

Response to Reviewer's comments (R1) on

The impact of atmospheric and oceanic circulations on the Greenland Sea ice concentration
by Sourav Chatterjee, Roshin P. Raj, Laurent Bertino, Sebastian H. Mernild, Nuncio Murukesh, and
Muthalagu Ravichandran

Reviewer's Comments:

In this manuscript the interannual variability of sea ice concentration in the Greenland Sea is investigated. The authors identify several atmospheric and oceanic processes that influence the sea ice concentration, and clarify how these are modulated by the large-scale atmospheric conditions. The authors conclude that the magnitude of the Greenland Sea Gyre circulation is of particular importance.

I think this is an interesting manuscript that highlights the importance of changing sea ice concentrations in the Greenland Sea. My main concern is that the changes in sea ice and ocean conditions over the period considered (1991-2017) are more appropriately characterized by secular trends than interannual variability, in particular reduced sea ice concentration and a warming ocean. I think the variability investigated in this manuscript needs to be discussed within the context of these long-term trends. As such, I recommend that the paper be revised before publication.

Authors' reply:

We thank the reviewer for the spending valuable time for going through the manuscript and providing constructive comments and references for improving the manuscript. A point by point response to the reviewer comments is listed below.

Major comment:

Sea ice concentration in the western Nordic Seas has steadily diminished over the past decades (Moore et al., 2015; Onarheim et al., 2018). In particular, the Odden ice tongue has rarely formed since the 1990s (e.g. Rogers and Hung, 2008). Over the same period equally remarkable changes in stratification and water mass transformation in the Greenland Sea have taken place (Ronski and Budéus, 2005; Latarius and Quadfasel, 2016; Lauvset et al., 2018; Brakstad et al., 2019). Yet these secular trends, which dominate the variability investigated in the manuscript, are barely, if at all, mentioned. This is important context that needs to be discussed and accounted for.

We thank the reviewer for raising this important issue. Indeed, the Greenland Sea water mass and the Sea ice concentration in the western Nordic Seas have been transforming with secular trend. We will incorporate these aspects in the revised manuscript, which will surely help to improve the manuscript.

Also please note that, our main objective is to find the process(es)/mechanisms through which Greenland Sea gyre (GSG) affects the sea ice concentration of the region. In the revised version we have shifted the focus to the western Greenland Sea, where the interannual variation and the effect of GSG is most prominent (Figure 2 and 3) instead of the 'Odden' region. The effect of the large scale GSG circulation on the 'Odden' formation is not very clear from our study. This may be due to the fact that the occasional 'Odden' formation depends on various small scale processes such as waves, eddies etc. The introduction is revised to incorporate the new changes.

Also note that to minimize the effect of the trends on the interannual variability all our statistical analysis we have performed with detrended data.

Specific comments:

Line 29:

The first two sentences of the introduction are too strong. As the source of dense overflow waters that supply the deep limb of the Atlantic Meridional Overturning Circulation, the Nordic Seas are indeed very important (e.g. Chafik and Rossby, 2019). But for the Greenland Sea to control regional and hemispheric climate, the Greenland Sea would have to be a main source of overflow water. This is likely not the case (Mauritzen, 1996; Eldevik et al., 2009).

Yes we agree. We will modify this part accordingly.

Lines 37-45:

Please clarify that the Odden ice feature rarely developed after the 1990s (e.g. Rogers and Hung, 2008) and that in the present climate only intermediate (not deep) waters are formed in the Greenland Sea (e.g. Brakstad et al., 2019).

We thank the reviewer for the valuable comment. We will discuss about it in the revised manuscript. Please note that, our main objective is to explain the mechanisms through which Greenland Sea gyre circulation effects the sea ice. Since the Odden has been rarely developed during the time period considered in our study, we focus to the western Greenland Sea where we find the effect of GSG circulation on sea ice is most prominent.

Line 57:

Please clarify where the high sea level pressure anomaly pattern would have to be located in order to result in anomalous southerly wind in the Greenland Sea.

Noted. Will be clarified in the revised version of the manuscript.

Line 70:

Please clarify how the Greenland Sea Gyre contributes to heat distribution in the Nordic Seas. It seems more plausible that heat inside a gyre would be trapped rather than distributed.

We will expand this discussion with more details. The main idea here is to highlight that, on the eastern side of the Nordic Seas GSG helps in propagation of northward flowing Atlantic water towards Fram Strait (Chatterjee et al., 2018), on its western side it brings the recirculated Atlantic water from Fram Strait to Greenland Sea region (Hatterman et al., 2016).

Line 74:

Please also clarify to what extent a strengthened western branch of the Greenland Sea Gyre circulation results in increasing Atlantic Water transport into the central Greenland Sea vs. Atlantic Water throughput as part of the East Greenland Current (Woodgate et al., 1999). The bulk of the Atlantic Water remains within the East Greenland Current and is transported toward Denmark Strait (Håvik et al., 2017).

Thank you for suggesting the point. The recirculation of Atlantic water (AW) with the GSG circulation has been reported by Hatterman et al. (2016). The warming signals along the GSG pathway (Figure 6) clearly shows the influence of GSG on warm AW transport in Greenland Sea.

Indeed, the strengthening of gyre through low SLP can strengthen the East Greenland Current (EGC), however, we don't see a clear warming along the EGC in Figure 6. Although in general the bulk of the Atlantic Water remains within the East Greenland Current and is transported toward Denmark Strait (Håvik et al., 2017), in a strong GSG condition, its contribution to AW recirculation can increase than normal. And also note that this AW recirculated by GSG, is warmer and thus important for sea ice.

Line 108:

Has TOPAZ been evaluated against observations in the central Greenland Sea? Latarius and Quadfasel (2016) or Brakstad et al. (2019) would be good points of comparison.

Evaluation of TOPAZ against observations will be added to the revised version of the manuscript.

Line 142:

Does the regression map show significant negative sea ice concentration in the central Greenland Sea when the Greenland Sea Gyre is strong?

It shows significant sea ice concentration pattern in the western Greenland Sea. Our current definition of 'central Greenland Sea' partly includes this region. We will modify the definitions of the regions to bring more clarity.

The regression map is shown in Figure 3, both with observation and TOPAZ and they show comparable patterns. In the map only significant values are shown. The region of our interest with maximum influence is marked.

Line 155:

Please clarify that it (presumably) is the large-scale atmospheric circulation associated with the Greenland Sea Gyre circulation that features an NAO-like pattern.

Yes we agree. The points will be clarified in the revised version of the manuscript. Figure 4a shows the SLP anomaly pattern effectively during the strong GSG periods, which is similar to NAO.

Line 159:

It is unclear how the low correlation between the gyre and NAO indices signifies an importance of NAO on the circulation in the Greenland Sea.

Here we tried to highlight that it signifies the importance of the **spatial variability** of NAO. Note that the NAO-like pattern associated with GSG (Figure 4a) has its centre north of its usual locations. The low correlation between GSG and NAO index (reflective of its usual spatial pattern with an Icelandic low) thus highlights the significance of the location of the SLP minimum in the Nordic Seas.

We agree that the above mentioned points are not clear and will be made clearer in the revised version.

Line 161:

Please clarify how winds influence the drift of sea ice. Is the drift primarily determined by Ekman transport or directly by the wind? To what extent does that depend on sea ice concentration?

We will clarify the point mentioned by the reviewer in the revised version of the manuscript. The sea ice in the Greenland Sea is either formed locally or exported through the Fram Strait. In the

latter case, it is heavily deformed and drifts almost freely under the actions of the winds and surface currents. This is even more true at ice concentrations lower than 80%.

Line 172:

The statement that wintertime Greenland Sea sea ice concentration and Fram Strait ice are flux are not strongly correlated appears to directly contradict the statement on line 35 that changes in ice export through Fram Strait influence the Greenland Sea sea ice concentration.

We will correct it.

Line 188:

Does the gyre bring Atlantic Water into the central Greenland Sea or circulate Atlantic Water around the periphery of the Greenland Sea?

We will concentrate more on the terminology. Central Greenland sea (at the core of the gyre) is not where we intend to focus for sea ice changes. The reason is mentioned on the second comment. We show that the AW causes sea ice changes in the western Greenland Sea.

Our results suggest that the gyre assist AW around the periphery of the Greenland Sea that in turn cause sea ice changes in the western Greenland Sea. We don't have clear evidence to claim the same in the central Greenland Sea (and/or Odden). This is made clear in the revised manuscript.

Line 230:

Please expand on how Atlantic Water anomalies would impact sea ice formation and how that may influence convection.

As suggested by the reviewer the discussion on the impact of AW anomalies on sea ice formation will be expanded. Furthermore new analysis will be included to show the relation more clearly.

Line 251:

The central Greenland Sea has largely been ice free since the 1990s (Moore et al., 2015; Brakstad et al., 2019). This large-scale sea ice retreat, consistent with sea ice loss across the entire Arctic region, is likely not related to the magnitude of the Greenland Sea Gyre circulation.

We agree and thank the reviewer for bringing our attention to this very important topic. Please note that the revised version of the manuscript focuses mainly on western Greenland Sea region. We, in the revised version, will highlight the role of GSG in bringing warm water to the western Greenland Sea, thus impacting the sea ice of the region.

Figure 1:

The black oval indicating the central Greenland Sea extends onto the Greenland shelf, which should not be considered part of the central Greenland Sea.

Thank you for pointing this out. The figure will be modified accordingly.

Figure 2:

Is it reasonable to average sea ice concentration over the entire 1991-2017 period if the variability is dominated by an ice Odden "on" or "off" state? To the extent that the Odden feature is binary (on or

off), the average would represent an in-between state that is never realized. Perhaps consider comparing instead observations and TOPAZ for years when Odden is present and for years when it is not.

In Figure 2, the standard deviation of the winter mean (DJF) for the study period is shown. Thus, one may expect that it is the binary feature of the Odden which is depicted in the figure. This will be made clear in the revised version of the manuscript.

Figure 6:

What are the correlations between salinity anomaly, temperature advection, and gyre index? Please clarify in the caption what temperature advection means. Is it heat transport or a product of temperature and velocity, and where is it evaluated?

The correlations between both salinity anomaly and temperature advection with Gyre index is 0.7 and is mentioned in the text. It is product of temperature and velocity in the marked box in Figure 3. This will be made clear in the revised version of the manuscript.

Figure 7:

It appears that one buoyancy frequency profile per year is shown in Fig. 7. Are the values annual means or summertime means? Please clarify. For most of the year the mixed-layer depth in the Greenland Sea is deeper than 50 m and the buoyancy frequency would be very low. I think it would be sensible to consider the stratification to a deeper level in the Greenland Sea. These days buoyancy frequency seems to be more commonly used than Brunt-Väisälä frequency.

The values are winter (DJF) means and clarified in the text. As per suggestion, the depth will be taken till 100 m in the new figure.

Detailed comments:

Line 32:

It should be "... from the central Arctic Ocean ..."

Will be Corrected

Line 59:

Although is misspelled.

Will be corrected

Line 70:

It should be "and" rather than a comma after the Hattermann and Chatterjee citations.

Will be corrected

Line 156:

It should be "north of their usual locations..."

Will be corrected

Line 193:

The expression "anomalous temperature anomaly" is unclear.

Will be corrected

Line 224:

Northeastward is one word.

Will be corrected

Line 226:

The last comma on this line should be removed.

Will be corrected

Line 300:

Dall'Osto is misspelled.

Will be corrected.