~~The impact of atmospheric and oceanic circulations on the Greenland Sea ice concentration.~~Combined impact of oceanic and atmospheric circulations on Greenland Sea I~~i~~ce concentration

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Abstract.

The amount and spatial extent of Greenland Sea (GS) ~~sea~~ ice are primarily ~~driven~~controlled by the sea ice export across the Fram Strait (FS) and by local seasonal sea ice formation, melting and sea ice dynamics. Maximum interannual sea ice concentration (SIC) variability is found along~~in~~ the marginal ice zone in the ~~and 'Odden' region in the central western~~ 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~~ Nordic Seas (NS) act in tandem to explain the SIC variability in the western GS. ~~During anomalous low SLP periods,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. strengthen/weaken the Greenland Sea Gyre (GSG) circulation. ordic Seas is found toAnomalous low/high sea level pressure (SLP) over the N n~~Northerly wind anomalies associated with anomalous low SLP over the NS reduce the sea ice export in the western~~central~~ GS due to westward Ekman drift of sea ice. On the other hand, the positive wind stress curl strengthens the cyclonic Greenland Sea Gyre (GSG) circulation in the central GS. An intensified GSG circulation may result~~s~~ in stronger Ekman divergence of surface cold and fresh waters away from the western GS. ~~Theseis~~Both of these processes ~~in turn decreases the freshwater content and~~ can reduce the freshwater content and weaken~~ns~~ the upper ocean stratification in the western~~central~~ GS. At the same time, warm and saline Atlantic Water (AW) anomalies are recirculated from the FS region to western GS by a stronger GSG circulation. ~~the GSG circulation which recirculates warm and saline Atlantic water (AW) into this region. the associated positive wind stress curl anomaly strengthens~~ Under a weakly stratified condition, enhanced vertical mixing of these~~these~~ subsurface AW anomalies can warm the surface waters and~~reach the surface to~~ inhibit new sea ice formation~~or may allow increased bottom sea ice melt~~, further reducing the SIC in the western~~central~~ GS. ~~GS SIC variability.centralThus, this study highlights combined influence of atmospheric and oceanic circulation in the~~

1 Introduction

The strength of the global thermohalineAtlantic meridional overturning -circulation partly depends on freshwater availability in the Greenland SeaGS (Serreze et al. 2007; Eldevik & Nilsen 2013; Buckley & Marshall 2016). The freshwater content in this region is primarily driven by the amount of sea ice thereinSea 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 also 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 one of the the main mechanisms contributing to the overall GS SIC, the relation between sea ice export through FS and GS SIC variability is not very robust (Kern et al. 2010). This further points to the importance ofand the local sea ice formation and sea ice dynamics in the central GS (Figure 1) (Kern et al. 2010)particularly, in the marginal ice zone (MIZ) and 'Odden' region of the GS largely contribute to GS SIC variability . The impact of these processes can be realized prominently in the marginal ice zone in the western GS and the "Odden" region in central GS (see Fig. 1 for approximate locations of the regions)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). These regions exhibit strong negative SIC trend during recent decades (Fig. 1a in Selyuzhenok et al. 2020). In fact, the central GS has been mostly ice free in recent years (Rogers and Hung, 2008, Moore et al., 2015) which has large implications on the open ocean convection in the central GS (Brakstad et al., 2019). Variability of SIC in this region can modify the deep water convection through influencing both the heat and salt budgets (Shuchman et al. 1998). Selyuzhenok et al. (2020) found that in spite of increasing sea ice export through the FS, the overall sea ice volume (SIV) in the GS has been decreasing during the period 1979-2016. They further attributed the interannual variability and decreasing trend of SIV to local oceanic processes, more precisely warmer AW temperatures in the Nordic Seas. 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). centralheOn the other hand, t 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). Further local meteorological parameters e.g. air temperature, wind speed and direction along with oceanic waves, eddies have also been found to influence the sea ice properties in the GS 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 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.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).

Besides the local factors, Ssea ice in the central GS also responds to large- -scale atmospheric forcing. For example, a high sea level pressure (SLP) anomaly patternover the NS 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' regioncentral GS (Germe et al. 2011). Selyuzhenok et al. (2020) also argued that consistent positive North Atlantic Oscillation (NAO) forcing in recent decades have led to warmer AW waters in the GS and declining trend in SIV. 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) circulation is known to respond to the atmospheric forcing in the NS and contribute to 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; Jeansson et al. 2017), increases the heat content in the centralwestern GS through a stronger and warmer recirculation of AW (Chatterjee et al. 2018). The return AW, even after significant modification, still remains denser than the local cold and fresh surface waters and thus mostly remain in the subsurface (Schlichtholz & Houssais 1999; Eldevik et al. 2009). However, enhanced vertical winter mixing, can cause warming of the surface waters in the GS (Våge et al., 2018). Further, the eastward flowing Jan Mayen Current (JMC), -originated from the East Greenland Current (EGC),- constitutes the south-western closing branch of the cyclonic GSG circulation in the central GS (Fig. 1). -The east-ward extension of thisthe cold and fresh JMC into the central GS basin helps in both new sea ice formation and advection of sea ice from the EGC (Wadhams & Comiso 1999). Changes in GSG circulation and associated AW recirculation in GS may also influence the JMC strength and temperature., leading to formation of the 'Odden' region. Thus given the potential role of GSG in modifying the oceanic conditions, it is important to understand how the response of GSG circulation to the atmospheric forcing can influence the SIC in GS.

In this study we hypothesize that the interannual winter mean SIC variability in the GS can be explained by the combined influence of the atmospheric and oceanic circulations, more precisely the GSG circulation.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.

-and/or AW redistribution.currentby influencing the JMC region GS centralthe sea ice variability in the to contribute can Thus, it is apparent that the GSG circulation Using a combination of satellite passive microwave SIC, a coupled sea ice ocean reanalysis and atmospheric reanalysis data, we show that GS region can be explained by the changes in GSG dynamics.centralthe oceanic control on the SIC variability in the changes in the GSG dynamics and resulting AW transport in the GS can potentially influence the SIC in the western GS. Further, it is shownwe also show that the atmospheric circulation associated with the GSG circulation variability provides the favourable conditions foralso helps in setting up the GSG's control on the SICa icese variability inof the westerncentral GS region. Section 2 and 3 describe the data and methods applied in the study following the results in section 4. Discussions and conclusions are mentioned in section 5.

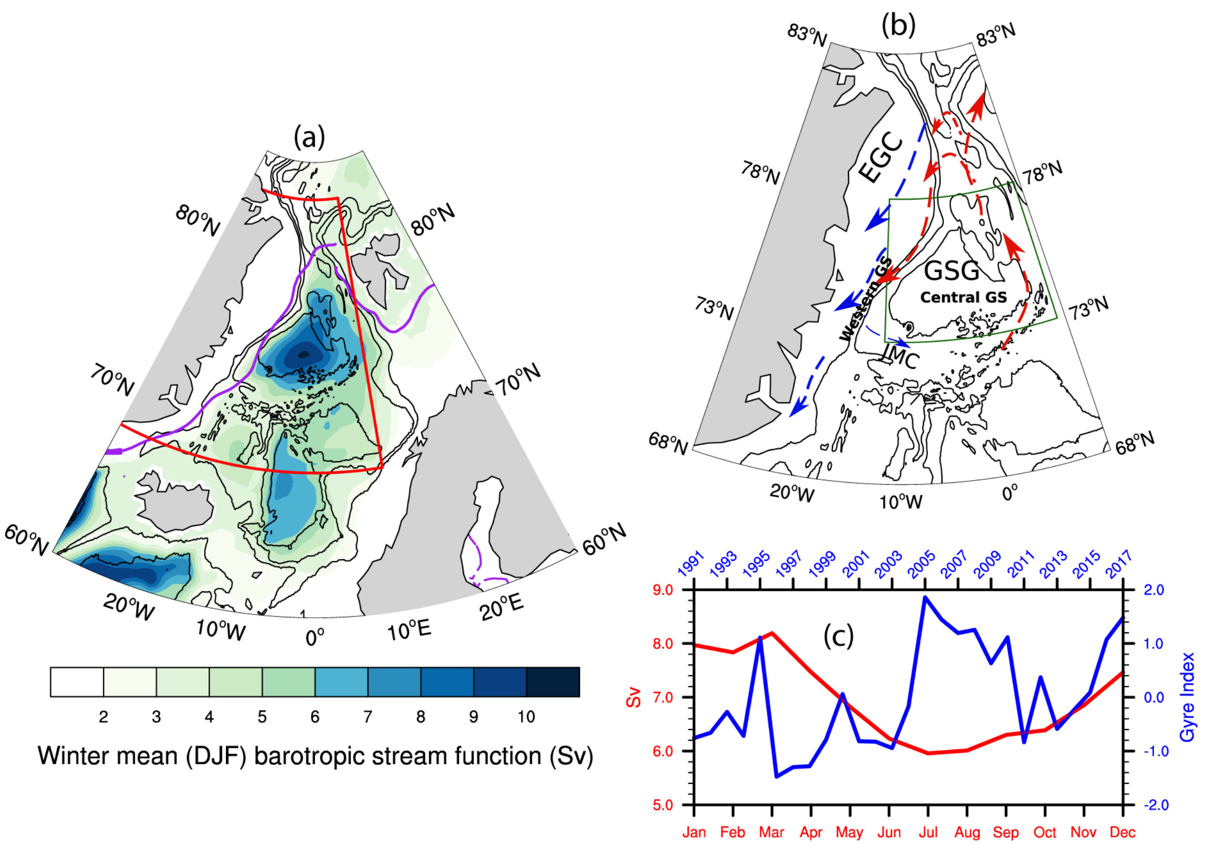

Figure 1: ~~Schematic map of the geographic regions used in this study. Colour shading indicates average annual mean barotropic stream function for the period 1991-2017. FS: Fram Strait; JMC: Jan Mayen Current; EGC: East Greenland Current; GSG: Greenland Sea Gyre. Warm currents are drawn in red and cold 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.~~ a) Winter mean (DJF) barotropic stream function for the period 1991–2017. The region marked in red indicates the Nordic Seas region. The purple line shows the mean DJF sea ice extent for the study period. b) Schematic of the major currents and discussed in the text. JMC: Jan Mayen Current; EGC: East Greenland Current; GSG: Greenland Sea Gyre. Warm currents are drawn in red and cold currents are in blue. Black contours are showing bottom topography drawn at every 1000 m. The thick black contour indicates the 3000m isobath. The marked region in dark green is used to calculate the 'gyre index' as detailed in the next section. c) The blue line indicates the gyre index used in this study and the red line shows the annual cycle of the strength of GSG circulation determined by averaging barotropic stream function within the 3000m isobath in the region marked in (b).

2. Data and Methods

2.1 Atmospheric data:

All atmospheric parameters such as SLP, 10m winds areMonthly mean sea level pressure (SLP) data was obtained from the ERA Interim reanalysis (Dee et al. 2011) for the period 1991-20171991–2017 on a 0.5 by 0.5 degree grid resolution. Monthly anomalies were calculated from the monthly climatology field using the full time period (1991–2017) and were averaged for December-Janaury-February (DJF). For the linear regression analysis the DJF averaged SLP anomalies were detrended.

2.2 Oceanic data:

Monthly mean Ooceanic data used in this study arewere taken 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 evaluated in earlier studies (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 (every week) observations from different platforms. 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. The detailed setup and performance of the TOPAZ4 reanalysis, including the counts of observations and the temporal variations of the data counts are described in Xie et al. (2017). Of particular relevance for the GS are the assimilation of Argo profiles, research cruises CTDs from Institute of Oceanology Polish Academy of Science (IOPAS) and Alfred-Wegener Institue (AWI) (Sakov et al. 2012), satellite sea ice concentration, sea surface temperature and sea level anomaly from the CMEMS platforms.

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 mean sea ice concentrations (SIC) from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data, Version 1 (Cavalieri et al. 1996) were~~are~~ obtained from the National Snow and Ice Data Centre for the period 1991–2017. The dataset provides a continuous time series of SIC on a polar projection at a grid scale size of 25km by 25km. Sea ice velocity data was~~is~~ taken from the Polar Pathfinder Daily 25 km EASE-Grid Sea Ice Motion Vectors (Tschudi et al. 2019).

2.4 Methods and Evaluation of TOPAZ4

We estimated the strength of the GSG circulation by area-averaging the winter-mean (DJF) barotropic stream function anomalies within the 3000m isobath in the region 73 N:78 N; 12 W:9 E (as marked with green box in Fig. 1b). The area-averaged values were then standardized over the complete time period 1991–2017 to estimate the 'gyre index' (Fig. 1c). In this study we focus only on the winter (DJF) season as the local sea ice in GS can only form during winter and also the strength of the GSG circulation peaks during winter (Fig. 1c). Composite analysis of DJF mean potential temperature anomaly was performed by averaging the same for strong and weak gyre index years which were determined when the gyre index crosses the 0.75 and -0.75 mark respectively. The 0.75 threshold was chosen to consider only the sufficiently strong/weak gyre circulation periods. Throughout the article, all regression and correlation analysis were performed with the detrended time series for the corresponding variables. Freshwater content was calculated using the following formula

$$\int_z \frac{S_{ref} - S}{S_{ref}} dz$$

where *S* is salinity and the reference salinity$S_{ref}$is chosen as 34.8 psu.

The standard deviation of winter-mean DJF SIC, in both observation and TOPAZ4, showed high variability along the MIZ in western GS and the Odden region in central GS (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). The sea ice model (Hunke and Dukowicz, 1997), used in TOPAZ4, has a narrower transition zone between the pack ice and the open ocean. Although assimilation of the sea ice observations does slightly improve the position of MIZ in TOPAZ4 compared to observation, the sharp transition in a narrow band still remains, which could have resulted in higher standard deviations in a narrow MIZ of TOPAZ4 as observed in Fig. 2b. However, as we will find in the next section, the sea ice response to the atmospheric and oceanic processes explained in the study can be significantly found in both the observation and TOPAZ4 with slightly higher signals along the MIZ in TOPAZ4. Thus the higher signal-to-noise ratio in TOPAZ4 should not affect the qualitative aspects of the processes and their influence on SIC, which is the main objective of the study.

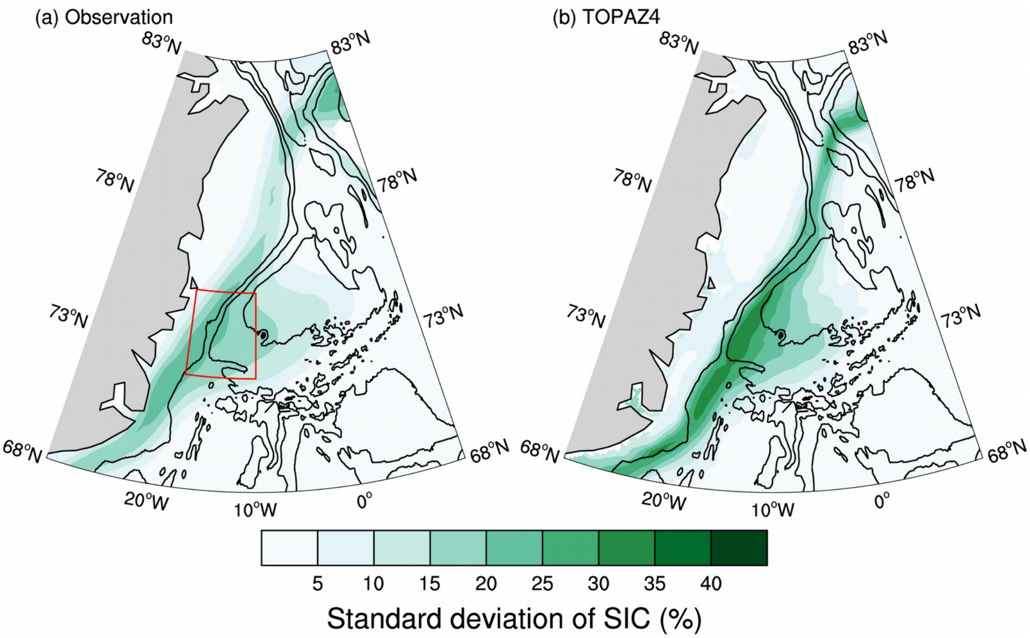

Figure 2: Standard deviations of DJF mean sea ice concentration for the period 1991–2017 from (a) satellite observations (b) TOPAZ4 reanalysis. The red box with high values is drawn over the region 72N:75N; 18W:10W and is referred to as western GS hereafter.

For evaluation of the oceanic conditions in TOPAZ4 we used temperature and salinity observations obtained from EN4 (version 4.2.1) quality controlled analyses with Levitus et al. (2009) corrections applied. Here we chose to compare the oceanic parameters in a region (as marked in Fig. 2) in western GS where the standard deviation of the SIC is found to be maximum both in TOPAZ4 and observations. Also we will find in the next section that SIC response to the processes described here is most profound in this region. Fig. 3 shows the spatio-temporal patterns of sea surface temperature (SST) and salinity (SSS) in this region of western GS as found in TOPAZ4 and EN4. Although the temporal evolution of these parameters are well captured in TOPAZ4, compared to observation, the west ward extension of the warm and saline waters was found to be less in TOPAZ4. This indicates that the front between the cold and fresh waters along the Greenland shelf and the warm and saline waters in the western GS is slightly towards the east in TOPAZ4 compared to observation. This is could be a reason for the fact that higher standard deviation of SIC is found slightly toward east in TOPAZ4 than observation (Fig. 2). Averaged over this whole region in the western GS, both the surface and subsurface temperature in TOPAZ4 was found to be colder compared to observation (Fig. 4). The negative biases in TOPAZ4 were more profound in the subsurface for both temperature and salinity. Using the potential density difference between 200m and the surface as an indicator of the stratification, we found that TOPAZ4 has weaker startification compared to observation (Fig. 4e). This may overestimate the vertical mixing in TOPAZ4. Consistent with the cold bias in TOPAZ4, winter-mean SIC in TOPAZ4 is higher than the satellite observation in the western GS (Fig. 4f). However, we found a strong correlation (r=0.9) between the SIC in observation and TOPAZ4. This indicates that the interannual variability of SIC, which is the focus of the study, is quite consistent in both TOPAZ4 and observation.

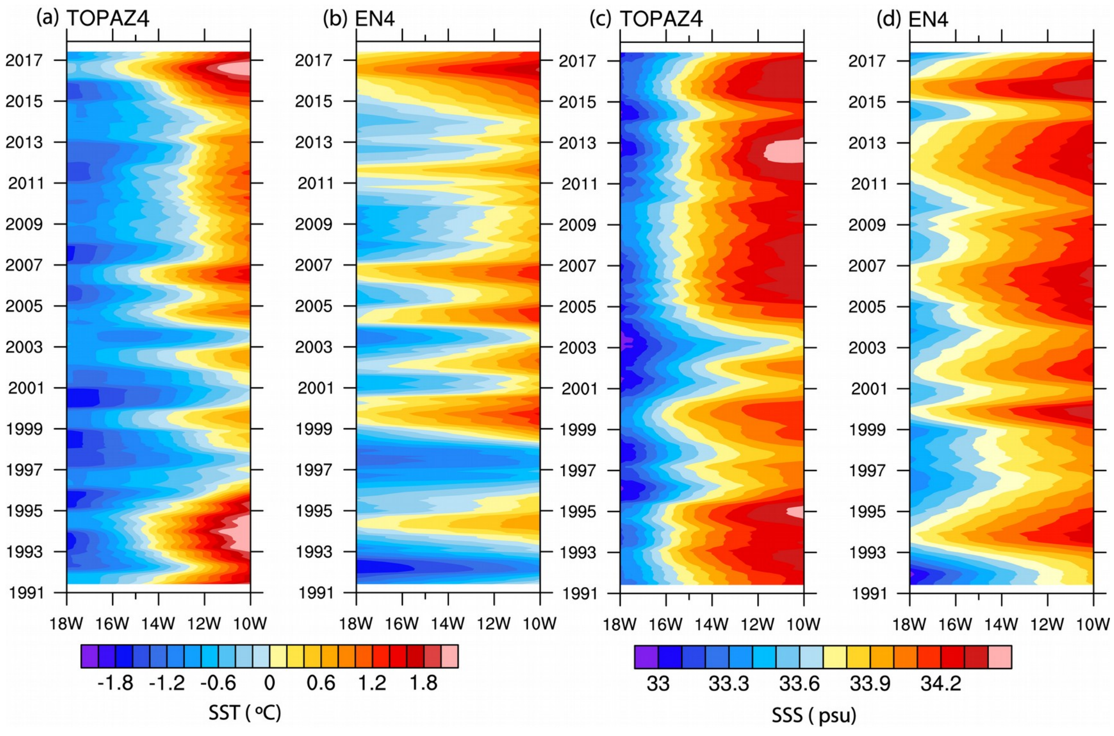

Figure 3: Hovmoller (longitude-time) diagram of the SST (°C; a,b) and SSS (psu; c,d) over the region over 72 N:75 N; 18 W:10 W in the western GS as marked in Fig. 2. (a) and (c) are for TOPAZ4 and (b) and (d) for EN4 observations. In all cases data were smoothed with one year running mean.

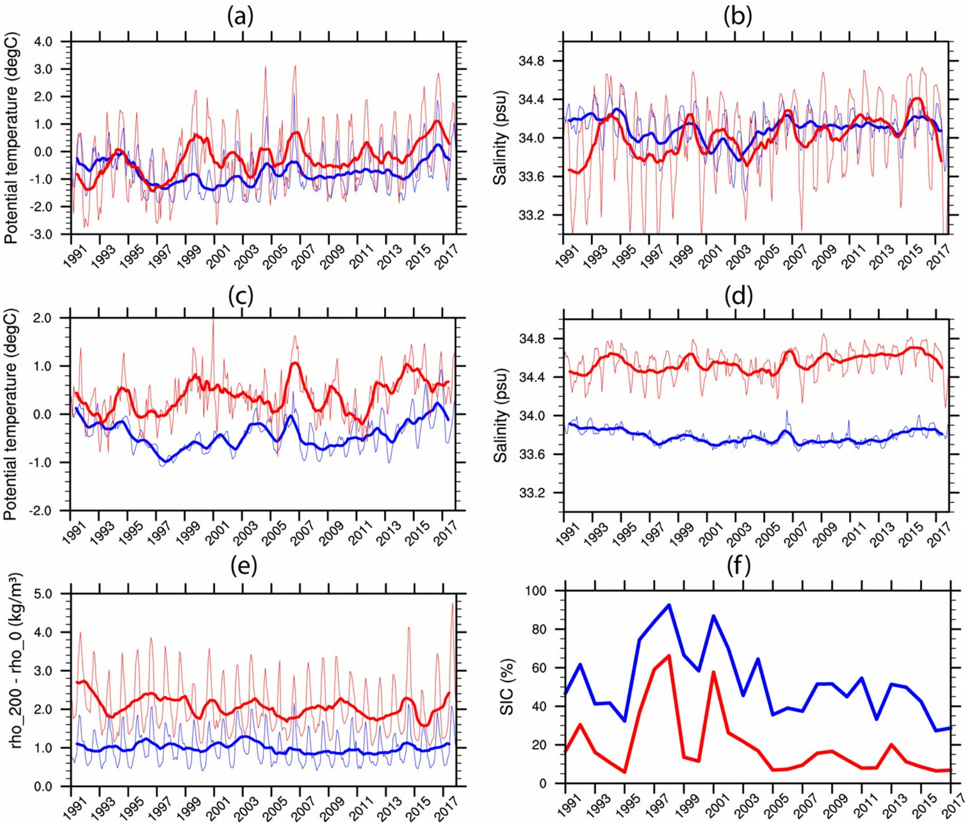

Figure 4: Comparison between EN4 observation (red lines) and TOPAZ4 (blue lines). Monthly mean (thin lines) and one year running mean (thick lines) of potential temperature (a,c), salinity (b,d) and stratification index (e, difference of potential density between 200m and surface) averaged over 72 N:75 N; 18 W:10 W in the western GS as marked in Fig. 2. (a,b) are for 0-50m depth average and (c,d) for 100-400m depth average. (f) DJF mean sea ice concentration in the same region from satellite observation (red) and TOPAZ4 (blue).

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).

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’ showeds significant negative SIC in the centralwestern GS (Fig. 53). The spatial pattern of the regression coefficients closely resembles the standard deviation of winter mean SIC in the GS, particulary over the western GS, as shown in Fig. 2. This indicates that considerable amount of the western GS SIC variability can be associated with GSG circulation. However, it should be noted that atmospheric forcing in the NS can influence both the GSG circulation (Aagaard 1970; Legutke 2002; Chatterjee et al. 2018) and SIC variability in the GS (Germe et al. 2011). , (Aagaard 1970; Legutke 2002; Chatterjee et al. 2018) 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. 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.

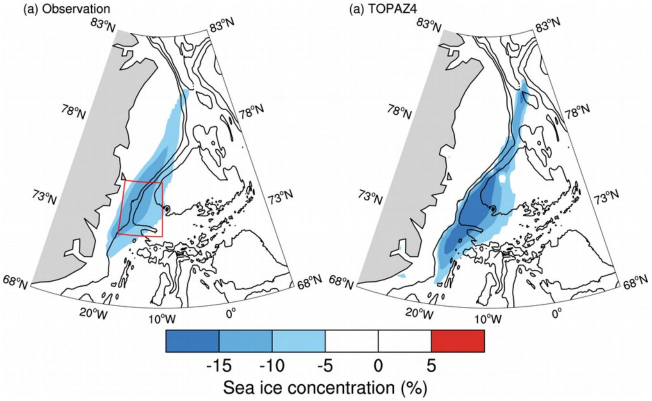

Figure 5: Linear regression of winter mean (DJF) sea ice concentration from (a) satellite observation (b) TOPAZ reanalysis on the gyre index. Only significant values at 95 % level are shown. Contours are bottom topography drawn at every 1000 m.

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.

To elucidate the possible influence of atmospheric ciruclation pattern associated with GSG circulation on the SIC variability in the GS, linear regression of the sea level pressure anomalies on the gyre index was calculated and shown in Fig. 6. Composite difference of SLP anomalies for the positive and negative GSG circulation periods (Fig. 4a) suggests that theThe large-scale atmopsheric circulation shows a NAO-like pattern associated with the GSG circulation, but with centres of action north of their usual locations (Fig. 6). The GSG circulation responds to the anomalous wind stress curl induced by the low SLP anomaly patterns in the NS (Chatterjee et al. 2018)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). ThusHowever, we found that 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'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. Also note that the low correlation could be due to the fact that the equatorward pole of NAO doesn't exhibit much significant regression patterns in Fig. 6.

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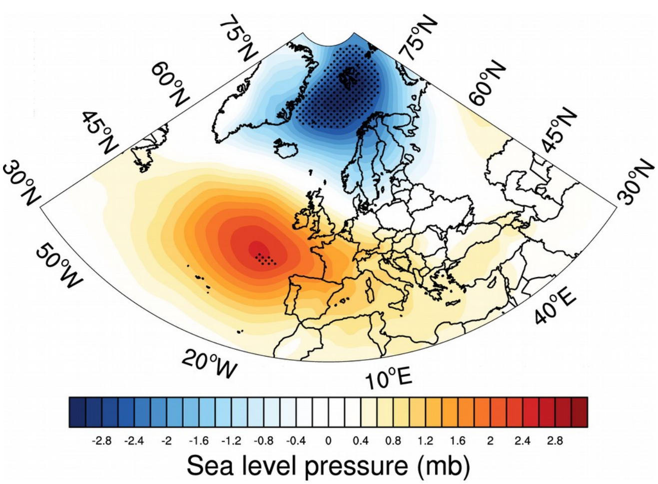

Figure 6: Linear regression of DJF mean sea level pressure anomaly on the gyre index. Regions with 95% statistical significance are dotted.

(Figs. 4b, c). The GSG circulation responds to the anomalous wind stress curl induced by this atmospheric circulation pattern

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).The mean southward sea ice export in the GS across the FS (Fig 7a) is strongly driven by the geostrophic winds in this region (Smedsrud et al. 2017). The low SLP pattern over NS associated with the GSG circulation can induce anomalous northerlies in the GS. Linear regression of sea ice velocitiesy on the gyre index'Gyre Index' showeds anomalous northwardsoutherly sea ice velocities in the MIZ and 'Odden' regionthe GS associated with increase in GSG strength (Fig. 75b). This indicates that the anomalous northerly winds 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 southwardnortherly sea ice velocities in this region (Fig. 75a). This could further lead to lessreduced sea ice export in this region and lowreduced SIC. dynamics of the ice export in this region. on 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 ratherNote 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

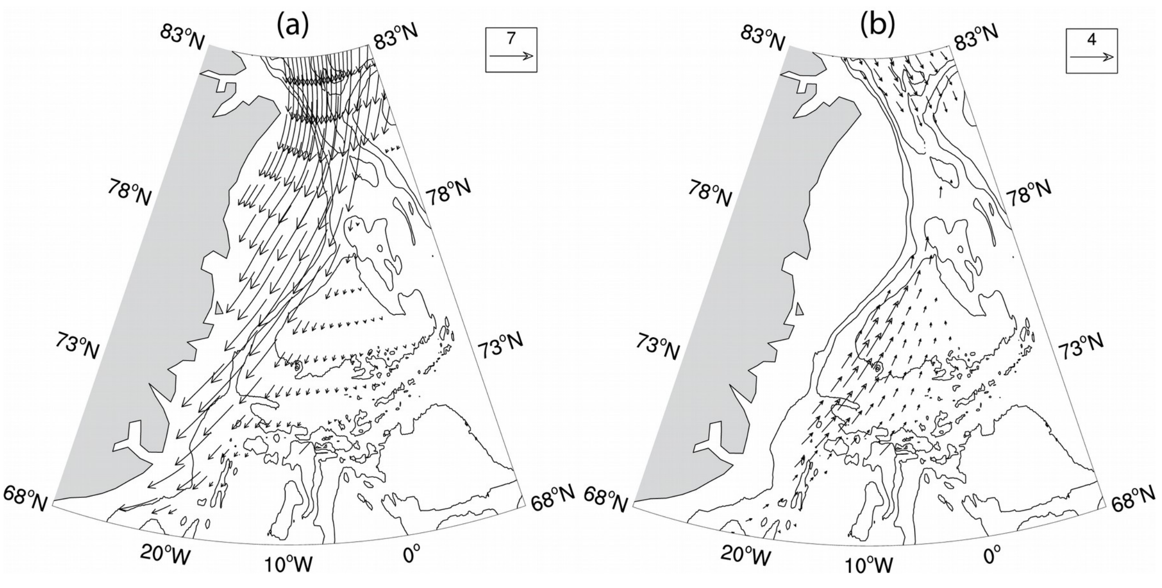

Figure 7: (a) Climatological (1991–2017) DJF sea ice velocity vectors (cm/s) from satellite observations. (b) Regression of DJF sea ice velocity anomalies (cm/s) on the gyre index. Only results significant at 95 % are shown for clarity. Contours are bottom topography drawn at every 1000 m.

~~**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.~~

~~**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,~~ Next, we investigate GSG's potential in influencing the oceanic conditions and hence the sea ice in the ~~central~~ GS, given that the local oceanic coditions largely affect the sea ice conditions therein (Johannessen et al. 1987; Visbeck et al. 1995; Kern et al. 2010; Selyuzhenok et al. 2020).

~~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 8a shows the difference in ocean temperature anomaly in the upper 400m averaged for the strong and weak GSG circulation years (marked in Fig 8b; see methods for definitions). ~~along the MIZ periods are foundpositive 'Gyre Index' anomalies during . Warm anomalous temperature anomaly in the upper 400 m between positive and negative 'Gyre Index' periodsFigure 6(a) shows the composite difference of~~The average temperature anomaly for the strong GSG circulation years was found to be $\sim$1°C higher than the same during weak GSG circulation years. The warm anomalies further ~~which in its southern part~~ extends eastward with the JMC towards the central GS and could potentially affect the sea ice formation in the Odden region.~~the 'Odden' region~~. ~~This is further confirmed in Fig. 6b, whereAs 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.~~ Further, we found s~~s~~ignificant positive correlation (r=0.7, Fig 8b) ~~found is~~between gyre index and temperature advection (in upper 400 m) in the western GS (marked region in Fig. 8~~3~~a)), where maximum GSG influence on SIC is found (Fig. 3a)~~'Gyre Index' and the)~~. This suggests that a strong GSG circulation recirculates the warm AW anomalies into the western GS from the FS. This is consistent with earlier study indicating an increased oceanic heat content in the western GS due to a stronger GSG circulation (Chatterjee et al., 2018)~~.~~ ~~Further, surface 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.~~

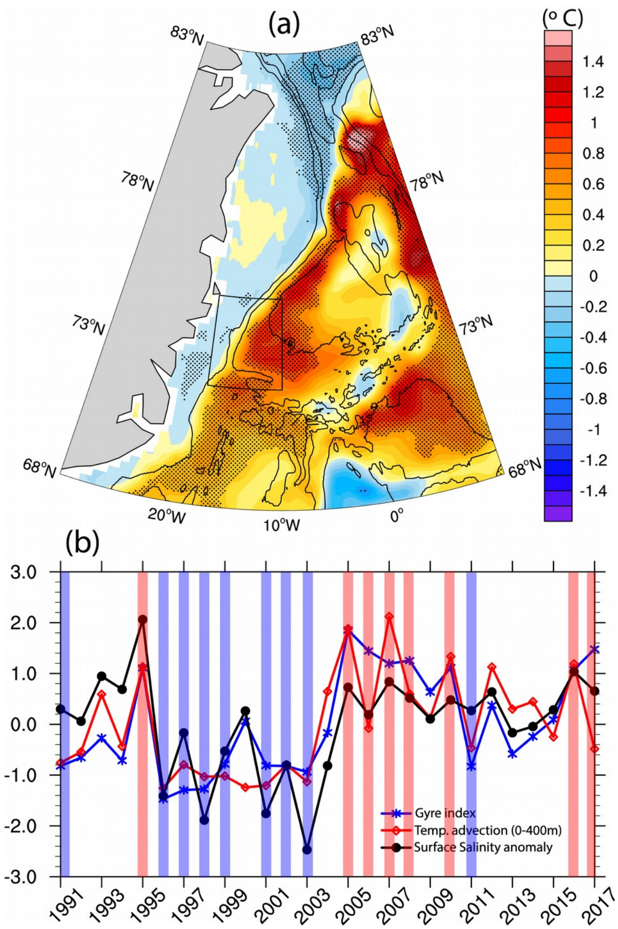

Figure 8: (a) Difference between 400 m depth averaged potential temperature anomalies (oC) averaged for strong (red bars in (b)) and weak (blue bars in (b)) gyre index years. (b) Gyre index (blue), and standardized surface salinity anomaly (black), temperature advection ($U . \nabla T$) in upper 400 m (red) for DJF over the region 72 N: 75 N; 18 W : 10 W, as marked in (a).

~~**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.~~

However, it should be noted that the recirculated AW in the GS still remains dense enough to be in subsurface (Schlichtholz & Houssais 1999; Eldevik et al. 2009) and needs to be vertically mixed to have an impact on the sea ice. ~~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~~ We found that the upper ocean stratification in the western GS strongly covaries with GSG circulation strength (Fig. 9a). ~~GSG circulation with a strengthening/weakening of thestratification in the upper column coincidesweakening/strengthening of the a indicates that~~ The analysis shows that a weakening of the stratification in the upper part of the water column coincides with a stronger GSG circulation and viceversa (Fig. 9a). Further, warm and saline signatures in the upper ocean can be found during strong GSG circulation, indicating enhanced vertical mixing of the AW in the western GS (Figs. 9b,c). The warm anomalies can further inhibit new sea ice formation and also may cause melting of existing sea ice from the bottom.~~SIC. surface oceanic conditions, hence the potentially influence the can under a weakly stratified condition and surface GSG can the GS by centralsupports that the warm anomalies advected towards further This 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.~~

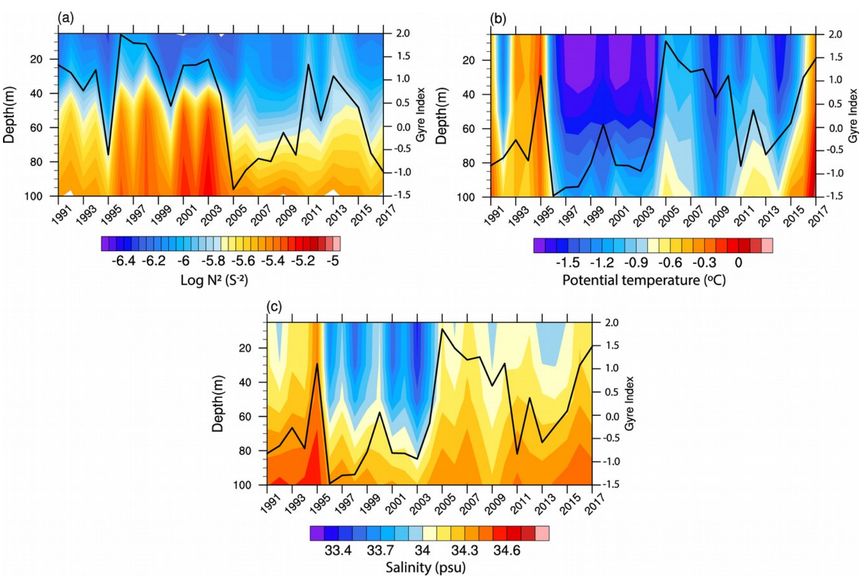

Figure 9: (a) Logarithm of squared Brunt-Väisälä Frequency (N2, colour shaded) (b) potential temperature (c) salinity for DJF over the region 72 N:75 N; 18 W:10 W, as marked in Figure 8a. The black timeseries against the right Y axis is the gyre index in all three panels. Note that the gyre index is plotted against a reversed Y axis in (a) for ease of comparison.

4. Discussions and Conclusions

Here we investigated the combined influence of atmospheric and oceanic circulations on the interannual variability of the winter mean SIC variability in the GS and We showed that NS, in particular the GSG circulation can significantly contribute to the western GS SIC variability. .Nordic Seas circulation in particular the GSG circulation has strong influence on the interannual variability of winter time GS SICthe Fig. 10 shows the flow chart and a schematic illustration of the mechanisms -proposed in this study. The large-scale atmospheric circulation pattern that influences the GSG circulation resembles a NAO-like pattern with its northern centre of action situated northeast of the typical NAO pattern. The cyclonic GSG circulation strengthens in response responds to the positive the wind stress curl induced by the low SLP anomaly in the NSatmospheric forcing over the Nordic Seas through wind stress curl (Legutke 2002, Chatterjee et al. 2018). The resulting norherly wind anomlies over GS can potentially alter the sea ice export across the FS (Kwok & Rothrock 1999; Jung & Hilmer 2001; Vinje 2001; Tsukernik et al. 2010; Smedsrud et al. 2011; Ionita et al. 2016). However, winter mean SIC in the GS and FS ice area flux are not strongly correlated (Kwok et al., 2004; Germe et al., 2011), suggesting that the SIC variability in the GS can be significantly influenced by the local sea ice dynamics and oceanic conditions. 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. such an atmospheric forcing canhave found Earlier studies

influence the sea ice condition in the MIZ and Odden region through Ekman drift of the sea ice(Germe et al., 2011) .

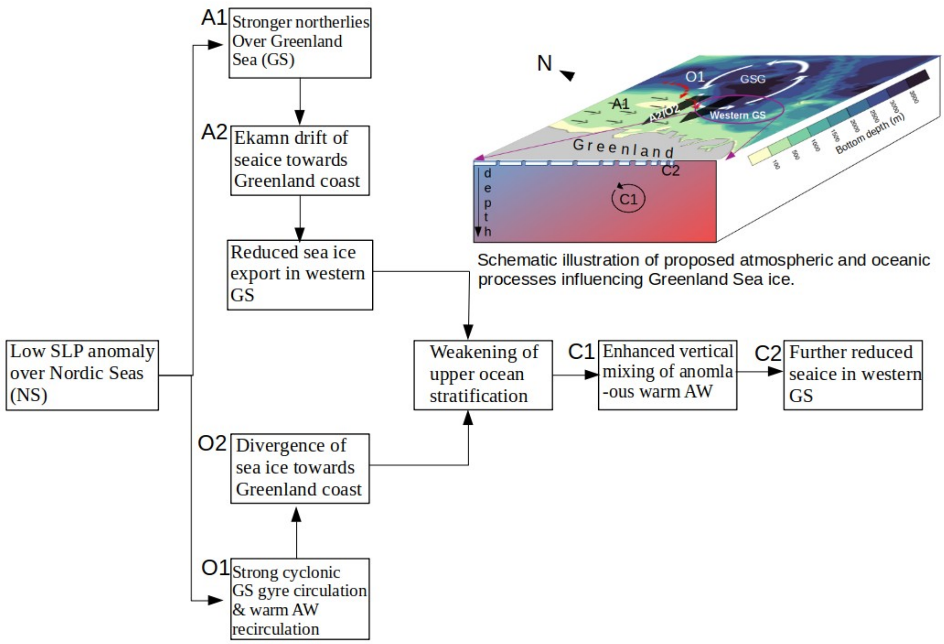

Figure 10: A flow chart and schematic diagram of the proposed processes influencing the SIC variability in the western GS.

Anomalous winds in the Nordic Seas are known to influence the SIC in the GS through Ekman drift of the sea ice (Germe et al., 2011). During time-periods with anomalously low SLP over NS, anomalous northerly winds and associated Ekman drift towards the Greenland coast that can reduce the sea ice export in the western and central GS (Fig 8b). ~~.and reduces the sea ice export in the central GSDuring 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~~ Enhanced Ekman divergence due to a strengthened GSG circulation can further lead to reduced freshwater and sea ice in the western GS (Fig. 11). We found that these can lead to ~~to a sleadis further Th~~weakening of the upper ocean stratification ~~in the upper water column~~in the western GS (Fig. 9a). At the same time, a stronger GSG circulation recirculates the warm and saline subsurface AW anomalies from the FS into the ~~central~~western GS (Fig 8a). These AW anomalies can warm the surface waters by enhanced vertical mixing~~and under~~in a weakly stratified condition (Fig. 9) and can cause ~~the AW anomalies can reach the surface and~~ further reduction of~~es the~~ SIC by inhibiting new sea ice formation or even melting the sea ice from bottom. Although our study doesn't show bottom melting of the sea ice, this can be realized from the findings by Ivanova et al. (2011) which showed enhanced bottom melting in this region during positive NAO periods. Thus, the SIC variability in the western GS~~GS SIC central~~ responds to simultaneous influences from the atmospheric and oceanic circulation (Fig. 10~~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.~~ Despite the known influences of smaller scale processes, such as eddies and wave interactions on the SIC in the western GS, our results show that the larger scale processes also can significantly be important for the SIC variability in the region, particularly on interannual timescales when the impacts of smaller scale processes can get largely cancelled out or may not be strong enough to dampen the impact of larger scale processes. However, as found in Raj et al., (2020), interactions between the gyre circulation and the eddies can be an important factor controlling the oceanic conditions and hence the SIC in the western GS.

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

~~**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.~~

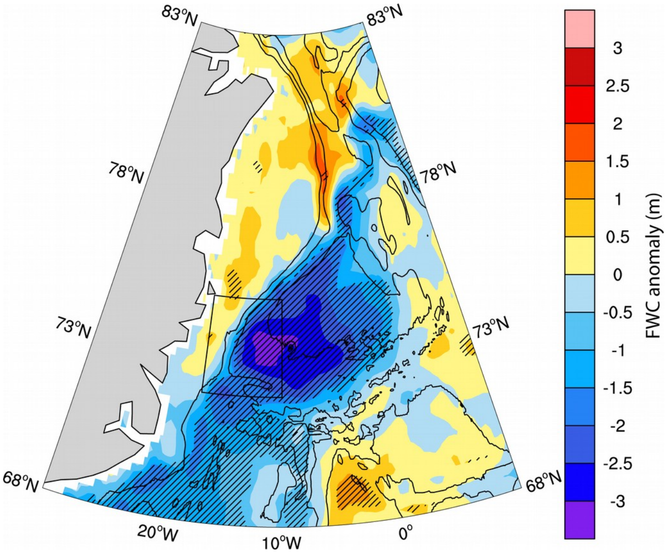

Figure 11: Difference in freshwater content (FWC) anomaly (m) between strong and weak gyre index periods. Significant differences at 95% level are stippled.

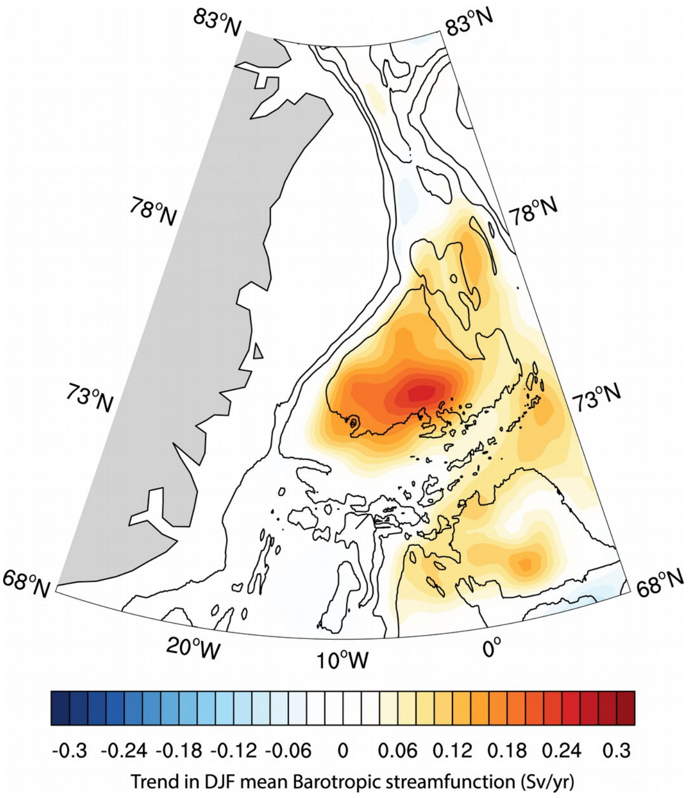

Figure 12: Linear trend (Sv/year) in winter mean (DJF) barotropic stream function for 1991–2017. Only significant values at 95 % level are shown for clarity. Contours are bottom topography drawn at every 1000 m.

~~GS SIC~~SIC in the GS 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 it~~the GS SIC~~. This study finds one of those mechanisms highlighting the role of large scale atmospheric and oceanic circulations in the ~~Nordic Seas~~NS. Observations and modelling results suggest stronger atmospheric forcing in the NS~~ordic Seas~~ due to spatial variation of the NAO (Zhang et al. 2008) 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. 11~~9~~). The response of GSG circulation to this altered atmospheric forcing can further be realized with increased GSG gtrength (Fig. 1c) and a sudden northeastward displacement of NAO's poleward centre of action in the Nordic Seas during early 2000s (Fig. 1a in Zhang et al., 2008). Recent observations suggest intensified convection in the GSG and resulting changes in watermass formation during the last two decades (Lauvset et al., 2018; Brakstad et al., 2019). Lauvset et al., (2018) futher discussed the role of recirculated AW on inducing intensified convection in the GSG through surface salinity anomaly. Consistent with this, our results show that the salinity anomalies and intensified convection in the GSG can be induced by a stronger GSG circulation (in response to the atmospheric forcing) which helps in recirculation of AW anomalies in the GS. 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

Thus we propose that the atmospheric forcing over the NS imposes a positive oceanic feedback (Fig. 13). The low SLP anomaly over the NS strengthens the GSG circulation. The ekman divergence pushes the freshwater and sea ice away from the GS interior towards the coast. Enhanced AW recirculation due to a stronger GSG and weakened stratification due to reduced freshwater allows the warm and saline AW anomalies to get vertically mixed and increase the temperature and salinity in the central GS. The increased salinity further helps in a stronger GSG circulation, completing the feedback loop. The findings of the study thus highlight that interaction between large scale atmospheric and oceanic circulation in NS is crucial for understanding the North Atlantic and Arctic oceanic connections.

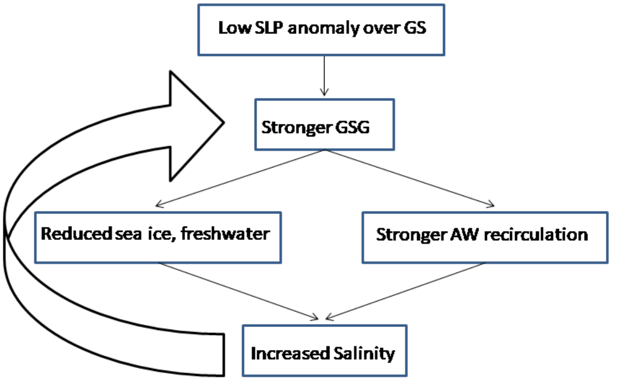

Figure 13: A proposed positive oceanic feedback induced by atmospheric forcing in NS.

Acknowledgments

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Declarations

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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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