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The impact of atmospheric and oceanic circulations on the Greenland Sea ice concentration.

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Abstract.

The amount and spatial extent of Greenland Sea (GS) sea ice are primarily driven by the sea ice export across the Fram Strait (FS) and by local seasonal sea ice formation, melting and sea ice dynamics. Maximum sea ice concentration (SIC) variability is found in the marginal ice zone and 'Odden' region in the central GS. In this study, using satellite passive microwave sea ice observations, atmospheric and a coupled ocean-sea ice reanalysis system we show that both the atmospheric and oceanic circulation in the GS act in tandem to explain the SIC variability in the GS. Anomalous low/high sea level pressure (SLP) over the Nordic Seas is found to strengthen/weaken the Greenland Sea Gyre (GSG) circulation. The large-scale atmospheric circulation pattern associated with this GSG variability features North Atlantic Oscillation (NAO) like SLP pattern with its northern center of action shifted north-eastward from its canonical position. During anomalous low SLP periods, northerly wind anomalies reduce the sea ice export in the central GS due to westward Ekman drift of sea ice. This in turn decreases the freshwater content and weakens ocean stratification in the central GS. At the same time, the associated positive wind stress curl anomaly strengthens the GSG circulation which recirculates warm and saline Atlantic water (AW) into this region. Under a weakly stratified condition, the subsurface AW anomalies can reach the surface to inhibit new sea ice formation, further reducing the SIC in the central GS. Thus, this study highlights combined influence of atmospheric and oceanic circulation in the central GS SIC variability.

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1 Introduction

The strength of the global thermohaline circulation partly depends on freshwater availability in the Greenland Sea (Serreze et al. 2007; Eldevik & Nilsen 2013; Buckley & Marshall 2016). Sea ice in the GS is the largest freshwater contributor in the Nordic Seas (Aagaard & Carmack 1989) and thus controls the regional and northern hemispheric climate (Johannessen et al. 2004). Apart from its influence on climate, GS sea ice is important in determining shipping routes (Instanes et al. 2005; Johannessen et al. 2007), as well as to the regional marine ecosystem due to its impact on the light availability (Grebmeier et al. 1995). Most of the sea ice in the GS is exported from the central Arctic across the Fram Strait (FS) and is largely controlled by the ice-drift with the Transpolar Current (Zamani et al. 2019). Anomalous sea ice export through the FS is associated with events like the 'Great Salinity Anomaly' (Dickson et al. 1988) which can have impact on the freshwater content in the Nordic Seas. Therefore, it is quite evident that the changes in sea ice export through the FS influence the GS sea ice and thus the freshwater availability in the Nordic Seas (Belkin et al. 1998; Dickson et al. 1988; Serreze et al. 2006).

Even though it is the main mechanism contributing to the overall GS SIC, the relation between sea ice export through FS and GS SIC variability is not very robust and the local sea ice formation in the central GS (Figure 1) particularly, in the marginal ice zone (MIZ) and 'Odden' region of the GS largely contribute to GS SIC variability (Kern et al. 2010). The 'Odden' region features a seasonal tongue-like patch of sea ice in the central GS with a spatial coverage of about 300,000 km^2 (Comiso et al. 2001). On the other hand, the central GS is one of the very few regions in the global open ocean where deep water convection takes place resulting in formation of deep waters (Killworth 1979; Schott et al. 1993). Variability of sea ice in this region can control the deep water convection through influencing both the heat and salt budgets (Shuchman et al. 1998). The ocean circulation around the central GS region can also be important in terms of interactions between different water masses or more precisely between AW and polar waters (Hopkins 1988).

Several studies have attempted to address the formation, temporal and spatial variability of the sea ice in the 'Odden' region in central GS (Campbell et al. 1987; Johannessen et al. 1987; Wadhams et al. 1996; Shuchman et al. 1998; Toudal 1999; Comiso et al., 2001). The sea ice in this region consists of either locally formed young and fragile sea ice or the old sea ice from the high Arctic, advected by the East Greenland Current (EGC) and Jay Mayen Current (JMC) to this region (Wadhams and Comiso 1999). The local ice formation is primarily controlled by the meteorological parameters e.g. air temperature, wind speed and direction (Shuchman et al. 1998). Comiso et al. (2001) found a strong negative correlation between air temperature in the Jan Mayen Island and sea ice extent in the 'Odden' region, both of which exhibit a decadal variability. While the warm air temperature can reduce the sea ice extent in the 'Odden' region by opposing new sea ice formation and enhanced surface melting, the presence of advected sea ice can inhibit the air-sea heat exchanges and increase ice-atmosphere interaction, keeping the air temperature low.

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Sea ice in the central GS also responds to large scale atmospheric forcing. For example, a high sea level pressure (SLP) anomaly pattern results in anomalous southerly wind in the GS. The associated Ekman drift towards the central GS may help in eastward expansion of the sea ice and increase SIC in the 'Odden' region (Germe et al. 2011). All though the corresponding large-scale circulation features a North Atlantic Oscillation (NAO) like pattern, the correlation between the NAO and 'Odden' ice extent is not very strong (Comiso et al. 2001). This indicates the importance of oceanic parameters in central GS sea ice variability. Selyuzhenok et al. (2020) recently showed that the winter time sea ice volume in the GS varies in opposite phase to FS sea ice volume export, indicating a contrasting response between sea ice in the western GS, influenced by sea ice export from FS, and central GS where oceanic conditions are important to determine the sea ice condition. The oceanic conditions in the central GS can be influenced by the recirculation of the warm and saline AW from the FS (Hattermann et al. 2016, Chatterjee et al. 2018). Further, the cold and fresh JMC can also contribute to the oceanic and sea ice conditions in the "Odden" region (Nansen 1924; Bourke et al. 1992; Wadhams & Comiso 1999).

The cyclonic Greenland Sea Gyre (GSG) is one of the important features of Nordic Seas circulation which largely contributes to AW heat distribution in the Nordic Seas (Hatterman et al. 2016; Chatterjee et al. 2018), open ocean convection (Marshall & Schott 1999; Moore et al. 2015). A stronger GSG circulation increases the AW temperature in the FS by modifying the northward AW transport in its eastern side (Chatterjee et al. 2018). Simultaneous increase in its southward flowing western branch, constituting the southern recirculation pathway of AW (Hattermann et al. 2016), increases the heat content in the central GS through a stronger recirculation of AW (Chatterjee et al. 2018). Further, the eastward flowing JMC originated from the EGC constitutes the south-western closing branch of the cyclonic GSG circulation in the central GS (Fig. 1). The east-ward extension of this cold and fresh JMC into the central GS basin helps in both new sea ice formation and advection of sea ice from the EGC, leading to formation of the 'Odden' region. Thus, it is apparent that the GSG circulation can contribute to the sea ice variability in the central GS region by influencing the JMC current and/or AW redistribution.

In this study we aim to understand the influence of oceanic circulation, more particularly the influence of GSG circulation on the variability of GS SIC. Using a combination of satellite passive microwave SIC, a coupled sea ice ocean reanalysis and atmospheric reanalysis data, we show that the oceanic control on the SIC variability in the central GS region can be explained by the changes in GSG dynamics. Further, it is shown that the atmospheric circulation associated with the GSG circulation variability also helps in setting up the GSG's control on the sea ice variability of the central GS region.

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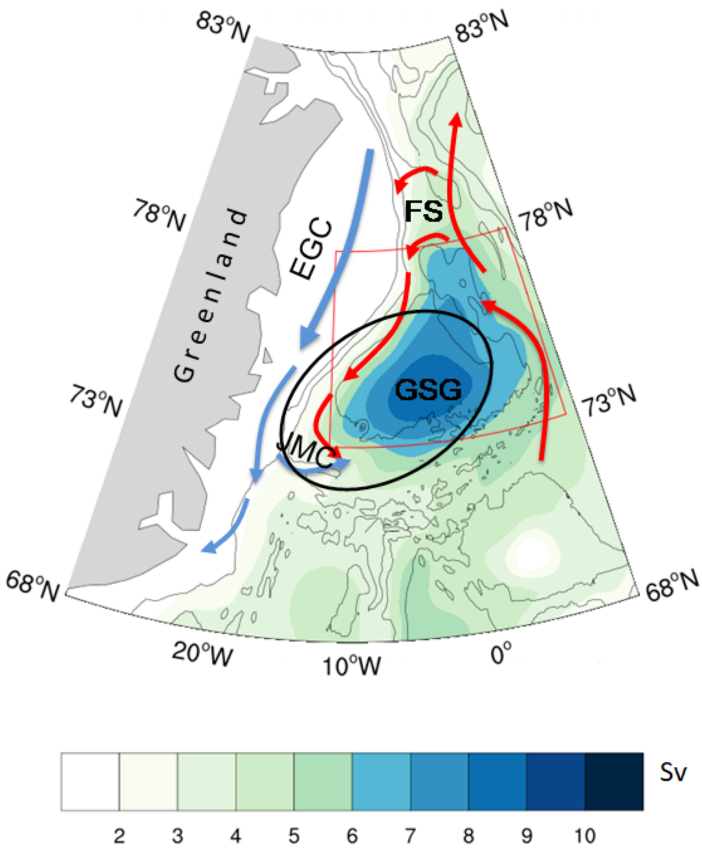

Figure 1: Schematic map of the geographic regions used in this study. Colour shading indicates average annual mean barotropic stream function for the period 1991-2017. FS: Fram Strait; JMC: Jan Mayen Current; EGC: East Greenland Current; GSG: Greenland Sea Gyre. Warm currents are drawn in red and cold currents are in blue. Grey contours are showing bottom topography drawn at every 1000 m. The marked region in red is used to calculate the 'Gyre Index' as detailed in next section. The black oval indicates the approximate region referred as central GS in the text.

2. Data and Methods

2.1 Atmospheric data:

All atmospheric parameters such as SLP, 10m winds are obtained from ERA Interim reanalysis (Dee et al. 2011) for the period 1991-2017 on a 0.5 by 0.5 degree grid resolution.

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2.2 Oceanic data:

Oceanic data used in this study are from TOPAZ4, a coupled ocean and sea ice data assimilation system for the North Atlantic and the Arctic. TOPAZ4 is based on the Hybrid Coordinate Ocean Model (HYCOM, with 28 hybrid z-isopycnal layers at a horizontal resolution of 12 to 16 km in the Nordic Seas and the Arctic) and the Ensemble Kalman Filter data assimilation, the results of which have been extensively validated (Lien et al. 2016; Xie et al. 2017; Chatterjee et al. 2018; Raj et al. 2019). TOPAZ4 represents the Arctic component of the Copernicus Marine Environment Monitoring Service (CMEMS) and is forced by ERA Interim reanalysis and assimilates observations including along-track altimetry data, sea surface temperatures, sea ice concentrations and sea ice drift from satellites along with *in-situ* temperature and salinity profiles.

Following Chatterjee et al. (2018), the strength of the GSG circulation is determined by area averaging the winter mean (DJF) barotropic stream function over the common region within 73 N:78 N; 12 W:9 E (as marked in Figure 1) and inside the 3000 m isobath contour. The area averaged values are then standardized over the full period (1991-2017) to get the 'Gyre Index'. For the composite analysis, positive and negative 'Gyre Index' periods are determined when the 'Gyre Index' crosses the 0.75 and -0.75 mark respectively. Throughout the article, regression and correlation analysis are performed with the detrended timeseries for the corresponding variables.

2.3 Sea ice data:

Monthly sea ice concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data, Version 1 (Cavalieri et al. 1996) are obtained from the National Snow and Ice Data Centre. Sea ice velocity is taken from the Polar Pathfinder Daily 25 km EASE-Grid Sea Ice Motion Vectors (Tschudi et al. 2019).

3. Results and Discussions

Although the sea ice in the central GS and 'Odden' region forms particularly during winter season, it exhibits large spatio-temporal variability in terms of occurrence, persistence and shape within the season and on longer timescale as well (Comiso et al. 2001). Apart from this, strong inter-annual variability in the 'Odden' makes this region important feature of the leading modes of north hemisphere SIC variability (Deser et al. 2000). In the Nordic Seas, Germe et al. (2011) showed the MIZ and the 'Odden' features as the leading mode of winter GS SIC variability explaining about 73% of the total variability. Consistent with these findings, the standard deviation of winter time (DJF) SIC shows high values along the MIZ and the 'Odden' region both in observation and reanalysis data (Fig. 2). Note that, the TOPAZ4 reanalysis data exhibits a more confined MIZ than observations, which is a known model deficiency (Sakov et al. 2012).

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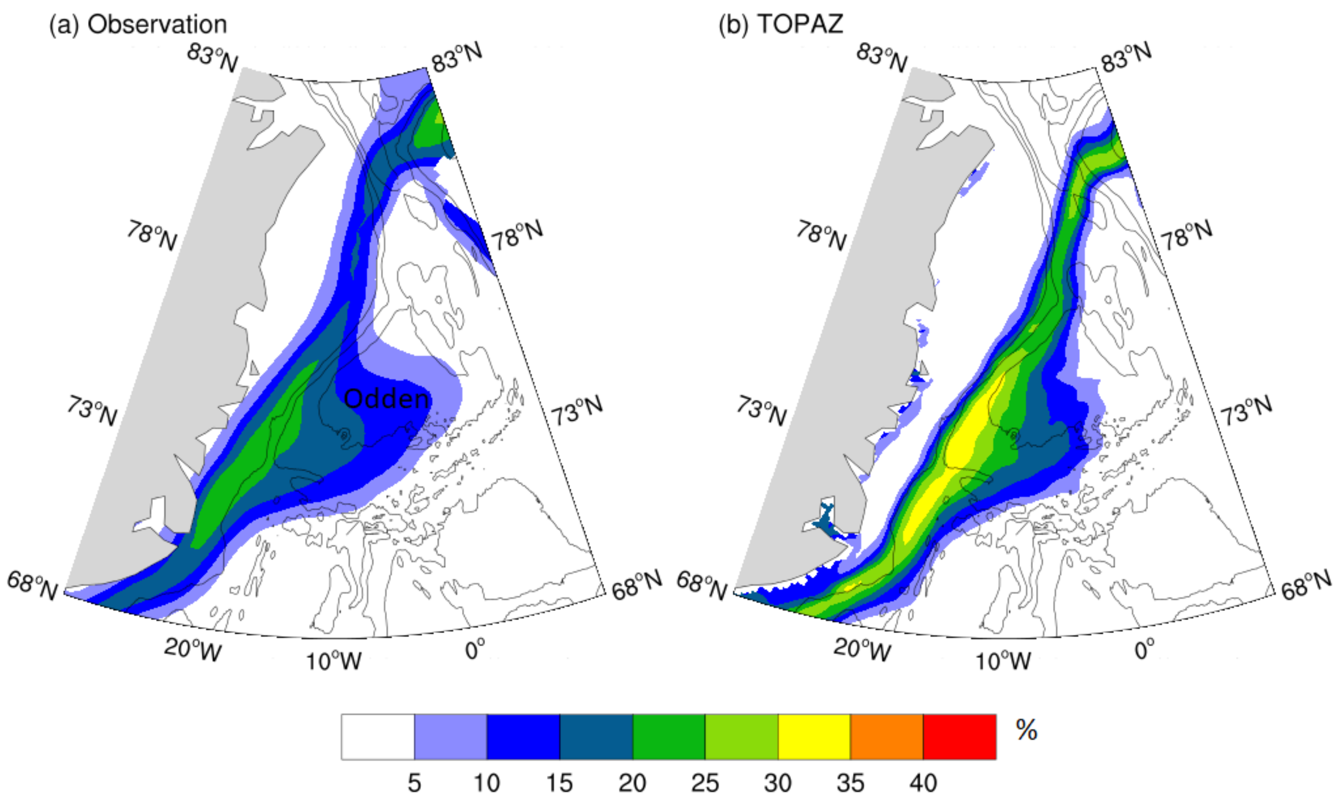

Figure 2: Standard deviations of winter (DJF) mean sea ice concentration for the period 1991-2017 from (a) satellite observations (b) TOPAZ reanalysis.

Considering GSG's role in AW recirculation and JMC being a part of its circulation which influences the sea ice in the central GS, it is apparent that GSG can potentially impact sea ice in the MIZ and 'Odden' region. The regression map of winter mean SIC on the 'Gyre Index' shows significant negative SIC in the central GS (Fig. 3). The spatial pattern of the regression coefficients closely resembles the standard deviation of winter mean SIC in the GS as shown in Fig. 2. This indicates that considerable amount of the GS SIC variability can be associated with GSG circulation. However, the atmospheric forcing in the central GS is known to influence the sea ice variability in the MIZ and 'Odden region' (Germe et al. 2011). Also note that the GSG is known to be influenced by the atmospheric forcing (Aagaard 1970; Legutke 2002; Chatterjee et al. 2018). So the GSG's influence in the sea ice as found in Fig. 3, could also be a result of the atmospheric control on the central GS SIC. Hence, the atmospheric circulation pattern associated with the GSG variability is further investigated.

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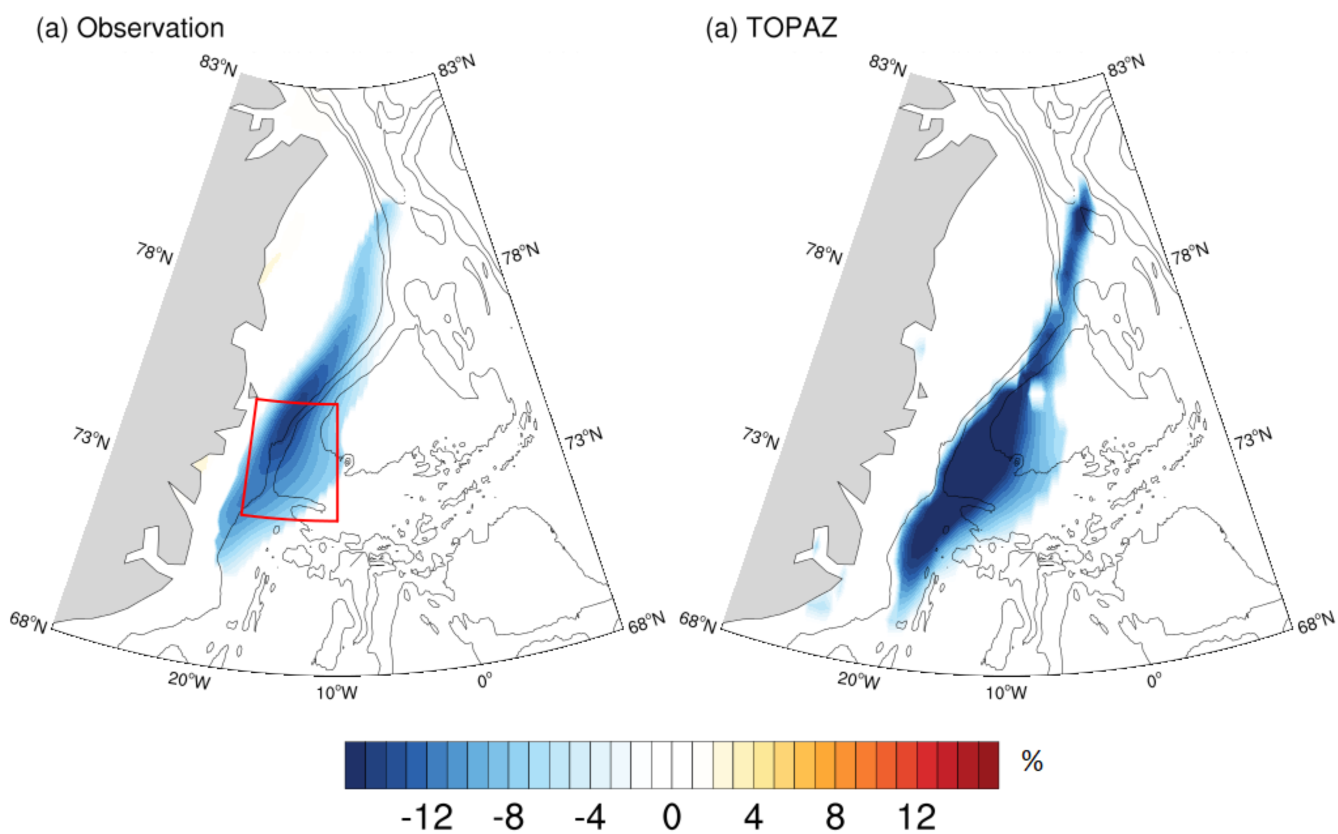

Figure 3: Linear regression of winter mean (DJF) sea ice concentration from (a) satellite observation (b) TOPAZ reanalysis on the 'Gyre Index'. Only significant values at 95 % level are shown. Contours are bottom topography drawn at every 1000 m.

Composite difference of SLP anomalies for the positive and negative GSG circulation periods (Fig. 4a) suggests that the large-scale circulation associated with the GSG circulation features a NAO-like meridional pattern although the SLP anomaly centers are located to the north to their usual locations near Iceland (Fig. 4a). Thus the principle components based winter mean NAO index, with its spatial feature highlighting the Icelandic low and Azores high, (https://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml) and the 'Gyre Index' have a low correlation (r = 0.2). This further points to the importance of the spatial variability of NAO (Zhang et al. 2008; Moore et al. 2012) and its influence on the Nordic Seas circulation. The GSG circulation responds to the anomalous wind stress curl induced by this atmospheric circulation pattern (Figs. 4b, c). However, at the same time the associated wind stress can influence the sea ice export in the central GS due to Ekman drift of sea ice. Anomalous northerly/southerly wind stress is found in the central GS during positive/negative GSG periods (Figs. 4b, c). Linear regression of sea ice velocity on the 'Gyre Index' shows

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anomalous southerly sea ice velocities in the MIZ and 'Odden' region associated with increase in GSG strength (Fig. 5b). This indicates that the northerly wind stress during a strong GSG circulation would lead to Ekman drift of sea ice which tends to push the sea ice towards the Greenland coast and reduce the mean northerly sea ice velocities in this region (Fig. 5a). This could further lead to less sea ice export in this region and reduced SIC. Note that Germe et al. (2011) also found a similar atmospheric circulation pattern associated with SIC variability in this region. Further, they highlight that although such an atmospheric circulation can potentially alter the ice flux through the FS (Kwok & Rothrock 1999; Jung & Hilmer 2001; Vinje 2001; Tsukernik et al. 2010; Smedsrud et al. 2011; Ionita et al. 2016), winter time GS SIC and FS ice area flux are not strongly correlated. Thus, it can be argued that the negative central GS SIC response to this atmospheric forcing as found in Figs. 3, 4 is not strongly dependent on the amount of ice imported through FS but rather on the dynamics of the ice export in this region.

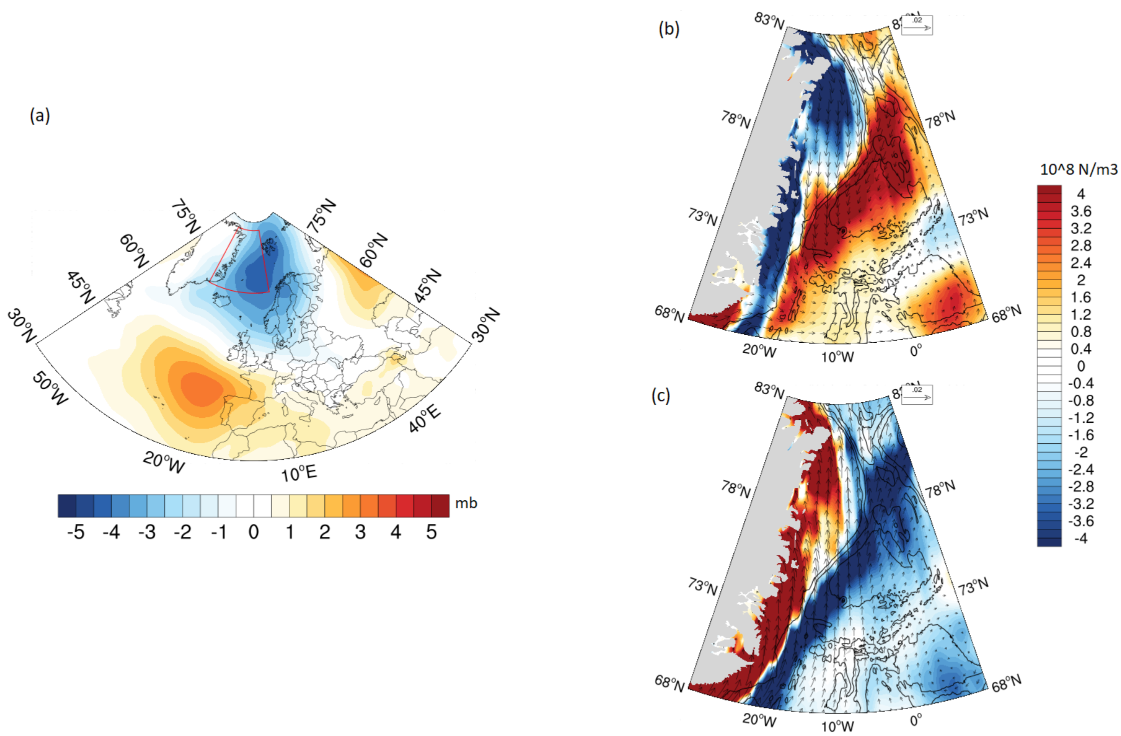

Figure 4: (a) Composite difference of winter mean (DJF) sea level pressure anomaly for positive and negative 'Gyre Index' periods. The marked region in red is enlarged and shown in (b) and (c). Anomalous wind stress (vectors, N/m^2) and wind stress curl (shade) for (b) positive and (c) negative 'Gyre Index' periods.

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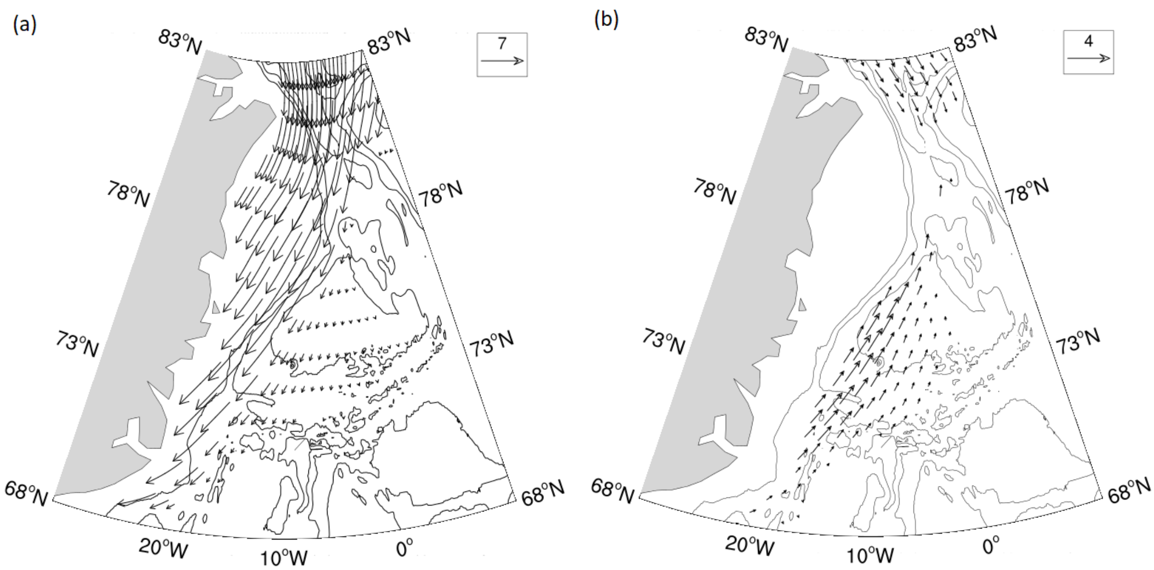

Figure 5: (a) Climatological (1991-2017) winter time (DJF) sea ice velocity vectors (cm/s) from satellite observations. (b) Regression of DJF sea ice velocity anomalies (cm/s) on the 'Gyre Index'. Only results significant at 95 % are only shown for clarity. Contours are bottom topography drawn at every 1000 m.

However, recent finding suggests a strong dependence of sea ice on the oceanic conditions in this region (Selyuzhenok et al. 2020). Various oceanic influences on the GS sea ice are also described in previous studies (e.g. Johannessen et al. 1987; Visbeck et al. 1995; Kern et al. 2010). Thus, we investigate GSG's potential in influencing the oceanic conditions and hence the sea ice in the central GS. The GSG circulation recirculates the AW from the FS into the central GS by its southward flowing western branch (Hatterman et al. 2016; Jeansson et al. 2017). The return AW, although it gets significantly modified, still remains dense enough to be in the subsurface under the colder and fresher polar waters (Schlichtholz & Houssais 1999; Eldevik et al. 2009). However, due to vertical winter mixing, the AW can warm the surface waters (Våge et al., 2018) which may further hinder the sea ice formation.

Figure 6(a) shows the composite difference of anomalous temperature anomaly in the upper 400 m between positive and negative 'Gyre Index' periods. Warm anomalies during positive 'Gyre Index' periods are found along the MIZ which in its southern part extends eastward towards the 'Odden' region. As mentioned earlier, a strong GSG circulation is known to cause warm AW anomalies in the FS (Chatterjee et al. 2018) which can further be recirculated back in the GS. This is further confirmed in Fig. 6b, where significant positive correlation (r=0.7) is found between temperature advection (in upper 400 m) in the GS (marked region in Fig. 3a, where maximum GSG influence on SIC is found) and the 'Gyre Index'. Further, surface

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salinity anomaly in the same region also shows similar relation (r=0.7) with the 'Gyre Index', indicating a surfacing of the AW anomalies recirculated by the GSG.

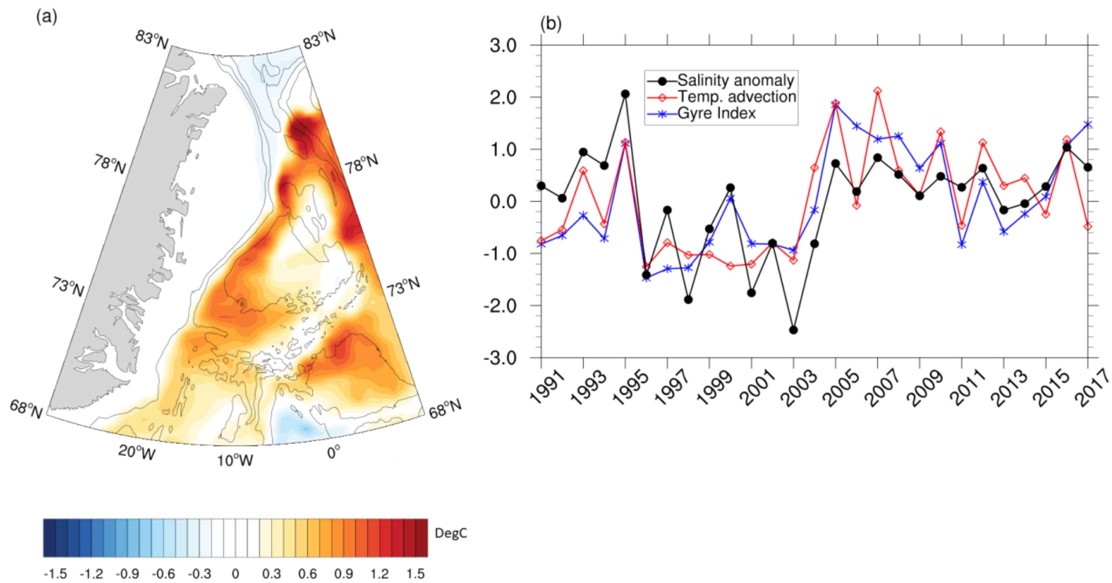

Figure 6: (a) Difference in 400 m depth averaged potential temperature anomalies between positive and negative 'Gyre Index' periods. (b) 'Gyre Index' (blue), and standardized surface salinity anomaly (black), temperature advection in upper 400 m (red) for DJF over the region 72 N: 75 N; 18 W : 10 W, as marked in Fig. 3a.

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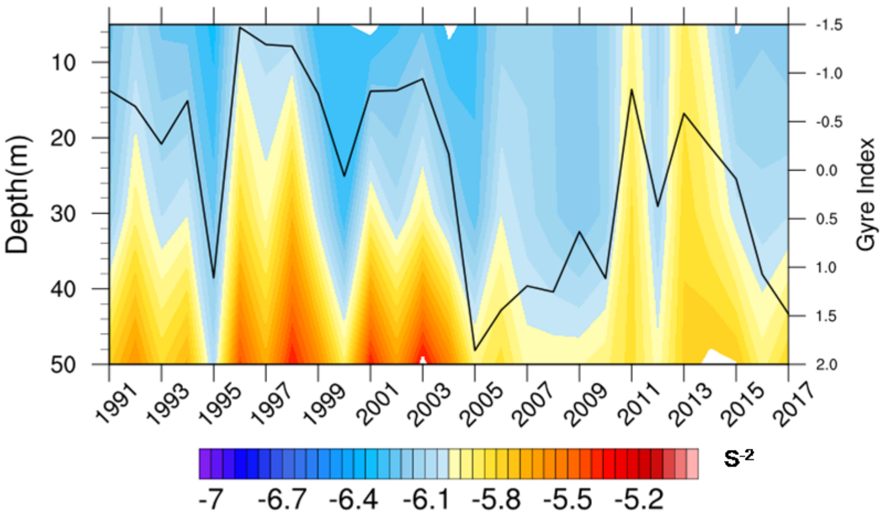

Figure 7: Logarithm of squared Brunt-Väisälä Frequency (N^2, colour shaded) for DJF over the region 72 N:75 N; 18 W:10 W, as marked in Figure 3a. The black timeseries is the 'Gyre Index' plotted against a reversed Y axis in the right side for comparison.

The reduced sea ice export in the MIZ due to the atmospheric forcing associated with the GSG circulation (Fig. 4 & 5) can reduce the stability of the upper water columns. This is further investigated through analysis of the Brunt-Väisälä frequency and its variation associated with the 'Gyre Index'. Figure 7 clearly indicates that a weakening/strengthening of the stratification in the upper column coincides with a strengthening/weakening of the GSG circulation. This further supports that the warm anomalies advected towards central GS by the GSG can surface under a weakly stratified condition and can potentially influence the surface oceanic conditions, hence the SIC. The warm anomalies can further be advected eastward towards the Odden region with the eastward flowing EGC, which constitutes the closing branch of the GSG circulation in its south-western end.

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4. Conclusions

We show that the Nordic Seas circulation in particular the GSG circulation has strong influence on the interannual variability of winter time GS SIC. The cyclonic GSG circulation responds to the atmospheric forcing over the Nordic Seas through wind stress curl (Legutke 2002, Chatterjee et al. 2018). The large-scale pattern influencing the GSG circulation resembles a NAO like pattern which has its northern centre of action moved northeast ward in the Nordic Seas. Earlier studies have found such an atmospheric forcing can influence the sea ice condition in the MIZ and Odden region through Ekman drift of the sea ice (Germe et al., 2011). During a strong GSG circulation, the anomalous low pressure over the GS, induces northerly wind anomalies which can push the sea ice towards the Greenland coast due to Ekman drift and reduces the sea ice export in the central GS. This further leads to a weakening of the stratification in the upper water column. At the same time, a stronger GSG circulation recirculates the warm AW anomalies from the FS into the central GS and under a weakly stratified condition the AW anomalies can reach the surface and further reduces the SIC by inhibiting new sea ice formation. Thus, central GS SIC responds to simultaneous influences from the atmospheric and oceanic circulation (Fig. 8). However, note that GS SIC can be influenced by several other factors such as thermodynamic effects, internal sea ice dynamics and small scale oceanic processes e.g. eddies, wave interactions etc. Consideration of all such factors and quantification of their relative importance would require a comprehensive and robust observation and modeling efforts which is beyond the scope of this study. This study only highlights the importance of the GSG circulation in determining the SIC in the GS.

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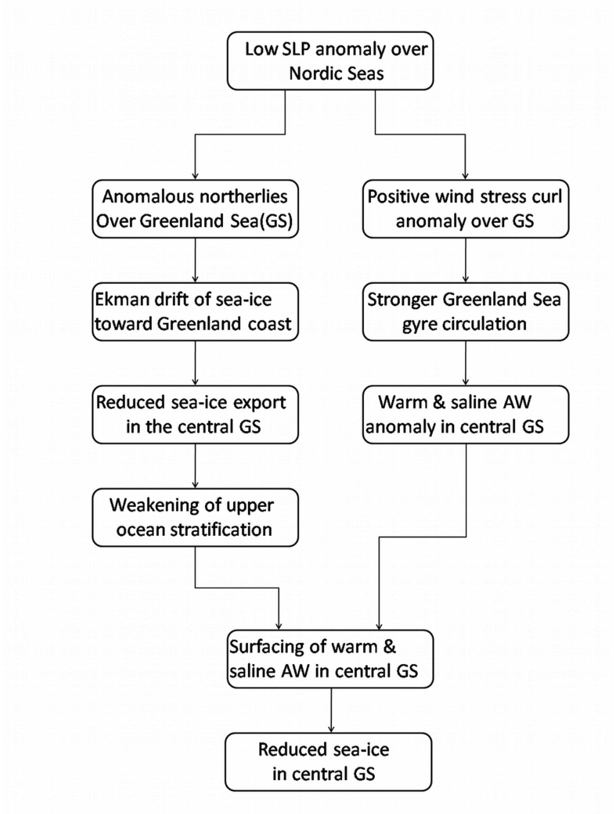

Figure 8: A flow chart of combined atmospheric (left side) and oceanic processes (right side) influencing the central GS SIC.

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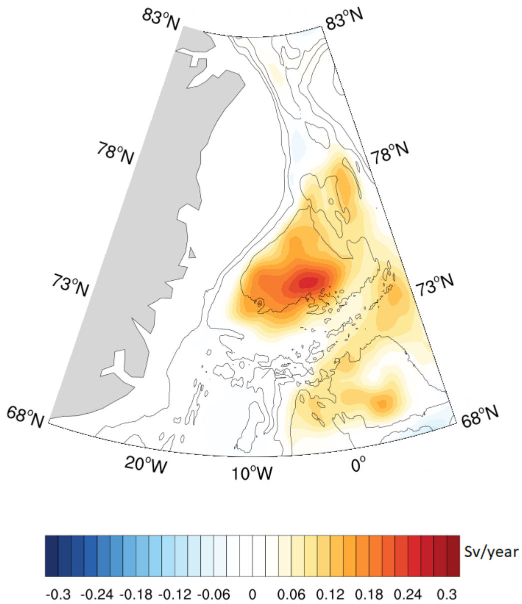

Figure 9: Linear trend in winter mean (DJF) barotropic stream function for 1991-2017. Only significant values at 95 % level are shown for clarity. Positive values indicate stronger cyclonic circulation. Contours are bottom topography drawn at every 1000 m.

GS SIC is an important component of the regional and global climate (Moore et al. 2015; Kopec et al. 2016; Dall'Osto et al. 2018). It is thus important to understand the driving mechanisms for the variability of the GS SIC. This study finds one of those mechanisms highlighting the role of large scale atmospheric and oceanic circulation in the Nordic Seas. Observations and modelling results suggest stronger atmospheric forcing in the Nordic Seas due to spatial variation of the NAO and its tendency towards positive phase in a warmer climate (Zhang et al. 2008; Bader et al. 2011; Stephenson et al. 2016). Consistent with that we also find a significant positive trend in the GSG circulation strength during the study period (Fig. 9). Our results suggest, this has potential to make the central GS ice free, confining the sea ice extent to the East Greenland coast and influencing the freshwater budget in this region.

Acknowledgments

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Declarations

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Not Applicable

Conflicts of interest/Competing interests (include appropriate disclosures)

Authors declare no Conflicts of interest/Competing interests

Availability of data and material (data transparency)

All the data used here are freely available on respective data portals (links provided in the 'Acknowledgements' section)

Code availability (software application or custom code)

All the codes are available on reasonable request to the corresponding author.

Authors' contributions

SC conceived the idea in discussion with RPR and wrote the manuscript. SC performed all the analyses. All authors contributed in improvement and writing of the manuscript.

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