A possible mechanism for the strong weakening of the North Atlantic subpolar gyre in the mid-1990s

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Received 13 May 2009; revised 23 June 2009; accepted 25 June 2009; published 1 August 2009.

[1] The extent and strength of the North Atlantic subpolar gyre (SPG) changed rapidly in the mid-1990s, going from large and strong in 1995 to substantially weakened in the following years. The abrupt change in the intensity of the SPG is commonly linked to the reversal of the North Atlantic Oscillation (NAO) index, changing from strong positive to negative values, in the winter 1995/96. In this study we investigate the impact of the initial SPG state on the subsequent behavior of the SPG by means of an ocean general circulation model driven by NCEP-NCAR reanalysis fields. Our sensitivity integrations suggest that the weakening of the SPG cannot be explained by the change in the atmospheric forcing alone. Rather, for the time period around 1995, the SPG was about to weaken, irrespective of the actual atmospheric forcing, due to the ocean state governed by the persistently strong positive NAO during the preceding seven years (1989–1995). Our analysis indicates that it was this preconditioning of the ocean, in combination with the sudden drop in the NAO in 1995/96, that lead to the strong and rapid weakening of the SPG in the second half of the 1990s. This hypothesis explains the diverging evolution of the strength of the SPG and the atmospheric forcing (winter NAO) after 1995, as has been suggested recently. **Citation:** Lohmann, K., H. Drange, and M. Bentsen (2009), A possible mechanism for the strong weakening of the North Atlantic subpolar gyre in the mid-1990s, *Geophys. Res. Lett.*, *36*, L15602, doi:10.1029/2009GL039166.

1. Introduction

[2] The North Atlantic subpolar gyre (SPG) has recently achieved considerable attention with regard to its strong and rapid variability, as well as far-reached consequences for the (marine) climate in the northern North Atlantic. *Hatun et al.* [2005, 2009a, 2009b] demonstrate that hydrography (temperature and salinity) and the temporal and spatial abundance of plankton and the spawning distribution of key fish species in the northeastern North Atlantic are tightly linked to the structure and intensity of the SPG. *Häkkinen and Rhines* [2004], using sea surface height (SSH) and hydrographic data, report a decline of the SPG strength in the mid-1990s, which goes along with low surface heat flux anomalies associated with low phase of the North Atlantic Oscillation (NAO). Due to only scattered SSH data between 1978 and 1992 (but continuous altimeter data after 1992), *Häkkinen and Rhines* [2004] could not determine whether the weakening was part of a decadal cycle or the beginning of a longer-term trend. *Böning et al.* [2006], using hindcast simulations with an ocean general circulation model (OGCM), as well as *Zhang* [2008], using observed sea surface temperatures and a control integration with a coupled atmosphere-ocean GCM, suggest that the decline in the SPG is part of a decadal variability. Likewise, for example, *Brauch and Gerdes* [2005] have demonstrated that the North Atlantic circulation is sensitive to both long-term and abrupt changes in the NAO forcing.

[3] Understanding the mechanisms behind the variability of the SPG is an issue of outmost importance for addressing the potential predictability of the climate in the North Atlantic sector. In a recent study, *Hatun et al.* [2009a] indicate that the strength of the SPG followed the atmospheric forcing (NAO) between the 1960's and 1995, but that it diverges thereafter. This indicates that the strong weakening of the SPG in the mid-1990s might not be explained by the actual atmospheric forcing alone (i.e., the abrupt drop in the NAO in the winter 1995/96). Considering the observed NAO index (Figure 1d), the 7-yrs period (1989–1995) prior to the winter 1995/96 was characterized by, on average, highly positive NAO winters. Recent findings by *Lohmann et al.* [2009, hereinafter referred to as LDB09] suggest that the SPG eventually weakens under a persistent positive NAO-like forcing. Combining these findings leaves the question: How important was the ocean initial state in 1995 for the strong weakening of the SPG in the second half of the 1990s? This question has, to the best of the authors' knowledge, not received any attention in the literature and will be addressed here by means of a series of hindcast sensitivity integrations with an OGCM.

2. Model Description

[4] The OGCM used in this study is the Nansen Center version of the Miami Isopycnic Coordinate Ocean Model [*Bleck and Smith*, 1990; *Bleck et al.*, 1992] forced with daily NCEP-NCAR reanalysis [*Kalnay et al.*, 1996] fields for the period 1948–2006. Because of the cyclic spin-up procedure of the model (K. Lohmann et al., On the recent weakening of the Atlantic meridional overturning circulation as seen in an isopycnal ocean general circulation model, submitted to *Ocean Dynamics*, 2009, hereinafter referred to as Lohmann et al., submitted manuscript, 2009), we only use the model data for the period 1960–2006 in the presented analysis. The model has a horizontal resolution of approximately 2.4° latitude by 2.4° longitude (plus a meridional refinement near the equator). In the vertical, there are 34 isopycnic layers and a bulk mixed layer on the top. The OGCM has been

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0094-8276/09/2009GL039166

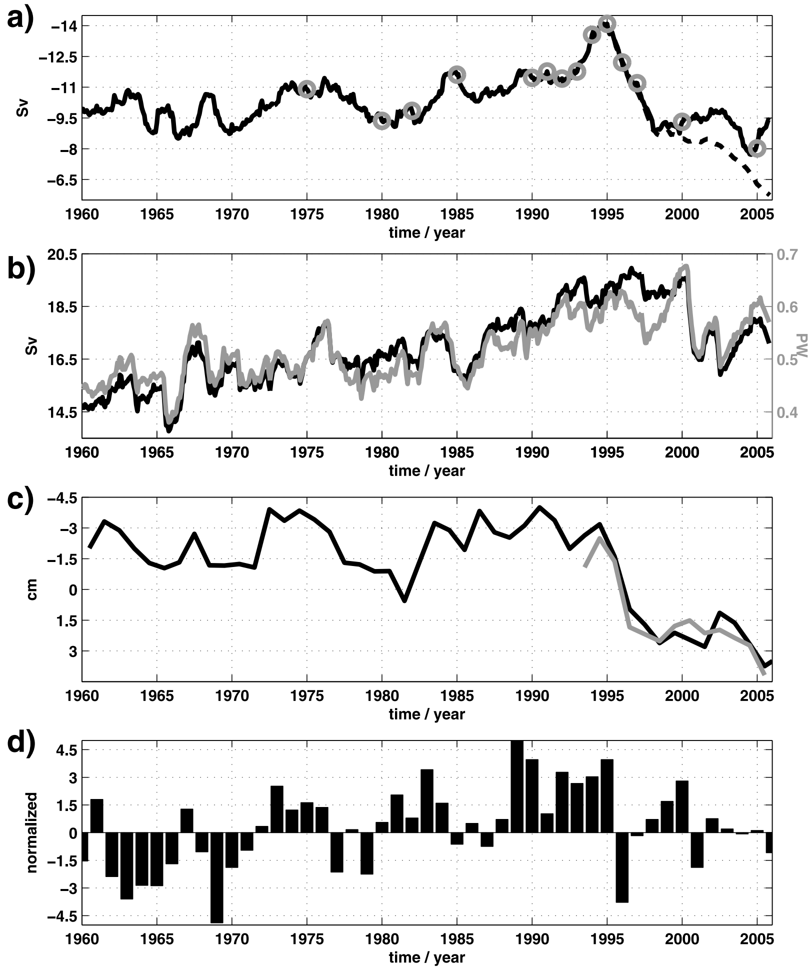

Figure 1. (a) Monthly barotropic streamfunction (Sv; 1 Sv = 10^6 m^3 s^{-1}) averaged over the North Atlantic SPG region (60°W–15°W, 48°N–65°N) for the control integration (black solid line) and a sensitivity experiment with zero wind stress forcing after 1995 (black dashed line). A one-year running mean filter is applied to the time series. The gray circles indicate the initial conditions in the sensitivity experiments shown in Figure 2. (b) Monthly maximum strength of the AMOC at 41°N (Sv, black line) and net heat transport across 41°N (PW, gray line; relative to a temperature of 0°C). A one-year running mean filter is applied to the time series. (c) Annual SSH anomalies (cm; with respect to the 1993–1999 mean) for the control integration averaged over the same region as in Figure 1a. The gray line is the corresponding SSH anomalies from the Ssalto/Duacs altimeter data. (d) Observed NAO index defined as difference of normalized winter (December through March, year corresponding to January) SLP between Lisbon, Portugal, and Reykjavik, Iceland. The data were obtained from http://www.cgd.ucar.edu/cas/jhurrel/indices.html.

assessed in several studies (see LDB09 for an overview) and has demonstrated skill in simulating key ocean circulation features in the region of interest.

[5] The control integration used in this study is identical with the one described in detail by Lohmann et al. (submitted manuscript, 2009). The strength of the SPG in the control integration, defined by averaging the barotropic streamfunction over the subpolar region, is shown in Figure 1a (solid line). The weakening of the SPG between 1995 and 1998 is about 5 Sv, or almost half of its long-term mean value. Figure 1c shows the strength of the SPG based on the subpolar SSH anomalies from the control integration (black line) and from altimeter data (gray line). It follows from this panel that the applied model realistically simulates the observed weakening of the SPG, at least in terms of the change in SSH averaged over the SPG region.

[6] To investigate the role of the ocean initial state on the simulated SPG response to atmospheric forcing, sensitivity experiments are performed with the same model set-up as in the control integration. In these sensitivity experiments, the atmospheric forcing fields starting from July 1995 and July 1982 (in the following referred to as the post-1995 and post-1982 forcing) are applied to ocean initial states in July of selected years, extracted from the control integration. We follow *Brauch and Gerdes* [2005] and start the sensitivity experiments in July to avoid a discontinuity in the forcing in boreal winter when the NAO forcing is most active.

[7] For the post-1995 experiments, ocean initial states are taken every pentad between and including 1975 and 2005, as well as every year between and including 1991 and 1997, yielding a total of 12 sensitivity experiments. The initial strength of the SPG for the selected years is indicated by the gray circles in Figure 1a. Similarly, the post-1982

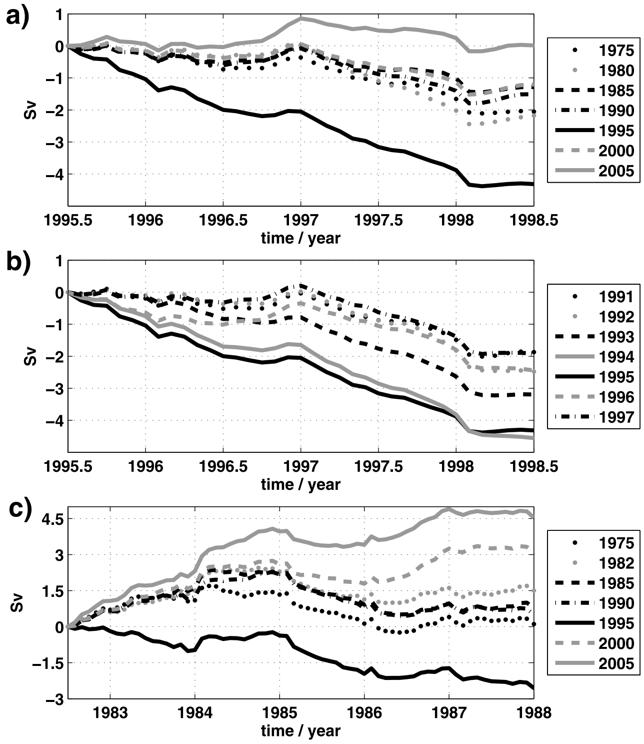

Figure 2. (a) Monthly barotropic streamfunction anomalies (Sv; with respect to the initial value) averaged over the North Atlantic SPG region (60°W–15°W, 48°N–65°N) for the sensitivity experiments in which the post 1995 atmospheric forcing is applied to ocean initial conditions every five years between and including 1975 and 2005. Line style according to legend. A one-year running mean filter is applied to the time series. The 1995 ocean initial condition is the control integration. (b) Same as Figure 2a but for ocean initial conditions every year between and including 1991 and 1997. (c) Same as Figure 2a but for the sensitivity experiments in which the post 1982 atmospheric forcing is applied. Note that the 1982 ocean initial condition is the control integration.

experiments start every pentad between and including 1975 and 2005.

3. Results

[8] The simulated strength of the SPG for the post-1995 experiments is provided in Figure 2a. The displayed period (1995 to 1998) corresponds to the strong weakening of the SPG in the control integration (Figures 1a and 1c). The strength of the SPG is defined in the same way as described for Figure 1a. To facilitate direct comparison of the SPG response from the different integrations, all time series are plotted as anomalies relative to their initial value.

[9] The simulated SPG responses show that none of the plotted ocean initial states reproduces the strong weakening of the SPG seen in the control integration (black solid line) of more than 4 Sv in three years. In fact, all other ocean initial states, except the 2005 one (gray solid line, see below), give almost identical responses, with a weakening of the SPG of about 1 to 2 Sv, or 25 to 50% of what is found in the control integration.

[10] The 1990 initial state (black dashed-dotted line) is interesting since the drop in the NAO index (from the 1990 to the 1996 value) is quite similar to the NAO drop between 1995 and 1996 (Figure 1d). Despite this similarity, the weakening of the SPG for the 1990 initial state is less than half of what is found in the control integration. It is also noteworthy that the difference in the initial strength of the SPG (Figure 1a) between 1995 and 1975/1985/1990 is comparable to the difference between 1975/1985/1990 and 1980/2000. Still, the response of the SPG is similar for the 1975, 1980, 1985, 1990 and 2000 initial states, but not for the control integration (the 1995 initial state). For the 2005 initial state (gray solid line), there is no weakening of the SPG at all, rather a tendency for increased strength, despite the applied reversal of the NAO forcing.

[11] We then refined the time period of the ocean initial states by applying the post-1995 atmospheric forcing to ocean initial states every year between and including 1991 and 1997. The simulated SPG responses are depicted in Figure 2b. We find that the 1994 initial state (gray solid line) gives a reduction in the strength of the SPG that is almost identical to that of the control integration (black solid line, same as black solid line in Figure 2a). This implies that if the reversal of the NAO index had occurred one winter earlier (the winter 1994/95), the (simulated) response of the SPG had been almost the same as for the winter 1995/96.

[12] The 1993 initial state (black dashed line) results in a weakening of the SPG of about 3 Sv, or 75% of what is found in the control integration (black solid line). The other ocean initial states give a SPG response similar to those found for the sensitivity experiments presented in Figure 2a (except the 2005 initial state that showed no weakening at all). During the first year, the 1996 initial state (gray dashed line) shows a stronger weakening than all but the 1994 and 1995 initial states. For the 1996 initial state, the atmospheric forcing corresponds to two adjacent years with a highly negative NAO (since forcing for the year from July 1995 to June 1996 is applied twice). During a negative phase of the NAO, both the heat flux and the wind stress curl over the northern North Atlantic act to weaken the SPG [e.g., *Häkkinen and Rhines*, 2004; H. Hatun, personal communication, 2008]. A thorough analysis of the relative role of the heat flux and the wind stress curl forcing is beyond the scope of this paper, except for a case with zero wind stress after 1995 which is presented in the discussion section.

[13] Apart from the post-1995 atmospheric forcing, which goes along with the strong weakening of the SPG, we also perform sensitivity experiments to examine the sensitivity of the strengthening of the SPG, based on the period after 1982 (Figure 1a). The post-1982 atmospheric forcing corresponds to a period with, in general, positive NAO years (Figure 1d). The resulting change in the strength of the SPG is shown in Figure 2c. Note that here the 1982 initial state (gray dotted line) corresponds to the control integration.

[14] We find that for the first 2 years, the various initial conditions cluster around the control integration (the 1982 initial state) with two exceptions, 1995 (decreasing) and 2005 (strongly increasing). For the 2005 initial state, the year with minimum SPG throughout the simulated period (Figure 1a), the strength of the SPG increases by 4 Sv in the

first 2 years, compared to about 2.5 Sv in the control integration. The anomalous response of the SPG for the 2005 initial state, for both the post-1995 and the post-1982 forcing, suggests that the evolution of a very weak SPG depends on both the ocean initial state and the atmospheric forcing. Idealized experiments, or longer time series with several minimum states of the SPG, for instance extracted from coupled climate models, are needed to further investigate this issue.

[15] Concerning the 1995 initial state (black solid line in Figure 2c), even a decrease in the strength of the SPG is obtained, despite the, in general, positive NAO forcing. The 1995 initial state corresponds to a state after a period with a highly positive NAO forcing (Figure 1d). Under positive NAO forcing, the strength of the Atlantic Meridional Overturning Circulation (AMOC) generally increases [e.g., *Häkkinen*, 1999], due to the formation of intermediate to deep water masses in the subpolar North Atlantic. The spin-up of the simulated AMOC at 41°N (defined as the maximum strength of the meridional overturning streamfunction at 41°N) during the 1980s and 1990s, when the NAO index was, in general, positive, is provided in Figure 1b (black line). The latitude of 41°N is chosen since it represents the mean location of the maximum AMOC in our model configuration, and also since it is close to the southern boundary of the simulated SPG.

[16] The spin-up of the AMOC and especially of its North Atlantic Current component, leads to poleward transport of warm and saline water from lower latitudes. The associated increase in the poleward flow of heat across 41°N, some of which will enter the subpolar region, is shown in Figure 1b (gray line). Apart from the (thermally driven) spin-up of the AMOC, the wind stress curl in the northeastern North Atlantic will contribute to the extension of subtropical water into the SPG region under positive NAO conditions (see, e.g., LDB09, Figure 10). Considering density changes caused by the advection of subtropical water, the thermal contribution dominates over the haline contribution (LDB09, Figure 8). Therefore, the transport of the warm subtropical waters tends to decrease the formation of intermediate to deep water masses within the SPG region. The latter weakens the doming structure of the subpolar isopycnals and slows down the SPG, despite a persisting positive NAO (black solid line in Figure 2c; LDB09).

[17] The advection of the subtropical water and the subsequent decrease in the formation of subpolar intermediate to deep water masses will also weaken the AMOC with a time lag of a few years. This well-known delayed negative feedback of the (thermally driven) AMOC on itself has been described in several previous studies [e.g., *Delworth et al.*, 1993; *Eden and Jung*, 2001; *Eden and Willebrand*, 2001; *Latif et al.*, 2006; *Zhang*, 2008]. The decrease in the strength of the AMOC after year 2000 in our control integration (black line in Figure 1b) appears to be a delayed response to the decrease in the formation of subpolar intermediate to deep water masses after year 1995, as is discussed in detail by Lohmann et al. (submitted manuscript, 2009).

4. Discussion

[18] Recent findings suggest that the variability of the SPG is mainly caused by the heat flux (buoyancy forcing) over the Labrador Sea and the wind stress curl over the northeastern North Atlantic [e.g., *Häkkinen and Rhines*, 2004; H. Hatun, personal communication, 2008]. To identify which forcing is mainly responsible for the weakening of the SPG in the mid-1990s, we perform an additional sensitivity experiment with the same model set-up as in the control integration, but with zero wind stress forcing from July 1995 onwards. The zero wind stress forcing was applied in July 1995, rather than at the beginning of the integration or prior to 1995, to ensure a realistic (and comparable) ocean initial state in July 1995.

[19] The simulated strength of the SPG in the vanishing wind stress experiment is displayed with the black dashed line in Figure 1a. Between 1995 and 1998 the strength of the SPG is practically indistinguishable from that of the control integration (solid line), indicating that the weakening of the SPG in the second half of the 1990s can solely be explained by the combined interplay between the actual ocean state and the buoyancy forcing. Of course, the wind stress is an important component of the ocean forcing in general (including prior to 1995), and thus vital to the establishment of the actual ocean initial state in 1995.

[20] It is interesting to note that in the vanishing wind stress integration, the weakening of the SPG continues from 1998 to present. This may indicate that the strengthening of the SPG between 1998 and 2003 as well as after 2005 seen in the control integration is caused by the wind stress (curl) forcing. For the latter strengthening this is supported by the fact that the wind stress curl (from the NCEP-NCAR reanalysis) over the northeastern North Atlantic shows a rather strong increase after year 2005, while the heat flux (from the NCEP-NCAR reanalysis) over the Labrador Sea remains low (H. Hatun, personal communication, 2008). A more detailed investigation of the recent SPG strength is beyond the scope of this paper, but understanding the mechanisms behind the variability of the SPG remains an important issue for future research.

[21] In the introduction we posed the question: How important was the ocean initial state in 1995 for the strong weakening of the SPG in the second half of the 1990s? Based on the results discussed in section 3, we suggest the following hypothesis:

[22] In 1995, the SPG was strong due to the persistently strong and positive NAO forcing over the preceding seven years (1989–1995). In fact, a strong SPG cannot be maintained under a persistently positive NAO forcing, due to advection of warm water from lower latitudes, which counteracts the local buoyancy forcing of the SPG. Therefore, a weakening of the SPG around 1995/96 would have happened irrespective of the actual atmospheric forcing at this time. The sudden drop in the NAO in the winter 1995/96 acted together with the unstable ocean state around 1995, resulting in an (over the simulated period) unprecedented weakening of the SPG. After the observed (and simulated) collapse of the SPG, a prolonged period of positive NAO years is required to rebuild the strength of the SPG, but there has been no persistent positive NAO-forcing up to now.

[23] The above hypothesis – the non-linear interplay between the ocean state and the atmospheric forcing – also explains the diverging strength of the SPG (weakening) and the atmospheric forcing (NAO; no multi-year trend) after 1995 [*Hatun et al.*, 2009a]. It further suggests that at least

the amplitude of the SPG weakening in the late 1990s is not part of a decadal-scale variability, but is rather caused by a (over the simulated period) unique atmospheric forcing history.

[24] A general perception in the literature is that a weakening of the AMOC leads to a decrease in the inflow of heat and salt to the northern North Atlantic and into the Nordic Seas. The weakening of the SPG, on the other hand, allows more spreading of the warm and saline subtropical water in the inflow region to the Nordic Seas [*Hatun et al.*, 2005], as well as along the rim of the SPG around southern Greenland [*Holland et al.*, 2008]. Therefore, the strength of the AMOC from models (since the AMOC is not observed) should not be taken as a general proxy for the transport of heat and salt to the northern North Atlantic. Certainly, the state of the SPG needs to be considered when decadal-scale variability and predictability in the North Atlantic sector are being assessed.

[25] **Acknowledgments.** This work has been supported by the European Union through the DYNAMITE (GOCE-003903) and DAMOCLES (EVG1-CT-1999-00007) projects and by the Research Council of Norway through the NorClim and NOTUR projects. The altimeter products were produced by Ssalto/Duacs and distributed by Aviso (http://www.jason.oceanobs.com/html/donnees/duacs/welcome_uk.html), with support from CNES. We thank two anonymous reviewers for their valuable comments on an earlier version of the manuscript. Fruitful discussions with other scientists from the Nansen and Bjerknes Centers, especially Hjalmar Hatun, are greatly acknowledged. This is contribution A238 from the Bjerknes Centre for Climate Research.

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