Multidecadal Variability of North Atlantic Temperature and Salinity during the Twentieth Century

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ABSTRACT

Substantial changes occurred in the North Atlantic during the twentieth century. Here the authors demonstrate, through the analysis of a vast collection of observational data, that multidecadal fluctuations on time scales of 50-80 yr are prevalent in the upper 3000 m of the North Atlantic Ocean. Spatially averaged temperature and salinity from the 0-300- and 1000-3000-m layers vary in opposition: prolonged periods of cooling and freshening (warming and salinification) in one layer are generally associated with opposite tendencies in the other layer, consistent with the notion of thermohaline overturning circulation. In the 1990s, widespread cooling and freshening was a dominant feature in the 1000-3000-m layer, whereas warming and salinification generally dominated in the upper 300 m, except for the subpolar North Atlantic where complex exchanges with the Arctic Ocean occur. The single-signed basin-scale pattern of multidecadal variability is evident from decadal 1000-3000-m temperature and salinity fields, whereas upper-ocean temperature and salinity distributions have a more complicated spatial pattern. Results suggest a general warming trend of $0.012^{\circ} \pm 0.009^{\circ}$ C decade⁻¹ in the upper-3000-m North Atlantic over the last 55 yr of the twentieth century, although during this time there are periods in which short-term trends are strongly amplified by multidecadal variability. Since warming (cooling) is generally associated with salinification (freshening) for these large-scale fluctuations, qualitatively tracking the mean temperature-salinity relationship, vertical displacement of isotherms appears to play an important role in this warming and in other observed fluctuations. Finally, since the North Atlantic Ocean plays a crucial role in establishing and regulating global thermohaline circulation, the multidecadal fluctuations of the heat and freshwater balance discussed here should be considered when assessing long-term climate change and variability, both in the North Atlantic and at global scales.

1. Introduction

The earth climate system exhibits fluctuations on a variety of time scales, and there is mounting evidence of multidecadal variability with a time scale of 50–80 yr.

Schlesinger and Ramankutty (1994) documented this variability in Northern Hemispheric surface air temperatures and found it to be particularly strong in the North Atlantic sector. These low-frequency fluctuations are also evident in various instrumental and proxy records from the Northern Hemisphere (see Delworth and Mann 2000 and references therein). Hibler and Johnson (1979) found low-frequency modulation of oxygen isotope records derived from Greenland ice

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cores. Cyclic variations with periods ranging from 50 to 400 yr were found in various proxy and long-term instrument records by Stocker and Mysak (1992), who emphasized that these variations, though global in extent, are most pronounced in the Atlantic Ocean. Folland et al. (1986) reached the same conclusion from an analysis of global sea surface temperatures. Surface marine observations in the North Atlantic display distinct basinwide patterns of multidecadal SST variability closely associated with spatial anomalies of the sea level pressure (Kushnir 1994). An extended (1856-1999) North Atlantic SST anomaly (SSTA) time series used by Enfield et al. (2001) identifies the so-called Atlantic Multidecadal Oscillation, where an anomalously warm Atlantic is associated with precipitation deficits in the midwestern United States.

Understanding the mechanisms behind multidecadal variability is nontrivial due largely to its poorly defined character and changing relationship with large-scale climate parameters like the North Atlantic Oscillation (NAO), the north-south-oriented dipole in sea level pressure over the Atlantic. However, spectral analysis of the NAO index time series from 1886 to 1994 shows significant power at periods of approximately 50 yr [Yi et al. (1999, their Fig. 9b); see also Visbeck et al. (2002) for an in-depth discussion of the role of NAO in longterm North Atlantic variability]. Model simulations suggest that atmosphere-ocean interactions play an important role in the excitation of oceanic variability at multidecadal scales. Strikingly similar low-frequency variability in the ocean-atmosphere system may result from solar variability (Cubasch et al. 1997; Waple et al. 2002) and greenhouse gas forcing (Delworth and Knutson 2000). Shindell et al. (2001) identified multidecadal variability in the North Atlantic in a study that forced an atmospheric GCM coupled to a mixed layer ocean with observed solar and ozone fluctuations. In nature, it is likely that a variety of forcings can excite these modes of low-frequency variability. In addition, it is expected that the climate response to increasing greenhouse gases also projects onto the fundamental modes of multidecadal variability (Stott et al. 2000; Crowley 2000). While the physical mechanisms for generation of multidecadal variability may differ from model to model (Latif 1998), there is a consensus that long-term changes of the thermohaline overturning circulation play a crucial role in establishing spatial and temporal SST patterns (e.g., Delworth et al. 1993, 1997; Timmermann et al. 1998; Delworth and Greatbatch 2000; Eden and Jung 2001; Häkkinen 1999).

Interplay between the shallow and deep layers in the North Atlantic is an essential part of the overturning circulation. While a significant body of research has been devoted to the impact that multidecadal variability has on ocean surface processes, there is still uncertainty about the role of low-frequency variability in the deeper ocean. A number of regional studies have discussed multidecadal NAO-driven variations in the deep North Atlantic but, as we will show later, regional analyses do not always reflect basin-scale tendencies. In addition, they cannot elucidate the spatial structure of low-frequency variability. A few studies have analyzed large-scale temperature and salinity fields in the North Atlantic; however, they focused on long-term trends or were limited to selected time intervals not suitable for documenting multidecadal variations. The goal of this observationally based study is to document long-term, large-scale variations in temperature and salinity in the upper-3000-m layer of the North Atlantic. Here we demonstrate, through the analysis of a vast collection of observational data, that the Atlantic Ocean exhibits multidecadal variability with prolonged large-scale temperature and salinity anomalies of opposite sign in upper and lower layers.

2. Data and methods

The analysis area of this study comprises the Northern Hemisphere ($<80^{\circ}N$) between $80^{\circ}W$ and $50^{\circ}E$. This longitudinal band includes the entire North Atlantic Ocean, except the Gulf of Mexico. The observational database used in this study combines three datasets. The first is the National Oceanographic Data Center (NODC) archive of oceanographic measurements, including a detailed description of data quality and spatial and temporal coverage (see information available online at http://www.nodc.noaa.gov/OC5/ indprod.html; see also Conkright et al. 2002; Stephens et al. 2002; Locarnini et al. 2002). Second, the World Ocean Circulation Experiment (WOCE: 1990-97) has provided one-time and repeat hydrographic measurements (WOCE Global Data Resource DVD, version 3.0). This dataset is available from the WOCE Web site hosted at NODC (online at http://woce.nodc.noaa.gov). Third, the Arctic and Antarctic Research Institute (AARI) has compiled a twentieth-century archive of oceanographic ship-based observations in the Greenland, Norwegian, and Barents Seas, totaling approximately 6000 oceanographic stations. This last dataset is not enough to make any noticeable changes in the composite time series for the entire North Atlantic; however, it is a valuable addition, complementing the first two datasets with high-latitude measurements that allow mapping of water temperature anomalies at high latitudes.

Most historical (prior to the 1980s) observations used Nansen bottles to obtain water samples and measure temperatures at standard levels. While having rather coarse vertical resolution, the data provide reasonable horizontal coverage for the purpose of this research, and the multiyear coverage makes the data an invaluable resource for understanding interannual variations of the water mass structure within the Atlantic Ocean. Typical measurement errors are 0.01°C for temperature and 0.02 psu for titrated salinity (Fuglister 1960). In recent years, the observations are based on CTD measurements, which have accuracies at least an order of magnitude greater than the bottle measurements.

For each oceanographic profile, potential temperature and salinity were integrated over 0-300-, 300-1000-, and 1000-3000-m depth intervals (since constantdepth layers were used for these estimates, vertically integrated potential temperatures are essentially equivalent to the heat content of the corresponding layers). If data were missing from the water column for sublayers greater than 200, 500, and 750 m for the above layers, respectively, these stations were omitted from further analysis. No vertical interpolation was used in this procedure. The total number of vertically averaged values available for the upper layer was 395 302, which is approximately five times the number of vertically averaged temperature and salinity values for the lowest layer. The decadal data coverage for the lowest (1000-3000 m) selected layer where the density of data coverage is the poorest is shown in Fig. 1. Clearly, the density of observations is low at the beginning of the twentieth century.

The vertically averaged water temperatures were then reduced to their anomalies (T') by subtracting local monthly means for the upper layer and local annual means for the two lower layers. Removing the annual cycle in the upper layer minimizes aliasing of seasonal variability into computed means and standard errors. Seasonal variability is small in layers below 300 m, so the use of an annual mean is appropriate for defining temperature and salinity anomalies. The local means were calculated by linear interpolation. Details of this procedure are discussed in the appendix. Anomalies exceeding five standard deviations (σ) from means for 2° squares centered around the location of the oceanographic station were omitted. This filtering has a negligible effect on the composite time series for the entire North Atlantic but was useful for mapping water temperature anomalies and removing bull's-eye-shaped structures on the maps (a similar filtering procedure was used by Levitus et al. 2000). Details of possible impacts that outliers may have on the computed time series can be viewed online (see Fig. W2 available at http://www.iarc.uaf.edu/images/publications/ipolyakov. php).

The temperature anomalies (T') were then used to compute composite time series of the water temperature anomalies (Fig. 2). Often, EOF-based or objective analyses are employed to compute time series based on gridded data (e.g., Kaplan et al. 1998; Levitus et al. 2000). Levitus (1990) emphasized that "the objective analysis procedure substantially smoothes out features with wavelengths less than several hundred kilometers." The same seems to be true when an EOF-based procedure is employed, judging by smoothness of the spatial SSTA distributions based on Kaplan et al.'s (1998) data (not shown). We employed a technique similar to that of the climate anomaly method (CAM), which is widely used in atmospheric sciences and is described by Jones et al. (1999). The same method was successfully used for the analysis of the long-term variability of the intermediate Atlantic layer of the Arctic Ocean (Polyakov et al. 2004). In this method, the North Atlantic is divided into a grid of N boxes and individual (snapshot) vertically averaged anomalies T' in these N boxes were averaged within a given year and box to produce N regional time series (\tilde{T}') . The resulting average regional time series of \tilde{T}' for each grid box are averaged again, taking into account the areas of each box, to obtain a single "global" time series. The same method was also used to generate composite time series of salinity anomalies. This technique provides a more accurate spatial representation of area-averaged indices since the results are less skewed by the density of the observations.

Since the density of data coverage is generally greater at high latitudes (Fig. 1), we employed a special grid dividing the area of the North Atlantic Ocean into boxes that allow relatively uniform data coverage in different regions of the North Atlantic. The grid has a $5.5^{\circ} \times 5.5^{\circ}$ resolution near the equator and the latitudinal increment decreases northward by a factor of $\cos\phi$ (ϕ is the latitude). In addition, the grid size also decreases owing to the northward convergence of meridians (Fig. 1). Sensitivity analysis shows that the results are robust to the choice of the grid (see the appendix). For convenience, the above method will be referred to as the grid-averaging method. Despite the relatively high level of noise in earlier parts of the composite temperature and salinity records, spatially and temporally averaged estimates provide a meaningful (temporally coherent) and valuable measure of trends in North Atlantic water temperature and salinity, as well as long-term variability. The salinity records are generally much noisier compared to temperature records. For ease of viewing, 2σ statistical confidence levels are shown for the salinity, and 3σ confidence limits for the temperature in section 3.



FIG. 1. Data coverage of hydrographic stations for the 1000-3000-m depth interval during the twentieth century. The second half of the century is displayed by decade and the first half of the century is displayed by 20-yr periods. Each dot signifies the location of a hydrographic station and the total number of stations is indicated by the value of N.

Long-term measurements of water temperature and salinity are available from two sites in the Atlantic Ocean associated with Station S (Bermuda at approximately 32°7.5'N, 64°30'W) and Ocean Weather Station Mike (66°N, 2°E). Data from Bermuda start in 1954 and continue until the present (T. Joyce 2004, personal communication). A continuous record at OWS Mike is available from 1948 through 1998 from the International Council for the Exploration of the Sea (ICES) Web site (online at http://www.ices.dk/ocean/INDEX. HTM).

3. Basinwide changes of water temperature and salinity

Multidecadal fluctuations with a time scale of 50–80 yr are evident from long-term records of the North Atlantic water temperature. This variability has been described in previous publications (see the introduction) and may be clearly seen in the SSTA time series based on the Kaplan et al. (1998) dataset. The SSTA record exhibits multidecadal variability with generally lower values before 1930 and between the mid-1960s and mid-



FIG. 2. Long-term variability of North Atlantic water temperature in the region between 0° and 80°N, 80°W and 20°E. (top) Annual-averaged (blue dotted line) and smoothed 6-yr running mean (blue thick line) values of SSTA are plotted (data from Kaplan et al. 1998). A smoothed (6-yr running mean) composite time series of 0–5-m temperature anomalies is shown in green. The correlation coefficient (*R*) between the 0–5-m-layer temperature and SSTA and their standard deviations σ are presented at the bottom of the panel. Low-frequency time series of the annual mobile NAO index is shown by a red long-dashed line (after Portis et al. 2001). (second panel to bottom) Time series of water temperature anomalies averaged over 0–300-, 300–1000-, 1000–3000-, and 0–3000-m layers, respectively. Annual temperature anomalies (blue dotted lines) and 6-yr running means (blue solid lines) (dashed segments represent gaps in the records), and their 98% confidence intervals (red dotted lines) are plotted. For comparison, a composite time series of temperature anomalies for the 0–3000-m layer from Levitus et al. (2000) is shown in bottom panel by a green line. For all plots, red horizontal lines show means computed for different intervals.

1980s, and higher values between the 1930s and the mid-1960s and from the mid-1980s to present [Fig. 2, upper panel, blue line; for details, see Enfield et al. (2001)]. For comparison, we also present time series of the water temperature anomaly in the upper-5-m layer based on the grid-averaging method (Fig. 2, top panel, green line). A relatively high correlation between these two curves and the identical timing of the cold and warm phases of multidecadal variability demonstrate the robustness of our estimates. Note, however, that the multidecadal peaks in the 1930–40s and in the mid-1970s are somewhat weaker in the 5-m temperature time series with a slightly lower standard deviation $\sigma = 0.18^{\circ}$ C compared with the SSTA $\sigma = 0.19^{\circ}$ C.

As may be expected, the timing of phases of the multidecadal variability of the SSTA and the upper-300-m temperature are similar and the temperature anomalies averaged over 0-300 m are weaker compared to the SSTA (Fig. 2). There is a strong resemblance between the time series of Levitus et al. (2000, 2005) and in our time series in the latter part of the records (cf. our Fig. 2 with an expanded version of Fig. 3 from Levitus et al. 2000, which can be viewed at Science online at http://www.sciencemag.org). For example, Levitus et al. (2000) found that temperature anomalies in the late 1990s were slightly higher than 0.5°C and in our times series the temperature anomaly is 0.46°C, which is statistically indistinguishable. In the late 1970s-early 1980s both annual time series show weak positive anomalies, which in the mid-1980s became weak negative anomalies. These two time series also display strong, statistically significant negative anomalies in the upper-300-m layer in the 1970s. However, in the late 1940s-1950s the Levitus et al. (2000) time series is dominated by cold anomalies, whereas our record reveals warm anomalies. Even though statistical significance of our estimates for particular years deteriorates in the earlier part of the record, a strong positive decadal mean anomaly in the 1940s, shown by a horizontal bar (Fig. 2), indicates that warming dominated the temperature anomalies during this decade at a 98% confidence level, which also agrees with the SSTA record.

At greater depths, we find that the sustained upper-300-m temperature anomalies are generally associated with temperature anomalies of opposite sign in the deep 1000–3000-m layer. For example, our record shows a strong cooling tendency at 1000–3000 m starting from the late 1970s through 1995, after which the temperature anomalies equilibrated at approximately -0.05° C. Cooling of the deep Labrador Sea in recent decades was also found in previous studies (see discussion in the next section), and the present analysis generalizes those findings to a larger spatial area: our time series shows that, starting from the late 1970s, cooling prevailed over the entire North Atlantic. In this, the 300–1000-m layer plays the role of an intermediate transition layer, sometimes resembling variations of the upper layer (e.g., 1985–2000) and sometimes reflecting those of the lower layer (e.g., 1955–75), resulting in generally weak anomalies compared with anomalies in the other two layers.

The deep ocean plays a substantial role in shaping temperature (and therefore heat content) trends for the entire 3000-m layer in the North Atlantic Ocean, as can be seen by comparing time series for 1000-3000 m and 0-3000 m (Fig. 2). Analysis of differences between our estimates of the mean 3000-m temperature anomalies and those of Levitus et al. (2000) (blue and green lines in Fig. 2, bottom) shows that the major differences come from the early 1950s and from the 1990s. During the 1990s strong negative anomalies dominate our time series, whereas Levitus et al. (2000) found strong positive anomalies. Inconsistencies in estimates of the temperature anomalies in the upper 3000 m cannot be explained by inclusion of the WOCE 1990-97 oceanographic data or the AARI data in our analysis, since removing these data had a negligible effect on our composite time series (not shown).

Why are our estimates of long-term North Atlantic water temperature variations are so different than the estimates of Levitus et al. (2000)? The major difference in methodologies seems to be associated with the treatment of areas that do not have observations in specific years. The grid-averaging method simply omits these areas. In the Levitus et al. procedure, temperature at a specified grid point and time is computed as a sum of a first-guess value and a correction. If there is no data in the vicinity of this point at this time, the correction is zero and the temperature is solely defined by the firstguess value. The first-guess value is computed using zonally averaged climatological temperatures for specified individual regions of the World Ocean for each 1° latitude belt. Therefore, for regions with data gaps for a particular period of time, the temperature values for this period are defined by a zonal average. For anomalies, zero is used as the first-guess value, resulting in the damping of average basin-scale anomaly estimates. This effect is most pronounced in the lower layers where observations have numerous gaps.

The time series of the North Atlantic salinity anomalies in the upper-300-m layer also display multidecadal variability with generally lower values before 1930 and between the mid-1950s and 1980 (cold phases of multidecadal variability) and higher values between 1930 and the mid-1950s and from the mid-1980s to



FIG. 3. Long-term variability of the North Atlantic water salinity (psu) in the region between 0° and 80° N, 80° W and 20° E: (top to bottom) water salinity anomalies depth-averaged over 0–300, 300–1000, 1000–3000, and 0–3000 m; annual anomalies are shown by blue dotted lines, 6-yr running means by blue solid lines; dashed segments represent gaps in the records and red dotted lines indicate 95% confidence intervals. For all plots red horizontal lines represent decadal means and green lines show water temperature anomalies for comparison.

the present (warm phases of multidecadal variability, Fig. 3). Salinity changes in the deep 1000–3000-m layer are roughly in opposition to those in the upper ocean layer. The coherence of salinity and temperature changes is striking. Figure 3 further illustrates the coordinated changes of water temperature and salinity, by showing similar temporal variability. Generally, there is a close match between prolonged phases of cooling (warming) and freshening (salinification) in the upper (lower) layers. Strong coupling between large-scale cooling and freshening (warming and salinification) can be explained through the temperature–salinity change due to the displacement of isopycnal surfaces. For example, Roemmich and Wunsch (1984) analyzed temperature differences from the 1957 and 1981 hydrographic sections and found that warming is associated with the downward movement of the isotherms. Comparing data from 1955–59 and 1970–74 Levitus (1989a,b) found that in the 1970s the North Atlantic was generally colder and fresher at intermediate (500– 1300 m) depths and warmer and saltier in deeper layers. Levitus attributes these tendencies to upward or downward heaving of isopycnal surfaces. Recent regional studies support this temperature–salinity relationship (e.g., Arbic and Owens 2001; Bryden et al. 1996; Joyce et al. 1999; Dickson et al. 2002; Curry et al. 2003).

4. Trends

The composite time series of the water temperature and salinity anomalies (Figs. 2 and 3) are used to evaluate long-term trends. Over a century-long record, the SSTA displays strong multidecadal variability with a statistically significant background positive trend of +0.032 °C decade⁻¹ (Fig. 2). Records of water temperature at greater depths also show warming with an average rate of 0.01°C decade⁻¹; however, they are only marginally significant at the 98% level. As a result, the upper 3000-m North Atlantic was warming over the last 55 yr at an average rate of 0.012° C decade⁻¹ (Fig. 2). This is equivalent to a gain of heat of 0.5×10^{22} J. approximately half the estimate of Levitus et al. (2000). The potential importance of this discrepancy for heat storage within the global climate system can be found in the discussion of Pielke (2003). A positive trend of 0.0032 psu decade⁻¹ dominates the long-term salinity change in the upper-300-m layer; at greater depths the North Atlantic is losing salt at an average rate of 0.001 psu decade⁻¹, which translates into a freshening rate of 0.0008 psu decade⁻¹ for the entire upper 3000-m ocean. Because of noise in the data, these estimates of salinity trends are not statistically significant at the 95% confidence level. Note that the above discussion does not distinguish the cause of the observed anomalies (i.e., whether changes are due to heaving of isopycnals or because of temperature and salinity increase or decrease on isopycnals).

Computed North Atlantic temperature and salinity trends depend on the phases and intensity of the multidecadal variability in addition to the underlying longterm trend. For example, during the previous 80 yr (i.e., since the 1920s) the North Atlantic water temperature trend in the upper-300-m layer was positive. However, water temperatures in the 1940s were higher relative to the 1970s, so over this period of time the data have a small but statistically significant cooling tendency. In the deeper (1000–3000 m) layer, the strongest warming trend of 0.10°C decade⁻¹ was found from the late 1950s through the late 1970s, which exceeds the average warming rate over the entire record by a factor of 3. Antonov (1993), analyzing North Atlantic temperatures from 1957 to 1981, also reported a warming trend of 0.04°C decade⁻¹; however, our estimate is somewhat stronger since the warming trend from Antonov (1993) is for the shallower 800–2500-m layer where trends are generally weaker (Fig. 2). According to our analysis, over the last 15-20 yr the 1000-3000-m ocean layer actually lost heat. Similar "discrepancies" may be found in the salinity records when short-term changes may differ drastically from long-term trends. This analysis

underscores the inherent difficulty in differentiating between trends and long-term fluctuations (see also Ghil and Vautard 1991). Regional estimates may also differ substantially from spatially averaged trends. Comprehensive analysis of regional temperature and salinity trends based on differencing data from hydrographic sections taken from different decades is presented by Arbic and Owens (2001). We present a detailed comparison of these regional trends with our estimates in the next section.

5. Spatial patterns of temperature and salinity change

Figures 4-7 display the spatial anomalies of ocean temperature and salinity in the upper 300 m and the 1000-3000-m layers of the North Atlantic averaged over the same decades as the panels of Fig. 1. A simple averaging of all available data within a circle of 500-km radius was used for interpolation; if no data were found within this circle, the area remained blank. A rather large radius of interpolation was chosen to suppress small scales of variability, similar to Roemmich and Wunsch (1984), who used a horizontal Gaussian filter. Time averaging led to increased statistical significance, sufficient for describing long-term variability of the temperature and salinity anomalies associated with multidecadal variations. Despite the scarcity of observational data in the earlier part of the twentieth century, especially in deeper ocean layers, spatially and temporally averaged estimates provide valuable insight into North Atlantic temperature and salinity variability.

Temporal averages support our conclusions, based on the analysis of the composite time series (Figs. 2 and 3), that multidecadal variability is evident in the water temperature and salinity variations. For example, in the 1990s and 1940s, associated with the positive phase of multidecadal variability, both composite time series (Figs. 2 and 3) and maps (Figs. 4 and 5) show strong warming and salinification in the upper 300 m. In contrast, the 1970s are characterized by negative water temperature and salinity anomalies in the upper 300 m. A transition from a warm salty phase (1970s) to the cold fresher phase (1990s) of multidecadal variability in the deeper 1000-3000-m layer is clearly seen in the decadal spatial distributions (Figs. 6 and 7), corroborating our earlier conclusions based on the composite time series (section 4).

There is a clear evidence for cooling and freshening in the subpolar North Atlantic over the past four decades. For example, Read and Gould (1992) found a decrease of water temperature and salinity through a



FIG. 4. Spatial distributions of the North Atlantic water temperature anomalies (°C) averaged over two decades starting from the 1910s through 1940s and over one decade starting from the 1950s through 1990s for the upper-300-m layer. Areas with statistical confidence less than 98% are stippled.

comparison of data from several hydrographic cross sections carried out between Greenland and the United Kingdom in 1962, 1981, and 1991. These changes originated in the Labrador Sea, where from 1962 to 1992 the 0–3000-m temperature and salinity have decreased by 0.46°C and 0.059 psu (Lazier 1995). Recent estimates confirm a freshening of the North Atlantic subpolar gyre (Boyer et al. 2005). There is reason to think

that these changes were due to different rates of renewed convective formation of intermediate water in the Labrador Sea, which led to a systematic freshening of the northern North Atlantic and a corresponding salinity increase in the upper water column at lower latitudes (Dickson et al. 1996, 2002; Curry and McCartney 2001; Curry et al. 2003). These cold Labrador Sea anomalies spread across the northern North Atlantic



FIG. 5. Spatial distributions of the North Atlantic water salinity anomalies (psu) averaged over two decades starting from the 1910s through 1940s and over one decade starting from the 1950s through 1990s for the upper-300-m layer. Areas with statistical confidence less than 95% are stippled.

surprisingly quickly (Sy et al. 1997). Levitus et al. (2000) and Dickson et al. (2002) concluded that these changes became sustained and widespread. Our results are consistent with the above discussion, showing that subpolar regions within the 1000–3000-m depth range were cooler and fresher overall in the 1990s compared with the 1960–80s (Fig. 6 and 7).

Decadal mean maps of 1000-3000-m temperature

and salinity anomalies confirm results of earlier studies that the subtropical North Atlantic was colder in the 1950s than in the 1960s, 1970s, or 1980s (Fig. 6). It was also fresher in the 1950s compared with the 1970s–80s (Fig. 7); however, the difference is not as noticeable as with the temperature change. A comparison of the 1000–3000-m temperature anomalies from the 1980s and 1990s shows that the latter decade was colder



FIG. 6. Spatial distributions of the North Atlantic water temperature anomalies (°C) averaged over two decades starting from the 1910s through 1940s and over one decade starting from the 1950s through 1990s for the 1000–3000-m layer. Areas with statistical confidence less than 98% are stippled.

throughout the North Atlantic. This result seems inconsistent with earlier observational studies, which analyzed hydrographic data along several sections and found warming and salinification in the intermediate southern North Atlantic waters (Roemmich and Wunsch 1984; Parrilla et al. 1994; Bryden et al. 1996; Joyce and Robbins 1996; Arhan et al. 1998; Joyce et al. 1999; Arbic and Owens 2001). In an attempt to understand this discrepancy we prepared annual maps (1980–99) showing temperatures and locations of all hydrographic stations used for preparation of decadal mean maps (Fig. 6) within the 0° -30°N zonal band (Fig. 8). These maps include hydrographic sections [e.g. 24°N (1981 and 1992), 52°W (1983 and 1997), and 66°W (1985 and 1997)] where previous studies showed significant warming but our



FIG. 7. Spatial distributions of the North Atlantic water salinity anomalies (psu) averaged over two decades starting from the 1910s through 1940s and over one decade starting from the 1950s through 1990s for the 1000–3000-m layer. Areas with statistical confidence less than 95% are stippled.

decadal maps show cooling (Fig. 6). Our calculation of averaged 1000–3000-m temperature trends along these sections confirm local warming with the rates of 0.084 (52°W), 0.043 (66°W), and 0.096 (24°N) (°C/decade), respectively. However, Fig. 8 shows that, in a broader spatial sense, negative anomalies dominated the 1990s (right panels, more blue in color) and positive anomalies dominated the 1980s (left panels, more red and green in color). This resulted in a generally cooler southern North Atlantic in the 1990s compared with the 1980s within the 1000–3000-m depth range (Fig. 6).

This conclusion is supported by time series of water temperature anomalies averaged over 1500–2500-m depth from Station S extended over the 1990s (Fig. 9). There is a clear signature of a cooling that started in the mid-1980s and dominates the latter part of the record.



FIG. 8. Annual maps showing locations of hydrographic stations (dots) and water temperature (color) averaged over the 1000–3000-m depth range between 0° and 30° N. Note that these data have also been used for maps of decadal mean temperature anomalies, shown in Fig. 6, where the 1980s are dominated by warm anomalies (red) and the 1990s are dominated by cold anomalies (blue).



FIG. 9. (Top) Time series of water temperature anomalies averaged over the 1000–2000-m depth from OWS Mike at 66°N, 2°E (Norwegian Sea, blue), and (bottom) time series of water temperature anomalies averaged over the 1500–2500-m depth from Station S (at approximately 32°7′N, 64°30′E). For comparison, in both panels composite time series obtained by the grid-averaging method are shown by dashed lines. The correlation coefficient (*R*) between these pairs of time series and their standard deviations σ are noted at the top of each panel.

Curry et al. (1998) found a relationship between Bermuda 1500-2000-m water temperature and Labrador Sea convective history, where negative decadal NAO phases are associated with suppressed convective deepwater production in the Labrador Sea and weaker export of these waters to the subtropics. Opposite tendencies dominate during positive decadal NAO phases. The recent cooling evident in the Bermuda record (Fig. 9) was discussed by Visbeck et al. (2002), who related this transition to the change of NAO phase from negative to extreme positive and to maximum production of Labrador Sea Water. Note that the Bermuda time series compares favorably with the composite time series of the 1000–3000-m temperature anomaly for the entire North Atlantic (Fig. 2), suggesting that the Labrador Sea Water production and export have widespread basin-scale impact. Note, however, that this suggestion requires further observational and/or modeling support.

Surprisingly, despite substantial gaps in data coverage, maps of temperature and salinity anomalies from the earlier part of the twentieth century are also in good agreement with the general temporal pattern of the multidecadal variability provided by the extended SSTA time series (Fig. 2, top). For example, in the 1910–20s (especially in the 1910s) when the SSTA time series shows strong cooling, the spatial distributions in the upper 300 m are also dominated by negative (cold and fresh) anomalies. At the greater 1000–3000-m depths, the opposite tendencies prevailed in the 1910s with weaker anomalies during the 1920s. Thus, these earlier maps also suggest anomalies of opposite sign in the 0–300- and 1000–3000-m North Atlantic layers. Because of a wide range of uncertainties owing to sparse data coverage in these decades (Fig. 1), our estimates must be viewed as approximate measures of long-term tendencies in the North Atlantic temperature and salinity.

The spatial distributions of temperature and salinity anomalies provide additional evidence that regional temperature and salinity changes are strongly coupled insofar as prolonged cooling (warming) phases are generally associated with freshening (salinification). For example, similarities between the temperature and salinity anomaly fields (both in the upper and lower layers) in the 1990s are striking. This conclusion is corroborated by the relatively high pattern correlation (R)between temperature and salinity fields: averaged over the nine decadal mean fields, R = 0.493 for the upper 300-m layer and R = 0.512 for the deeper 1000–3000-m layer. Note that Reverdin et al. (1997) found a strong (weak) correlation between temperature and salinity fluctuations in the northwest (northeast) Atlantic when analyzing variability of the upper North Atlantic subarctic gyre.

To distinguish the causes of the observed anomalies (i.e., whether these changes are due to the heaving of isopycnals or attributable to temperature and salinity changes on isopycnals), we computed temperature and salinity changes along isopycnal surfaces similar to those of Bryden et al. (1996). In these experiments we used basinwide-averaged temperature and salinity profiles. Despite this averaging, numerous gaps in data coverage in the lower layers resulted in noisy vertical profiles, precluding meaningful conclusions (not shown). Therefore, owing to rather poor data coverage this important question remains unanswered. However, the analysis was helpful in emphasizing the importance of vertical averaging used to construct the time series (Figs. 2 and 3) and maps (Figs. 4–7).

6. Synthesis

We examine long-term variability of the North Atlantic temperature and salinity using hydrographic measurements starting in the early part of the twentieth century. Our analysis shows that multidecadal fluctuations with a time scale of 50–80 yr are common in the North Atlantic, despite gaps in the records. These fluctuations are reminiscent of low-frequency variability found in the North Atlantic SST instrumental records (e.g., Schlesinger and Ramankutty 1994; Kushnir 1994; and references therein) and tree-ring-based reconstructions (Delworth and Mann 2000; Gray et al. 2004). Our analysis of the spatially averaged temperature and salinity suggests an out-of-phase low-frequency variability in the upper (0-300 m) and lower (1000-3000 m) layers, where sustained phases of cooling and freshening of the upper ocean are associated with warming and salinification of the deeper North Atlantic, and vice versa. This opposition is consistent with the notion of the thermohaline overturning circulation shaping North Atlantic low-frequency fluctuations, as suggested earlier by Bjerkness (1964), Stocker and Mysak (1992), Delworth et al. (1993, 1997), Kushnir (1994), Mann and Park (1996), Griffies and Bryan (1997), Timmermann et al. (1998), and Delworth and Mann (2000). While discerning the detailed causes of the observed variability will require further investigation of observational and modeling data, our analysis supports a possible linkage between the low-frequency variations in the intensity of the Labrador Sea convective ventilation and the prolonged phases of widespread cooling and freshening (warming and salinification) occurring in the North Atlantic intermediate waters suggested by Sy et al. (1997), Dickson et al. (1996, 2002), Curry et al. (1998, 2003), and Curry and McCartney (2001) [see also Fig. W1 at http://www.iarc.uaf.edu/images/publications/ ipolyakov.php, showing vertical cross sections of potential temperature and salinity anomalies averaged over positive and negative phases of multidecadal variability, with suggested paths of water temperature and salinity anomalies from the Labrador Sea in the deeper (1000–3000 m) layer of the North Atlantic Ocean].

In addition to documenting the temporal variability, our analysis reveals a single-sign basin-scale anomaly pattern of multidecadal fluctuations in 1000-3000-m North Atlantic temperature and salinity fields. Kushnir (1994), Delworth and Greatbatch (2000), and Eden and Willebrand (2001) have shown that the low-frequency SST variations have a widespread hemispheric pattern, in contrast to higher-frequency interannual fluctuations dominated by a tripolar SST pattern, identified by Deser and Blackmon (1993), Kushnir (1994), Battisti et al. (1995), and Masina et al. (2004) [see also Visbeck et al. (2002) for further discussion and references therein]. The basin-scale pattern of variability is not as evident in the upper-300-m ocean; prolonged upper-ocean temperature and salinity anomalies, well captured by composite time series (Figs. 2 and 3), seem to be masked by higher-frequency variations in the decadal fields. Relatively moderate pattern correlations between the SST and upper 300-m ocean temperature with $R \sim 0.4$ over the last five decades, and even lower ($R \sim 0.2$) values for the earlier decades, also suggest that further analysis will be required to discern the detailed pattern of the observed variability in the upper, more variable, layer.

Numerous observational (e.g., Bjerkness 1964; Deser and Blackmon 1993; Kushnir 1994; Dickson et al. 1996, 2002; Curry et al. 1998, 2003; Curry and McCartney 2001; Visbeck et al. 2002) and modeling (e.g., Timmermann et al. 1998; Delworth and Greatbatch 2000; Eden and Jung 2001; Häkkinen 1999) studies point to the importance of the NAO in forcing long-term changes in the North Atlantic Ocean. However, a comparison of long-term NAO and SSTA changes over the last century (Fig. 2, upper panel, red long-dashed and solid blue lines, respectively) shows that relatively good correlations between these two time series over the last 80 years are preceded by a rather poor match between NAO and SST anomalies in the earlier part of the twentieth century. Analyzing Arctic air temperatures, Bengtsson et al. (2004) also found that, in contrast to the warming of the 1990s, the warm period in the 1930s did not coincide with a positive phase of the NAO, which has led Bengtsson et al. to argue that the early twentieth century warming is associated with local Arctic air-sea ice interactions. Our analysis suggests that the 1900-20s mismatch between the NAO and SST time series has a widespread (not local Arctic) pattern, and the Bengtsson et al. (2004) conclusion may have a broader context. However, this discrepancy alone clearly points out the complex nature of large-scale long-term atmosphere-ocean interactions.

Indeed, a lack of observations places strong constraints on our ability to establish spatial and temporal patterns of multidecadal variability and to define mechanisms driving coherent low-frequency temperature-salinity variations. For example, the relatively short temperature and salinity instrumental records make it difficult to infer firm, statistically sound conclusions about the exact time scales of multidecadal variability. Large-scale decadal maps are well defined for several of the recent decades, however, the spatial coverage rapidly deteriorates toward the earlier part of the twentieth century. Inadequate annual spatial coverage, even in the recent decades (e.g., mid-late 1990s; cf. Fig. 8), may become a major obstacle to the understanding of mechanisms critical in the transition from one phase of multidecadal variability to another. It certainly has some impact on the computed annual anomalies presented by the composite North Atlantic time series, which is expressed by widened uncertainty margins in the earlier parts of the records (especially



FIG. 10. (top) Comparative evolution of key components of the Arctic climate system. Composite time series of the Arctic surface air temperature (SAT) anomalies (green), annual intermediate Atlantic Water core temperature (AWCT) anomalies (red line with dashed segments representing gaps in the record), and anomalies of fast ice thickness in the Kara Sea (Hice, blue): all curves are smoothed using 6-yr running mean. (bottom) Comparison between variables in the Arctic and North Atlantic. The AWCT (red) and normalized North Atlantic SST anomalies (green) are shown. All curves are normalized by their respective standard deviations (σ). The time series show striking resemblance. Adapted from Polyakov et al. (2004).

salinity). The same is true for the deeper North Atlantic layers where the number of observations is substantially lower than in the upper ocean, which may impact the estimates of magnitude of the temperature and salinity anomalies. Both the lack of observational data in the earlier part of the records and the large-amplitude multidecadal climate variability affecting the North Atlantic temperature and salinity may confound detection of the true underlying climate trend over the past century attributable to anthropogenic effects.

High-latitude regions play a special role in shaping long-term variability in the North Atlantic through the regulation of convection in the Labrador and Greenland Seas via freshwater exchanges (e.g., Dickson et al. 1996, 2002; Visbeck et al. 2002). Several pulses of freshwater coming from the Arctic region were observed in the northern North Atlantic over the last decades (Dickson et al. 1988; Belkin et al. 1998), which may have affected the strength of the overturning circulation (Häkkinen 2002). The latest pulse, that of the 1990s, has been described by Belkin (2004), who compared all three salinity anomalies documented so far and, based on their apparent propagation speed, found that the subarctic gyre spun up between the early 1970s and the mid-1990s. Häkkinen and Rhines (2004) used more recent data to show that the subarctic gyre slowed down in the late 1990s-early 2000s. A stronger subarctic gyre has a deeper baroclinic structure and a stronger T-S correlation throughout the water column. Polyakov et al. (2004), using extended observational records, showed sustained coherent phases of warming and salinification (cooling and freshening) in the Arctic Ocean and Greenland and Norwegian Seas and demonstrated out-of-phase variability between these basins and the Labrador Sea. The striking resemblance between multidecadal variability of North Atlantic SST and arctic surface air temperature, fast-ice thickness, and Arctic Ocean temperature (Fig. 10) supports a possible linkage of low-frequency variations occurring in the Arctic and North Atlantic. Further research is required to elucidate the origin of, and links between, long-term subsurface changes found in the North Atlantic with the arctic multidecadal fluctuations.

With the above discussion as background, we summarize our primary conclusions as follows:

- Analysis of North Atlantic 0–3000-m temperature and salinity demonstrates significant multidecadal variability.
- Spatially averaged temperature and salinity anomalies in the 0–300- and 1000–3000-m layers vary in opposition with prolonged periods of cooling and freshening (warming and salinification) in one layer associated with opposite tendencies in the other layer. This is consistent with the notion of thermohaline overturning circulation shaping North Atlantic low-frequency fluctuations, as suggested in earlier studies. For example, in the 1990s, *warming* and *salinification* dominated the upper-300-m layer (except the subpolar North Atlantic) and widespread *cooling* and *freshening* dominated the 1000–3000-m layer.
- Single-sign basinwide spatial patterns of multidecadal variability are evident from the decadal 1000–3000-m temperature and salinity fields; the upper-ocean temperature and salinity distributions have a more complicated spatial pattern, probably due to complex Arctic–North Atlantic interactions.
- Temperature and salinity show coherent long-term large-scale fluctuations, with warming (cooling) generally associated with salinification (freshening). This is consistent with vertical displacement of isohalines and isotherms.

Finally, we note that, since the North Atlantic Ocean plays a crucial role in establishing and maintaining global thermohaline circulation, multidecadal fluctuations of heat and freshwater discussed here should be taken into account when assessing long-term climate change and variability in the North Atlantic and over broader spatial scales. Understanding the key factors influencing the North Atlantic multidecadal variability may provide a reasonable means for developing climatic forecasts of widespread persistent anomalies.

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APPENDIX

Robustness of Analyses

a. Sensitivity of anomalies to radius of interpolation

The mean temperature and salinity values (both monthly and annual) used to calculate anomalies (T')were constructed by computing local means for the location of each oceanographic station separately. Linear interpolation of all available data started within a search radius of $R_{\rm sh} = 0.15^{\circ}$ latitude; $R_{\rm sh}$ was gradually increased, if necessary, by an increment of 0.15° until at least two measurements were found within the circle. Note that the maximum value of the search radius $R_{\rm sh}$ was constrained to 5° of latitude; however, in 99% of the cases the search of data for interpolation was finished after three iterations, that is, far below the $R_{\rm sh}$ limit. This suggests that the data coverage was sufficient for this purpose. Note that excessively large values of $R_{\rm sh}$ do not provide a statistically sound estimate of the means, and the resulting anomalies are exaggerated because these means are not representative of local means. On the other hand, small $R_{\rm sh}$ values restrict search by only a few stations, resulting in poorly defined statistical estimates. To evaluate the sensitivity of the computed anomalies to the choice of the initial $R_{\rm sh}$ in a quantitative way, we performed a set of experiments in which composite (entire North Atlantic) time series of temperature anomalies within the 1000-3000-m layer were computed with different initial $R_{\rm sh}$. In Fig. A1, the line with stars represents a measure of variance of the computed composite time series with different initial $R_{\rm sh}$ values estimated by three standard deviations $3\sigma^{tp}$ (note that σ^{tp} is a *temporal* standard deviation). A measure of errors of the computed local means as a function of the initial $R_{\rm sh}$ is shown in Fig. A1 by the line with diamonds. These estimates are spatial averages of local errors calculated by $3\sigma^{sp}/\sqrt{n}$, where $\sigma^{\rm sp}$ is the *spatial* standard deviation and *n* is the number of observations used to define the local mean. Figure A1 shows that estimates of local means with initial $R_{\rm sh}$ $< 0.15^{\circ}$ of latitude should be avoided since the errors dominate the useful signal. Based on these estimates we selected initial $R_{\rm sh} = 0.15^{\circ}$ as the optimum value.

b. Sensitivity of anomalies to the choice of grid

Sensitivity of the computed water temperature anomalies (Fig. 2) to the choice of grid was also evaluated. This analysis shows the robustness of our esti-



FIG. A1. Choice of the initial search radius ($R_{\rm sh}$, abscissa) for computing local means (ordinate shows standard deviations in °C). The line with stars shows a three standard deviation measure of temporal variability derived from the time series of the 1000–3000-m temperature anomalies as a function of initial $R_{\rm sh}$. The line with diamonds shows a measure of spatially averaged errors of the estimates of local means as a function of initial $R_{\rm sh}$. Estimates of local means with initial $R_{\rm sh} < 0.15^{\circ}$ of latitude should be avoided as the level of errors exceeds the level of useful signal.

mates. For example, two different grids were used to calculate the composite ("global") time series of T'. One grid (standard) had a $5.5^{\circ} \times 5.5^{\circ}$ resolution near the equator with a northward reduction of grid cells along latitude (see the detailed description in section 2). The second (test) spherical grid used a spatially uniform $4^{\circ} \times 4^{\circ}$ resolution. Thus, near the equator the area of grid cells of the standard grid was almost twice the area of the test grid, whereas at 80° N the situation was reversed with the test grid cell area approximately three times larger than the area of the standard grid cell. With these big differences, the composite T' time series computed for the 0–300-m layer remain similar, displaying a strong positive correlation (R = 0.852) and practically indistinguishable σ (cf. $\sigma = 0.119^{\circ}$ and $\sigma = 0.120^{\circ}$ C).

c. Additional check of robustness of grid-averaging method

To further test the grid-averaging method, we generated additional time series for two locations of the North Atlantic where long-term observations are available. The first site is OWS Mike, located in the Norwegian Sea, and the second site is Station S. Observational time series of water temperature anomalies, averaged over the 1000–2000-m depth from station Mike and over the 1500–2500-m depth from Station S, are shown in Fig. 9. For comparison, time series based on the gridaveraging method are also shown. These time series were obtained by applying the grid-averaging method for a $2^{\circ} \times 2^{\circ}$ area around each oceanographic station. A comparison of the original and reconstructed time series indicates that the grid-averaging method provides a reasonable tool for constructing spatially averaged time series composition. Moreover, it may be used to close gaps in the observational records.

d. Spatial anomaly test

Statistical uncertainties of spatial patterns (shown by stippling in Figs. 4-7) are measured by the standard deviation of the mean (standard error), computed at each grid point in the maps. At each grid point all measurements from within a radius of 500 km are used to calculate error statistics. For the deeper (1000–3000 m) layer all data are used and no attempt is made to remove the small influence of the seasonal cycle. In the shallow (0-300 m) layer, where seasonality is much stronger, anomalies are computed relative to the mean seasonal cycle, and corresponding standard errors in Figs. 4 and 5 represent variability about the mean seasonal cycle. For temperature maps, anomalies smaller than 3σ are judged to be insignificant and are stippled in the figures, while for salinity a 2σ criterion is used. In recent decades where the density of observations is high, computed anomalies are found to be statistically reliable in most areas. However, in earlier decades (especially prior to 1960) computed values are found to be uncertain over large parts of the geographic area covered by this analysis.

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