On the effect of the North Atlantic Oscillation on temperature and salinity of the subpolar North Atlantic intermediate and deep waters

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The close relationship between the observed water mass properties and the winter North Atlantic Oscillation (NAO) index (1950–2000s; $r^2 \approx 0.65$) implies that changes in the NAO-related atmospheric forcing may account for up to two-thirds of thermohaline changes at the intermediate and deep levels in the subpolar North Atlantic on a decadal time-scale. Persistent NAO decline (amplification) results in increase (decrease) in temperature and salinity in the intermediate–deep water column. A general mechanism explaining the close link between the NAO and coherent decadal changes in the intermediate and deep-water temperature and salinity in the region is inferred from the observed changes in the regional circulation and water mass properties. Two factors dominate this link: (i) intensity of convection in the Labrador Sea controlling injection of relatively cold freshwater into the intermediate layer, and (ii) zonal extension of the Subpolar Gyre that regulates the relative contribution of cold fresh subpolar water and warm saline subtropical water to the deep-water formation.

Keywords: Labrador Sea Water, long-term changes, North Atlantic Oscillation, overflow, Subpolar Gyre, Subtropical Gyre.

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Introduction

The North Atlantic Oscillation (NAO) quantitatively expressed as changes in the NAO index—the normalized sea-level pressure difference between the Azores and Iceland—represents the leading mode of atmospheric variability over the North Atlantic (NA) (Hurrell, 1995). High NAO indices indicate a high difference between the Azores High and Icelandic Low, coupled with strong westerly winds and a well-developed storm track in the subpolar region.

Large-scale changes in the atmospheric forcing associated with multiyear changes in the NAO affect the ocean circulation and air–sea exchange of heat and freshwater, resulting in changes in the upper-ocean hydrographic conditions and deep convection intensity in the subpolar NA and Nordic Seas and therefore affect the properties of the intermediate and deep waters formed in the region (Dickson *et al.*, 1996, 2002; Bersch, 2002; Pickart *et al.*, 2002; Visbeck *et al.*, 2003; Lozier *et al.*, 2008).

During nearly three decades, from the mid-1960s to the mid-1990s, when the winter NAO index evolved from extreme negative to extreme positive values (Figure 1d), the strengthening of northwesterlies over the Labrador Sea resulted in an increase in winter heat loss to the atmosphere and thus favoured the intensification of local deep convection and formation of large volumes of cold and fresh Labrador Sea Water (LSW) (Lazier *et al.*, 2002; Pickart *et al.*, 2002). This resulted in cooling and freshening at the intermediate levels in the entire subpolar NA (Curry *et al.*, 2003; Lozier *et al.*, 2008). The sustained long-term freshening of LSW was accompanied by the freshening of the Nordic overflow-derived deep waters—the Iceland–Scotland Overflow Water (ISOW), in the western NA also known as the Northeast Atlantic Deep Water (NEADW), and the Denmark Strait Overflow Water (DSOW)—because of the combined effect of freshening in the Nordic Seas and freshening of the upper intermediate Atlantic waters and LSW entrained into the overflows (Dickson *et al.*, 2002). As a result, the entire water column in the subpolar NA freshened on average by ~0.03 (Curry *et al.*, 2003), and substantially cooled (Lozier *et al.*, 2008) between the 1960s and 1990s.

Weakening of westerlies associated with the NAO index decline in the mid-1990s to mid-2000s (Figure 1d) caused a reduction in convection intensity in the Labrador Sea (Lazier *et al.*, 2002; Yashayaev, 2007), a slowing and contraction of the Subpolar Gyre, a northwestward shift of the Subpolar Front (SF) in the eastern basin, and a corresponding northward advance of warm saline subtropical waters (Bersch, 2002; Häkkinen and Rhines, 2004; Hátún *et al.*, 2005; Bersch *et al.*, 2007; Holliday *et al.*, 2008; Sarafanov *et al.*, 2008). Being rapidly transferred to deeper levels by a number of processes discussed in this study, the NAO-induced upper-ocean changes resulted in the well-documented abrupt reversal of the 1960–1990s freshening trend at the intermediate and deep levels throughout the subpolar NA (Sarafanov *et al.*, 2007, 2008; Yashayaev, 2007; Yashayaev and Dickson, 2008).

Intense temperature and salinity increases have been observed since the mid-1990s in the major part of the intermediate–deep

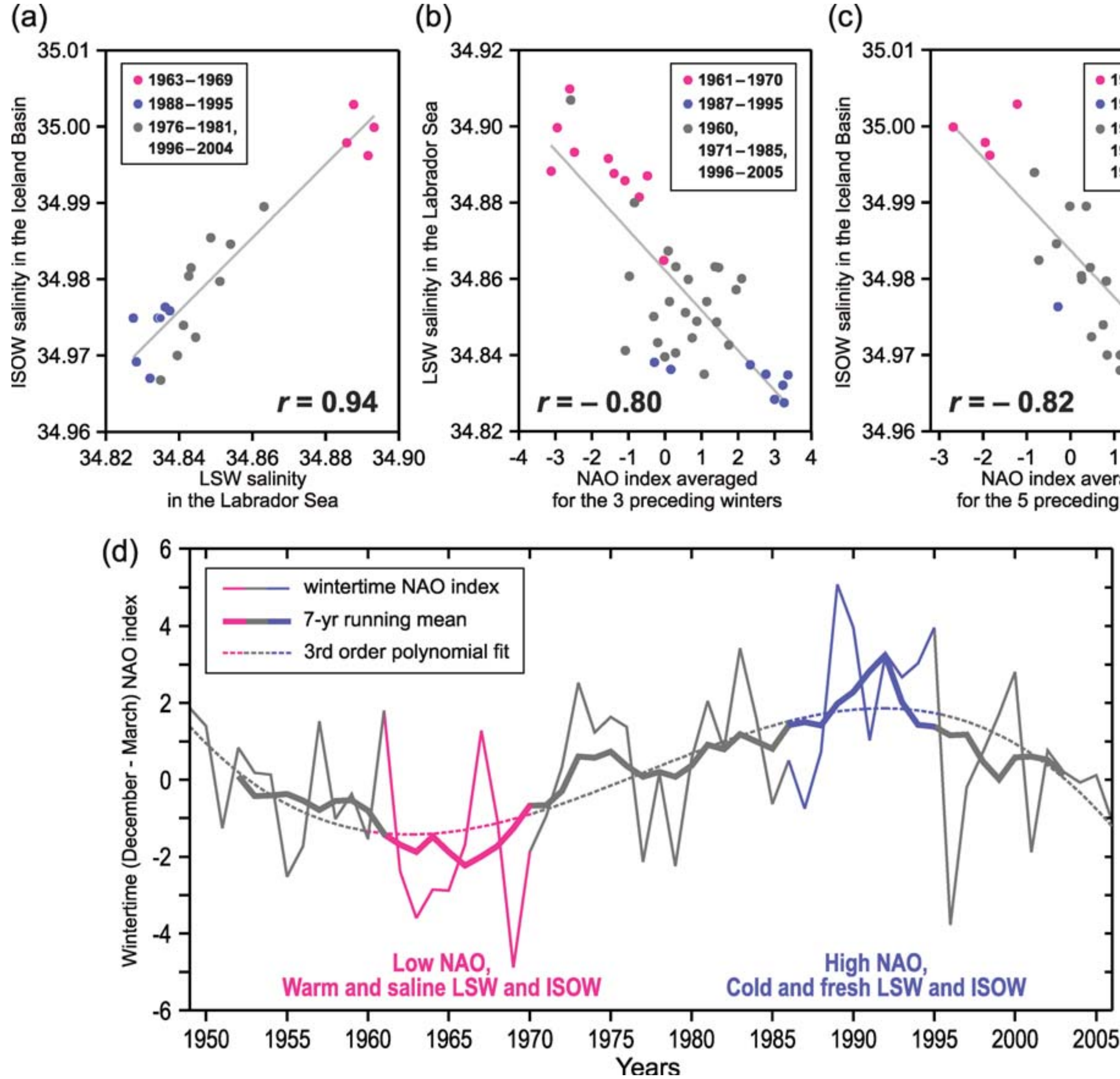

Figure 1. Coherence of decadal changes in the LSW and ISOW salinities and their dependence on the NAO. (a) Mean salinity in the LSW reservoir (150 – 2000 m) in the central Labrador Sea (Yashayaev, 2007) plotted against salinity in the ISOW core in the Iceland Basin (57 – 59.5°N ~30 – 32°W; Boessenkool *et al*., 2007; Sarafanov *et al*., 2007) for the period 1963 – 2004. (b) Mean salinity in the LSW reservoir vs. the mean winter NAO index for the three winters preceding the salinity measurements (1960 – 2005). (c) Salinity in the ISOW core in the Iceland Basin vs. the mean winter NAO index for the five preceding winters (1947 – 2006). Linear regressions are displayed; *r*, correlation coefficient. (d) Time-series of the winter NAO index, after (Hurrell, 1995), overlaid by 7-year running-mean, and third-order polynomial fit. Data collected during the 1960s (1961 – 1970, low NAO), the decade preceding the 1995/1996 NAO decline (1986 – 1995, high NAO), and during the transition periods are presented in pink, blue, and grey, respectively.

water column—from the intermediate levels dominated by waters of southern origin and LSW to the abyss occupied by the Nordic overflow-derived waters (Bersch *et al*., 2007; Sarafanov *et al*., 2007, 2008; Yashayaev, 2007). Estimates based on data from the repeated 60°N transatlantic section reveal that for nine years (1997–2006), the intermediate–deep water stratum became 0.036 saltier and ~0.3°C warmer (Sarafanov *et al*., 2008); this is comparable with the net magnitude of the preceding long-term freshening (~0.03).

This study focuses on the following issues: to what extent the observed water mass property changes may depend on the NAO on a decadal time-scale, which factors are dominant in transition of the NAO-induced upper-ocean changes to the deep ocean, and how fast do these factors, acting together, affect temperature and salinity in the entire intermediate–deep water column in the subpolar NA?

Below, it is argued that the NAO is responsible for the greater part of the coherent changes in the LSW and ISOW salinities since the beginning of the record. The causes of the fast response of the ISOW salinity to the recent NAO decline are examined, and an explanation is proposed for the close relationship between the NAO and decadal changes in the intermediate and deep-water temperature and salinity in the region. The overall objective of this paper is to combine the main causal links between the NAO and thermohaline changes in the water column, inferred from the observed hydrographic and circulation changes in the region into a single general mechanism. Identifying the specific dynamic and thermodynamic processes that drive these relationships is, however, beyond the scope of this paper.

Coherence of the long-term changes in the LSW and ISOW salinities and their link to the NAO

LSW and ISOW (NEADW) are the main water masses of subpolar origin occupying intermediate–deep levels in both the western and eastern basins of the subpolar NA. Sarafanov *et al.* (2007) noted that the sustained LSW and ISOW salinity changes occurred during practically the same periods since salinity records first became available. Indeed, both LSW and ISOW became warmer and saltier in the 1950–1960s (Lu *et al.*, 2004) and in the mid-1990–mid-2000s (Sarafanov *et al.*, 2007). The long-term freshening of deep waters between the mid-1960s and the mid-1990s was likewise accompanied by the sustained, but non-steady freshening and cooling of LSW (Dickson *et al.*, 2002).

Salinity data from the hydrographic observations in the Labrador Sea (Yashayaev, 2007) and Iceland Basin (Boessenkool *et al.*, 2007; Sarafanov *et al.*, 2007) reveal that salinity of LSW in its formation region, the central Labrador Sea, and the ISOW salinity at the eastern flank of the Reykjanes Ridge (57–59.5°N) in the Iceland Basin, i.e. nearby the ISOW source, are closely correlated ($r = 0.94$; $p < 0.001$) on a decadal time-scale (1963–2004; Figure 1a), reflecting the noted coherence.

The LSW properties are strongly dependent on the NAO. High NAO conditions favour intense convection in the Labrador Sea, which results in cooling and freshening in the LSW reservoir, and vice versa (Yashayaev, 2007). The two events of sustained increase in temperature and salinity of LSW in the 1950–1960s and mid-1990–mid-2000s, and the prolonged period of the LSW cooling and freshening, correspond to decadal changes in the NAO index. The index decreased in the 1950–mid-1960s and mid-1990–mid-2000s and increased during the three decades between the mid-1960s and the mid-1990s (Figure 1d). This relationship is indicated by the strong negative correlation ($r = -0.80$; $p < 0.001$) between the LSW salinity (1960–2005) and the mean winter NAO index for the three winters preceding the salinity measurements, i.e. the 3-year running-mean NAO index lagged by 1 year (Figure 1b).

Similarly, the ISOW salinity in the Iceland Basin (1947–2006) is negatively correlated with the NAO index ($r = -0.82$, $p < 0.001$) averaged for the 5 preceding years, i.e. the 2-year-lagged running-mean NAO (Figure 1c). The above implies a fast response of the ISOW salinity to the NAO. This response is indeed fast. The recent phase of the ISOW salinity increase in the Iceland Basin began in 1996/1997 (Sarafanov *et al.*, 2007), just 1–2 years after the abrupt decline in the NAO index between winters of 1994/1995 and 1995/1996.

Now consider the likely causes of the ISOW freshening reversal in 1996/1997. The ISOW properties in the Iceland Basin result from mixing of the convectively formed Norwegian Sea waters entering the NA over the Iceland–Scotland Ridge with the overlying warm saline Atlantic waters (the "entrainment"; ∼500–1000 m layer in the northern Iceland Basin) and LSW (Dickson *et al.*, 2002). All three water masses have freshened since the mid-1960–early-1970s, which collectively has resulted in a persistent long-term freshening of ISOW (Dickson *et al.*, 2002). The abrupt reversal of the freshening of the ISOW in 1996/1997 implies the concurrent increase in salinity of at least one of the ISOW source components.

The 1–2 year lag between the ISOW salinity increase and the NAO index decline means that this increase occurred independently from the NAO-related increase in the LSW salinity, because the Labrador Sea–Iceland Basin transit time for LSW is approximately five years (Yashayaev *et al.*, 2007). Consequently, the ISOW salinity increase was initiated by an increase in salinity of overflow and/or entrainment.

The intense increase in salinity and temperature of the upper-ocean and upper intermediate waters contributing to the Atlantic inflow to the Norwegian Sea, and directly entrained into the ISOW layer, occurred south of the Iceland–Scotland Ridge since 1996/1997 through the mid-2000s (see Dickson *et al.*, 2002, their Figure 2; Holliday *et al.*, 2008; Sarafanov *et al.*, 2008). This was caused by the northward advance of subtropical waters associated with the NAO-induced contraction of the Subpolar Gyre and a northwestward shift of the SF that had started 1–2 years after the NAO decline (Bersch, 2002) and continued through 2005 (Sarafanov *et al.*, 2008). Therefore, the reversal of the freshening of the ISOW had occurred almost simultaneously with that of Northeast Atlantic waters, and this suggests that the NAO-induced change in a relative contribution of subpolar and subtropical waters to the entrainment into the ISOW layer was the major factor responsible for the ISOW salinity increase.

The positive upper-ocean temperature and salinity anomaly associated with the NAO-induced SF shift took ∼1–2 years to be advected from the Faroe–Shetland Channel to the Norwegian Sea interior (Holliday *et al.*, 2008). Additional time was required for convective overturning of the Atlantic inflow-derived waters into the deep layers, then to reach and overflow the Iceland–Scotland Ridge and enter the Iceland Basin. Therefore, the Norwegian Sea overflow-water properties would have taken several years to be modified in response to the 1995/1996 decrease in the NAO and affect the ISOW properties in the Iceland Basin, whereas the observations indicate that the ISOW freshening trend ceased and reversed more rapidly than would be consistent with changes in the Norwegian Sea overflow properties.

Not surprisingly, no overflow freshening reversal was observed in the Faroe–Shetland Channel during the mid-1990s (Yashayaev and Dickson, 2008). The sustained downstream observations in the Faroe Bank Channel demonstrated the overflow salinity increase since the mid-1990s through the mid-2000s. The salinity increase occurred mostly in the upper warm part of the overflow (Hansen and Østerhus, 2007), and this also makes the case for a major role of entrainment in the salinity increase of the ISOW, which reversed the freshening trend, and a minor role for Norwegian Sea waters, which dominates the overflow's coldest part.

Certainly, the sustained ISOW salinity increase that followed the freshening reversal in the mid-1990s could be maintained and reinforced by the lagged effect of the NAO-induced increase in the overflow and LSW salinities, but the initial fast response of the ISOW salinity to the declining NAO resulted primarily from increasing salinity of the Atlantic waters entrained into the Iceland–Scotland overflow.

The time-series of salinity anomalies in the 500–1000 m layer at the head of the Iceland Basin [SEI in Dickson *et al.* (2002)] indicates that from 1996 to 2000, the salinity of the entrainment increased by ∼0.05; that is ∼3.5 times as high as the 1996–2000 salinity increase in the ISOW core at the eastern slope of the

Reykjanes Ridge (0.014). Given this increase, allied with the ∼30% entrainment fraction in the "overflow–entrainment–LSW" mixture (Dickson *et al.*, 2002), the net increase in the ISOW salinity in the Iceland Basin, at least in the second half of the 1990s, can be explained solely by the increase in salinity of the entrained waters.

Can the entrainment and ISOW freshening reversal in the mid-1990s be attributed to the regional air–sea freshwater flux changes, rather than to the NAO-induced circulation change? Josey and Marsh (2005) reported an increase in the difference between precipitation and evaporation (P–E) in the eastern subpolar NA between the 1960s and the 1990s (not directly associated with the NAO) and assumed that the resulting decrease in the sea surface salinity might be partly responsible for the deep-water freshening in the northern NA. It should be noted, however, that the P–E increase in the time-series (Josey and Marsh, 2005, their Figure 3a) is evident for the first half of the 1970s only, whereas no significant long-term trend can be claimed for the two following decades (mid-1970–mid-1990s), when, nevertheless, the ISOW salinity persistently decreased (Dickson *et al.*, 2002). What is more important for the current discussion is that nothing remarkable, except for a strong year-to-year variability is evident in the P–E record in the 1990s, and no P–E decrease since the mid-1990s can be distinguished.

According to Thierry *et al.* (2008), variability of the air–sea freshwater and heat fluxes cannot explain the persistent increase in temperature and salinity of the Subpolar Mode Water—the water mass contributing to the entrainment into ISOW (Yashayaev and Dickson, 2008)—that was observed at the eastern flank of the Reykjanes Ridge in the mid-1990–mid-2000s. On the contrary, Thierry *et al.* (2008) attribute the increase in temperature and salinity of this water mass to the NAO-induced redistribution of subpolar and subtropical waters in the Iceland Basin.

Therefore, the LSW and ISOW salinities are closely correlated on a decadal time-scale, because they both appear to be strongly dependent on the NAO. Given the magnitude of the correlation coefficients of the LSW and ISOW salinities with the lagged-mean NAO index of −0.80 and −0.82, respectively, the NAO could account for roughly two-thirds (64–67%) of the variance in the LSW and ISOW salinity time-series. A prolonged decrease in the NAO index results in an increase in salinity of LSW and ISOW, and vice versa.

Mechanism explaining the close link between the decadal property changes in the intermediate–deep water column and the NAO

The ocean response to the NAO decline in the mid-1990–mid-2000s has provided new information that allows us to identify the key factors contributing to the decadal changes in temperature and salinity at the intermediate and deep levels of the subpolar NA. The scheme proposed in Figure 2 generalizes a number of documented interrelated processes leading to increases (decreases) in temperature and salinity in the intermediate–deep water column in the region, in response to changes in the surface forcing associated with a long-term decrease (increase) in the winter NAO index.

During prolonged periods of NAO decline, as in the mid-1990–mid-2000s (Figure 1d), a weakening of northwesterly winds over the subpolar NA results in a reduction in winter heat loss in the Labrador Sea and a consequent reduction in convective renewal of LSW, which becomes warmer and saltier via mixing with relatively warm and saline waters carried into the Labrador Sea by the Irminger Current (Lazier *et al.*, 2002; Pickart *et al.*, 2002; Yashayaev, 2007). From the Labrador Sea, the signal of increasing temperature and salinity is transferred by LSW into the Irminger Sea (with approximately a 2-year lag), the Iceland Basin (approximately a 5-year lag), and the Rockall Trough (approximately a 10-year lag). This results in (i) warming and increase in salinity at the intermediate levels throughout the Subpolar Gyre (Falina *et al.*, 2007; Sarafanov *et al.*, 2007; Yashayaev *et al.*, 2007), and (ii) affects properties of the Nordic

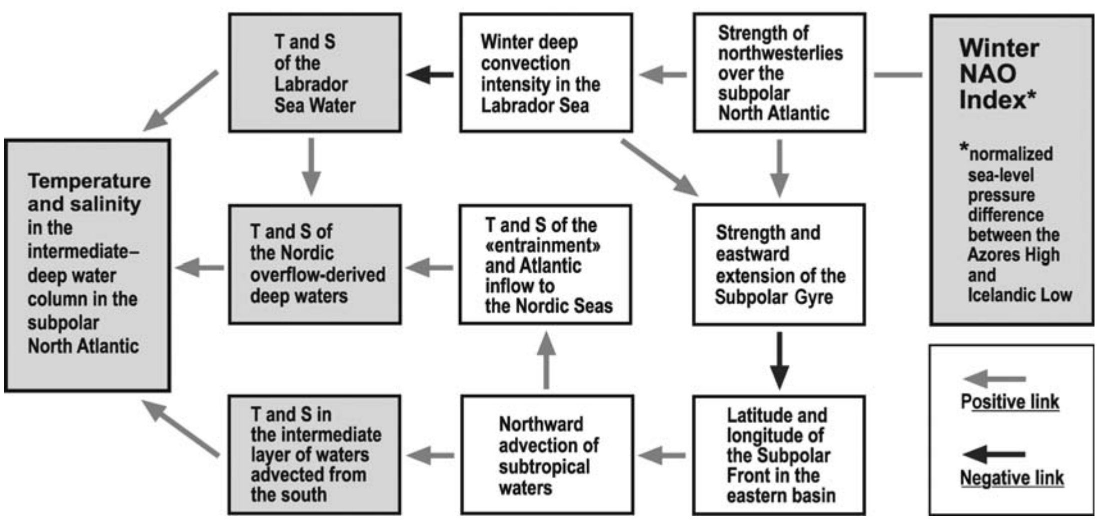

Figure 2. Schematic representation of the mechanism behind the NAO effect on decadal changes in temperature (T) and salinity (S) in the subpolar NA intermediate–deep water column inferred from the documented changes in the deep convection activity, regional circulation, and water mass distribution and properties. Positive (negative) link between a cause and consequence means here that changes in "causative" and "consequential" characteristics have the same (opposite) sign(s). The overall effect of the NAO change on temperature and salinity in the water column is negative: persistent NAO index decrease (increase) results in increase (decrease) in temperature and salinity in the water mass layers; this is reflected by the negative correlation of salinity and the NAO index for LSW and ISOW, as illustrated in Figure 1.

overflow-derived deep waters as LSW is entrained into the latter (Dickson *et al.*, 2002).

Reduction in the strength of northwesterly winds, allied with a decrease in the intensity of winter overturning in the Labrador Sea, results in slowing and contraction of the Subpolar Gyre and corresponding northwestward shift of the SF in the northeastern NA, which starts within ~2 years after the decline in the NAO index (Bersch *et al.*, 2007). The fast response of the gyre circulation to the NAO-related changes in windstress over the NA, and in the convection intensity in the Labrador Sea, has been inferred from shipboard, satellite, and moored observations (Bersch, 2002; Häkkinen and Rhines, 2004; Bersch *et al.*, 2007; Lozier and Stewart, 2008; Sarafanov *et al.*, 2008), and reproduced by modelling (Eden and Willebrand, 2001; Gulev *et al.*, 2003). The underlying mechanisms of this response have been investigated and reported on by several authors (e.g. Eden and Willebrand, 2001; Häkkinen and Rhines, 2004; Bersch *et al.*, 2007).

Northwestward displacement of the eastern limb of the SF results in an intense increase in temperature and salinity in the upper ocean and at the upper intermediate levels in the Rockall Trough and Iceland Basin (Bersch *et al.*, 2007; Holliday *et al.*, 2008; Lozier and Stewart, 2008; Sarafanov *et al.*, 2008), owing to enhanced northward advection of warm saline waters from the subtropics (Bersch, 2002), which originate mostly in the eastern NA Water at the upper levels (Holliday *et al.*, 2008) and the Mediterranean Overflow-derived Water (MOW) at the intermediate levels (Lozier and Stewart, 2008; Sarafanov *et al.*, 2008).

As discussed earlier, the upper-ocean warming and salinity-increase signals are transferred into the deep levels (i) instantly via entrainment, and likely (ii) indirectly via an increase in the temperature and salinity of the Atlantic inflow (Hátún *et al.*, 2005; Holliday *et al.*, 2008) and subsequent increase of temperature and salinity in the Nordic Seas (Polyakov *et al.*, 2005; Holliday *et al.*, 2008), where the overflow waters originate. It should be noted that the sustained increase in temperature and salinity of the overflow-derived waters in response to weakening of the NAO-related surface forcing is currently evident only for the ISOW, whereas the strong year-to-year variability of the DSOW properties masks a probable multiyear tendency and does not allow one to claim the reversal (or continuation) of the 1960–1990s freshening trend for this water mass (Sarafanov *et al.*, 2007).

The ISOW temperature and salinity increase is likely to be maintained by enhanced northward advection of the subtropical intermediate waters. These waters (i) are likely to be directly entrained into ISOW south of the Iceland–Scotland Ridge, because both the overlying mode waters and underlying LSW are entrained there into the ISOW layer (Dickson *et al.*, 2002), and (ii) may contribute to the Atlantic inflow to the Norwegian Sea, thus increasing temperature and salinity of the convectively formed waters, constituting the Iceland–Scotland overflow. The latter process—penetration of the intermediate waters from the subtropics into the Norwegian Sea—could be possible under low-NAO conditions, when the strongly modified waters of Mediterranean origin propagate far north in the Rockall Trough (Lozier and Stewart, 2008).

Approximately five years after the reversal of the ISOW long-term freshening (1960–1990s) in the Iceland Basin, and within 6–7 years of the NAO decline, the signal of the ISOW temperature and salinity increase *passed through* the Irminger and Labrador Seas (Sarafanov *et al.*, 2007; Yashayaev, 2007), thereby reversing the ISOW freshening in all three main basins of the subpolar NA. Given this (6–7 year) lag and the ~10 years required for LSW to reach the most distant location in the subpolar region, the Rockall Trough, it takes 7–10 years for the NAO-induced upper-ocean changes to be transferred to the deeper levels, mostly via the deep overturning and mixing in the Labrador Sea and the entrainment of the upper-ocean and upper intermediate waters into the overflow-water layer, and to modify temperature and salinity in the bulk of intermediate–deep waters throughout the subpolar NA.

During the period of the persistent NAO increase in the mid-1960–mid-1990s (Figure 1d), the long-term changes in the water mass properties and circulation of the subpolar NA were opposite to those discussed above. Strengthening of deep convection in the Labrador Sea resulted in the long-term cooling and freshening of LSW: in the first half of the 1990s, temperature and salinity of LSW reached their absolute minima in the record (Yashayaev, 2007). Moreover, under extremely high-NAO conditions in the early 1990s, additional convective renewal of LSW is likely to have occurred in the Irminger Sea (Pickart *et al.*, 2003; Falina *et al.*, 2007). Concurrently, the eastern limb of the SF moved eastwards, reflecting the Subpolar Gyre expansion that limited northward advection of warm, saline upper-ocean, and intermediate subtropical waters (Bersch, 2002; Lozier and Stewart, 2008) and thus resulted in freshening of the northeast NA waters, which are directly entrained into the Iceland–Scotland overflow and contribute to the Atlantic inflow to the Norwegian Sea (see Dickson *et al.*, 2002; Holliday *et al.*, 2008). As a result, the entire water column in the subpolar NA cooled (Lozier *et al.*, 2008) and freshened (Curry *et al.*, 2003) substantially between the 1960s and 1990s.

The SF position is clearly one of the key factors in the link between the NAO and temperature and salinity changes in the intermediate–deep water column in the subpolar NA, and an analysis of the hydrographic data collected in the eastern basin since the 1960s has revealed the strong negative correlation ($r \approx -0.81$) between the SF longitude and the NAO index on a decadal time-scale (Lozier and Stewart, 2008). Being induced mostly by the SF displacements, the salinity anomalies at the MOW level in the Rockall Trough also correlate negatively ($r \approx -0.85$) with the NAO index (Lozier and Stewart, 2008). The close negative correlation ($r \approx -0.8$) between the LSW and ISOW salinities and the NAO index was highlighted in the previous section. Therefore, given the typical salinity–NAO index correlation of -0.8 at the MOW–LSW–ISOW levels and the fact that the salinity (freshwater content) trends in the northern NA are accompanied by consistent trends in temperature (heat content; $r^2 \approx 0.87$, 1950–2000s; Boyer *et al.*, 2007), the NAO may account for up to two-thirds of the decadal temperature and salinity changes at the intermediate–deep levels in the region.

Summary and discussion

Changes in the NAO-related atmospheric forcing may account for a major part (roughly two-thirds) of the observed coherent thermohaline changes in the intermediate–deep water column in the subpolar NA on a decadal time-scale. Phases of the long-term increase (decrease) in temperature and salinity in the water column are clearly linked to phases of the long-term decrease (increase) in the NAO index.

Two factors appear to dominate the link between the NAO and the intermediate and deep-water properties: (i) the intensity of

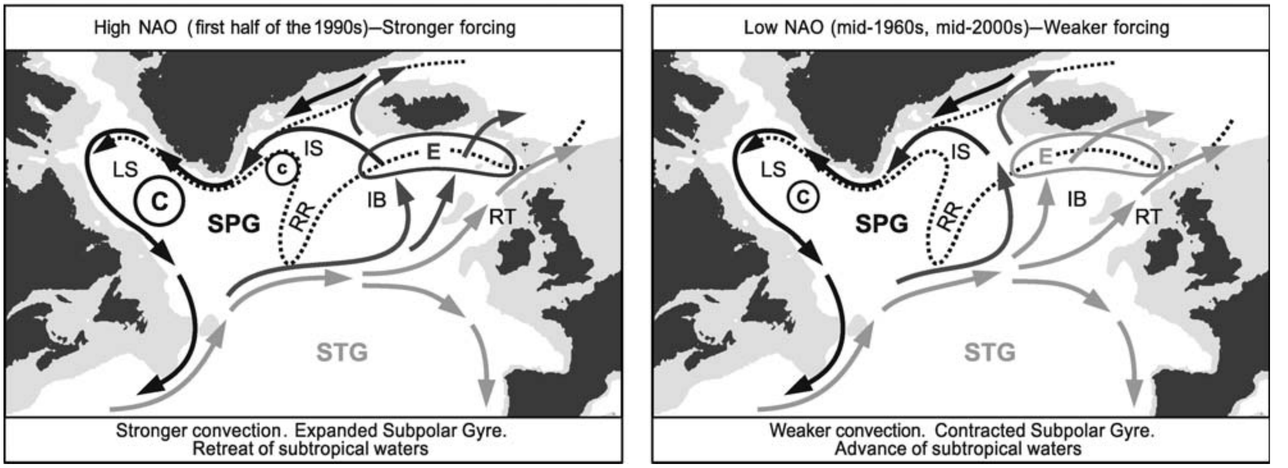

Figure 3. Simplified schematic representation of the upper-ocean circulation and convection intensity in the subpolar NA under high (left) and low (right) NAO conditions. Darker (lighter) solid arrows indicate the upper-ocean flows with higher fraction of colder fresher subpolar (warmer saltier subtropical) waters. The main pathways of the Nordic overflow-derived deep waters are indicated by dotted arrows. "C" and "E" symbols are used to denote, respectively, the deep convection sites and the domain where the Atlantic waters are entrained into the Iceland–Scotland overflow. Larger (smaller) circles indicate stronger (weaker) convection. SPG and STG, the Subpolar and Subtropical Gyres, respectively; LS, Labrador Sea; IS, Irminger Sea; RR, Reykjanes Ridge; IB, Iceland Basin; RT, Rockall Trough. Depths $<$500 m are shaded.

winter deep overturning in the Labrador Sea, which governs cold freshwater injection into the intermediate layer, and (ii) the intensity and eastward extension of the Subpolar Gyre, which regulates redistribution of cold fresh subpolar waters and warm saline subtropical waters supplying the Nordic Seas with heat and salt, and is instantly entrained into the overflow layer. Therefore, two key sites for the rapid transfer of the NAO-induced upper-ocean changes to the intermediate and deep levels can be identified: the Labrador Sea and the subpolar NA northeastern periphery. Under high (low) NAO conditions, intense (weak) convection, coupled with decreased (increased) northward advection of subtropical waters, as schematically illustrated in Figure 3, results in a decrease (increase) in temperature and salinity in the intermediate–deep water column in the northern NA.

The two specified factors are "internal" to the northern NA–Nordic Seas domain, whereas the 1960–1990s freshening of deep water in the subpolar NA and freshening in the Nordic Seas have been attributed to a combination of the "external" factors, namely, increased ice melt, elevated net precipitation at high latitudes and increased river discharge to the Arctic Ocean (Curry *et al*., 2003; Peterson *et al*., 2006). The rapid response of the ISOW salinity to the recent weakening of the surface forcing associated with the decline in the NAO index implies that the "internal" factors of the deep-water property changes may dominate the "external" ones. Indeed, despite a long-term increase in freshwater input to the Arctic, freshening of the ISOW and the subsurface layers of the Nordic Seas reversed rapidly during the second half of the 1990s (Sarafanov *et al*., 2007; Holliday *et al*., 2008), owing to the NAO-induced northward advance of subtropical waters.

Certainly, anomalies of freshwater export from the Arctic, coupled with net precipitation variability, affect the upper-ocean salinity in the Subpolar Gyre, and the air–sea freshwater fluxes affect salinity in the Subtropical Gyre to some extent. However, given a persistent dramatic contrast in temperature and salinity between the subpolar and subtropical waters, decadal variability in their relative contribution to deep-water formation is very likely to be a much more important mechanism behind the deep-water thermohaline anomalies than changes in properties of each of these two water types. This view is consistent with a recent model study of decadal changes in freshwater and heat content in the subpolar NA, including a prominent freshening between the 1960s and 1990s (Scheinert, 2008). The modelling indicates that the integral changes in the subpolar NA have largely resulted from freshwater and heat exchanges between the Subpolar and Subtropical Gyres, and variability in the subtropical-subpolar fluxes can be understood in terms of the response of the gyre circulation to atmospheric forcing variability associated with the NAO. In contrast to previous suggestions, the model experiments indicate a secondary contribution to the subpolar NA freshwater changes by freshwater export from the Arctic.

From a large-scale perspective, salinity (or freshwater content) in the subpolar NA and Nordic Seas is determined for the most part by an interplay between freshwater advection from the Arctic and saline water advection from the subtropics. The NAO-dependent zonal extension of the Subpolar Gyre controls the relative contribution of these "parent" waters to deep-water formation and hence affects thermohaline properties of the subpolar NA deep waters on a decadal time-scale.

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