https://doi.org/10.17895/ices.pub.8013

ICES Marine Science Symposia, 219: 15–24. 2003

The North Atlantic Oscillation and the ocean's response in the 1990s

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Dickson, B., and Meincke, J. 2003. The North Atlantic Oscillation and the ocean's response in the 1990s. – ICES Marine Science Symposia, 219: 15–24.

The North Atlantic Oscillation (NAO) is the dominant recurrent mode of atmospheric behaviour in the North Atlantic sector, dictating much of the climate variability from the eastern seaboard of the United States to Siberia and from the Arctic to the subtropical Atlantic, especially during boreal winter. During the 1990s, the behaviour of the NAO became extreme in two main ways, both of which had deep-reaching effects on Atlantic hydrography and on the marine ecosystem. First, in the early 1990s (1989–1995 approximately), the NAO Index evolved to its most extreme positive state in a 175-year instrumental record, following a long if irregular amplification over the previous three decades. Then, after a brief return to extreme NAO-negative values in 1996, the NAO dipole pattern in sea-level pressure (slp) showed some tendency to shift eastward as the Index recovered to more positive values. Through the associated variability in the intensity of open-ocean deep convection, in the production-rates and characteristics of the main convectively formed mode waters, in the freshwater accession to the Nordic Seas and in the hydrography of the dense northern overflows, these extreme trends in NAO behaviour have been associated with radical effects throughout the water column of the North Atlantic. The evidence for this is described.

Keywords: climate change, hydrographic change, North Atlantic Oscillation, ocean circulation, overflow.

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Introduction

The NAO in the 1990s

The period under review is a most unusual one in the climatic history of the North Atlantic, one in which the NAO Index evolved to extreme positive values unprecedented in the instrumental record (Figure 1, updated from Hurrell, 1995a). The NAO is not of course the only source of variability in Atlantic climate; it accounts for about one-third of the variance in Atlantic sea-level pressure (slp) during December to March. And the NAO pressure pattern does not simply change sign as it switches from one extreme state to the other; the chaotic nature of the atmospheric circulation means that at most times there are significant local departures from the idealized NAO pattern. However, the importance of the recent unprecedented long-term shift in the NAO lies in the wide range of variables attributed to it which have the potential to cause change in the marine environment. These include variations in wind speed, latent and sensible heat flux (Cayan, 1992a,b,c), evaporation/precipitation (Cayan and Reverdin, 1994; Hurrell, 1995a), the distribution, prevalence, and intensity of Atlantic storms (Rogers, 1990, 1994, 1997; Hurrell, 1995b; Alexandersson *et al.*, 1998), hence effects on the wave climate (Bacon and Carter, 1993; Kushnir *et al.*, 1997; Carter 1999), sea surface temperature (Cayan, 1992c, Hansen and Bezdek, 1996), the strength of the Labrador Current (Myers *et al.*, 1989), the characteristics and distribution of water masses (Lazier, 1995; McCartney *et al.*, 1997; Joyce and Robbins, 1996; Houghton, 1996; Molinari *et al.*, 1997; Sy *et al.*, 1997; Joyce *et al.*, 1999; Curry *et al.*, 1998; Curry and McCartney, 2001), the extent of the marginal ice zone (Fang and Wallace, 1994; Mysak *et al.*, 1996; Deser *et al.*, 2000), Davis Strait ice volume (Deser and Blackmon, 1993), the iceberg

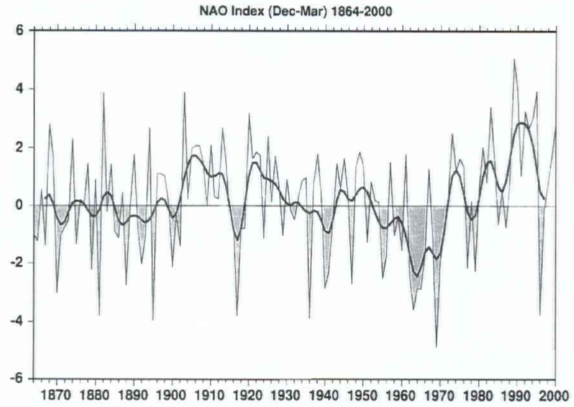

Figure 1. Winter (December–March) index of the NAO based on the difference of normalized sea level pressure (slp) between Lisbon, Portugal, and Stykkisholmur/Reykjavik, Iceland from 1864 through 2000. The indicated year corresponds to January (e.g. 1950 is December 1949 to March 1950). The average winter slp data at each station were normalized by division of each seasonal pressure by the long-term mean (1864–1983) standard deviation. The heavy solid line represents the index smoothed to remove fluctuations with periods less than 4 years.

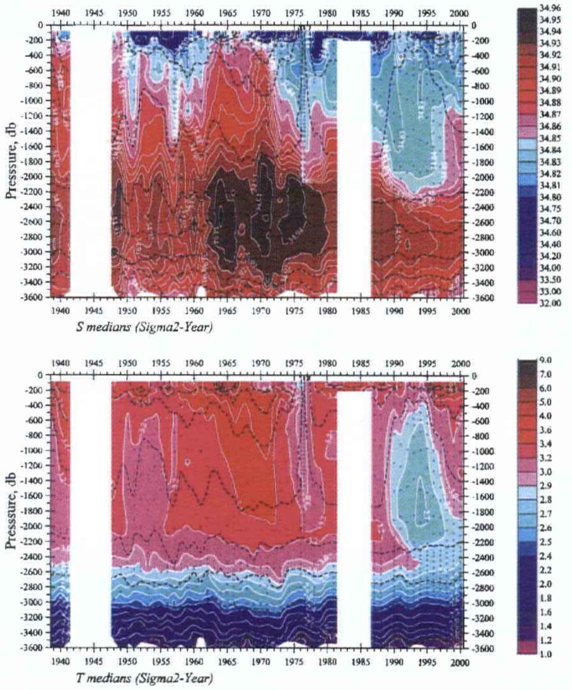

Figure 2. Changes in the salinity (upper panel) and potential temperature (θ; lower panel) of the water column in the Central Labrador Sea over the complete period of the hydrographic record since 1938. The data set was selected to lie within the 3300 m isobath of the Labrador Sea, and the plots represent the median values of vertical property profiles, binned according to σ_2 density intervals. Kindly provided by Igor Yashayaev, Bedford Institute of Oceanography, Dartmouth, N.S., Canada, pers. comm.

flux past Newfoundland (Drinkwater, in Rhines, 1994), and the intensity of deep convection at the main Atlantic sites (Greenland Sea, Labrador Sea, and Sargasso; Dickson *et al.*, 1996; Talley, 1996; Dickson, 1997; Joyce *et al.*, 2000).

It is beyond the scope of this work to document all of these changes as they occurred during the 1990s. In the sections which follow, we focus on a subjective selection of four chains of response which best illustrate the full-ocean and full-depth nature of these events.

1. Spin-up of the North Atlantic gyre circulation

In our first example, we highlight the radical interannual and interdecadal changes in the production of the convectively formed mode waters of the West Atlantic (Labrador Sea Water (LSW) and '18-Degree Water') which Dickson *et al.* (1996) suggest to be part of a coordinated pan-Atlantic pattern of convective activity, driven by the changing NAO. Following the trend in the NAO Index, convective activity at all three main sites has evolved over decades between opposite extrema. From the NAO minimum of the 1960s, when the ventilation of the Greenland Sea and Sargasso was at a maximum and that of the Labrador Sea was tightly capped, convective activity evolved towards the opposite extreme state in the early 1990s, in which convection in the Greenland Sea and Sargasso was suppressed but vertical exchange in the Labrador Sea was reaching deeper than previously observed.

The mechanism is thought to involve the sort of change in the distribution of Atlantic winter storm activity that has long been associated with opposite extreme states of the NAO (Rogers, 1990), and which latterly brought an intense storminess and a record northwesterly windstress to the Labrador Sea during winters of the early 1990s. The result was intensifying and deepening ventilation of the Labrador Sea, with a progressive cooling and freshening of LSW into the 1990s (Figure 2, from Igor Yashayaev, pers. comm.), and ultimately, during the deepest-reaching convection since 1992, to an increase in LSW density as convection began to excavate the cold but saline sublayer of North Atlantic Deep Water (Dickson *et al.*, 1996). Thus in the early 1990s LSW was fresher, colder, and denser than at any other time in the history of deep measurements in the Labrador Sea. From 1966 to 1992, in what we believe to be the largest change in the modern instrumental oceanographic record, the overall freshening of the water column of the Labrador Sea was equivalent to mixing-in an extra

6 m of freshwater at the sea surface (7 m if we extend the period to 1994), and its cooling has been equivalent to a loss of 8 W m^{-2} continuously for 26 years (Lazier, 1995). (Beneath the convective layer, the freshening by ≈ 0.01 per decade over the past three to four decades, apparently still continuing (Figure 2), reflects the recent large-scale freshening of the upper Nordic Seas transferred via the dense northern overflows through Denmark Strait and the Faroe Bank Channel; see below. As the net result of both these changes, the steric height in the central Labrador Sea in the mid-1990s was typically 6–9 cm lower than in the late 1960s).

These changes in the mode water of the Labrador Sea have a value in identifying the rates and pathways by which LSW spreads across the basin (e.g. Sy *et al.*, 1997]. However, their major importance is likely to lie in their influence on the Atlantic gyre circulation itself. As Curry and McCartney (2001) point out, the main North Atlantic Current is driven by the gradient of potential energy anomaly (PE') across the mutual boundary between the subtropical and subpolar gyres. Since PE' reflects the vertical density structure and heat content of the upper ocean to well below the wind-driven layer, it follows that coordinated changes of opposite sign in the production and characteristics of the mode waters in each gyre will have the potential to drive deep-seated changes in the PE' gradient and hence in the strength of the Atlantic gyre circulation. And if these changes in the density and heat content of mode waters are attributable to the NAO, then the amplification of the NAO to extreme values over the past three or four decades is likely to have been followed by a corresponding multi-decadal spin-up of the Atlantic gyre circulation.

From the observed PE' differences between the centres of the two gyres, Curry and McCartney calculate that the long-term increase in the NAO Index to the mid-1990s was accompanied by a 30% increase in the 0–2000 dbar east-going baroclinic mass transport along the gyre:gyre boundary, from 50 Mts^{-1} (= Sv = $10^6 m^3 s^{-1}$) in 1970 to 65 Mts^{-1} in the mid-1990s. Both subpolar and subtropical gyres contributed equally to the changes in their transport index (shown schematically in Figure 3). Thus, in response to the NAO, the North Atlantic gyre circulation during the period under review is likely to have been at its strongest for more than a century.

2. Altered patterns of exchange with the Nordic Seas during the 1990s

Though their wider influence is certainly regulated by the gaps and passageways that form their connections to neighbouring seas, the Nordic Seas are potentially important as a source of change for both the climatically sensitive Arctic Ocean and for the northern overflows which form the deep south-going limb of the meridional overturning circulation (MOC). It is worth recording, then, that over much of the water column the hydrographic character of these seas during the 1990s was beyond the range of our past experience; and that in one way or another these extreme anomalies appear to have arisen through a changing balance, sense, or pattern of "exchange". We note four changes in particular.

The 1990s were remarkable both for our increased ability to measure or estimate the Atlantic inflow to Nordic Seas and for the evidence of change that these studies revealed. Modern estimates based on direct measurements (e.g. Hansen and Osterhus, 2000; Orvik *et al.*, 2001) describe two main branches of inflow to the Norwegian Sea carrying a total mean transport of order 7 Sv (a third inflow of order 1 Sv passes north to the west of Iceland). The eastern branch appears as a narrow, topographically trapped current carrying order 4 Sv northward

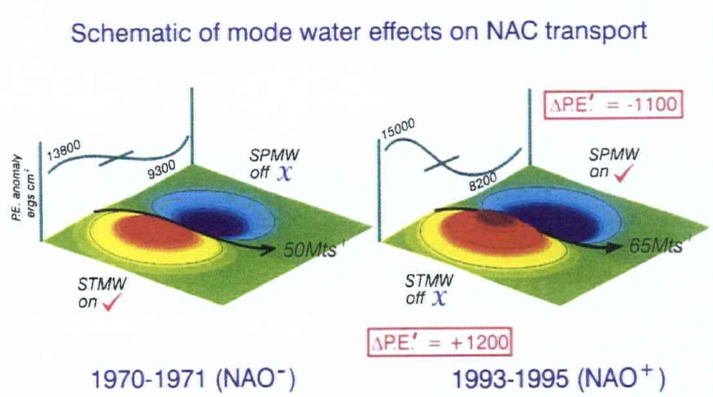

Figure 3. Schematic of mode water effects on the North Atlantic gyre circulation during opposite extreme states of the NAO. Based on the analysis by Curry and McCartney (2001)

against the upper continental slope. The offshore branch takes the form of an unstable frontal jet about 400 m deep and is less well measured in consequence, carrying an estimated transport of order 3 Sv into the central Norwegian Sea.

These two inflow streams thus carry only a small fraction of the Atlantic Water transport brought east by the North Atlantic Current and the variations in inflow, at least for the main branch passing through the Faroe–Shetland Channel, are ascribed to changes in the local windfield rather than to the large-scale changes in the Atlantic gyre circulation, just described (section 2.3). As the dominant mode of slp variability in the Atlantic sector, the NAO can be expected to be implicated in these changes, and in fact specific associations with NAO variability have been described for the inflow and subsequent northward transport of Atlantic Water through the eastern Norwegian Sea.

First, using a box inverse method, Dye (1999) uses the century-long hydrography from the Faroe–Shetland and Nolso–Flugga standard sections to identify long-term changes in the upper layer transport through the Channel, continuously since 1946, discontinuously before that. Perhaps because the box inverse method does not, in this case, give complete access to the barotropic component, the transports calculated are no more than half of the order 4 Sv that we believe passes north along the Scottish Continental Slope. However, this analysis does demonstrate a clear association between inflow and the NAO, with the upper-layer transport increasing steadily by a little more than 1 Sv after the mid-1960s, in parallel with the NAO Index; the Faroe–Shetland through-flow (or at least this component of it) was at a century-long maximum in the early 1990s. The hydrographic analysis of data from the Svinoy Section by Mork and Blindheim (2000) would appear to support this conclusion. They find that the NAO Index is closely associated with the temperature, salinity, and transport variations on this Section, which intercepts the inflow some 350 km further north at 62°–64°40′N. They suggest that since 1978 (thus covering much of the recent long-period change in the NAO Index) the transport through the whole section has increased by 1.1 Sv, mostly in the eastern branch. The current may also have narrowed. Using the 35 isohaline as a proxy for its westward extent, Blindheim *et al.* (2000) show that the width of the Norwegian Atlantic Current (NwAC) at 65° 45′N has been closely (inversely) correlated with the winter NAO Index since 1963 ($r = 0.86$ for a 2-year delay). Since NAO-positive conditions are associated with a greatly strengthened southerly airflow west of Norway (see Dickson *et al.*, 2000, their Figure 2e), these changes in the transport and width of the NwAC are both perhaps in the expected sense.

Upper-ocean temperatures in the Nordic Seas have also reflected the recent extreme amplification of the NAO. During winters of positive NAO index, the northeastward extension of Atlantic winter storm activity to the Nordic Seas together with the outflow of cold and dry air from the Canadian Arctic results in broadscale cooling across Atlantic mid-latitudes from the Davis Strait and West Greenland Banks across the Labrador and Irminger Seas to Iceland, Faroes, and much of the Nordic Seas. By contrast, as already mentioned, the warm, moist southerly airflow that is directed along the eastern boundary of the North Atlantic under these NAO-positive conditions is held responsible for driving a warmer (Dickson *et al.*, 2000), stronger (Dye, 1999; Mork and Blindheim, 2000; Orvik *et al.*, 2001), and probably narrower (Blindheim *et al.*, 2000) flow of Atlantic Water northwards to the Barents Sea and Arctic Ocean (Quadfasel, *et al.* 1991; Tereschenko, 1996; Grotefendt *et al.*, 1998), resulting in very warm SSTs west of Norway along the domain of the Norwegian Atlantic Current despite a parallel increase in windspeeds there. The rising trend and interannual variability in the NAO Index since the 1960s is for this reason reflected in a similar rising trend in upper-ocean temperatures in the eastern Fram Strait over the past few decades (Figure 4A, B, updated from Dickson *et al.*, 2000) and it will be suggested below that we can trace the propagation of this characteristic temperature pattern around the boundary of the Nordic Seas to the Denmark Strait and from there into the abyssal layers of the Labrador Sea.

A third notable change in these waters during the period under review is a large-scale, large amplitude freshening that has taken place in the upper 1–1.5 km of the Nordic Seas over the past three or four decades. Once again the cause is largely attributed to the amplifying NAO, but with a variety of area-specific mechanisms: (a) The direct export of sea ice from the Arctic Ocean is one such cause (Vinje *et al.*, 1998; Kwok and Rothrock, 1999). A combination of current measurements, upward-looking sonar, and satellite imagery reveals that the annual efflux of ice through the western Fram Strait increased with the NAO to a record volume flux of 4687 km^3 $year^1$ in 1994–1995. Although the relationship is not robust in the longer term, each 1-sigma increase in the NAO Index since 1976 has been associated with an approximately 200 km^3 increase in the annual efflux of ice to the Greenland Sea (Dickson *et al.*, 2000). (b) Throughout the marginal ice zone of the Nordic Seas, a steady decrease in the local late-winter production of sea ice has accompanied the increasing trend in the NAO over the past 40 years (Deser *et al.*, 2000). (c) The extension of storm activity to the Nordic Seas under extreme NAO-positive conditions is calculated to increase precipitation along the Norwegian Atlantic Current by approximately 15 cm per winter compared with the

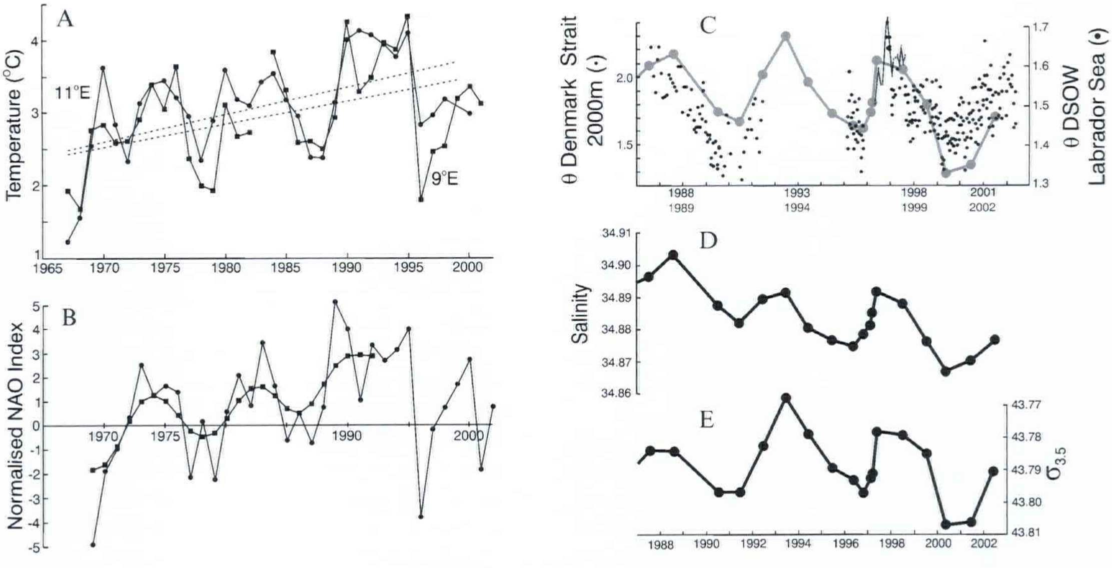

Figure 4. Transfer of a climatic signal from the upper high-latitude ocean to the deep Atlantic. The mean temperatures in the eastern Fram Strait reflect the increased southerly airflow west of Norway associated with NAO-positive conditions. Shown are (A) the 50–500 m mean temperatures (°C) in August–September at 9°E and 11°E on the Sorkapp Section, 76°20'N, 1967–2002, compared with (B) the normalized winter NAO Index (updated from Dickson *et al.*, 1999, 2000). In turn, the temperature of the Denmark Strait overflow 2500 km further south appears to be the lagged reflection of Fram Strait temperatures 3 years earlier. Shown are (C) the 30-day mean temperatures at 2000 m in the overflow core off Angmagssalik SE Greenland (dots). And the temperatures of the descending plume off SE Greenland affect the hydrographic character of the abyssal Labrador Sea a further 1 year later. Shown as circles in (C), (D), (E) are the potential temperature, salinity, and density of the DSOW-derived bottom layer of the Labrador Sea, with time-scales shifted by 1 year.

equivalent NAO-negative conditions (Dickson *et al.*, 2000). Other factors and mechanisms have undoubtedly contributed to the long and gradual but dramatic freshening of the European subarctic seas in recent decades, most of them associated in some way with the amplifying NAO. Blindheim *et al.* (2000) describe a range of factors internal to the Nordic Seas, including an increased freshwater supply from the East Icelandic Current and the narrowing of the salty Norwegian Atlantic Current towards the Norwegian Coast. Thus, while it may not yet be possible to partition the recent freshening of the Nordic Seas into its individual contributory components, it will become clear below that the change is sufficiently widespread and has occurred over a sufficiently deep layer to affect the hydrographic character of both dense overflows crossing the Greenland–Scotland Ridge.

As with the Labrador Sea, a radical interdecadal change in the depth and intensity of open-ocean convection was a fourth major change to affect the Nordic Seas, part of the same coordinated pan-Atlantic pattern of convective activity driven by the changing NAO that we described earlier (Dickson *et al.*, 1996; Verduin and Quadfasel, 1999). From the NAO minimum of the 1960s, the intensity of deep convection in the Greenland Sea became progressively more suppressed as the NAO Index amplified to extreme positive values in the early-to-mid-1990s. At the same time, a steady deepening of intermediate and deep isopycnals in the Greenland Sea from the early 1980s (Boenisch *et al.*, 1997) provides evidence of a collapse of the "domed" density structure in the Greenland Sea as a reduced windstress curl (Jonsson, 1991) supported a less intense cyclonic basin circulation there (Meincke *et al.*, 1992; Rudels and Quadfasel, 1991). Perhaps in compensation there is evidence of an increased influx of deep waters from the Arctic Ocean into the Greenland Sea basin at intermediate depths (Meincke and Rudels, 1995; Meincke *et al.*, 1997).

3. Changes in overflow hydrography: the propagation of the climate signal to the deep Atlantic

The overflow and descent of cold dense water from the sills of the Denmark Strait and Faroe–Shetland Channel is the principal means by which the deep ocean is ventilated and so these overflows are key elements of the global thermohaline circulation (THC). In the period under review, we have evidence that hydrographic variability induced by climate forcing at the surface of the high latitude ocean is being passed on via both intermediate-depth overflows to affect the hydrographic character of the deep and abyssal ocean south of the Greenland–Scotland Ridge. Two such climate "signals" are apparent.

The transfer of near-surface temperature variability from the upper waters of the eastern Fram Strait to the abyssal Labrador Sea: 30-day means of temperature from the core of the Denmark Strait overflow at ~2000 m off Southeast Greenland have provided evidence of a well-defined multiannual-to-decadal variability (dots, Figure 4C). Following Dickson *et al.* (1999), this pattern of change in overflow temperature appears to correspond to the temperature variability of the upper 500 m of the eastern Fram Strait, some 2500 km upstream and 3 years earlier (Figure 4A). In other words, we believe we see evidence – admittedly from short and gappy records – that the hydrographic character of the overflow waters descending from the Denmark Strait sill (DSOW) may be the lagged reflection of high-latitude climate-forcing of the surface ocean in Fram Strait. Tracking these changes further downstream, we also appear to find a clear correspondence between the temperature at 2000 m in the Denmark Strait Overflow core off Angmagssalik, Southeast Greenland and the temperature, salinity, and density of the abyssal layer of the Labrador Sea a further 1 year later (circles, Figure 4C–E), perhaps an early demonstration of a direct climatic effect on the abyssal limb of the Atlantic Thermohaline Circulation.

Transfer of the multi-decadal freshening signal of the Nordic Seas via both overflows to the deep and abyssal layers of the North Atlantic: Below the convectively formed mode water layer of the Labrador Sea in depths of 2300–3500 m, repeat hydrography has indicated a steady freshening over the past three to four decades. At these depths, beyond the reach of deep convection, such a change cannot be due to local climate forcing. Instead, it appears to reflect the large-scale freshening of the upper 1–1.5 km of the Nordic Seas, already described, transferred to the deep Atlantic via both dense overflows.

Hydrographic sections monitoring the outflow of Norwegian Sea Deep Water and Arctic Intermediate Water (NSDW and NSAIW) through the Faroe–Shetland Channel confirm that salinities have decreased almost linearly by ~ 0.01 per decade since the mid-1970s (Turrell *et al.*, 1999); and by constructing salinity time-series at intervals along the spreading pathways of both overflows from their sills to the Labrador Sea, Dickson *et al.* (2002) confirm that the entire system of overflow and entrainment that ventilates the deep Atlantic has rapidly freshened over the past four decades. Both dense overflows, therefore, appear to have tapped and delivered to the headwaters of the THC the freshening signal of the upper Nordic Seas. (For changes in overflow transport, see section 5 below.)

4. Eastward shift of the NAO dipole pattern during the late 1990s

Following its long period of amplification, the winter NAO index suddenly underwent a sharp decrease to a short-lived minimum in the winter of 1995–1996 (Figure 1) with radical and recognizable changes in Atlantic sea level, in the poleward transport of heat by ocean currents, in the pattern of the Atlantic gyre circulation, in the storm climate and precipitation regime over northwest Europe, in the efflux of ice from the Arctic, and on cod recruitment. Since that temporary minimum, as the NAO Index recovered towards more positive values, we have noted a new type of NAO behaviour. Comparing the Atlantic sea level pressure anomaly pattern for the early 1990s with those for winters 1999 and 2000, we find that the NAO pattern in these recent winters was displaced slightly towards the east or northeast.

This subtle change had little effect on the subtropical gyre of the Atlantic or along its eastern boundary to the Barents Sea, where there was evidence of the widespread warming we would normally associate with the positive NAO. However, in the northwest Atlantic, this slight eastward retraction of the "normal" NAO pattern made an important difference to the marine climate of the Labrador Sea and West Greenland Banks. Instead of a chill and strong northwesterly airflow promoting cooling there as it did in the early 1990s with intense and deep-reaching convection (to > 2300 m) in the Labrador Sea, we now find that any northwesterly airflow is mainly confined to the east of Greenland so that the Labrador Sea is instead occupied by light or southerly anomaly winds.

Thus reports from the West Greenland Banks in these winters were of continued warmth rather than cooling, and convection in the Labrador Sea remained weak and shallow. The latter change was particularly dramatic. The intense and deep-reaching convection that we have come to associate with NAO-positive conditions not only produces a deep homogeneous LSW water mass, but drives a strong cyclonic circulation in the Labrador Sea. With that stimulus removed, the centre of the Labrador Sea was occupied in these two anomalous winters by a stack of different water masses, reflecting not only the past products of a weakening convection, but the lateral intrusion of other water masses from a variety of sources around the boundary.

This observation (that NAO-positive conditions can locally drive quite different ocean responses depending on the detailed configuration of the associated slp pattern) offers a timely reminder of the limitations of using a simple 2-point pressure difference as our index of NAO behaviour. It may offer a convenient shorthand indication of atmospheric behaviour and ocean response but it may not capture important detail. It remains to be seen whether this eastward shift in the NAO dipole is just further evidence of the chaotic nature of the atmospheric circulation (NAO noise) or part of a more concerted trend in NAO behaviour. Hilmer and Jung (2000) suggest that the centres of maximum interannual variability in slp associated with the NAO have been located further to the east since the late 1970s, and some climate simulations (Ulbrich and Christoph, 2000) suggest that one accompaniment of CO_2 warming will be an eastward or northeastward shift in the locus of the two cells that form the NAO dipole. So it is possible (but not yet "likely") that the more easterly distribution we have experienced in winters 1999 and 2000 may be part of that shift.

5. Issues of NAO forcing in the Atlantic sector: detection, prediction, and change

Of the 13 recurrent atmospheric circulation modes world-wide considered by Barnston and Livesey (1987), the NAO is among the most robust. During the decade under review, the winter NAO attained its most extreme and persistent positive state in the instrumental record and, unsurprisingly, the ocean-atmosphere system reflects this. Century-long extrema were experienced in parameters as diverse as storminess over the Norwegian Sea, the strength of the Atlantic gyre circulation, the depth and intensity of Labrador Sea convection, and the hydrographic character of the northern overflows. All of these changes (and others) are in some way attributable to NAO forcing. And these four cases are enough to explain why the signature of NAO forcing is identifiable from the ocean surface to abyssal depths.

Three main scientific issues remain: (1) detecting the NAO response in our sparse observing system of standard stations and sections, (2) assessing the causes, effects, and predictability of change in the NAO itself, and (3) determining the mutual involvement of the Atlantic's ocean and atmosphere in global change. These issues are not mutually exclusive.

Even with what might be termed 'standard' NAO behaviour, the ocean or ecosystem response is likely to exhibit different degrees of delay, from the local and immediate to the multi-year delays imposed by advection. Very recent model experiments (Eden and Willebrand, 2001) alert us to the probable co-existence of a fast (intra-seasonal) barotropic response and a delayed (time scale 6–8 year) baroclinic response to the same NAO-positive forcing. The difficulties of detecting and tracing the ocean's response in our available record are compounded by the fact that NAO behaviour may not be standard. The slight eastward shift of the NAO dipole pattern in certain winters of the late 1990s (section 5 above) was enough to reverse the cooling and freshening tendency of the Northwest Atlantic mode water in the early 1990s (one of the largest changes in oceanography) and warm the West Greenland Banks, despite a positive NAO Index. Yet some such eastward shift is an anticipated part of NAO behaviour in some simulations (Ulbrich and Christoph, 1999).

'Detection' would thus seem to presuppose some knowledge of how the NAO might vary. In the instrumental record in fact there is little evidence for the NAO to vary on any preferred time scale. Large changes can occur from one winter to the next, and there is also a considerable amount of variability within a given winter season (Nakamura, 1996). This is consistent with the notion that much of the atmospheric circulation variability in the form of the NAO arises from processes internal to the atmosphere, in which various scales of motion interact with one another to produce random (and thus unpredictable) variations (Wallace and Lau, 1985; Lau and Nath, 1991; Ting and Lau, 1993; Hurrell, 1995b).

There are, nonetheless, periods when anomalous NAO-like circulation patterns persist over many consecutive winters, as with the persistent NAO-positive conditions of most of the 1990s. In fact, as already described, the magnitude of the recent upward trend is unprecedented in the observational record (Hurrell, 1995a; Thompson *et al.*, 2000) and, based on reconstructions using palaeoclimate and model data, perhaps over the past several centuries as well (Osborn *et al.*, 1999; Stockton and Glueck, 1999). The question therefore arises as to whether such unusual behaviour is explicable – even predictable. But whether such low frequency (interdecadal) NAO variability arises from interactions of the North Atlantic atmosphere with other, more slowly varying, components of the climate system such as the ocean (McCartney *et al.*, 1997; Rodwell *et al.*, 1999; Mehta *et al.*, 2000; Hoerling *et al.*, 2001), whether the recent upward trend reflects a human influence on climate (Corti *et al.*, 1999; Osborn *et al.*, 1999; Shindell *et al.*, 1999; Ulbrich and Christoph, 1999; Fyfe *et al.*, 1999; Gillett *et al.*, 2000 and in press; Monahan *et al.*, 2000), or whether the longer time scale variations in the relatively short instrumental record simply reflect finite sampling of a purely random process (Wunsch, 1999), is a topic which remains, for the present, unresolved.

The onset of global change adds an additional unknown to NAO variability. The analysis of temperature change by latitude and time (Delworth and Knutson, 2000) appears to show clearly enough that the recent observed warming is global and thus quite distinct from the earlier episode of high latitude warming in our sector during the middle decades of this century. The third IPCC Report concludes more categorically than before that "there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities" (Anon., 2001). And coupled climate models seem to be reaching some kind of consensus that a slowdown of North Atlantic Deep Water (NADW) production will be one outcome. However, the issue of whether such effects are yet evident in our ocean time-series remains open. For the first time, Hansen *et al.* (2001) have been able to couple a moderately long, modern set of direct flow measurements to a half-century of frequent hydrography at OWS M to provide evidence of a 20% decrease in the coldest and densest part ($t < 0.3°C$, $\sigma t > 28.0$) of the overflow from the Faroe Bank Channel since 1950, but the necessary companion data sets on Denmark Strait outflow or on Atlantic inflow to the Nordic Seas are not yet adequate to confirm the point. Overflow hydrography has detected a multi-decadal freshening of both overflows that can be followed into the deep and abyssal layers downstream (Dickson *et al.*, 2002), but we are only just beginning to detect the subtle effects of this change on deep and abyssal density.

Conclusion

In a decade of stark climatic signals, these unresolved issues leave only one conclusion. Our past hydrographic record has provided clear enough evidence of the socio-economic impacts of ocean climate changes in our sector, and our present records are already hinting that certain important global change processes may be controlled or modulated by the oceanic exchanges that connect the Arctic Ocean to the open Atlantic via Nordic Seas. Our observational series must be maintained to keep pace with such changes, and broadened in key locations until present uncertainties are resolved.

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