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Interactive comment on "Sea ice volume variability and water temperature in the Greenland Sea" *by* Valeria Selyuzhenok et al.

Anonymous Referee #2

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Summary:

This study investigates the temporal development of sea ice volume in the Greenland Sea between 1979 and 2016 based on the PIOMAS model. Changes in sea ice volume, as well as import and export of sea ice are used to compute the evolution of total sea ice volume loss in the region. The authors find that the sea ice volume has decreased through the period even though the import of sea ice has increased. They explain this development by increased melting in the region as a result of higher ocean heat content in the marginal ice zone (MIZ) in the Greenland Sea. Hydrographic data from the ARMOR data set is used to show that the temperature in the MIZ has increased as a result of warmer Atlantic Water flowing into the region and due to increased mixed-layer depths that entrain more heat from the water column below.

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I found this study interesting to read. The description of long-term variations in sea ice volume in the Greenland Sea and its link to changes in mixed-layer properties in the MIZ make this study an important contribution to the literature on Arctic and Subarctic sea ice variability. Hence, I recommend this paper to be published in “The Cryosphere”.

However, I do think there are a number of issues that the authors have to address before the paper is ready for publication. My main concerns are listed under general comments. Then follows several specific comments and technical corrections, many of which are related to unclear text and English grammar.

General comments:

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 as well as the east Greenland shelf in the west. I would rather say that you study the sea ice volume in the Nordic Seas or western Nordic Seas with a focus on the marginal ice 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 not clear to me over which region you actually computed the sea ice volume.

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 and Schott (1999); Moore et al. (2015); Brakstad et al. (2019).

Some statements about the amount of available data in the MIZ (in the ARMOR data set) are required. How does the generally sparse data coverage along the east Greenland shelf affect your results? It would also be good to compare your mixed-layer

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properties with observations (i.e. Nilsson et al., 2008; Pawlowicz, 1995; Brakstad et al., 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?

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 Fram Strait. 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.

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 et al., 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.

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Specific comments:

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

Page 2 - Line 1: Approximately 50% of the freshwater anomaly at the surface or of the entire 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 also important (ie. Lauvset et al., 2018; Mork et al., 2019).

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).

Page 2 – Line 14: Please clarify what you mean by “even stronger linked to the Arctic Dipole pattern”. In addition, you should briefly introduce the Arctic Dipole pattern, as it may not be clear to all readers what this is.

Page 2- Line 17: The Odden sea ice tongue has not been formed in the Greenland Sea 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.

Page 3 – Line 4: The detected variations of what?

Page 3 – Line 25: How is monthly sea ice thickness from the Cryosat-2 satellite data-set obtained?

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

Page 4 – Line 11: Include reference to the method used in the World Ocean Atlas data-set.

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”.

Page 5 – Line 10-11: Denmark Strait is between Greenland and Iceland, not all the way 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 one east of Iceland).

Page 5 –Line 17: What do you mean by "due to thermodynamically within the Greenland Sea"? Please clarify.

Page 5 – Line 29: How were the density profiles filtered?

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 Våge et al., 2015, respectively).

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)?

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 the Atlantic 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".

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".

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).

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.

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)

Page 8 – Line 17: Clarify what you mean by "overall year mean increase of temperature".

Page 8 – Line 19-22: These lines are confusing and hard to read. What do you mean by "decreasing the interannual trends to insignificant"? Please be more specific.

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 "observed".

Page 8 – Line 28-30: Explain how this increases ice melt.

Page 8 – Line 30-32: As stated in the general comments: How does your definition of the MIZ and the data coverage in the MIZ affect the results?

Page 8 – Line 34-35: This corroborates the results of Lauvset et al. (2018) who examined the relationship between hydrography (and MLD) in the Greenland Sea and the temperature/salinity of the northward flowing Atlantic Water.

Page 9 – Line 6-7: The 20% depend on how you define the Greenland Sea.

Page 9 – Line 7: "additional heat release": In addition to what?

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.

Page 9 – Line 15-16: What about increasing atmospheric temperature?

Page 9 – Line 28: Clarify what you mean by "the discussed above general PIOMAS tendency"

Page 9 – Line 29: Figure 2i does not exist.

Page 10 – Line 6: This sentence is not in agreement with Page 8 – Line 6-7 where you state 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.

Page 10 – Line 11-12: “almost twice of” what? Please clarify.

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-phrase and be more specific.

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

Page 11 – Line 2: Raj et al. (2018) show a 50% increase in volume transport not oceanic heat flux. (See general 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.

Page 11 – Line 23-24: This sentence contradicts line 19, where you state that the summer NAO is not important?

Page 11 – Line 25: What do you mean by “main currents in the Greenland Sea”? Be more specific.

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 MLD in 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.

Page 12 – Line 9: Smeed et al. (2014) show a weakened AMOC.

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.

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Page 12 – Line 28: In the last paragraph: The link to NAO is speculative, and you have not shown this link in this paper.

Technical corrections:

Page1 - Line 16: Replace “The 2/3” with “Two thirds”

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

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.)

Page 2 – Line 9: Should be “drive” not “drives”

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.

Page 2 – Line 34: Replace “Oddin” with “Odden”.

Page 3 – Line 15: Singular vs plurals: Use either “the spatial pattern of PIOMAS ice thickness agrees” or “the spatial patterns of PIOMAS ice thickness agree”.

Page 3 – Line 15: Remove comma after “those”.

Page 3 – Line 25: Should be “provides” not “provide”

Page 3- Line 26: Insert “the” before “CS2 data-set”.

Page 4- Line 3: Insert “the” before “ARMOR data-set”.

Page 4 – Line 7: Insert “depth” before “levels”.

Page 4- Line 9: Replace “all observed in situ” with “all in situ observations”.

Page 4 – Line 18: Remove comma before “used” and after “paper”.

Page 4 – Line 19: Replace “quire” with “quite”

Page 4 – Line 21: Use “a” instead of “the” in “kriging with the 30-km window”.

Page 4 – Line 25: Remove comma after “Note”.

Page 5 – Line 9: Remove “s” in “months”.

Page 5 – Line 10: Denmark Strait should be with capital S.

Page 5 – Line 11: Replace “access” with “assess”.

Page 5 – Line 13: Should be “were adopted” not “was adopted”.

Page 5 – Line 13: Add “the” before “other”.

Page 5 – Line 14: Replace “also is” with “is also”.

Page 5 – Line 15: Should be “data-sets” not “data-set”.

Page 5 – Line 27: Add “the” before “ARMOR data-set”.

Page 6 – Line 3: Remove “de Boyer”. It is written twice.

Page 6 – Line 19: Should be “underestimates” instead of “underestimate”.

Page 6 – Line 20: Remove “the” before CS2. Also the case on line 21.

Page 6- Line 20: Remove “s” in “values”.

Page 6 – Line 21: Remove “the” before “Spitsbergen”. Also the case on line 23.

Page 6 – Line 23-24: Either use “PIOMAS tend to overestimate” or “PIOMAS overestimates”.

Page 6 – Line 24: Remove “thickness”.

Page 6 – Line 26: “discrepancies” should be singular => “discrepancy”.

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

Page 6 – Line 31: Replace “all are” with “are all”.

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

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

Page 7 – Line 16: Replace “comprises” with a more appropriate term (“was”?).

Page 7 – Line 22: Remove “for” before “about”.

Page 7 – Line 23: Should be “significant effect” rather than “significantly effect”. Also replace “the sea” with “the Greenland Sea”.

Page 8 – Line 1: Add “the” before “climatology”.

Page 8 – Line 9: “approaches” is an odd choice of tense when you talk about something that happened from 1990s to 2000s. Replace with “approached” or “propagated towards”.

Page 8 – Line 10: It should be “Jan Mayen” not “Yan Mayen”.

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)?

Page 8 – Line 12: The “tendencies” are shown in figure 5d. Replace “Fig. 4d” with “Fig. 5d”.

Page 8 – Line 23: nearly doubles from 1993 to ?

Page 9 – Line 12: Remove “the” after exceeds. It is written twice.

Page 9 – Line 22: Remove “thickness” after “thick ice”.

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” or something similar.

Page 9 – Line 27: Remove “the” before “data”.

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

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

Page 10 – Line 17: “brining” should be “bringing”.

Page 10 – Line 18: “later” should be “layer”.

Page 10 – Line 19: Write “Nansen Basin” with capital B.

Page 10 – Line 29: Replace “Further” with “Farther”.

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”.

Page 10 – Line 34: Remove “in” after “confirmed by”.

Page 11 – Line 1: Use capital S in “Nordic Seas”. Also the case for line 10 and 20.

Page 11 – Line 5: Remove “of” after “NAO phase increases”.

Page 11 – Line 10: “Fram Strat” should be “Fram Strait”.

Page 11 – Line 11: Replace “through” by “across” and use capital R in “Faroe-Shetland Ridge”.

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.

Page 11 – Line 28: Replace “is” with “was” after “more ice”.

Page 11 – Line 29: Add “the” before “Odden ice tongue”.

Page 12 – Line 7: Remove “the” after “favours”.

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

Page 12 – Line 23: Add “heat” before “necessary”.

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

Figure 1: The color in the right color bar is missing.

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

Figure 4: Please write out what the legends “w”, “s”, and “a” mean.

Figure 5: The color bar in panel “d” has the wrong units. The panel shows change in salinity, but have units of °C.

Figure 6: In the figure caption: Remove parenthesis after “cold season”.

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.

Table 3: Explain all columns. (i.e. what is correlated in the column r2?)

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Smeed et al. 2014 Observed decline of the Atlantic Meridional Overturning Circulation 2004–2012.Ocean Science, 10 (1). 29-38. https://doi.org/10.5194/os-10-29-2014

Visbeck et al. (1995): Preconditioning the Greenland Sea for deep convection: Ice formation and ice drift. J. Geophys. Res., 100, 18 489–18 502, https://doi.org/10.1029/95JC01611.

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