On the mechanism of interannual variability of the Irminger Water in the Labrador Sea

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[1] The mechanism of variability of the North Atlantic subpolar gyre (SPG) and its relation to the North Atlantic Oscillation (NAO) is investigated using an ocean general circulation model. In this study we conducted three model experiments. The first two were forced with idealized positive (NAO^+) and negative (NAO^-) NAO-like forcing, including variations at decadal time scales. The third experiment was forced with the National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) reanalysis. The decadal variability of the volume transport, the sea surface temperature in the North Atlantic Current (SSTA1), and the Irminger Water temperature (IWT) in the NAO^- experiment have 2–3 times smaller magnitude than in the NAO^+ experiment. The decadal variations in the strength of circulation in the NAO^+ experiment covaries negatively with SSTA1 and IWT anomalies. A similar covariability of these parameters is not found in the NAO^- simulations. The results from the model experiment forced with the NCEP/NCAR reanalysis from 1958 to 2005 show a shift in the subpolar ocean response to the atmospheric variability in the early 1980s. The amplitude of quasi-decadal variability of the IWT and SSTA1 and their correlation are high after 1980 ($r = 0.79$) and weaker in the period between 1958 and 1980 ($r = 0.1$). The IWT after 1980 is well correlated ($r = 0.67$) to the subpolar gyre transport index (SPGI, defined as the minimum value of the annual mean anomaly of the model barotropic stream function). This correlation is weaker and negative ($r = -0.09$) in the period from 1958 to 1980. We explain this shift in the covariability of the SSTA1, IWT, and SPGI with the antisymmetric response of the SPG to atmospheric variations at decadal time scale under positive and negative NAO index. The NAO sign changed in the early 1980s from predominantly negative to positive phase. In the 1980s and 1990s the model SPGI variability follows closely the decadal variations of the NAO index with a delay of about 3 years. Similar covariability between the SPGI and the NAO and related negative covariance of SSTA1 and IWT with the SPGI are not observed in the model simulations of the period from 1958 to 1980.

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1. Introduction

[2] Cyclonic circulation in the subpolar North Atlantic (Figure 1) is an important contributor to the global ocean water and heat transport. The observed cyclonic volume transport in the Labrador Sea is 40–50 Sv, which consists of 30–38 Sv “throughput” in the subpolar gyre (SPG) and 10–14 Sv in the local recirculation [*Pickart et al.*, 2002]. The deep component of this flow feeds the Meridional Overturning Circulation (MOC). The SPG is bounded to the east by the warm and salty North Atlantic Current (NAC) (Figure 1). In the subpolar area, the surface NAC water is cooled through the heat exchange with the atmosphere and a portion of it penetrates into the subsurface cyclonic flow. This so-called Irminger water (IW) is observed as a salty and warm water mass below 150 m depth which influences the stratification and intensity of the vertical mixing in the SPG. *Myers et al.* [2007] found that the Labrador Seawater (LSW) formation is correlated ($r = 0.51$) to the IW transport at Cape Farewell with a lag of 1 year.

[3] The temperature of the NAC surface water in area A1 (see Figure 1) increased by 1°C between late 1980s and 1990s. *Marsh et al.* [2008] explained this change by the anomalous convergence of ocean heat transport associated with the overturning and horizontal circulation. The Irminger Water temperature (IWT) in the Labrador Sea during the late 1990s was warmer than usual [*Myers et al.*, 2007]. *Holland et al.* [2008] suggested that the related increase of the subsurface ocean temperature along the west coast of

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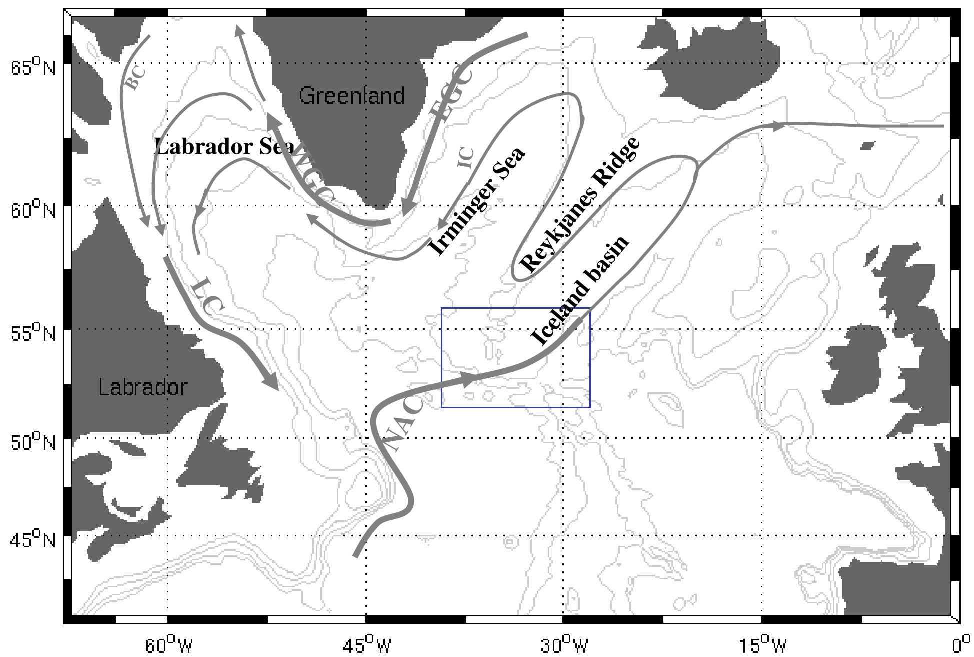

Figure 1. Map of the subpolar North Atlantic. The isobaths are 700, 2000, 3000, 3500, and 6000 m (light contours). Arrows depict schematically the surface current system (NAC, North Atlantic Current; EGC, East Greenland Current; WGC, West Greenland Current; LC, Labrador Current; IC, Irminger Current; BC, Baffin Island Current). The blue line defines the borders of area A1 used in calculation of SSTA1.

Greenland was the most likely cause for the sudden switch of Jakobshavn Isbrae from slow thickening to rapid thinning in 1997. *Holland et al.* [2008] also explained the warming of the IWT with the weakening of the SPG at the end of 1990s [*Häkkinen and Rhines*, 2004] and related westward movement of the polar frontal system [*Hátún et al.*, 2005]. The weakening of the SPG in the 1990s was linked to an increase in the volume of the NAC surface water mass and record high salinities in the Atlantic inflow to the Nordic Seas [*Hátún et al.*, 2005]. The ocean model simulations of *Böning et al.* [2006] demonstrated that the decay of the circulation and related variability of the SPG in the late 1990s was part of long-term decadal variability of the SPG.

[4] The mechanism of the SPG interannual variability in the 1980s and 1990s has received considerable attention. Among other mechanisms, a number of studies [see *Hurrell*, 1995; *Visbeck et al.*, 2003; *Lohmann et al.*, 2009] have linked the SPG variability with the North Atlantic Oscillation (NAO). Positive (negative) NAO is associated with stronger (weaker) than normal winds and cold (warm) winters in the subpolar North Atlantic. *Lohmann et al.* [2009] demonstrated that the SPG response is asymmetric to steady NAO-like forcing. In the positive NAO case the SPG circulation strengthens during the first 10 years and then it warms and weakens. In the simulations with negative NAO forcing, the tendency in the strength of SPG circulation shows a persistent weakening and does not involve a sign reversal. *Lohmann et al.* [2009] related the asymmetric SPG response to the sign of persistent NAO-like forcing to the nonlinearity in the North Atlantic circulation.

[5] The time series of the NAO index in recent years [see *Greatbatch*, 2000] has revealed a period of low values from the early 1950s to the early 1970s, relatively high values in the early part of last century, and high values in the last 25–30 years, during which time the index shows also a strong decadal variability. The NAO variations at decadal time scale had a strong impact [see *Greatbatch*, 2000] on the subpolar atmosphere in the 1980s and 1990s. The winters of the late 1980s and early 1990s were cold with strong surface winds while the winters of late 1990s were anomalously warm. The related variations in the surface forcing had an impact on the deep convection and MOC causing the largest variations in the properties of the LSW observed in the past 60 years [*Yashayaev*, 2007].

[6] The aim of the present work is to extend the study of *Lohmann et al.* [2009] and to explore the response of the SPG to the decadal variability under positive and negative NAO-like forcing. More specifically, here we address two questions.

[7] 1. How does the asymmetric nature of the relation between the SPG and NAO-like forcing impact the response of the SPG to the quasi-decadal variations in the NAO?

[8] 2. What is the impact of the atmospheric decadal variability on the SPG in the late 1990s?

[9] The article is organized as follows: section 2 describes the model setup, section 3 discusses the model response to idealized positive and negative NAO-like forcing, section 4 presents results from model simulations of the North Atlantic forced with 1948–2005 National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) reanalysis. Section 5 offers conclusions.

2. The Model

[10] The ocean model is the Nucleus for European Models of the Ocean (NEMO) model [*Madec*, 2008]. It is a z coordinate, primitive equation, free surface ocean model

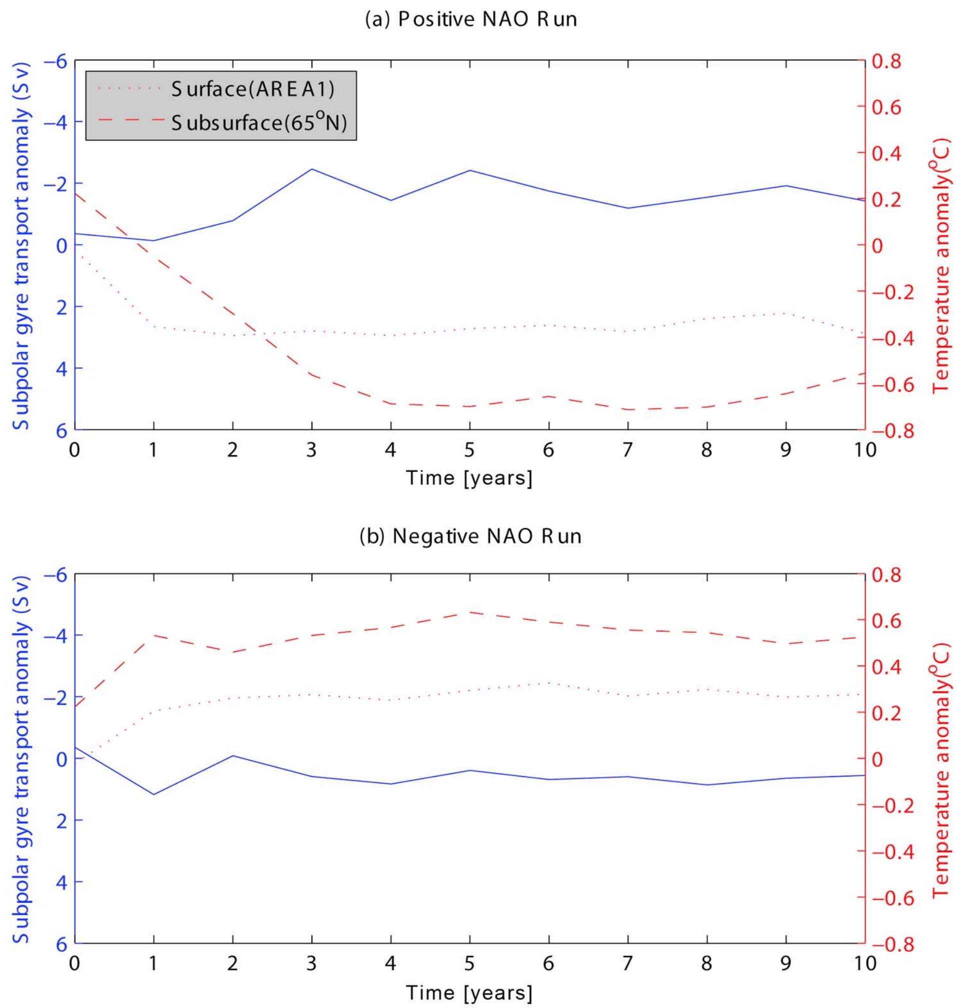

Figure 2. The SPGI (blue solid curve), the surface temperature averaged over area A1 (red dotted curve), and the subsurface temperature off the west Greenland coast (a) from the positive NAO run and (b) from the negative NAO run (red dashed curve, defined as the temperature at 483 m averaged 56°W onshore along 65°N). Note that the subsurface temperature anomalies (red dashed curve) have been multiplied by a factor of 2.

coupled with the multilayered sea ice LIM2 model [*Fichefet and Morales Maqueda*, 1997]. The domain covers the North Atlantic from 7°N to 67°N, with horizontal resolution of $\frac{1}{4}^{\circ}$ in longitude and $\frac{1}{4}^{\circ}$ $\cos\phi$ in latitude ϕ, and 46 vertical levels. The model is forced with NCEP/NCAR reanalysis data [*Kalnay et al.*, 1996] from 1948 to 2005. The open boundary conditions (OBC) are imposed on the northern and southern boundaries from the Simple Ocean Data Assimilation (SODA) data set [*Carton et al.*, 2005]. The model is initialized from a 30 year run forced with NCEP monthly mean surface atmospheric fields. A spectral nudging scheme [*Thompson et al.*, 2006] is applied to reduce model bias and drift on the climatological time scale. The model temperature and salinity are nudged toward the observed climatology with a prescribed frequency–wave number band and is not constrained outside of this interval. In the following experiments, the nudging scheme is applied to the surface 30 m layer and in the layer deeper than 560 m. In this way the IW properties and their interannual variability are not affected directly by the spectral nudging.

[11] In this article we present results from three model experiments. The first two model runs are forced with idealized NAO-like (NAO^+ and NAO^-) surface fluxes. The atmospheric forcing in the third model experiment is from the 6 h NCEP/NCAR reanalysis. The first 10 years of NAO^+ and NAO^- simulations are performed with forcing calculated as daily composites of NCEP/NCAR atmospheric fields for years of positive and negative NAO correspondingly. In the positive NAO case these years are 1983, 1989, 1990, 1992, 1994, 1995, 2000 and for the negative NAO the years are 1963, 1964, 1965, 1969, 1977, 1979 and 1996. Starting from the 11th year of NAO^+ and NAO^- simulations, the forcing includes a decadal variability. The near surface atmospheric parameters are calculated as sum of monthly mean plus 6 h variability. The monthly mean fields are computed using monthly composites for years of positive, negative and neutral NAO. The years of neutral NAO are 1972, 1978, 1980, 1982, 1987, 1988. The monthly forcing every 10th year in the NAO^+ run, i.e., 10th year, 20th, 30th years, etc., is set equal to the positive NAO fields. The monthly mean forcing in years

15th, 25th, 35th, etc., is equal to the neutral NAO fields. In between, the monthly forcing evolves smoothly from the positive NAO case to the neutral NAO case and then back to the positive NAO case within every decade. The 6 h deviations from the monthly mean are from selected NAO$^+$ and NAO^n years (and calculated with respect to monthly means of the individual year). The atmospheric forcing is calculated similarly for the NAO$^-$ run.

3. Response of the SPG to Positive and Negative NAO Forcing

[12] Figure 2 shows the variability of the subpolar gyre transport index (SPGI), sea surface temperature (SST) in the North Atlantic Current (SSTA1), and the IWT in the NAO$^+$ and NAO$^-$ simulations. The anomalies are calculated with respect to the mean of the run forced with 1948–2005 NCEP/NCAR reanalysis. In both simulations, the NAO$^+$ and NAO$^-$, the SPGI, SSTA1 and IWT reach equilibrium after the first 5 years of simulations. Figure 2 shows the well known [see *Lohmann et al.*, 2009] property of strengthening of the SPG and cooling of IWT in the NAO$^+$ run and weakening of SPGI and warming of IWT in the NAO$^-$ simulations. In years of positive NAO the winters are colder and the winds are stronger than normal over the subpolar ocean. The intensified winter convection in these years results in stronger than usual intensity of the processes of deep water formation and spreading of cold surface and intermediate water masses. The horizontal gradients in the density doming structure in the SPG strengthen and the SPG circulation intensifies. The change of the circulation of the SPG under positive NAO is spatially inhomogeneous (see Figure 3). The intensification of the SPG is strongest in the areas along the west coast of Greenland, northern Labrador Sea and in eastern part of the SPG (Figure 3c). These are also the areas of largest difference of the (SST (Figure 4) and temperature at intermediate depths (Figure 5c) in the NAO$^+$ and NAO$^-$ experiments. The intermediate waters the SPG are warmer in the NAO$^-$ experiment by about 0.5°C–1.5°C (Figure 5). This increase of the temperature in the SPG under negative NAO$^-$ forcing (Figures 5a and 5b) is related to the increasing of the volume of the IW. The difference of the IWT in the NAO$^+$ and NAO$^-$ runs have large magnitudes of about 1.5°C in the eastern part of the SPG and in northern Labrador Sea.

[13] The strongest intensification of the SPG transport in the NAO$^+$ simulations (Figure 3c) is about 8 Sv and is present a relatively narrow area along the east coast of Greenland. The mechanism of intensification of the cyclonic flow in this area is related to the effect of the bottom topography on the SPG boundary current. The bottom pressure torque [*Mellor et al.*, 1982; *Greatbatch et al.*, 1991] is calculated as

$$BPT = -\frac{J(p_B, H)}{\rho_0 f_0}$$

where p_B is the bottom pressure, H is bottom depth, ρ_0 is mean ocean density and f_0 is the Coriolis parameter. The bottom pressure torque has strongest impact on the flow along the west coast of Greenland and off the coast of Labrador (see Figures 6a and 6b). Under positive NAO, the bottom pressure torque effect increases by up to 25% off the west coast of Greenland. This change is primarily driven by the intensified wind stress and leads to local intensification of circulation.

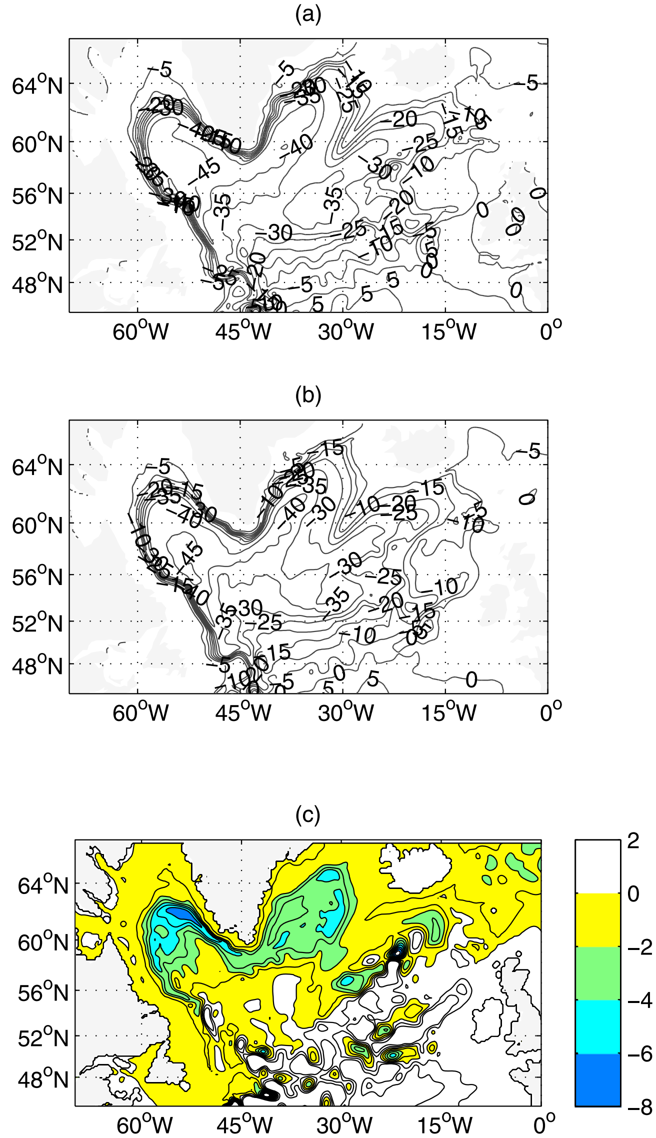

Figure 3. The barotropic stream function averaged over years 6–10 in (a) the positive NAO run and (b) the negative NAO run. (c) The difference between Figures 3a and 3b. Contour interval is 5 Sv in Figures 3a and 3b and 1 Sv in Figure 3c.

[14] After the 10th year of simulation, the surface forcing in the two model experiments, NAO$^+$ and NAO$^-$, includes variations at decadal time scale (see section 2). The analysis of the time evolution of the model parameters (not shown here) suggests that the model solution adjusts to the variable surface wind and buoyancy forcing through propagation of topographic Rossby waves which travel along the coast of the subpolar ocean for about 2–3 years. This time scale is consistent with findings of *Eden and Willebrand* [2001], *Brauch and Gerdes* [2005], and *Lohmann et al.* [2009] that the SPG responds with a delay of 2–3 years to the changes in the surface forcing.

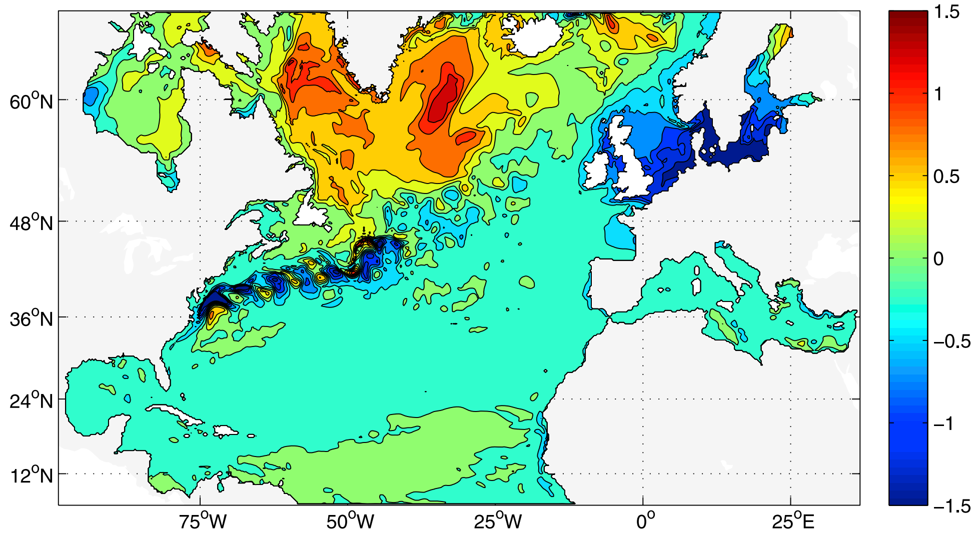

Figure 4. Difference in the mean (years 6–10) simulated SST between the negative NAO run and the positive NAO run. Contour interval is 0.25°C.

[15] The SPGI, SSTA1 and IWT from the 11th to 23rd years of simulations are shown in Figure 7. Like in the simulations with steady NAO-like forcing, the ITW and SSTA1 anomalies are mostly positive in the NAO^- and negative in the NAO^+ simulations. The two parameters correlate well with $r = 0.67$ in the NAO^+ run and $r = 0.62$ in the NAO^- experiment. However, the amplitude of variations of the ITW is two to three times higher in the NAO^+ experiment. In this run, the ITW variability follows the variations of the NAO index. The maximums and minimums in the IWT in NAO^+ experiment (see Figure 7a) occur 1–2 years after the time of neutral NAO index (15th year) and maximum NAO index (22th year), respectively. The IWT variations in the NAO^- experiment are less consistent with the variability of the NAO index (Figure 7b) and does not show a clear connection with the changes of NAO from neutral phase in the 15th year to negative phase in 20th year. The intensity of SPG circulation is stronger than normal in the NAO^+ run (blue curve in Figure 7a) and weaker than normal in the NAO^- simulations (Figure 7b). More detailed information about changes in the volume transport related to the NAO variations is given by the spatial distribution of the stream function for the two runs in Figures 8 and 9.

[16] Figure 8 shows the decadal mean barotropic stream function over years from 13 to 23 (Figure 8a) and the difference of the volume transport in years 17 and 22 (Figure 8b) in the NAO^+ run. The same characteristics but for the NAO^- experiment are shown in Figures 9a and 9b. The decadal mean volume transport in both experiments are similar to the results from the first 10 years of the NAO^+ and NAO^- simulations forced with NAO-like forcing without interannual and decadal variations (Figures 3a and 3b). The differences of the volume transport in the 17th and 22nd years (Figures 8b and 9b) define the spatial patterns of the magnitude of volume transport variations driven by the atmospheric decadal variability. In the NAO^+ run the decadal variations of the volume transport have a magnitude of about 4–6 Sv in the northern part of the Labrador Sea and above 8 Sv in the eastern part of the SPG (Figure 8b). The amplitude of decadal variability of the volume transport in the NAO^- experiment is much smaller and below 3 Sv in the whole SPG (Figure 9b).

[17] Similarly, the decadal variations of the SST and IWT are stronger in the NAO^+ run (see Figure 10) than in the NAO^- run (see Figure 11). The decadal variation of the surface and intermediate layer temperatures in the NAO^+ case have a magnitude of about 2°C in the eastern part of the SPG in the areas of formation and spreading of the IW into the SPG. The warming of the surface and intermediate waters during NAO^- years has a lower magnitude of about 0°C–0.5°C and is more homogeneously distributed over the SPG.

4. Interannual Variability of the Subpolar Gyre and IW Temperature From 1958 to 2005

[18] In this section we discuss the variability in the ocean model simulations driven by the NCEP/NCAR reanalysis from 1958 to 2005. Following the results in section 3, here we identify the main differences in the model SPG and IW characteristics and their variability between periods 1958–1981 (hereafter period I) and 1982–2005 (period II). The NAO index in most of the years of period I was negative, while in period II it was mostly positive. At the same time previous studies showed that the NAO variations at decadal time scale had a strong impact [see *Greatbatch*, 2000] on the subpolar atmosphere in the 1980s and 1990s. The winters of late 1980s and early 1990s were cold with strong surface winds while the late 1990s were anomalously warm. Here we discuss the impact which this variability had on the variations of the strength of the SPG circulation, IWT and SSTA1 in the 1980s and 1990s.

[19] Figure 12a shows the mean barotropic stream function over 1958–2005. The averaged “throughput” in the subpolar gyre is about 35 Sv, which is consistent with observations of *Pickart et al.* [2002]. The interannual variability of the circulation defined by the SPGI is shown in Figure 12b. The SPGI (Figure 12b) declines from 1993 to

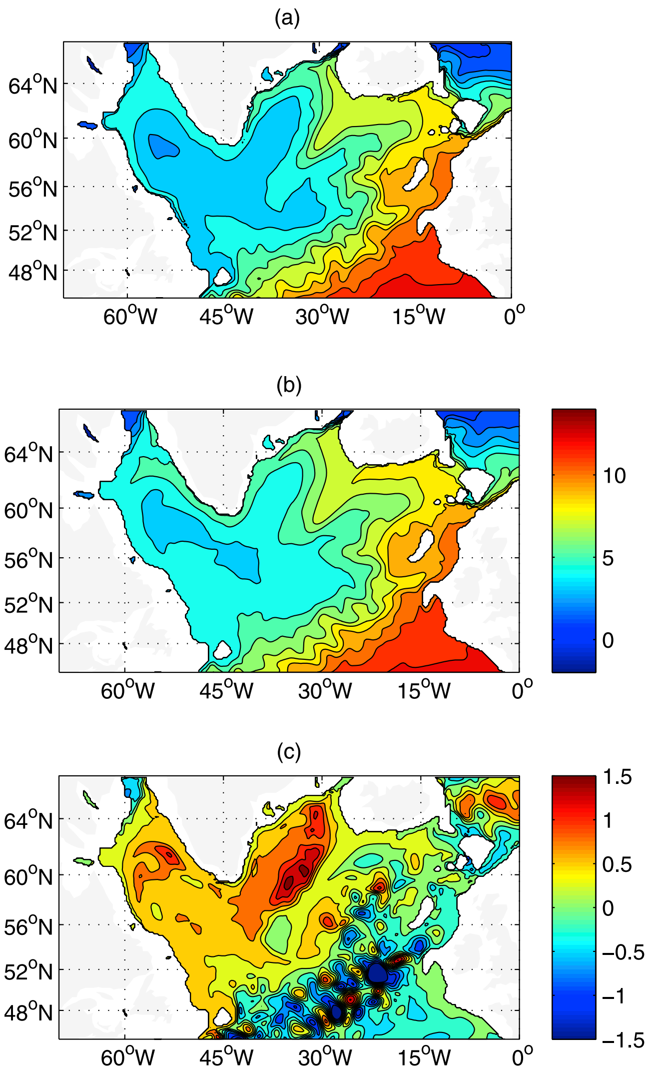

Figure 5. (a) The annual mean temperature at 483 m depth from the 10th year of (a) the positive NAO run and (b) the negative NAO run. (c) The difference between Figures 5b and 5a. Contour interval is 1°C in Figures 5a and 5b and 0.25°C in Figure 5c.

1998 by about 9 Sv and then rises by 4–5 Sv over 1999–2002. This variability is consistent with the previous observational studies of *Häkkinen and Rhines* [2004], *Häkkinen et al.* [2008], and *Dengler et al.* [2006]. In particular, the SPGI in the 1990s (Figure 12b) follows a trend similar to the first EOF of velocity computed from altimeter observations by *Häkkinen and Rhines* [2004] and *Häkkinen et al.* [2008]. The observational study of *Dengler et al.* [2006] found that the subpolar circulation intensified between 1999 and 2002 similarly to the observed increasing trend of the SPGI in Figure 12b. The SPGI time evolution (Figure 12b) also supports the results of *Böning et al.* [2006] that the decay of the SPGI in the 1990s is a part of the long-term interannual and interdecadal variability of the subpolar gyre.

[20] Figure 13 presents the annual mean temperature along a section of 65°N off the coast of west Greenland in some years from 1990 to 2005. Two water masses are present below the surface layer. The first one consists of cold waters which are transported southward in the western part of the North Atlantic subpolar ocean. The second one consists of warm IW transported northward by the Irminger Current in the eastern part of the Labrador Sea. The IWT was relatively low in the early 1990s and experienced a sudden increase in 1997–1998. Previous studies of *Hátún et al.* [2005] and *Holland et al.* [2008] found that there is a relation between the properties of the water masses and intensity of circulation in the subpolar North Atlantic in the 1990s. The decay of the subpolar gyre in the late 1990s (see Figure 12b) was linked in these studies to the observed shift of the position of the subpolar gyre westward *Holland et al.* [2008] and to increased volume and temperature of the IW in the Labrador Sea (see Figure 13). The variability of the North Atlantic gyre circulation during this period of time was also related to the increase in the temperature [*Marsh et al.*, 2008] and salinity [*Hátún et al.*, 2005] of the surface waters in the NAC, which gives origin to the IW. Figures 12 and 13 show that our model simulations represent well the observed negative correlation between the intensity of the subpolar gyre and the IWT in the 1990s.

[21] *Marsh et al.* [2008] found that in the late 1990s there was warming by about 1°C of the midlatitude North Atlantic surface waters, which was caused by anomalous convergence of ocean heat transport associated with the overturning and horizontal circulation. In our model simulations this warming is seen in the southeastern part of the subpolar gyre where the SSTA1 increases by about 1°C (Figure 14) between the periods of time over 1985–1994 and 1995–2003 (the periods of time used by *Marsh et al.* [2008]). The trend in the SST was positive in the whole subpolar area between these two periods of time. In the subtropics, the surface temperature is also increased but with a smaller

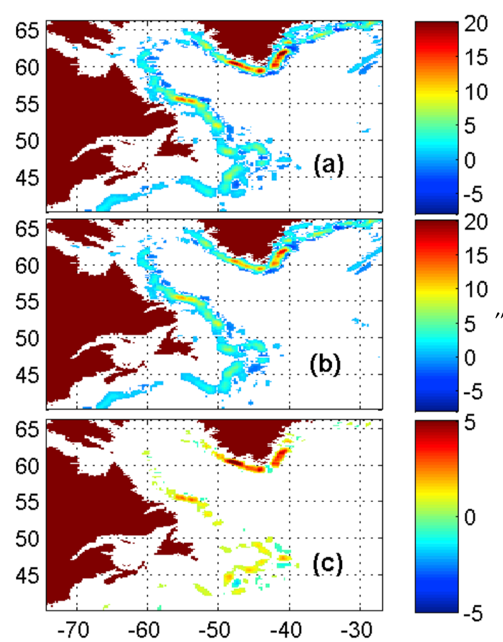

Figure 6. The bottom pressure torque (10^{-6} N/m^3) in the tenth year of (a) the NAO$^+$ run and (b) the NAO$^-$ run. (c) The difference between Figures 6a and 6b.

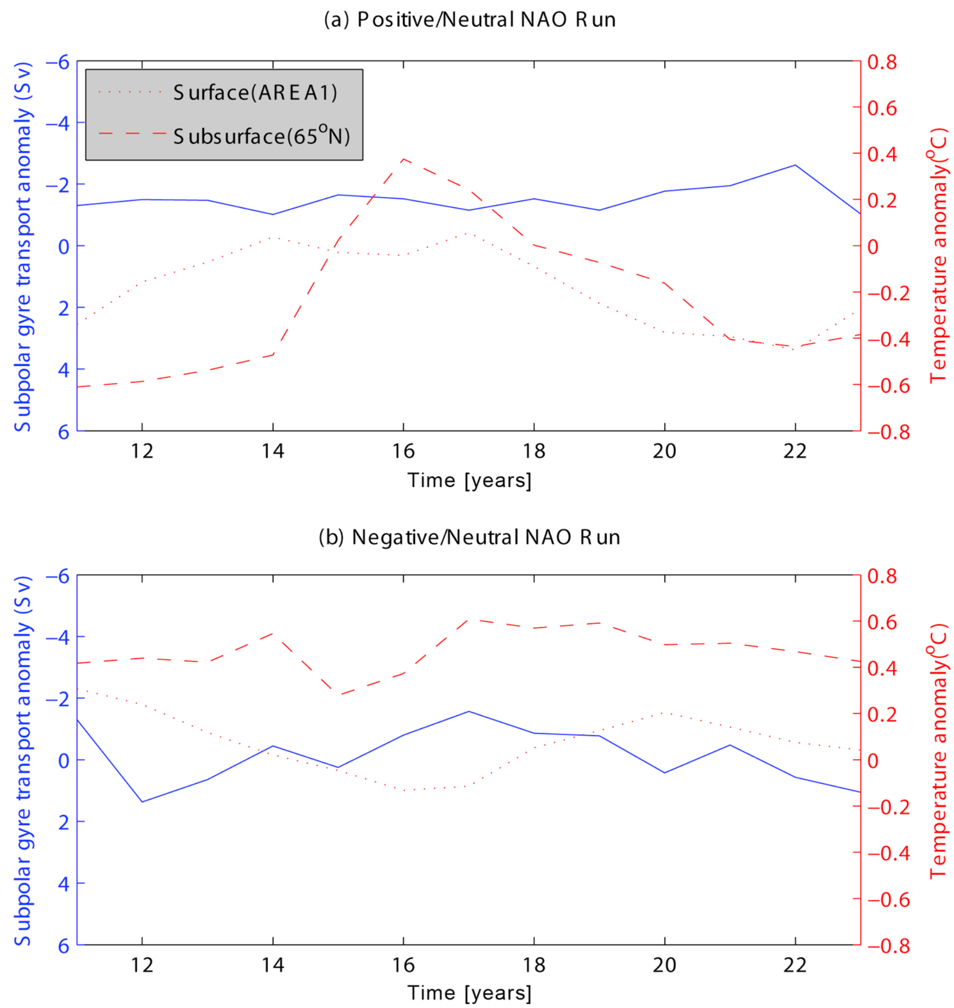

Figure 7. The SPGI (blue solid curve), the surface temperature averaged over AREA1 (red dotted curve), and the subsurface temperature off the west Greenland coast (a) from the positive NAO run and (b) from the negative NAO run (red dashed curve, defined as the temperature at 483 m averaged 56°W onshore along 65°N). Note that the subsurface temperature anomalies (red dashed curve) have been multiplied by a factor of 2.

amplitude below 0.2°C and mostly in the eastern part of the basin.

[22] The time variability of the SPGI, SSTA1 and IWT from 1958 to 2005 is shown on Figure 15a. The SSTA1 and IWT correlate well under positive and negative NAO-like forcing (see section 3). The physical reason for this correlation is related to the fact that the IW forms in the area A1 and its surroundings. The time variability of the model IWT shows many similarities to the SSTA1. Both temperatures are relatively high over 1963–1967, 1995–1998, 2003–2005 and low over 1962, 1980–1983, and 1990–1995 (Figure 15a). At the same time there are periods, like in the 1970s, when the IWT and SSTA1 vary differently. The maximum correlation between model SSTA1 and IWT over the period 1958–2005 for lag of 1 year with SSTA1 leading is $r = 0.64$ with a 99% significance. This correlation is lower when calculated only for period I ($r_1 = 0.1$) and higher for period II ($r_2 = 0.79$).

[23] The correlations between SPGI and SSTA1 over period I is r_1 (SPGI, SSTA1) = −0.15 and over period II is r_2 (SPGI, SSTA1) = 0.52. In period II the strength of the subpolar circulation and SSTA1 covaries negatively (please notice: negative values of SPGI mean stronger than mean cyclonic circulation). This result supports the conclusion of *Hátún et al.* [2005] that the weakening of the SPGI is linked to high NAC inflow in the subpolar area in the 1990s. This correlation is smaller in period I. The weakening of the subpolar gyre in some years during period I did not cause such strong changes in the SSTA1 as in the end of 1990s. For instance the lowest intensity of the subpolar gyre during the whole period of simulations was observed between 1969 and 1971. The corresponding increase of SSTA1, however, was almost 0.3°C, i.e., much lower than the 1.8°C increase of SSTA1 over 1994–1997. A similar tendency is observed in the correlation between SPGI and IWT, which is r_1 (SPGI, IWT) = −0.09 in period I and r_2 (SPGI, IWT) = 0.67 in period II. These results suggest that in the beginning of the 1980s there was a shift in the thermal regime of the IW and surface waters in area A1 which was related to an increase in the impact of the horizontal transport. The fact

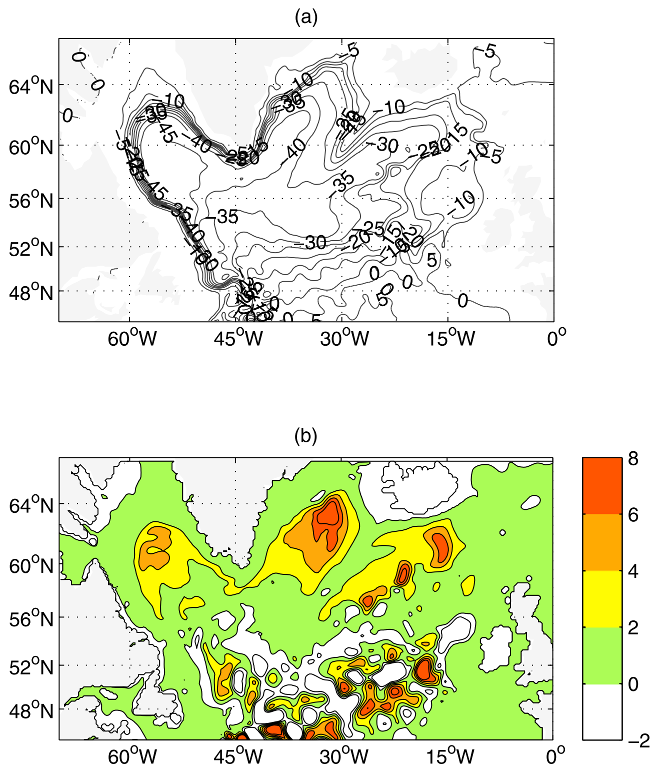

Figure 8. (a) The barotropic stream function averaged over years 17–22 from the positive/neutral NAO run and (b) the difference of barotropic stream function between year 17 and year 22. Contour interval is 5 Sv in Figure 8a and 2 Sv in Figure 8b.

that in period I the horizontal transport had a smaller influence on the heat balance in area A1 means that other factors like surface heat loss and mixing processes had a higher importance. This result is in particular confirmed by the correlation between the surface heat flux Q_S and SSTA1 which is r_1 (SSTA1, Q_S) = 0.59 during period I and to r_2 ($SSTA1$, Q_S) = 0.28 during period II.

5. Conclusion

[24] The climate of the North Atlantic is largely controlled by the NAO. The NAO intensity influences the surface buoyancy flux and wind stress over the subpolar ocean [*Hurrell*, 1995] and has an impact on the winter vertical convection [*Dickson et al.*, 1996] and intensity of subpolar ocean circulation [*Eden and Willebrand*, 2001]. *Curry and McCartney* [2001] found that the North Atlantic gyre circulation intensified in the late 1980s and early 1990s in response to the change of the NAO sign from predominantly negative to positive (Figure 15b). Our model results suggest that the mean barotropic transport in the subpolar gyre increased by 3 to 5 Sv in period II with respect to period I (Figure 12c). The SSTA1 and IWT (Figure 15a) also reveal an increasing trend in period II. Another striking difference between period I and period II is the presence of a strong decadal time variability of the SSTA1, IWT and SPGI in period II. The decadal variations of these parameters is much weaker during period I. This decadal variability of the SPG in the 1980s and 1990s was found in previous model and observational studies of *Hátún et al.* [2005], *Böning et al.* [2006], *Marsh et al.* [2008], *Häkkinen and Rhines* [2004], and *Marsh et al.* [2008].

[25] The mechanism of formation of decadal variability in the SPG by positive NAO-like surface forcing was previously studied by *Lohmann et al.* [2009]. These authors found in particular that decadal variations in the SPG can be forced by intensified steady NAO-like atmospheric forcing in years of positive NAO. The mechanism of formation of this variability is due to the link which exists between the intensity of the SPG circulation, intermediate water mass properties and the temperature of the IW and its amount in the SPG. *Lohmann et al.* [2009] showed that the response of the SPG to the NAO-like forcing is asymmetric to the sign of NAO. While the steady positive NAO forcing can generate strong decadal variability in the SPG, the negative NAO-like surface atmospheric forcing does not create similar variability at decadal or interannual time scales.

[26] The time series of the NAO index in recent years showed NAO variations at decadal time scales which had a strong impact [see *Greatbatch* [2000] on the subpolar atmosphere in the 1980s and 1990s. Our model results suggest that the atmospheric variability related to the decadal variations of NAO forced a strong decadal variability in the SPG (Figure 15). This response of the SPG to the NAO decadal variations is asymmetric to the sign of NAO. The NAO related atmospheric decadal variability is more efficient in forcing variations in the SPG circulation and water mass properties during periods of positive NAO than when

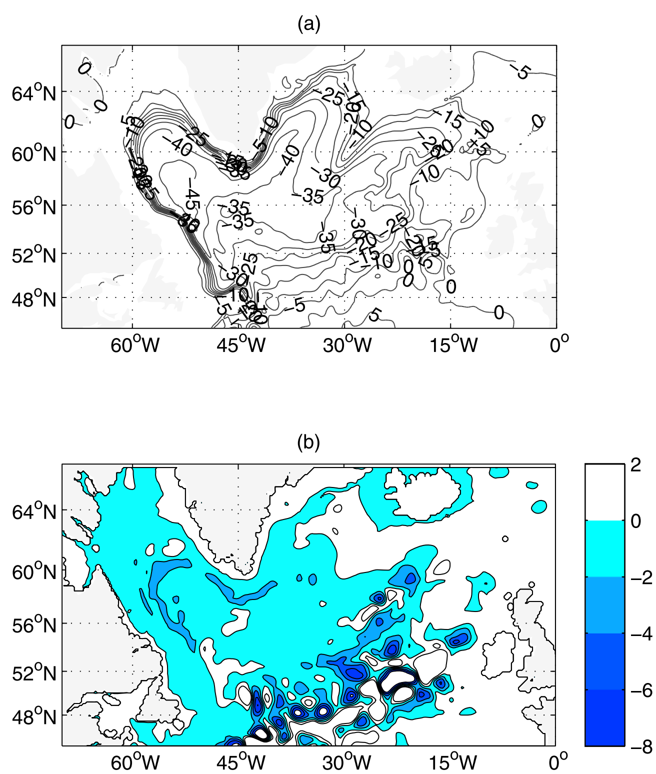

Figure 9. (a) The barotropic stream function averaged over years 17–22 from the negative/neutral NAO run and (b) the difference of barotropic stream function between year 17 and year 22. Contour interval is 5 Sv in Figure 9a and 2 Sv in Figure 9b.

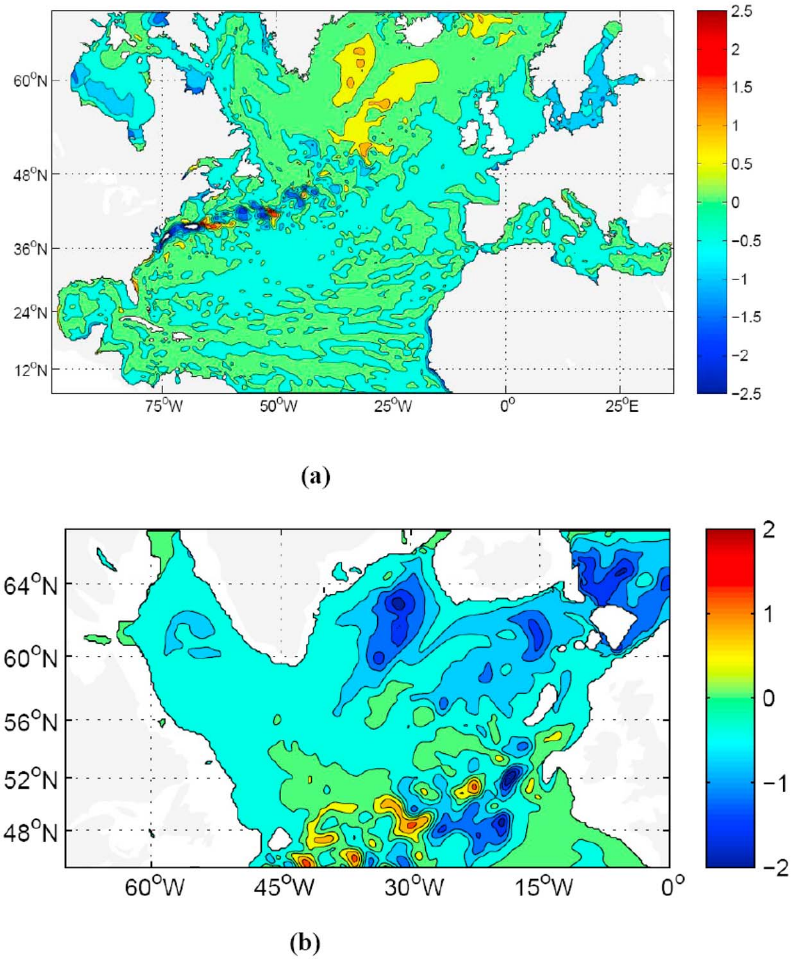

Figure 10. (a) Difference in the simulated SST from positive/neutral NAO run year 17 and year 22. Contour interval is 0.5°C. (b) Difference of the temperature at 483 m depth between year 17 and year 22. Contour interval is 0.25°C.

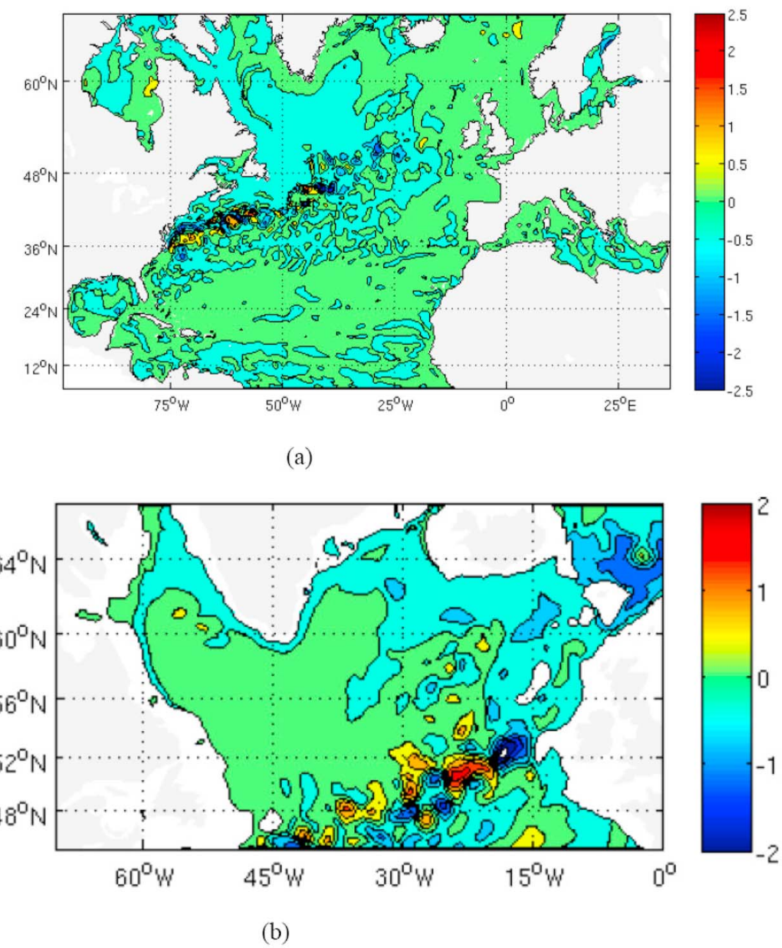

Figure 11. (a) Difference in the simulated SST from negative/neutral NAO run year 17 and year 22. Contour interval is 0.5°C. (b) Difference of the temperature at 483 m depth between year 17 and year 22. Contour interval is 0.25°C.

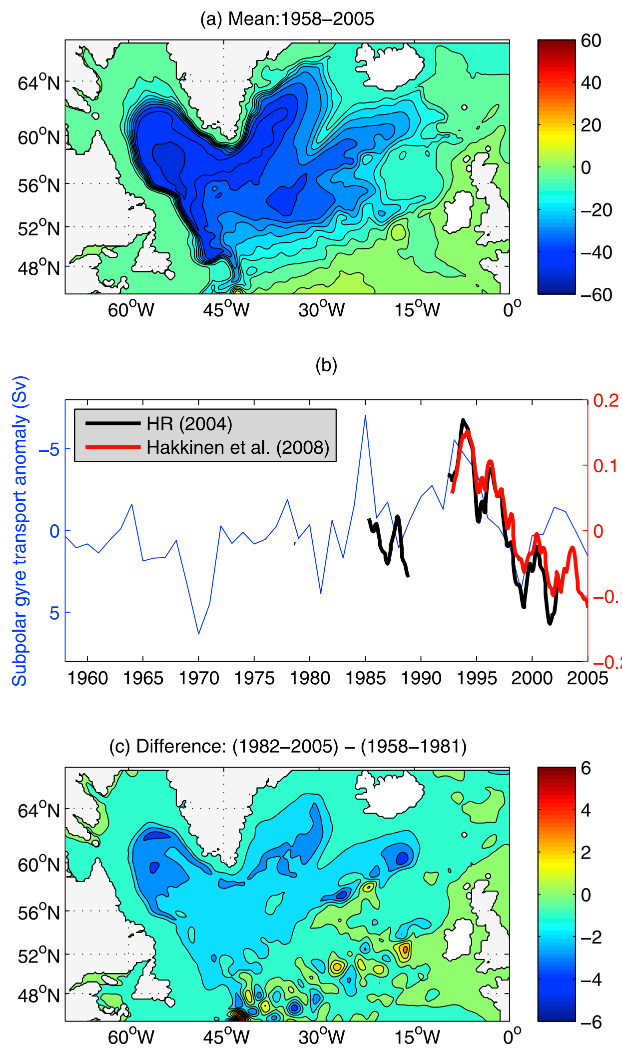

Figure 12. (a) The barotropic stream function averaged over 1958–2005. Contour interval is 5 Sv. (b) The SPGI (blue curve), the first PC of altimetric velocity from *Häkkinen and Rhines* [2004] (black curve), and improved estimation of the first PC of altimetric velocity from *Häkkinen et al.* [2008] (red curve). (c) The difference between barotropic stream function fields averaged over 1982–2005 and 1958–1981.

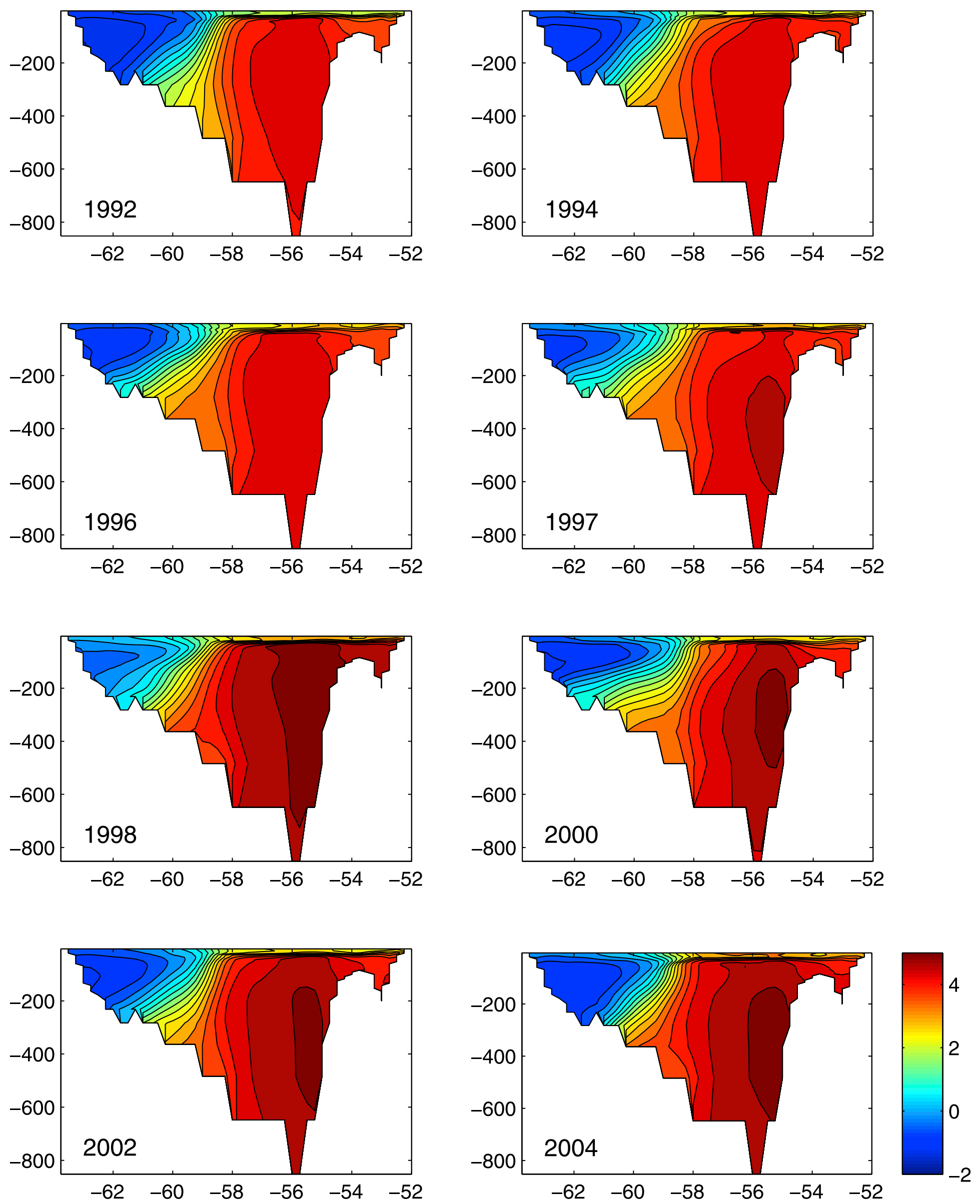

Figure 13. The annual mean temperature along a section of 65°N off the west Greenland coast from 1990 to 2005. Contour interval is 0.5°C.

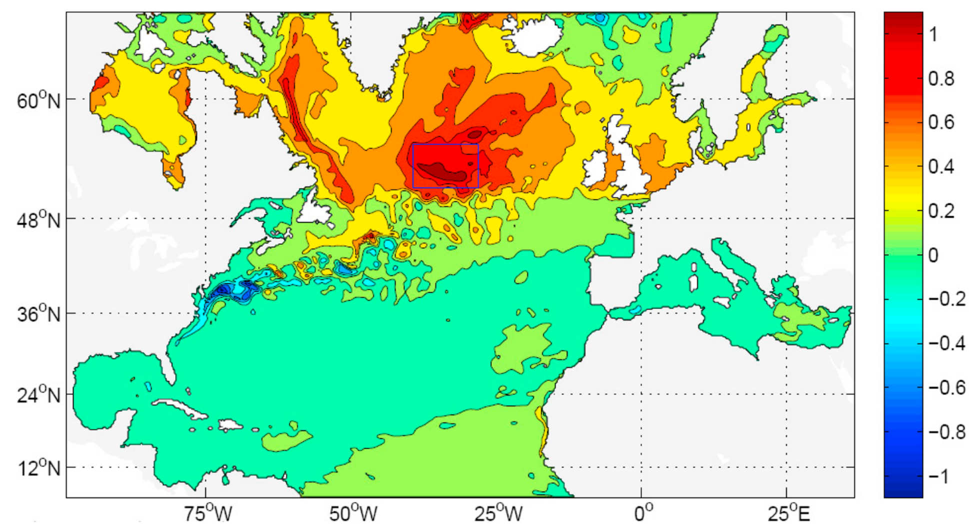

Figure 14. Difference in the simulated SST averaged over 1995–2003 and SST averaged over 1985–1994. Contour interval is 0.2°C.

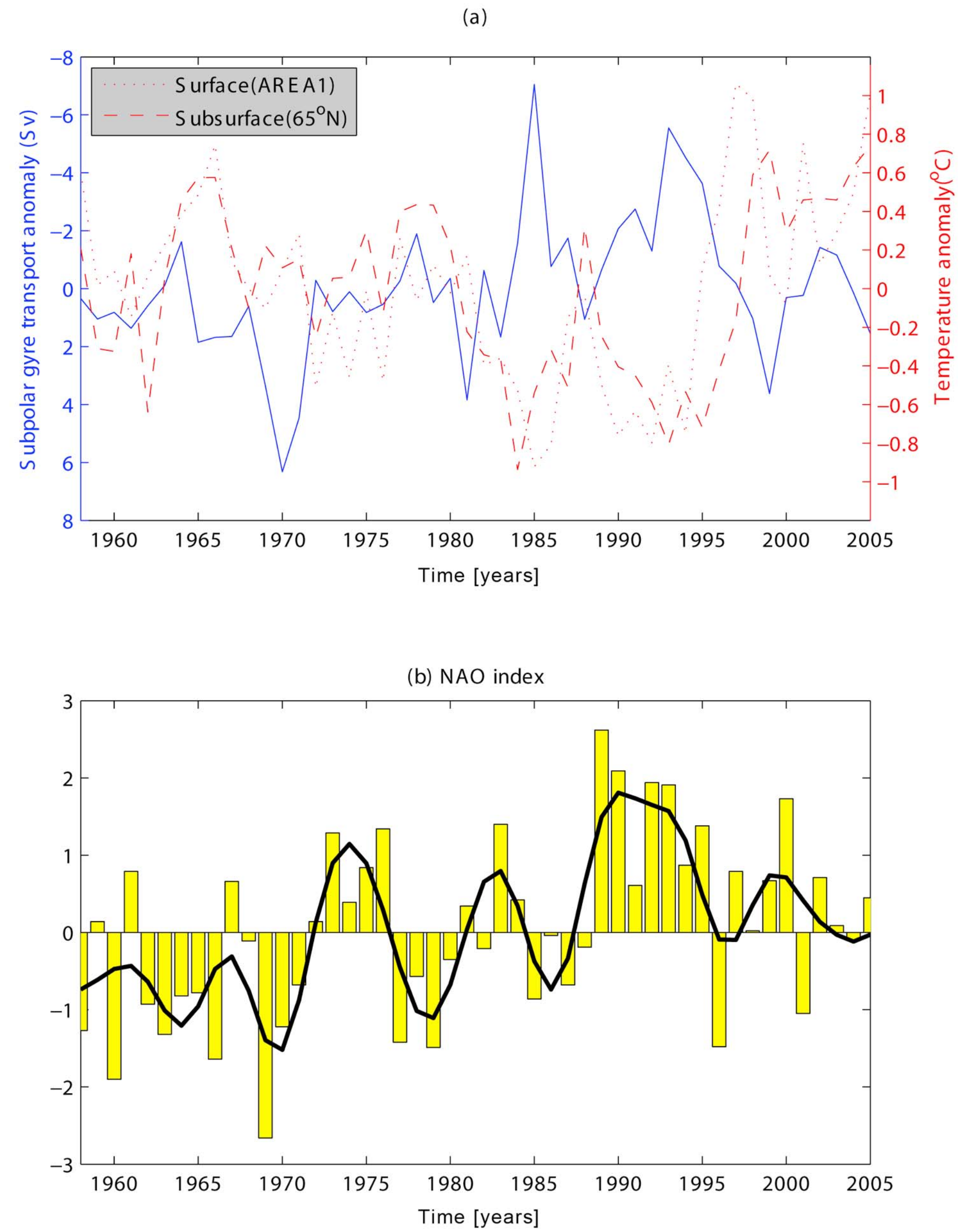

Figure 15. (a) The SPGI (blue solid curve), the surface temperature averaged over AREA1 (red dotted curve), and the subsurface temperature off the west Greenland coast (red dashed curve, defined as the temperature at 483 m averaged 56°W onshore along i65°N). (b) The North Atlantic Oscillation index (data from J. W. Hurrell, available at http://www.cgd.ucar.edu/cas/jhurrell/indices.html).

NAO is in a negative phase. One physical reason for the asymmetric SPG response to decadal variability of the NAO-like forcing is the difference of mean volume transport in the SPG under positive and negative NAO (see Figure 3c). The mean transport (Figure 3) and the volume and temperature of IW (Figure 5) in the SPG are higher than normal in the NAO$^+$ experiment. The relatively warm and salty subsurface IW in the SPG in the NAO$^+$ experiment intensify the cross-surface temperature gradients and strengthens the surface buoyancy fluxes during the cold winters. Hence, the observed [see *Yashayaev*, 2007] and simulated in our model experiments deep convection in the Labrador Sea is most intense in the early 1990s when the anomalous cold winters occurred during a period of high NAO index (Figure 15a). At the same time in some years in the second half of period II the NAO index was close to neutral. The transport of IW into the Labrador Sea during these earned relatively weak vertical convection contribute to the warming of intermediate layers of the SPG and the weakening of the SPGI. Therefore, during period II, between the cold years with high NAO and relatively warm years with neutral NAO, the stronger than normal mean transport in the SPG under positive NAO-like surface forcing intensifies the amplitude of decadal variations as well as covariance between the IWT and intensity of SPG circulation (Figure 15a).

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