annual	0.96 (0.88%)	0.09	0.53	0.08
	winter	1.36 (1.25%)	0.08	0.82	0.10
	summer	0.56 (0.52%)	0.09	0.32	0.08
Tw, °C year^{-1}	annual	0.015 (1.50%)	0.23	0.007	0.04
	winter	0.008 (0.01%)	0.05	0.007	0.29
	summer	0.026 (3.00%)	0.29	0.008	<0.01
Q_{Svinoy}, TW year^{-1}	annual	1.84 (1.39%)	0.48	0.41	<0.01
	winter	1.83 (1.38%)	0.35	0.54	<0.01
	summer	1.82 (1.37%)	0.36	0.53	<0.01
T_{WSC},°C ~~/year~~year^{-1}	annual	0.036 (0.60%)	0.30	0.30	<0.01