tc-2020-127

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

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.

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.

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).

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).

Line 57:
Please clarify where the high sea level pressure anomaly patter would have to be located in order to result in anomalous southerly wind in the Greenland Sea.

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.

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).

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.

Line 142:
Does the regression map show significant negative sea ice concentration in the central Greenland Sea when the Greenland Sea Gyre is strong?

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.

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.

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?

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.

Line 188:
Does the gyre bring Atlantic Water into the central Greenland Sea or circulate Atlantic Water around the periphery of the Greenland Sea?

Line 230:
Please expand on how Atlantic Water anomalies would impact sea ice formation and how that may influence convection.

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.

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.

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.

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?

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.

Detailed comments:

Line 32:
It should be "... from the central Arctic **Ocean** ..."

Line 59:
Although is misspelled.

Line 70:
It should be "and" rather than a comma after the Hattermann and Chatterjee citations.

Line 156:
It should be "north **of** their usual locations..."

Line 193:
The expression "anomalous temperature anomaly" is unclear.

Line 224:
Northeastward is one word.

Line 226:
The last comma on this line should be removed.

Line 300:
Dall'Osto is misspelled.

References

Brakstad A, Våge K, Haavik L, Moore GWK. 2019. Water mass transformation in the Greenland Sea during the period 1986-2016. *Journal of Physical Oceanography* **49**: 121–140, doi:10.1175/JPO–D–17–0273.1.

Chafik L, Rossby T. 2019. Volume, heat, and freshwater divergences in the Subpolar North Atlantic suggest the Nordic Seas as key to the state of the Meridional Overturning Circulation. *Geophysical Research Letters* **46**: doi:10.1029/2019GL082 110.

Eldevik T, Nilsen JEØ, Iovino D, Olsson KA, Sandø AB, Drange H. 2009. Observed sources and variability of Nordic Seas overflow. *Nature Geoscience* **2**: 406–410, doi:10.1038/NGEO518.

Håvik L, Pickart RS, Våge K, Thurnherr AM, Beszczynska-Möller A, Walczowski W, von Appen WJ. 2017. Evolution of the East Greenland Current from Fram Strait to Denmark Strait: Synoptic measurements from summer 2012. *Journal of Geophysical Research: Oceans* : doi:10.1002/2016JC012 228.

Latarius K, Quadfasel D. 2016. Water mass transformation in the deep basins of the Nordic Seas: Analyses of heat and freshwater budgets. *Deep Sea Research I* **114**: 23–42, doi:10.1016/j.dsr.2016.04.012.

Lauvset SK, Brakstad A, Våge K, Olsen A, Jeansson E, Mork KA. 2018. Continued warming, salinifiction and oxygenation of the Greenland Sea gyre. *Tellus A* **70**: doi:10.1080/16000 870.2018.1476 434.

Mauritzen C. 1996. Production of dense overflow waters feeding the North Atlantic across the Greenland-Scotland Ridge. Part 1: Evidence for a revised circulation scheme. *Deep Sea Research I* **43**: 769–806.

Moore GWK, Våge K, Pickart RS, Renfrew IA. 2015. Open-ocean convection becoming less intense in the Greenland and Iceland Seas. *Nature Climate Change* **5**: doi:10.1038/nclimate2688.

Onarheim IH, Eldevik TE, Smedsrud LH, Stroeve JC. 2018. Seasonal and regional manifestation of Arctic sea ice loss. *Journal of Climate* **31**: 4917–4932, doi:10.1175/JCLI–D–17–0427.1.

Rogers JC, Hung MP. 2008. The Odden ice feature of the Greenland Sea and its association with atmospheric pressure, wind, and surface flux variability from reanalyses. *Geophysical Research Letters* **35**: L08 504, doi:10.1029/2007GL032 938.

Ronski S, Budéus G. 2005. Time series of winter convection in the Greenland Sea. *Journal of Geophysical Research* **110**: C04 015, doi:10.1029/2004JC002 318.

Woodgate RA, Fahrbach E, Rohardt G. 1999. Structure and transports of the East Greenland Current at 75°N from moored current meters. *Journal of Geophysical Research* **104**: 18 059–18 072.