Response of the eastern North Atlantic subpolar gyre to the North Atlantic Oscillation

Christophe Herbaut, Marie-Noëlle Houssais

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[1] The salinity changes in the subpolar gyre (SPG) in response to the North Atlantic Oscillation (NAO) are studied in idealized numerical experiments. In the eastern SPG, anomalies of similar amplitude as those observed during the 1995–1996 shift of the NAO are mainly driven by the local response to the wind stress, through the set-up of an anticyclonic "intergyre" anomaly. In positive NAO, this anomalous circulation advects altogether (i) fresh, cold water from the western to the eastern SPG, contributing there to the formation of negative salinity anomalies, and (ii) warm, saline subtropical water to the south of Newfoundland, forming positive anomalies there. The latter are subsequently transported with the North Atlantic Current to the eastern SPG where they could act to weaken the low-salinity signal. The occurrence of this signal is concomitant with the acceleration of the gyre but, in contrast to earlier findings, is not subject to it.
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1. Introduction

[2] Hydrographic observations accumulated over the past 50 years in the subpolar gyre (hereafter SPG) have revealed drastic changes which were concomitant with a substantial variability of the gyre intensity. The latter, diagnosed from satellite observations as the first principal component (PC) of the North Atlantic sea surface height (SSH) (the so-called gyre index), underwent a remarkable weakening during the 1990s which was shown to be mainly controlled by the intensity of the convection in the Labrador Sea [*Häkkinen and Rhines*, 2004]. Still, hindcast simulations reproducing the decadal gyre variability of the last 50 years suggest an additional influence of the wind stress [*Böning et al.*, 2006]. With regards to the eastern SPG, it is unclear to which extent the gyre index, which has enhanced signature in the Labrador-Irminger Sea, can be considered as a relevant measure of the circulation changes. In particular, while the increased proportion of warm and saline subtropical water observed in the Atlantic inflow to the Nordic Seas in the late 1990's-early 2000's can be related to the shrinking of the SPG [*Hátún et al.*, 2005] the link between the shape of the gyre and its strength remains unclear.

[3] In the North Atlantic, the dominant patterns of the air-sea fluxes and SPG circulation anomalies are connected to the North Atlantic Oscillation (NAO). In particular, the changes recently observed in the intensity of the SPG have been related to the 1995–96 shift of the NAO [*Flatau et al.*, 2003] and more specifically to the variability of the Labrador Sea convection in relation to the NAO [*Bersch et al.*, 2007]. The response of the gyre strength to the NAO would occur with a delay of about 2–3 years [*Mauritzen et al.*, 2006].

[4] In the eastern SPG, numerous studies have highlighted the prominent role of shifts in the NAC-subarctic front system in the observed hydrographic changes [*Holliday*, 2003; *Bersch et al.*, 2007] with air-sea heat or freshwater fluxes playing only a minor role [*Thierry et al.*, 2008]. These shifts occurring in response to the drop in the NAO index in the mid-90s, have been mostly related to changes in the SPG strength controlling either the NAC intensity [*Flatau et al.*, 2003] or the cross-frontal advection of cold, fresh water from the western SPG [*Bersch et al.*, 2007]. Although the role of the wind stress variability in the observed changes is often mentioned in these analyses, the exact mechanisms are not clearly identified. Still, both the enhanced signature of the wind stress curl (contrasting with the buoyancy flux) in the eastern SPG and the large vertical extent of the water mass variations [*Johnson and Gruber*, 2007] observed there provide evidence of a substantial wind-driven barotropic response in the eastern SPG. A specific pattern of the wind-driven response, the so-called intergyre gyre, has indeed been identified in conceptual [*Marshall and Goodman*, 2001] as well as realistic [*Eden and Willebrand*, 2001] modelling studies. Although its net effect on the meridional heat transport could be estimated, its actual impact on the regional redistribution of the T-S properties in the eastern SPG was little analysed.

[5] In the present study we investigate more precisely the role of the NAO on the variability of the eastern SPG. In particular we contrast this variability with that of the western SPG and try to clarify its link to the strength of the gyre. Numerical experiments forced by wind stress and buoyancy fluxes representative of the NAO are performed. The experimental protocol bears some resemblance to *Eden and Willebrand* [2001] except that our domain includes the Arctic and forcing fields are constructed differently. The analysis focuses on the distribution of salinity, considered at these latitudes as a passive tracer (as opposed to temperature) of the circulation [*Mauritzen et al.*, 2006], being also less affected by air-sea exchanges.

2. Experimental Set-up

[6] The ice-ocean model is based on NEMO version 1.9 [*Madec*, 2008] including the LIM2 sea ice model. The domain encompasses the Arctic Ocean and the Atlantic Ocean with open boundaries at 30°S in the Atlantic and

[1]LOCEAN, IPSL, Université Pierre et Marie Curie, Paris, France.

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50°N in the Pacific along which the velocity and tracer distributions are prescribed from the monthly climatology of a global simulation. The model grid has horizontal resolution varying from 20 km in the Arctic to 50 km at the equator. The equations are discretized on 46 vertical levels with thickness varying from 6 m at the surface to roughly 250 m at the deepest model level.

[7] The model is initialized from rest with temperature and salinity distributions from the PHC 3.0 global ocean climatology updated from *Steele et al.* [2001]. The surface forcing is based on daily atmospheric fields from the ERA40 reanalysis (1958–2001) with some regional corrections to improve the radiation flux over the North Atlantic and the precipitation and surface air temperature over the Arctic. The river runoff is prescribed from a monthly climatology (http://www.R-ArcticNET.sr.unh.edu). The top layer salinity is restored to the PHC climatology with a time scale of 30 days.

[8] The model is spun up for 23 years from 1979 to 2001. The hindcast experiment is then performed using the complete 44-year cycle of the reanalysis. In order to build initial conditions for the sensitivity experiments close to a neutral state with regards to the NAO, the integration is pursued from 1958 until 1968. Starting in 1968, positive (NAO^+) and neutral (NAO^n) NAO-like forcing fields are then used to force the model for an additional 10-year period. The NAO forcings are composites based on the NAO index defined as the first PC of the winter (NDJFM) North Atlantic SLP. The NAO^+ years (a year is defined from July to June) are those for which the NAO index exceeds one standard deviation. NAO^n years are those for which the NAO index is between -0.25 and 0.25 standard deviation. Through this procedure, 9 years are actually selected for both the neutral and positive NAO forcings. To build each of the composite forcing, the 9-year time series of each atmospheric field is filtered with a 15-day low pass filter. Then a "low frequency" climatological year is built by averaging the low pass filtered years. To keep the daily variability, the high frequency (obtained by substracting the "low frequency" part of each individual year) of each year is added to the low frequency climatological year to form 9 years of NAO^+ and NAO^n like forcing fields. In addition to the two integrations forced respectively with NAO^+ (herafter NAO experiment) and NAO^n conditions, two sensitivity experiments with same initial conditions have been conducted to study the separate influence of the wind stress. In the first one (WIND), the NAO^+ wind stress is prescribed while the other forcing fields correspond to the neutral conditions. In the second one (WIND_ARCT), conditions are similar to the WIND experiment except that the NAO^+ wind stress is only applied to the north of Davis Strait and the Greenland-Scotland Ridge (see Figure 1). For each experiment, anomaly fields are obtained by subtracting the fields of the NAO^n experiment from those of the experiment.

3. Results

[9] In response to the NAO, negative salinity anomalies develop in the top 500 meters at the periphery of the SPG, whereas the central Labrador Sea and the southern part of the Irminger Sea become saltier (Figure 1a). Between 200 and 500 meters, the salinity distribution is more contrasted between the eastern and the western SPG as negative anomalies reaching up to 0.1 psu are concentrated in the eastern North Atlantic (Figure 1b). The contrast also exists between the vertical extent of the anomalies in the two regions (Figure 2), suggesting a different origin for these anomalies. Typically, in the western SPG, anomalies have maximum amplitude in the upper 100–150 meters and exhibit a sharp decrease underneath to vanish at about 500 m. In the eastern SPG, negative salinity anomalies occupy the top 2000 m of the water column, with a core at about 200–300 depth.

[10] In the NAO experiment, the surface salinity anomalies in the western SPG are mainly caused by a wind-driven increase of the freshwater export from the Arctic. Similar anomaly patterns are indeed generated in the western SPG when the NAO+ wind stress is only applied north of the Davis Strait and Greenland-Scotland Ridge (experiment WIND-ARCT, Figure 1c). Additionally, the increase of the fresh water export through these two passages, averaged over the first two years of the experiments, has same order of magnitude in WIND-ARCT and NAO experiments, summing to a total of 40 mSv and 28 mSv, respectively. On the other hand, the drastic weakening of the anomaly pattern in the eastern SPG in WIND-ARCT experiment compared with NAO experiment, which occurs at all levels (Figure 2), suggests that formation of salinity anomalies in this region involves a regional forcing and cannot only be the result of advection of anomalies from the western SPG. When only the effect of NAO-related wind stress changes are considered (WIND experiment), the pattern obtained between 200 and 500 meters remains fairly unchanged (compare Figures 1b and 1d) as does the vertical distribution of the anomalies (Figure 2). This result suggests that the wind is a major forcing for these anomalies, while excluding buoyancy driven changes of the gyre dynamics or modifications in the regional surface fresh water flux as main driving mechanisms. Taking into account the changes in the surface salinity restoring flux, as a result of different surface salinities, between NAO and WIND experiments (Figure 2), would not alter this conclusion. These changes are indeed very small in the eastern SPG while, in the western SPG, they contribute to increasing the SPG intensity, and therefore its possible impact on the eastern SPG which is yet demonstrated to be small.

[11] That wind driven gyre circulation changes are the main driver of the salinity changes in the eastern SPG is further confirmed by the SSH pattern in the WIND experiment. The latter displays a persisting anticyclonic circulation anomaly between 35°N and 55°N (Figure 3a) which also dominates the response of the eastern SPG when all NAO forcings are considered (Figure 3b). This SSH pattern is very similar to the intergyre gyre proposed by *Marshall et al.* [2001]. Superimposed to a mean horizontal distribution of salinity characterized by a sharp southwest-northeast front, this circulation anomaly tends to advect cold, fresh water from the western to the eastern SPG in its northern branch, while reducing northeastward advection of warm, saline subtropical water. Both processes act to decrease the salinity in the eastern SPG. Concomitantly, positive salinity anomalies are formed to the south of Newfoundland which

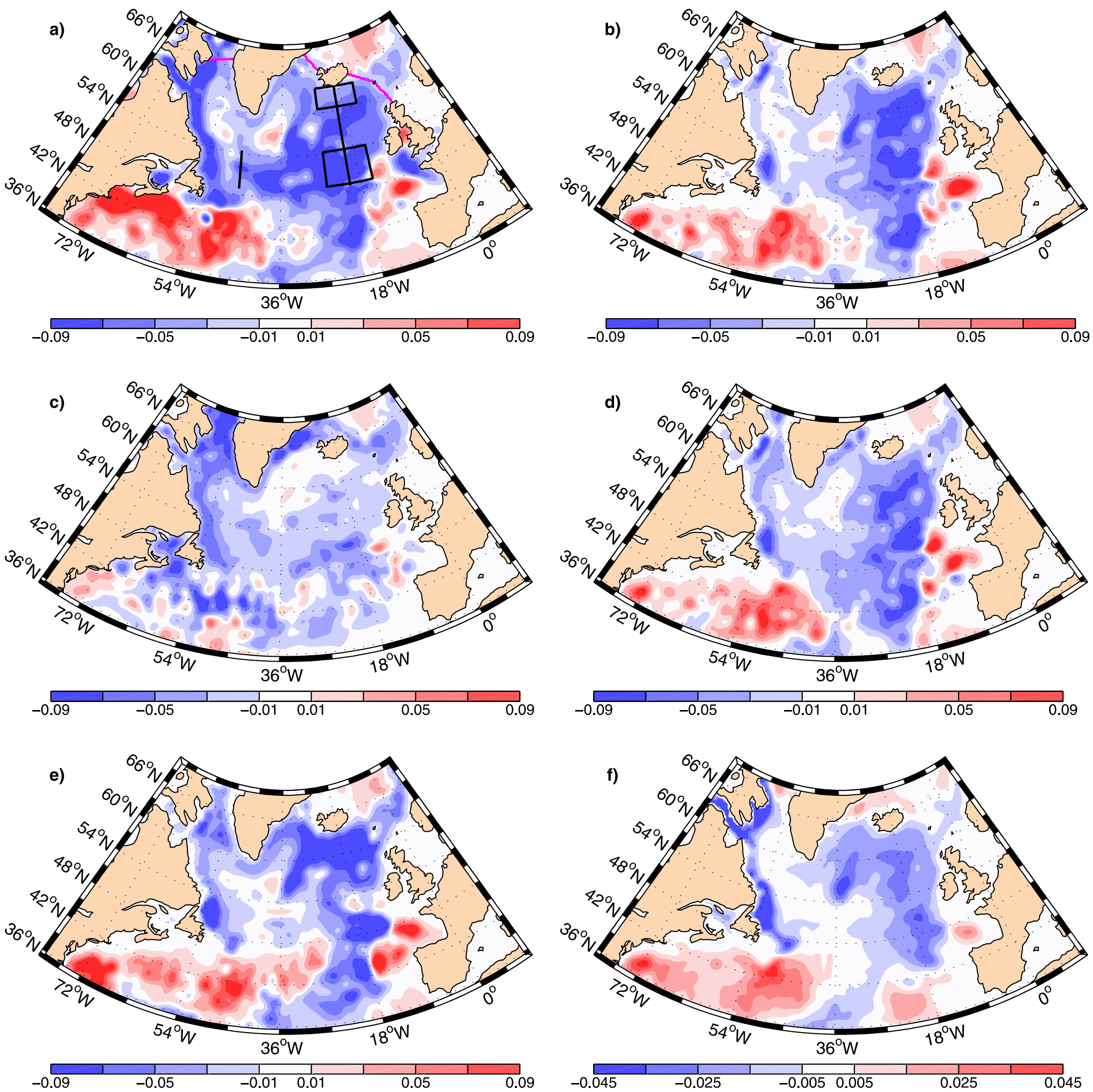

Figure 1. Mean annual salinity anomaly in year 5 in (a) experiment NAO in the upper 500 m, (b) experiment NAO in the 200–500 m layer; (c) experiment WIND-ARCT in the upper 500 m layer; (d) experiment WIND in the 200–500 m layer; (e) Mean annual salinity anomaly in year 7 in experiment NAO in the 200–500 m layer; (f) First EOF of the mean annual salinity in the 200–500 m layer in the hindcast experiment. Also shown as solid lines are the sections and boxes for the salt budget analysis (black) and the southern limits (Davis Strait and the Greenland-Scotland Ridge) of the wind stress forcing in experiment WIND-ARCT (magenta).

are clearly to be associated with a northward shift of the Gulf Stream frontal system, a scenario which has also been suggested by others [e.g., *Frankignoul et al.*, 2001].

[12] The contribution of the circulation changes to the salinity changes in the intergyre region can be estimated by considering a box centred around 20°W–51°N (cf. Figure 1) and extending between 0 and 500 m (Figure 4a). As the lower limit of the box extends well beyond the mixed layer depth which averages to about 250 m, vertical advection and entrainment are small. As expected, the time evolution of the mean salinity anomaly within this box (light solid) is dominated by changes in horizontal advection (bold). The part achieved by changes in the Ekman transport is small, mostly due to the eastward orientation of the mean salinity gradient in the region. The contribution of the anomalous horizontal circulation (bold dashed) to the advection changes dominates the formation of the salinity anomalies in the first five years but the growth of the anomalies is hampered by advection of salinity anomalies (dashed dotted). By contrast, in the region to the south of Iceland (Figure 4b), the salinity evolution is dominated by advection of salinity anomalies. The opposite sign of this term between the two regions suggests that the negative salinity anomalies are exported from the intergyre region of the eastern SPG to the northern part of the SPG by the mean gyre circulation.

[13] Export of the eastern SPG negative salinity anomalies to the north certainly contributes to their damping after year 6 but the latter could also be due to advection by the NAC of the positive anomalies formed to the south of Newfoundland. This is suggested by the eastward propaga-

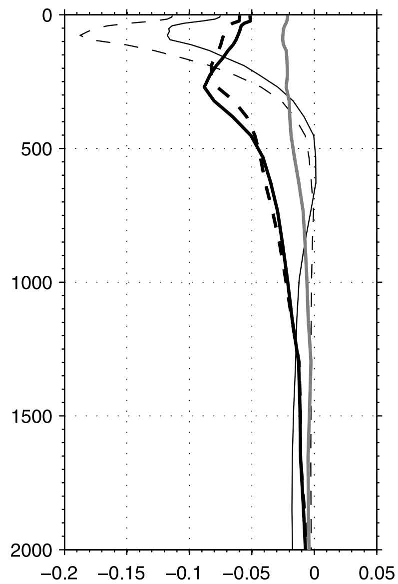

Figure 2. Mean annual salinity averaged along a meridional transect at 20°W (bold line) and 45°W (light line) in experiments NAO (black solid), WIND (black dashed) and (only for 20°W) WIND-ARCT (grey solid).

tion of the positive salinity anomalies between year 5 (Figure 1b) and year 7 (Figure 1e) in the NAO experiment.

4. Discussion

[14] The pattern of salinity anomalies between 200 and 500 meters in the SPG, as simulated in experiment NAO, bears strong resemblance with the first empirical orthogonal function of the same field in the hindcast experiment (Figure 1f), suggesting that the NAO drives the leading mode of variability of the salinity. In the eastern SPG, the simulated salinity changes are consistent with the variability observed over the recent period of rapidly changing NAO. Between 1993 (a period of high NAO) and 2003 (a period of lower NAO), *Johnson and Gruber* [2007] report an increase of the mean salinity of the Subpolar Mode Water on the order of 0.1 psu along a section extending at 20°W from south of Iceland to 40°N. The increase has similar magnitude as the response to the NAO in our simulation (0.07 psu).

[15] Our idealized experimental set-up allows us to better understand the response of the ice-ocean system to the NAO, and additionally to separate the impacts of the wind-stress and of the surface heat and freshwater fluxes. The sensitivity experiments suggest that salinity changes in the eastern SPG are mostly due to the set-up of an "intergyre gyre" in response to the wind-stress anomalies rather than to an enhancement of the gyre circulation due to the buoyancy flux. As shown by the *Marshall et al.* [2001] conceptual framework, this intergyre mainly increases the northward heat transport while the fresh water transport anomalies in our experiments are rather correlative of a heat transfer from the eastern to the western SPG. Our SSH anomaly pattern resembles the instantaneous response of the gyre transport to the wind stress given by *Eden and Willebrand* [2001] idealized experiments. While this pattern persists more or less unchanged throughout the WIND experiment, a different delayed response is given by *Eden and Willebrand* [2001] with strengthening of the subpolar and subtropical gyres.

[16] As expected, enhanced deep water formation in NAO+ has a strong dynamical impact on the western SPG leading to a spin-up of the cyclonic circulation as evidenced by the drop of SSH in the central Labrador and Irminger seas in experiment NAO (Figure 3b). The consistent continuous decrease of the SSH anomalies in the central Labrador Sea is concomitant with the freshening and the cooling in the eastern North Atlantic. Still, comparing experiments WIND and NAO shows that, contrary to the suggestion of *Hátún et al.* [2005] and *Bersch et al.* [2007], this acceleration of the gyre does not force the changes in the eastern North Atlantic.

[17] When wind stress anomalies are restricted to the Arctic domain arctic fresh water anomalies are exported to the Labrador Sea but they can hardly be traced beyond the Newfoundland region. It is possible that excessive model diffusion be responsible for part of the damping of the anomalies along their advective path. Would our result still be robust, it would contradict *Dickson et al.*'s [1988] hypothesis that salinity anomalies observed around the SPG are mostly advected with the mean gyre circulation. Their conclusions may have suffered from insufficient observational coverage which prevents adequate sampling of the time-space distribution of the anomalies.

[18] Our idealized experiments indicate a partial recovery of the salinity in the eastern gyre after 5–6 years (Figure 4a), which is even more evident when all the components of the NAO forcing are considered (not shown). The damping suggests a feedback which could partly occur through advection of the positive salinity anomalies formed to the

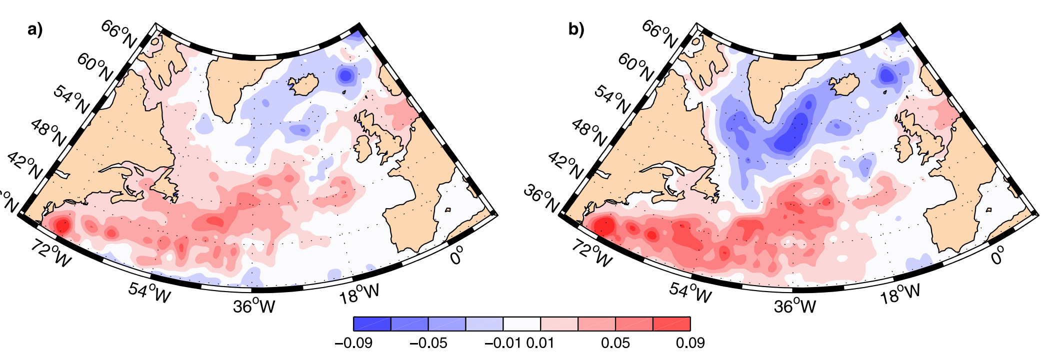

Figure 3. Two-year (year 5 to 6) average of the SSH anomaly (in m) in experiments (a) WIND and (b) NAO.

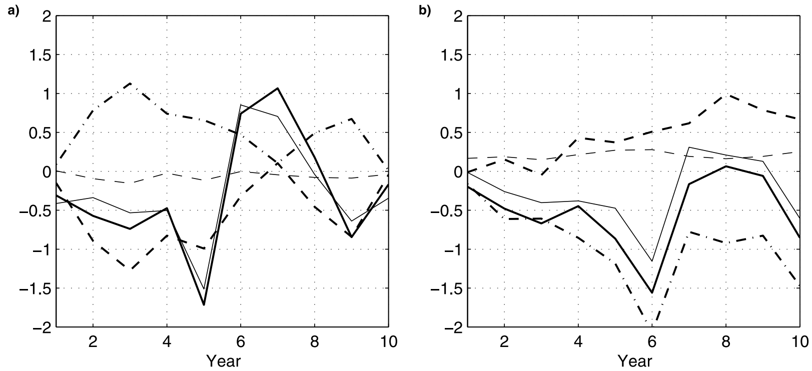

Figure 4. Rate of salinity change (in 10^{-9} psu s^{-1}) during the 10 years of experiment WIND averaged within (a) the southern box and (b) the northern box indicated in Figure 1: net rate of change (light solid) and contribution from the horizontal advection anomaly (bold solid). Also detailed are contributions to this horizontal advection anomaly due to the Ekman component (light dashed), the anomalous circulation (bold dashed) and the advection of salinity anomaly (bold dashed-dotted). The last two contributions have been divided by 5 in (a).

south of Newfoundland into the SPG. Advective feedbacks have also been mentioned in earlier studies. In the 40-year idealized experiment by *Lohman et al.* [2008], the feedback involves a strengthened meridional overturning circulation advecting more warm, saline subtropical water into the SPG and ultimately leading to a change of sign of the gyre response to the NAO.

[19] Our experiments also suggest that there may be a feedback of the eastern SPG changes onto the western SPG at intermediate depths where negative anomalies formed in the eastern SPG progress with the mean cyclonic circulation along the northern slope of the subpolar gyre into the Labrador Sea (compare Figures 1d and 1e). The advection time scale of 4–5 years from the Iceland Basin into the Labrador Sea is somewhat shorter than the 7 years observed by *Bersch et al.* [2007] for the 1995/1996 temperature and salinity anomalies.

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C. Herbaut and M.-N. Houssais, LOCEAN, IPSL, Université Pierre et Marie Curie, 4, place Jussieu, T45-55, 4ème étage, case 100, F-75252 Paris CEDEX 05, France. (ch@locean-ipsl.upmc.fr)