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Variability in the ICES/NAFO region between 1950 and 2009: observations from the ICES Report on Ocean Climate

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The ICES Report on Ocean Climate presents the latest information on the status and trends of sea temperature and salinity in the North Atlantic and Nordic Seas. It is the main product of the ICES Working Group on Oceanic Hydrography, published annually. Bringing together multiple time-series from across the ICES and NAFO regions offers insight into the concurrent spatial and temporal trends in ocean temperature and salinity. This paper presents an overview of the physical variability in the North Atlantic Ocean at decadal and longer time-scales and reviews the current state of understanding of the causes and mechanisms of this variability. Between the 1960s and the 1990s, the North Atlantic Oscillation (NAO) index increased from a persistent negative phase in the 1960s to a strong positive phase during the 1980s and early 1990s. However, during the decade 2000–2009, because of shifts in atmospheric pressure patterns, the NAO was weak and the NAO index was not a good indicator of atmospheric forcing. Marked changes were also observed in oceanographic indices such as the Subpolar Gyre index during the mid-1990s and, as a consequence, conditions in the decade 2000–2009 have been very different from those of the previous four decades.

Keywords: circulation, multidecadal variability, North Atlantic, salinity, temperature.

Introduction

Each year since 1999, the ICES Working Group on Oceanic Hydrography (WGOH) has generated a summary of atmospheric and hydrographic conditions in the North Atlantic, published as the ICES Report on Ocean Climate (IROC), with the latest edition at the time of writing being Hughes *et al*. (2010), describing the year 2009 (hereafter referred to as *IROC2009*). The data presented in the IROC are described to provide a record of observed physical variability in the North Atlantic over the past decade and to put this into the context of known longer-term patterns of variability. The discussion is restricted to patterns of variability significant at multidecadal and decadal time-scales rather than examining in detail changes within the decade.

A thorough review of the large body of relevant atmospheric and oceanographic research across the North Atlantic is beyond the scope of this paper. Holliday *et al*. (2011a) prepared a recent review of the hydrographic variability across the North Atlantic, and Dickson *et al*. (2008) examined the linkages between the North Atlantic and Arctic in relation to the climate change. Previous decadal symposia and review publications (Meincke *et al*., 1984; Dickson *et al*., 1992; Turrell *et al*., 2003; Colbourne and Drinkwater, 2004) also offer excellent records of the developments in understanding of physical variability in the North Atlantic and its influence on marine ecosystems. We therefore acknowledge the large number of papers cited within the above reviews and limit citations here to publications from the period 2001–2011.

The ICES Report on Ocean Climate

The aim of IROC is to provide relevant and useful annual summaries of physical oceanographic conditions in the North Atlantic. The time-series data presented in the report are derived from regularly occupied hydrographic sections, high-quality data that are only available at a limited number of stations throughout the North Atlantic. Although the IROC presents data at some 32 sites around the North Atlantic, with most areas represented, there are gaps in the coverage particularly in the central ocean basins. With fewer than ten stations with data extending back before the 1950s, spatial coverage reduces significantly for the earlier periods.

To fill the gaps in time and space, the *in situ* oceanographic measurements can be supplemented with other datasets that offer a more global coverage, e.g. global gridded sea surface temperature (SST) datasets such as those of OISST and HADISST. A comparison of gridded SST datasets with the *in situ* IROC data (Hughes *et al*., 2009) revealed some marked differences, particularly in the northern latitudes and at monthly time-scales which, although not significant enough to detract from the overall value of the datasets for climate studies (Hansen *et al*., 2010), do pose limits to their usefulness as proxies for *in situ* data to ecosystem research.

Although the 2011 report will be the 11th edition, the content of the IROC is still being developed. During the past few years, a new gridded dataset (North Atlantic Gridded Data) has become available and is now presented annually (Figures 4–7 of *IROC2009*). Combining oceanographic data from stations, buoys, and moorings submitted in near real time with profile data from ARGO floats, temperature and salinity fields are estimated on a half degree grid (Gaillard *et al*., 2009). This dataset offers a snapshot of both temperature and salinity at surface and subsurface levels. As a new product, however, it has limited temporal coverage (starting in 2003) and rather sparse coverage in shallower shelf regions. The current sparsity of data in coastal regions is not filled by ARGO floats, because they are designed for deep water, but could be improved if more institutes reported their oceanographic data in near real time to the appropriate data centres. Although the North Atlantic Gridded dataset is still in development, it offers great potential, and a review/validation of the gridded data with the *in situ* data from the IROC is in preparation.

A potential future use of the North Atlantic Gridded dataset is in the examination of spatial and temporal variability of the mixed layer depth (MLD; Figure 8 of *IROC2009*). The variability of the mixed layer controls the biological productivity of the ocean, and understanding the processes that govern changes in the MLD will aid understanding of physical controls on ecosystem processes. The simple calculation of MLD presented in the IROC is based on temperature only and is not suitable for areas, e.g. those in which salinity is important (e.g. the Gulf of Lion, the Labrador Sea, and the Greenland coast), or where stratification is weak. Despite this limitation, it is hoped that the product will have some value for future ecosystem studies.

North Atlantic circulation

A description of the key circulation features in the North Atlantic can be found in Holliday *et al*. (2011b) and summarized below. The Atlantic Ocean circulation (Figure 1a) is dominated by two systems: first, in the upper layer, there is wind-driven circulation of two large gyres (subtropical and subpolar); second, there is Meridional Overturning Circulation (MOC), which draws warm saline surface waters towards the Arctic, with a return of colder, fresher water at depth. The MOC and thermohaline circulation are similar and related concepts, and the difference between the two is explained by Rahmstorf (2006).

The deep and intermediate circulation that forms the lower limb of the MOC is shown in Figure 1b. The Atlantic MOC is thought to be vulnerable to changes in global climate, and if it ceased, the climate of northern Europe could cool considerably (Vellinga and Wood, 2008). Models used to predict future ocean circulation under various climate scenarios predict long-term (multidecadal) slowing of the MOC as carbon dioxide concentrations rise (although with a high level of uncertainty; Meehl *et al*., 2007). For this reason, monitoring and understanding the variability of ocean circulation and its driving processes is an important part of climate research, and continuation of the existing monitoring network such as that presented in IROC is an essential component.

Drivers/indicators of variability in the North Atlantic

Global warming/climate change

The decade 2000–2009 was the warmest decade in the instrumental record. Global average (land and sea) temperatures reached record high levels in 2009 (Hansen *et al*., 2010). This global trend of increasing temperature is the result of the anthropogenic input of greenhouse gases into the atmosphere: the global warming/climate change signal (Bindoff *et al*., 2007). Temperatures over the land have warmed at a faster rate than those in the ocean, because of the thermal inertia of the oceans (Hansen *et al*., 2010). The global temperature signal shows some evidence of multidecadal variability (Figure 2a), but not as large as that observed in North Atlantic mean SSTs.

Anthropogenically driven climate change has led to other changes in the ocean–atmosphere system, not just warming. As temperatures increase, the atmosphere is able to hold and transport more water vapour, and this is likely to result in enhancement of the hydrological cycle and a resultant increase in precipitation. As measurements of the global water cycle are difficult, and records sparse and incomplete, researchers have examined trends in ocean salinity data, which provide evidence of such enhancement over the past 30–50 years (Durack and Wijffels, 2010; Helm *et al*., 2010). Investigations of the global water cycle are likely to become an important focus of climate research, and there is a need to increase the volume and quality of salinity data collected in the ocean (Lagerloef *et al*., 2010).

Atlantic multidecadal variability/oscillation

Although the surface temperature of the North Atlantic shows a marked warming trend, the variability is much greater than observed in the global climate trend. The strong pattern of multidecadal variability was termed the Atlantic multidecadal oscillation (AMO; after Kerr, 2000), and the term Atlantic multidecadal variability (AMV) is also used (e.g. Sutton and Hodson, 2003; Keenlyside *et al*., 2008; Frankcombe *et al*., 2010). Variability at these time-scales has been observed in SST and parameters such as salinity (Reverdin, 2010), sea level, and sea-ice transport (Frankcombe *et al*., 2010). There is evidence that the signal of observed multidecadal variability can also be seen in ecosystem parameters, examples including salmon recruitment (Friedland *et al*., 2009), cod populations (Drinkwater *et al*., 2009), and coastal phytoplankton distribution (Dixon *et al*., 2009).

The difference in terminology from "oscillation" to "variability" is important. The term oscillation implies that we know that there is a driving mechanism that will change between a positive and a

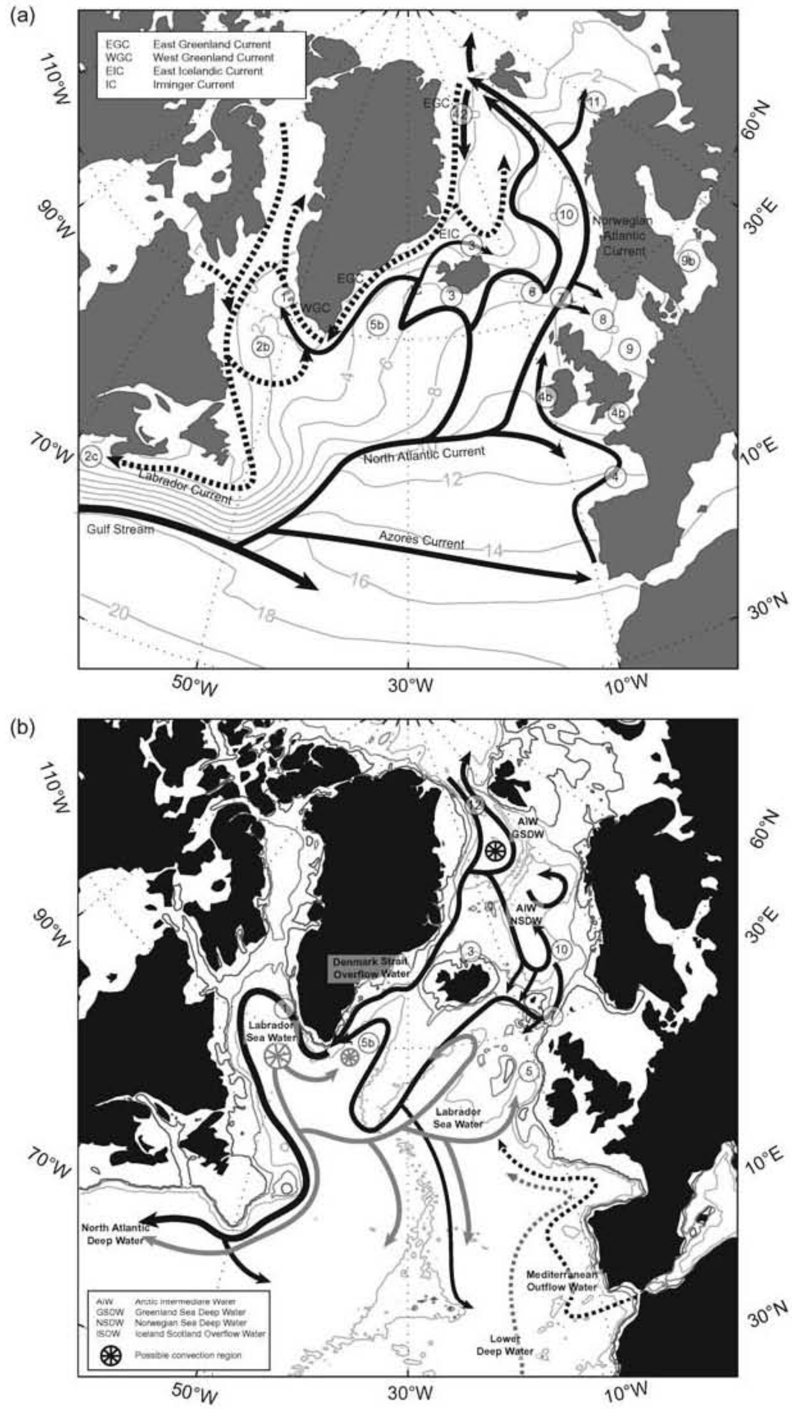

Figure 1. (a) Schematic of the pathways of the major near-surface currents of the North Atlantic, superimposed on a map of average SST for February (1971–2000) SST data from www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.html. Solid arrows represent the warm, saline waters originating in the Gulf Stream/North Atlantic Current, and dashed arrows represent cold, fresher water originating in the Arctic Ocean. (b) Schematic of the major pathways of the intermediate (light grey) and deep (dark grey) waters of the North Atlantic superimposed on a map of the bathymetry. Dashed lines indicate warmer intermediate waters originating in the subtropical region.

negative state over some known period. Using the term variability, perhaps more accurately reflects the irregular periodicity of the variability. Estimates of between 20 and 100 years exist in the literature, as reviewed by Frankcombe *et al.* (2010), both in the instrumented observations and in re-creations using proxies (e.g. Knudsen *et al.*, 2011). Franckombe *et al.* (2010) also show that choosing smaller or larger regions to calculate the index could identify two distinct but related modes of variability, with periods of 20–30 and 50–70 years. The term AMO is, however, still in common use, and we refer to it here in relation to the AMO index.

The AMO index has been developed as an indicator of the pattern of multidecadal variability and is typically derived by

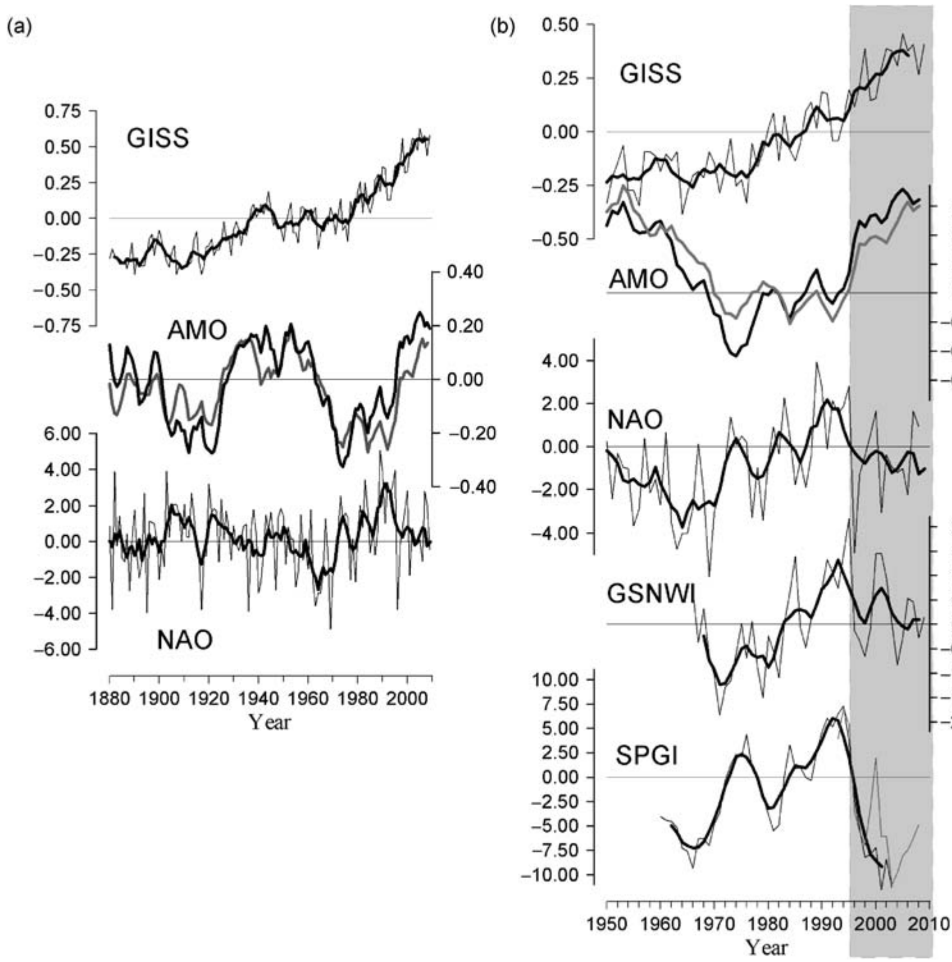

Figure 2. Selected indicator time-series for the North Atlantic. (a) Data period 1880 – 2009, with anomalies referenced to the long-term mean: global land and ocean temperature (GISS), the AMO (v. 1 in black and v. 2 in grey), and the NAO. Thin black lines show the annual values, and thick lines are the 5-year running means. (b) Shorter time-series over the period 1950 – 2009, with anomalies referenced to the 1971 – 2000 mean: GISS, the AMO (v. 1 in black and v. 2 in grey), the NAO, the GSNWI, and the SPGI. Thin lines show the annual values, and thick lines are the 5-year running means. The shaded area highlights the period 1995 – 2010. Data sources are: GISS, annual mean, http://data.giss.nasa.gov/gistemp/; AMO v. 1, annual mean, http://www.esrl.noaa.gov/psd/data/correlation/amon.us.long.data, using the method proposed by Enfield *et al.* (2001), with the Kaplan SST dataset and removing the global climate signal as a linear trend; AMO v. 2, annual mean, http://www.cgd.ucar.edu/cas/catalog/climind/AMO.html, using the method proposed by Trenberth and Shea (2006), using the HADISST dataset and removing the global climate signal as the mean global SST; NAO, December – March, http://www.cgd.ucar.edu/cas/jhurrell/nao.stat.winter.html; GSNWI, annual mean, http://www.pml-gulfstream.org.uk/data.htm; SPGI, after Hátún *et al.* (2005), extended to 2008, with the black line representing the gyre index calculated from modelled data (1960 – 2005) and the grey line showing the gyre index obtained from altimetry observations (1992 – 2008).

averaging the SST over a selected area of the North Atlantic and removing the fitted trend (upwards), which represents the global warming response (Enfield *et al.*, 2001; Knight *et al.*, 2006). Therefore, the AMO index intends to represent variability in the North Atlantic caused by mechanisms other than anthropogenic climate change. For this purpose, it is important that the index does not alias the anthropogenic climate-change signal, and this is one obvious difficulty with it. To address this difficulty, alternative methods to derive an AMO index have been derived, and these can produce slightly different results (Figure 2a). The methods differ in the way they calculate the signal of anthropogenic climate change, either assuming it to be a linear trend (e.g. Kerr, 2000; Enfield *et al.*, 2001) or using global mean temperatures as a proxy for anthropogenic climate change (e.g. Trenberth and Shea, 2006; Ting *et al.*, 2009). Two versions of the AMO index are presented in Figure 2. Although there are small differences, both versions have colder periods between 1900 and 1920 and between 1970 and 1990, and warmer periods between 1930 and 1960 and in the present period since the mid-1990s. The long periodicity of the AMO index leads to difficulties with calculating a reference mean, and this should be considered when examining the time-series. Although this does not affect the pattern, it means that there is little point in attaching significance to the timing of crossing points (change from negative to positive index), because this is heavily dependent on the reference period. Figure 2a and b illustrates this point by plotting the AMO index with two different reference periods.

The Gulf Stream north wall

The transport and location of the Gulf Stream provides a key link between processes in the subtropics (and tropics) and the Subpolar Gyre. The Gulf Stream transport is highly wind-driven and very variable from year to year, but there is no observational evidence for a trend over the past 50–80 years (Rossby *et al.*, 2010). There is evidence that the position of the Gulf Stream is linked to atmospheric patterns such as the North Atlantic Oscillation (NAO; Hameed and Piontkovski, 2004). Observational (Rossby *et al.*, 2010) and modelling studies (Joyce and Zhang, 2010) indicate a link between the position of the Gulf Stream and the MOC. A common thread in all these results is that the position of the Gulf Stream is affected by the production of cold, fresher water in the Labrador Sea and the surrounding shelves (also related to the NAO and the strength of the Labrador Current; Petrie, 2007), which then spreads south towards the Gulf Stream.

As the largest current in the North Atlantic, the Gulf Stream is an obvious indicator of environmental conditions, and an index known as the Gulf Stream north wall index (GSNWI) was derived in 1980 by Taylor (2002). The GSNWI has been used to describe conditions on the eastern seaboard of the United States (Borkman and Smayda, 2009), but it has also been used as a descriptor for environmental conditions farther afield, including plankton on the European shelf (Taylor, 2002; Allen *et al.*, 2006; Eloire *et al.*, 2010). The strong relationship between the NAO and the GSNWI is clear in Figure 2. The index shows a similar pattern to the NAO over the period of observation, and it has been relatively low and variable throughout the decade 2000–2009 (Figure 2b).

Subpolar Gyre

The circulation of the Subpolar Gyre changes on interannual and decadal time-scales (Curry and McCartney, 2001; Bersch, 2002; Hakkinen and Rhines, 2004), and it has been shown to have an influence on the properties of water masses circulating along the eastern side of the North Atlantic. This is because expansion or contraction of the gyre leads to changes in the position of the Subpolar Front. When the Subpolar Gyre weakens/contracts, the Subpolar Front will move west, resulting in more water from the eastern North Atlantic (warmer and more saline) travelling polewards along the eastern boundary of the North Atlantic. Conversely, a stronger Subpolar Gyre leads to more water from the western North Atlantic, which is colder and fresher (Holliday, 2003; Hátún *et al.*, 2005). Hátún *et al.* (2005) developed a Subpolar Gyre index (SPGI) which shows that the gyre strengthened from the start of the record (1960s) to the mid-1990s, then decreased rapidly (Figure 2b).

An alternative way to measure the effects of Subpolar Gyre forcing has been used by Hakkinen and Rhines (2009). They use the relationship between windstress and northward current transport: where the windstress curl is negative, transport is northwards. The line of zero windstress curl therefore marks the boundary between regions with northward and regions with southward transport. Hakkinen and Rhines (2009) demonstrated that marked changes in the position of this line in recent decades (since the mid-1990s) relate to transport pathways as measured by ocean drifters.

Atmospheric forcing

As well as driving ocean circulation, atmospheric processes are important drivers of the exchange of heat between ocean and atmosphere (heat flux) and the changing freshwater content of the ocean (evaporation–precipitation balance, and freshwater inputs). Holliday *et al.* (2011b) review the links between ocean and atmospheric processes in the North Atlantic.

The subpolar North Atlantic is a region where on average the oceans give off heat to the atmosphere, whereas in the subtropical gyre, the oceans gain heat from the atmosphere. In shallower coastal regions, however, net heat flux is usually around zero. As a result of the evaporation–precipitation balance, the high-latitude North Atlantic has a net gain of freshwater, whereas the subtropical North Atlantic is mainly evaporative (as illustrated in Figure 1 of Lagerloef *et al.*, 2010).

The NAO is one of the dominant patterns of atmospheric pressure variability and has a significant impact on oceanic conditions (Visbeck *et al.*, 2001). The NAO is closely related to the larger pattern of the Arctic Oscillation (Ambaum *et al.*, 2001; AMAP, 2009) and the more regionally important pattern known as the East Atlantic pattern. The NAO index is a simple device that has been used to describe the state of the NAO (Hurrell, 1995; Hurrell and Deser, 2009), and the Hurrell winter (December–March) NAO index is most commonly used and is the index presented in the IROC. During winters with a strong NAO index, the ocean responds quickly and the effects can continue throughout the following year. The NAO winter index has the potential therefore to be used as a predictor for conditions in the following year, and during the early 1990s, it was used in this way within the IROC.

Although the NAO is the dominant pattern of atmospheric pressure in winter, it is not the only one. Hurrell and Deser (2009) show that there are four typical winter atmospheric states, and in additional to NAO positive and NAO negative, they describe patterns termed “Blocking High” and “Atlantic Ridge”. Over the Atlantic as a whole, the NAO pattern only accounts for one-third of the total variance in winter sea level pressure (SLP).

Between the 1960s and the 1990s, the NAO index increased from a persistent and negative phase in the 1960s to a strongly positive phase during the 1980s and early 1990s (Figure 2). However, in 1997, this trend came to an abrupt end. Examination of SLP anomalies (Figure 3a) during the decade 2000–2009 reveals an eastward shift in the centres of the Atlantic Low and Azores High. By examining the strength of the monthly NAO index, it is possible to calculate the dominance of the NAO signal during each winter period. Using the Hurrell (1995) definition of a strong index as >1 or <-1, the occurrence of strong negative or strong positive NAO phases can be counted to determine the overall dominance or strength of the NAO pattern in each decade.

In the decade 2000–2009, only about half (21 of a possible 40) of the winter (December–March) months had a strong NAO index, and this is the lowest value of any decade in the record. In this way, we define 2000–2009 as a weak NAO decade (Figure 3b). The decadal mean value of the annual winter NAO index (0.53) was low, and despite there being some strongly positive and strongly negative years (Figure 3a), these did not persist for more than 1 year, compared with the period between 1960 and 1997, when strong positive/negative states were observed to persist for up to 3–5

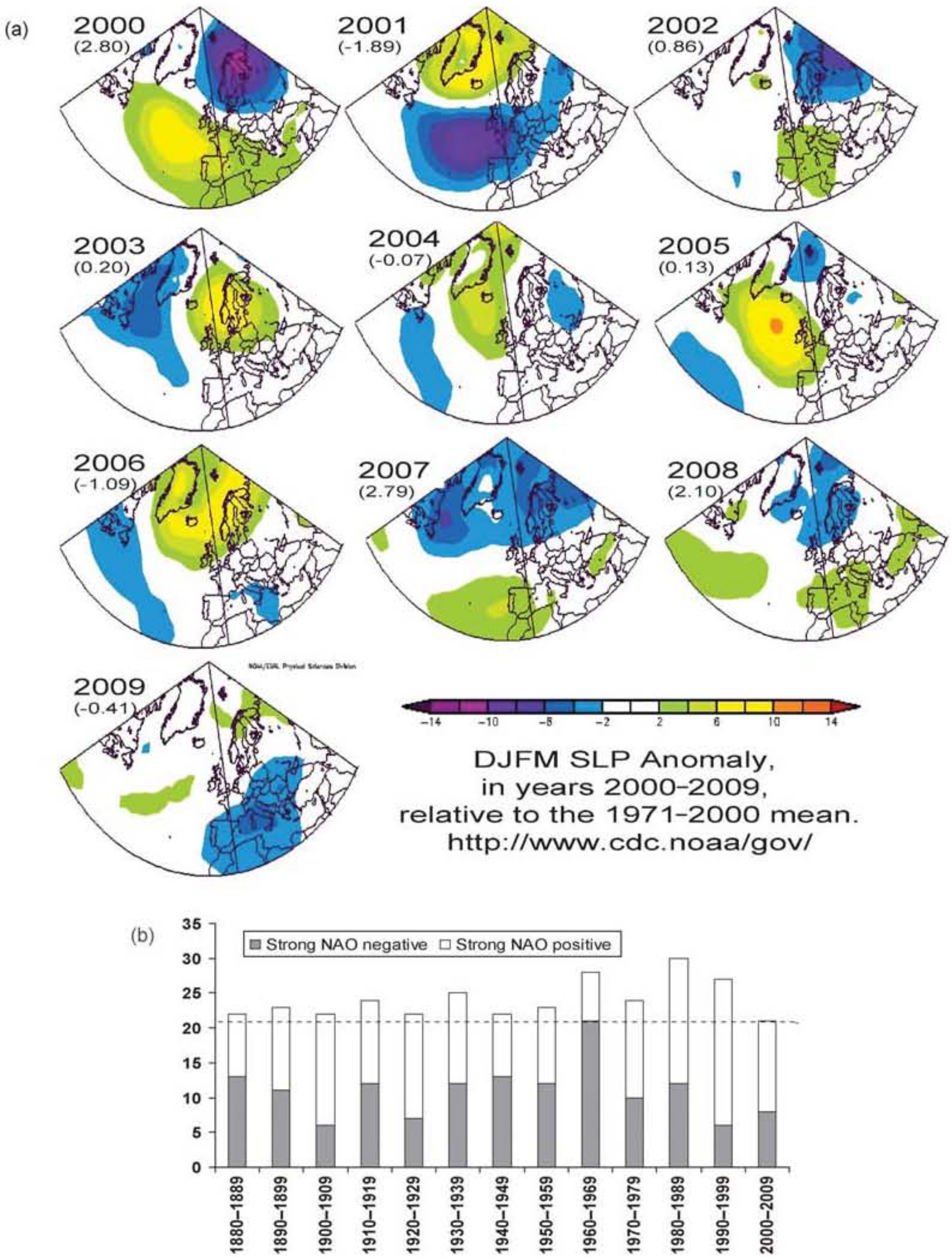

Figure 3. (a) Mean winter (December–March) SLP anomaly for the years 2000–2009 relative to the long-term mean for 1971–2000. Data from http://www.cdc.noaa/gov/. Values in parenthesis indicate the Hurrell winter (December, January, February, March; DJFM) NAO index for that year. (b) Decadal occurrence of strong monthly NAO+ and NAO− states for the winter period (DJFM) using the Hurrell winter (DJFM) NAO index. A strong positive (negative) index is defined as greater (less) than +1 (−1), following Hurrell (1995). The decade 2000–2009 had the least occurrence of a strong NAO pattern in the record and is defined here as a weak NAO decade. This finding is not sensitive to the threshold chosen; the decade could be defined as a weak decade at any chosen threshold between 0.5 and 2.

years (Hurrell *et al*., 2003). For this reason, we describe 2000–2009 as a variable NAO decade. It should be noted that winters of 2010 and 2011 were characterized by strongly negative NAO patterns.

Hydrographic conditions in the North Atlantic

The interannual variability in the upper ocean over the past decade is summarized in Figures 1 and 2 and Tables 1 and 2 of *IROC2009*, which show temperature and salinity anomalies at specific locations around the North Atlantic for the period 2000–2009. Using the same datasets, Figure 4 shows the multidecadal variability as pentadal mean temperature and salinity anomalies since 1950. Averaging the data in 5-year chunks removes higher frequency variability (it is a helpful coincidence that some of the marked changes in conditions arise at the end of pentads) and

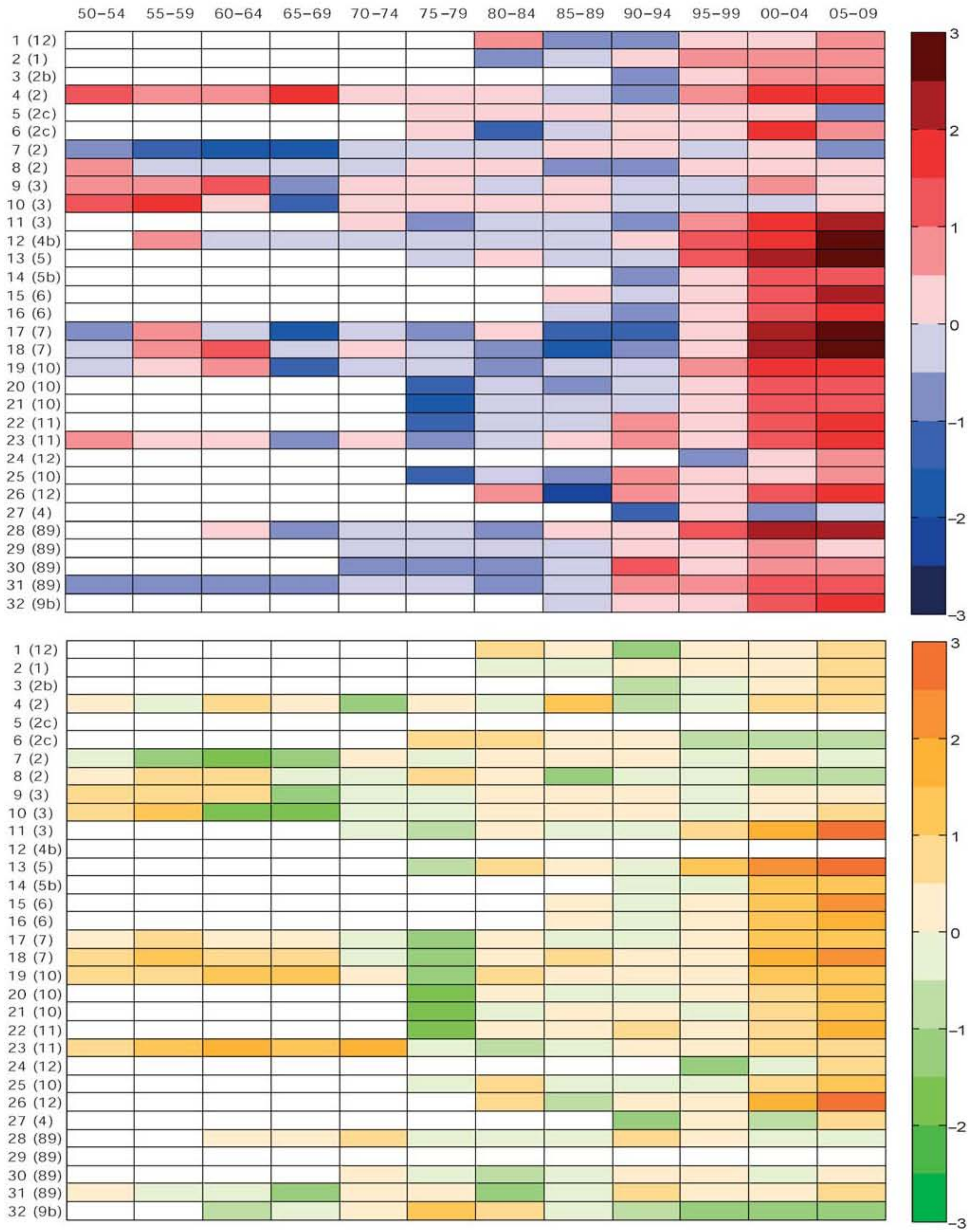

Figure 4. Pentadal mean upper ocean temperature (upper) and salinity (lower) anomalies at 32 selected locations across the North Atlantic since 1950 (including bottom temperature and salinity over two shallow banks). The anomalies are calculated relative to a long-term mean and normalized with respect to the standard deviation (e.g. a value of +2 indicates 2 s.d. above normal). Colour intervals of 0.5; red/oranges are positive/warm/saline, blue/greens are negative/cold/fresher. Index numbers refer to the datasets as described in Table 3 of *IROC2009*, and numbers in parenthesis refer to areas marked indicated in Figure 1.

illustrates the long-term trends more clearly. When interpreting the patterns in Figure 4, the uneven spatial distribution of the time-series should be noted, particularly the bias towards the eastern North Atlantic.

The presentation of data in Figure 4 illustrates the overall concurrent trends, but there is also a number of marked regional differences in the patterns of variability between various regions of the North Atlantic. As an example of this variability, Figure 5a

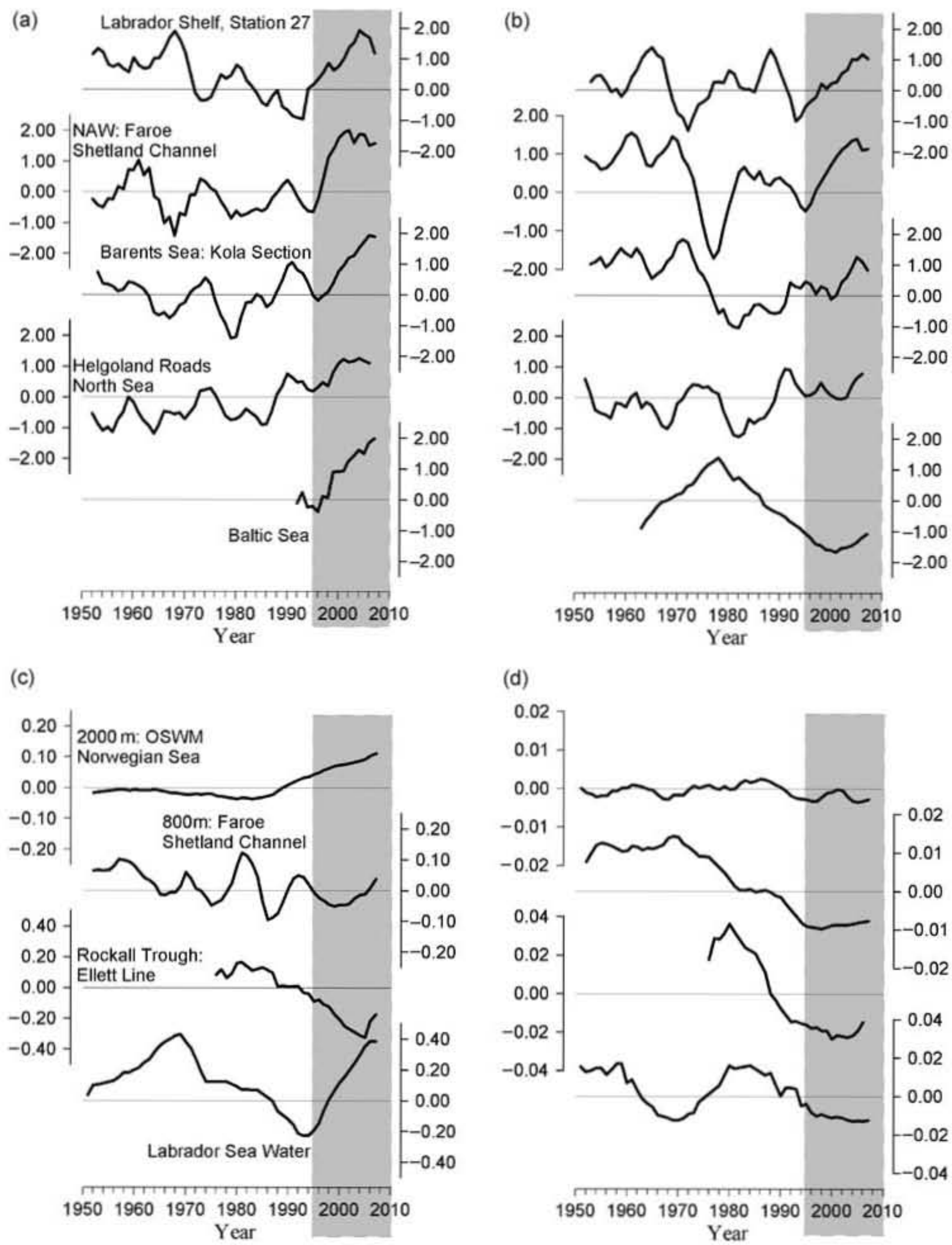

Figure 5. Selected time-series of smoothed (5-year running mean) ocean temperature (left) and salinity (right) anomalies, 1950–2009. Upper panel, normalized anomalies (units are standard deviations from the 1971–2000 mean) from five stations in the upper layer of the North Atlantic and Nordic Seas. Lower panel, anomalies (difference from the 1971–2000 mean) at four stations in the deep and intermediate layers. The shaded area highlights the period 1995–2010. Temperature and salinity anomalies are published in the IROC, which is available online from: http://www.ices.dk/marineworld/oceanclimate.asp. Data providers are: Barents Sea, Kola Section, Knipovich Polar Research Institute of Marine Fisheries and Oceanography, Russia; eastern North Atlantic, North Atlantic Water, Faroe–Shetland Channel, Marine Scotland, Aberdeen, UK; western North Atlantic, Labrador Shelf, Station 27, and Station BY15, Northwest Atlantic Fisheries Centre, Canada; North Sea, Helgoland Roads, German Bight, Biologische Anstalt Helgoland, Germany; Baltic Sea, east of Gotland, Station BY15, Swedish Meteorological and Hydrological Institute; Norwegian Sea, Ocean Weather Station "M", Geophysical Institute, University of Bergen, Norway; Overflow, 800 db level, Faroe–Shetland Channel, Marine Scotland Science, Aberdeen, UK; North Atlantic Intermediate, Ellet Line, Rockall Trough, Scottish Association for Marine Science (SAMS), Oban, and National Centre for Oceanography, Southampton, UK; central Labrador Sea, AR7W Section, Bedford Institute of Oceanography, Fisheries and Oceans, Canada.

and b shows the smoothed (5-year running mean) trends in temperature and salinity anomaly at five different sites in the upper layers (broadly representative of the western North Atlantic, the eastern North Atlantic, high latitudes, the North Sea, and the Baltic Sea).

Although most of the data presented in the IROC are from the upper ocean, there are some time-series extracted from deep and intermediate waters. Temperature and salinity anomalies from the four stations with the longest dataset are presented in Figure 5c and d. Data from 2000 m at Ocean Weather Station Mike (OWSM) in the Norwegian Sea show conditions in the Nordic Seas. Data at 800 m in the Faroe Shetland Channel are broadly representative of the waters overflowing into the North Atlantic (Dickson *et al.*, 2002). Data from the Labrador Sea at 1300 m show the properties of this deep layer, and data from 1800–2000 m in the Rockall Trough are representative of Intermediate Waters in the North Atlantic (mostly influenced by Labrador Sea Water).

Upper layers of the North Atlantic Ocean

The temperature time-series (Figures 4a and 5a) clearly show a warming trend in the upper ocean, with higher than normal temperatures in most of them, and record high temperature anomalies in 25 of the 32 time-series during the decade 2000–2009. A strong multidecadal signal can also be seen in the upper-layer temperature and salinity data. Warmer than normal conditions have persisted since 1995, and for those time-series that are long enough, there was seemingly also an earlier warm period in the 1950s and 1960s (Figures 4 and 5). Before the 1990s, temperature variability in the eastern and western North Atlantic appeared to have been out of phase (Figure 5a), but during the past decade, temperatures on both sides of the Atlantic have been high.

A strong decadal to multidecadal pattern can be observed in the salinity signal, with a marked salinity minimum in 1970–1974 with further salinity minima in the 1980s and 1990s. Since the mid-1990,s salinity has increased significantly in the Northeast Atlantic and Nordic Seas. Although salinities in the past decade have in some places reached record high values. The time-series that are long enough show that the period 1950–1960 was also one of high salinity (e.g. in the Kola section and the Faroe–Shetland Channel). Surface data from the North Atlantic collected from underway measurements show the same pattern of high salinity in the 1950s and 1960s (Reverdin, 2010).

Like other areas of the North Atlantic, an increasing trend in SST has been observed in the Baltic. In the IROC, temperature and salinity since the 1960s in the Baltic proper are used to describe conditions, alongside the winter ice extent (IROC, Area 9b). Although the temperature time-series reported in the IROC only extends back to the 1990s, there is evidence from other measurements of a strong warming trend (Siegel *et al.*, 2008). As the temperature of the Baltic has increased, so ice cover has declined, with the least ice extent since the 1960s observed during winter 2007/2008 (Figure 62 of *IROC2009*).

The pattern of surface salinity in the Baltic, however, is totally opposite (Figure 5b) to that of the eastern North Atlantic and Nordic Seas (e.g. OWSM). Salinity in the Baltic Seas reached a maximum in the period 1975–1979 as a result of sporadic (usually annual) inflows of Atlantic water (Matthäus *et al.*, 2008). These inflows stopped between 1978 and 1993, and as a result, the surface salinity reached a minimum value at the end of the 1990s. Inflows have been more sporadic since 1993, with an apparent enhancement and change in dynamics since 2002/2003 (e.g. Borenäs and Piechura, 2007). As a result, surface salinity increased during the decade 2000–2009 (Figure 5b).

Deep and intermediate waters

As a consequence of the lack of deep convection since the early 1970s, the intermediate layers of the Greenland, Iceland, and Norwegian Seas are now filled with water that comes from the Arctic (Blindheim and Østerhus, 2005). As this water mass is warmer than the water that would be formed during deep convection, the temperature in the deep layer has increased steadily since the mid-1990s. At the 2000 m depth at OWSM, temperature has increased since around 1985 and salinity has decreased slightly since the mid-1990s (Figure 5b). The warming observed at that site is reflected in other deep stations, in the Greenland Sea and Iceland Sea (Figures 75 and 76 of *IROC2009*), although those time-series only extend back to the 1990s. At the very bottom of the Norwegian Sea, some of the warming is thought to be due to geothermal heating (Østerhus and Gammelsrod, 1999).

The creation of Labrador Sea Water during deep convection in the Labrador Sea forms cool, fresher water that can be traced as the water mass spreads. Prolonged deep convection occurred in the years 1972–1976, 1987–1994, and 1999–2000. Van Aken *et al.* (2011, updating data in Yashayaev *et al.*, 2007, to the end of 2009) show that the properties of Labrador Sea Water measured at 1500 m in the Labrador, Irminger, and Iceland Basins also have a strong multidecadal variability, with high temperature and salinity in the mid 1960s and early 1970s decreasing to a minimum in the 1980s and 1990s (Figure 5b). Since the 1990s, however, the temperatures have increased again and become warm and saline.

Labrador Sea Water spreads across the North Atlantic and we expect to see a similar pattern of variability within the Rockall Trough, but with a delay of around a decade. However, the warming observed in the Labrador Sea region since the beginning of the 1990s has not been seen at this level in the Rockall Trough (Figure 5b), and temperatures remained relatively low during the decade 2000–2009. This is not entirely unexpected because the Labrador Sea Water mixes with other water masses as it spreads, so the influence of source properties is reduced by the time it reaches the Rockall Trough.

Since the late 1990s, the overflow waters at some of the sills have increased in temperature and salinity (Eldevik *et al.*, 2009). In the Faroe–Shetland Channel, waters at the overflow level (800 m) decreased in salinity from the 1960s to the 1990s and have changed little since then, with perhaps a slight increase in temperature and salinity since 1995 (Figure 5b).

Discussion

A comparison of the key indices of North Atlantic variability (Figure 2) clearly shows that, as well as the long-term trend attributable to anthropogenic climate change, there are complex patterns of multidecadal and decadal scale variability. Since 1880, the AMV, as represented by the AMO index, has had two positive phases and two negative phases (Figure 2a), and the current phase is positive. Over the period 1960–1990, the AMO increased and continued to increase in the decade 2000–2009 (Figure 2b). The earlier increase in the AMO (1920s–1930s) is associated with very strong warming in the Arctic and along Greenland (Drinkwater, 2009; Polyakov *et al.*, 2010; Yamanouchi, 2011). This early 20th century warming was a significant event, but the sparsity of data in this early period and the current limitations of models mean that the mechanisms behind the warming are not yet well understood.

Examination of all the atmospheric indices since the 1960s shows that the NAO index changed from a strongly negative phase in the 1960s to a strongly positive phase by the early 1990s. Over the same period, there was an increase in both the GSNWI and the SPGI. In the mid-1990s (the exact year varies between each index), the NAO and the GSNWI weakened and there was a rapid decrease in the SPGI. Over the decade 2000–2009, the SPGI has been low and the NAO weak. Before the 1960s, the decadal NAO was also relatively weak (Figure 3b), with the highest NAO indices in this earlier period during the 1920s. The statistical significance of the NAO as an indicator of northern hemisphere temperature appears to vary over multidecadal time-scales (Haylock *et al.*, 2007), with the lowest correlations between 1910 and 1940.

These marked change in atmospheric drivers coincided with similar changes in hydrographic conditions. The long-term trend in the North Atlantic since 1960 shows an overall warming and salinification in the upper layers in most areas, the main departure from this pattern being a decrease in salinity in the Nordic Seas. These patterns are consistent with anthropogenic-induced warming (Hansen *et al.*, 2010) and enhancement of the global water cycle (Durack and Wijffels, 2010). The rate of temperature change in North Atlantic temperatures is higher than the global mean temperature trend. This is clear from the surface temperature averages (e.g. Knudsen *et al.*, 2011; Figure 1) and from the calculations of upper ocean heat content, which has increased in the North Atlantic since the 1960s at a rate greater than anywhere else on the globe (Levitus *et al.*, 2009).

Variability at decadal to multidecadal time-scales makes estimation of trends difficult, especially when examining a time-series shorter than 50 years. As a consequence of the complex circulation in the North Atlantic, there is also marked variability across different regions, and this complicates the picture somewhat. Cooling and freshening was observed in the upper layers of the subpolar North Atlantic and Nordic Seas between 1960 and 1990 (Curry *et al.*, 2003), and this also extended to intermediate and deep layers (Dickson *et al.*, 2002). As a result, it was widely reported that the freshwater content of the North Atlantic and Nordic Seas increased from the 1960s to the 1990s (e.g. Curry and Mauritzen, 2005).

The cooling and freshening trend was limited to the Subpolar Gyre region, because between 1960 and 1994, Mediterranean Overflow Water (MOW) near the Strait of Gibraltar became warmer and more saline (Potter and Lozier, 2004), with similar trends in the Bay of Biscay (Michel *et al.*, 2009). Similar regional patterns can be seen in alternative parameters. For example, Carton *et al.* (2008) and Henson *et al.* (2009) describe an increase in MLD in the Subpolar Gyre during the 1970s and 1980s, and the opposite trend (shallowing of MLD) has been found farther south in the North Atlantic (e.g. Paiva and Chassignet, 2002). No clear temporal trend in MLD has been detected in the Norwegian Sea (Nilsen and Falck, 2006).

The cooling and freshening of the subpolar North Atlantic was linked to strengthening of the NAO and changes in upper ocean circulation (Blindheim and Østerhus, 2005; Dickson *et al.*, 2008), and some modelling studies suggested potential disruption of the MOC (e.g. Hu and Meehl, 2005), leading to concern about a slowdown of this circulation with subsequent wide-ranging climate and ecosystem effects. Estimates of the strength of the MOC were made within the subtropical North Atlantic at 26.5°N and at the points where the inflows and overflows are more confined, such as the Faroe–Shetland Channel region. In the early 2000s, initial results did present evidence that the MOC had decreased (Hansen *et al.*, 2001; Bryden *et al.*, 2005).

The source of the additional freshwater that accumulated in the Subpolar Gyre was shown to be the Arctic (Peterson *et al.*, 2006). However, the links between the export of Arctic freshwater and the MOC are still the subject of debate. The Arctic undergoes multidecadal periods of accumulation and discharge of freshwater, likely driven by polar atmospheric conditions related to the NAO (McPhee *et al.*, 2009). Those high-latitude processes have a significant role to play in subpolar conditions through the advection of cold, fresher water. Although it is apparent from model studies that an extreme input of freshwater to convection sites can disrupt the MOC, the impact of the observed redistribution of freshwater on the Subpolar Gyre circulation and the MOC is not yet clear (Vellinga *et al.*, 2008). A limiting factor to model studies is that neither coupled climate nor high-resolution ocean-ice models currently reproduce the narrow boundary currents (shallow and deep) that carry the freshwater into the Subpolar Gyre and beyond.

Since around 1995, a change has been observed in the circulation patterns of the North Atlantic, as demonstrated by the assorted indices (Figure 2b). Very different atmospheric conditions in the decade 2000–2009 resulted in a weak NAO pattern (Figure 3). A weakened Subpolar Gyre (the Subpolar Front moved westwards) resulted in much warmer, more-saline water flowing polewards along the continental margin of the eastern North Atlantic and Nordic Seas (Holliday *et al.*, 2008), and the calculated freshwater content of the upper layers of the North Atlantic and Nordic Seas reduced (Boyer *et al.*, 2007). There has also been a progressive reduction in MLDs in the Subpolar Gyre since the mid-1990s (Carton *et al.*, 2008), but a deepening of MLDs farther south in the North Atlantic. Lozier and Stewart (2008) suggested that the northward penetration of MOW increased when the Subpolar Gyre was weak, leading to positive salinity anomalies at the depth of MOW in the Rockall Trough.

The marked increase in salinity and temperature since 1995, and the association with an increase in the AMO index, invites the explanation that the MOC has intensified and that the observed changes are a result of enhanced poleward transport of heat and salt. Links between the MOC and the AMO have already been suggested (e.g. Baines and Folland, 2007; Parker *et al.*, 2007), although again there is much uncertainty. However, improved measurement techniques and the addition of new data to measured estimates of the MOC now indicate unchanging transport since the 1950s (Olsen *et al.*, 2008; Hernández-Guerra *et al.*, 2010), although there is some evidence for a slight enhancement between 1992 and 2002 (Willis, 2010). Moreover, there is no strong evidence for changing transport in the upper layers, e.g. in the Gulf Stream since the 1950s (Rossby *et al.*, 2010) or the Norwegian Atlantic Current since the 1990s (Mork and Skagseth, 2009).

In summary, observations suggest that the major currents of the MOC have not changed over the long term, but that at the same time the exchange of saline water with the subtropics and freshwater with the Arctic has changed under the influence of wind patterns. Those advective changes are strongly influencing the AMO in a way that masks the global trend and that is not apparent when viewing overturning simply as northward flow at the surface and southward flow at depth.

As both the upper ocean of the Subpolar Gyre and the Labrador Sea have become warmer and more saline since the mid-1990s, as described above, North Atlantic Deep Water is also beginning to warm and become more saline (Dickson *et al*., 2008), with increases in temperature and salinity seen in the very deepest parts of the Labrador Sea from around 2003 on. A warming signal is also being seen at great depth within the Greenland Sea. Although the warming trend at OWSM began in the mid-1980s, Eldevik *et al*. (2009) suggest that the increase in the temperature of the deep and intermediate waters since the beginning of the 1990s is a result of the advection of anomalies brought into the Nordic Seas in the Atlantic inflow. Therefore, the changing properties of deep overflows are also strongly linked to the warming and salinification of the North Atlantic during the decade 2000–2009.

During the period 1960–1990, the eastern North Atlantic showed variability at decadal time-scales that was out of phase with that of the western North Atlantic (Figure 5a and b; Drinkwater *et al*., 2012). The clearest demonstrations of this phenomenon are the three periods of salinity minima, the first and strongest of which was termed the Great Salinity Anomaly. This was explained as a slow advection of a "slug" of cold freshwater around the North Atlantic, so the minimum in salinity in the eastern North Atlantic is observed some years after that seen in the western North Atlantic (Figure 2b). After reviewing data at many stations around the North Atlantic from two subsequent salinity minima (mid-1980s and mid-1990s), Sundby and Drinkwater (2007) proposed a different mechanism: periodic increases in the volume flux led to positive anomalies (warmer, more-saline water) in the eastern North Atlantic at the same time as the negative anomalies (more cold, fresher water) in the western North Atlantic, and following this a weakening led to the opposite effect. The salinity minima are associated with variability in the NAO and were observed during a period of significant enhancement of the NAO and strong deep convection in the Subpolar Gyre, which led to similar cooling and freshening in intermediate and deeper waters. However, the warming and salinification since the mid 1990s has occurred on both sides of the Atlantic at the same time (Figure 5), requiring an alternative explanatory mechanism.

The deep North Atlantic Ocean is bordered by extensive shallow shelf seas. Although the dynamics of these shallow regions can differ considerably from the deep ocean, the long-term variability in conditions is closely linked to that of the deep ocean because of the fluxes of heat and salt from the ocean and the complex links to atmospheric variability (e.g. Drinkwater *et al*., 2009). Strong patterns of multidecadal variability are evident in data from coastal areas such as the North Sea and Baltic, although it is clear that the driving mechanisms are different (Figure 5).

Reliable predictions of future climate conditions are important, for example, to inform the management of ecosystem resources and to inform climate policy, and this is as important in the marine environment as it is on the land. In the North Atlantic region, where the multidecadal variability in temperature is of a similar order of magnitude to the predicted anthropogenically forced temperature rise (Hawkins and Sutton, 2009), it is important to understand the trend of natural variability or at least to be able to describe the level of uncertainty adequately. A temporary downward trend in natural variability could cancel out or reverse the anthropogenic warming trend, and a further upward trend could continue to accelerate it. A temporary downward trend could be misinterpreted by a climate-sceptic public, and it is important for policy-makers to understand and explain it (Keenlyside *et al*., 2008).

Predictions of future conditions in the ocean attributable to climate change include the warming trends caused by anthropogenic forcing, but to be accurate in the North Atlantic at decadal scales, they also need to be able predict the multidecadal variability, which is currently difficult. The intensification of the NAO up to 1997 was thought to be a consequence of anthropogenic climate change, and a future intensification has been predicted (Woollings *et al*., 2010). The intensification was abruptly reversed in 1997, and we described the NAO as weak and variable between 2000 and 2009. However, in 2010 and 2011, there were strong negative NAO conditions. Some authors have suggested an imminent downturn of the AMO, based on its apparent cycle and the observed reduction in temperatures in some parts of the North Atlantic since 2003 (e.g. Knight *et al*., 2006) but accurate predictions of variability at this scale will not be possible without further developments in coupled ocean climate models. Contrary to the suggested decline, the AMO index in 2010 was high, so more years of data will be needed to determine the recent trend confidently. To improve the decade-scale predictions and reduce the uncertainty, there is much work to be done to improve coupled ocean–atmosphere models and to understand the dynamics better. Maintaining and even expanding the ocean observing system is a vital part of this work (Latif and Keenlyside, 2011).

The changes in Subpolar Gyre circulation since 1995 have strong effects throughout different trophic levels (Hátún *et al*., 2009). In a similar way, the NAO index has been used by researchers previously. Strong correlation between the NAO index and ecosystem variables offered a simple tool for examining the effects of physical changes on complex ecosystems (e.g. Marshall *et al*., 2001). As a consequence of the unusual conditions over the decade 2000–2009, we have shown that the NAO pattern was weak and variable (Figure 3), so the NAO index did not describe the atmospheric variability adequately. Many of the clear correlations between the NAO index and other oceanographic or ecological variables observed during the period 1960–1999 are likely to have broken down or changed (e.g. SST in the Barents Sea; Drinkwater *et al*., 2012). Stenseth *et al*. (2003) explain a number of atmospheric indices, offer suggestions as to the best way to utilize them in ecosystem research, and describe ways of avoiding common pitfalls. Further to this, using the NAO as an example, it is important to consider temporal changes in significance of various indices. Although there is no doubt that the atmosphere is clearly still an important driver of changes in the ocean, the NAO index cannot be considered to be the single useful measure of such atmospheric forcing over the decade 2000–2009.

The broad correlation of temperature and salinity changes throughout the North Atlantic implies a dynamic origin to much of the multidecadal and decadal variability, and changes in the Subpolar Gyre have been shown to be important. Although presented as separate indicators, the AMO, NAO, and Subpolar Gyre and oceanic drivers such as the MOC and Open Ocean Deep Convection are all part of the complex ocean–atmosphere system and are not independent of each other. Polyakov *et al*. (2010) offer a useful conceptual model of the North

Atlantic, examining both surface and deep-water fluctuations, and offer an assessment of the relative contribution of the long-term anthropogenically driven changes combined with regional patterns driven by multidecadal variability.

More research is needed, however, to untangle the complexity in the patterns of temperature and salinity variability, the controlling mechanisms, and how they vary in space and time. Important questions remain, such as whether the MOC circulation drives property changes or responds to property changes (Lozier *et al.*, 2010) or whether the AMO is forced internally or externally (e.g. Ottera *et al.*, 2010). Present-day climate models also lack realistic narrow boundary currents and other fine-scale processes; advances in our understanding of multidecadal variability in the North Atlantic will come with improved models and new views of the MOC in the Subtropical and Subpolar Gyres.

Although the driving processes are still not yet untangled, it is clear that the decade 2000–2009 was unusual compared with the previous four decades, with a marked reversal (e.g. Subpolar Gyre freshening) or enhancement (e.g. North Atlantic SST) of previously understood trends in many areas. There are very few long oceanographic time-series with data earlier than 1950, but those that are available support the observations of an earlier warm period that began in the 1920s and continued through to the early 1960s. Therefore, although conditions in the past decade have been unusual in the time-frame of the majority of our observations (1950–2009), there have been warming events of similar magnitude before. As a result of the combined effects of anthropogenically driven climate change and multidecadal warming, the highest ocean temperatures in the 100-year record in the eastern North Atlantic and Barents Sea were observed during the latter part of the 2000s (*IROC2009*).

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