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Recent changes in the surface salinity of the North Atlantic subpolar gyre

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[1] Sea surface salinity (SSS) was measured since 1896 along 60°N between Greenland and the North Sea and since 1993 between Iceland and Newfoundland. Along 60°N away from the shelves, and north of 53°N, the amplitude of the seasonal cycle is comparable to or less than interannual variability. In these parts of the North Atlantic subpolar gyre, large-scale deviations from the seasonal cycle correlate from one season to the next. This suggests that in these regions, summer and autumn surface data are useful for monitoring changes in upper ocean salinity best diagnosed from less common winter surface data. Further south near the subarctic front, the Labrador Current or near shelves where seasonal variability is strong, this is not the case. Along 60°N, the multiannual low-frequency variability is well correlated across the basin and exhibits fresher surface water since the mid 1970s than in the late 1920s to 1960s. SSS in the Irminger Sea along 60°N lags by 1-year SSS farther east in the Iceland Basin. Variability between Iceland and Newfoundland within the Irminger Sea north of 54°N presents similar characteristics to what is observed along 60°N. Variability near the northwest corner of the North Atlantic Current (52°N/45°W) is larger and is not correlated to what is found further north. Maps of SSS were constructed for a few recent seasons between July 1996 and June 2000, which illustrate the fresh conditions found usually during that period across the whole North Atlantic subpolar gyre, although this includes an episode of higher salinity. The SSS anomaly maps have large uncertainties but suggest that the highest SSS occurred before the spring of 1998 in the Iceland Basin, and after that, in the Irminger Sea. This is followed by fresher conditions, first in the Labrador and Iceland Basin, reaching recently the Irminger Sea. *INDEX TERMS:* 4536 Oceanography: Physical: Hydrography; 4215 Oceanography: General: Climate and interannual variability (3309); 4223 Oceanography: General: Descriptive and regional oceanography; *KEYWORDS:* salinity, North Atlantic, climate variability

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1. Introduction

[2] The objective of this study is to construct SSS fields in the North Atlantic subpolar gyre to explore the nature of interannual variability as documented by those fields. However, the data coverage is limited and only a few fields could be constructed for recent seasons since 1996. To put these observations into perspective, this paper will also discuss the variability observed in April–November across the subpolar gyre near 60°N between Greenland and the North Sea since 1896, and between Iceland and Newfoundland in all seasons since 1993.

[3] Surface data [*Reverdin et al.*, 1997] and model studies [*Häkkinen*, 1999] document interannual variations of surface salinity in the North Atlantic subpolar gyre. Large interannual to decadal changes in convective mixing have been observed in the Nordic Seas and in the Labrador Sea [*Lazier*, 1980; *Dickson et al.*, 1996; *Curry and McCartney*, 2001]. These changes seem to occur in relation to changes in the atmospheric circulation, in particular, those related to the North Atlantic Oscillation [*Dickson et al.*, 1996]. Within the ocean, this variability is manifested by changes in haline stratification. In areas prone to sea ice formation north of Iceland and in the Labrador Sea, changes in near surface haline stratification also appear to affect sea ice formation [*Mysak et al.*, 1990; *Marsden et al.*, 1991].

[4] Model studies suggest that the changes in convective activity are inducing changes in the deep meridional overturning cell [*Mauritzen and Häkkinen*, 1999; *Eden and Willebrand*, 2001], which in turn must affect the transport

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of salty tropical water to the subpolar gyre and thus the salinity of the subpolar gyre. Observed changes in surface salinity have also been diagnosed as indicative of changes in surface circulation (horizontal or vertical) [*Bersch et al.*, 1999; *Reverdin et al.*, 1999] or as resulting from advection by the average currents [i.e., *Dickson et al.*, 1988; *Reverdin et al.*, 1997].

[5] What contributes to changes in SSS and how such changes affect the oceanic circulation remains poorly documented, because surface and upper ocean salinity have not been surveyed as well as temperature. Even the origin of the spectacular occurrence of anomalously fresh surface water in the Labrador Sea is not that clear. Hydrographic data [*Lazier*, 1980; *Dickson et al.*, 1988; *Curry and McCartney*, 2001] indicate two such occurrences: the two so-called Great Salinity Anomalies (GSA) in the western subpolar gyre (in 1968–1972 and 1982–1984) [*Dickson et al.*, 1988, 1996; *Belkin et al.*, 1998]. Data [*Dickson et al.*, 1988; *Hilmer and Jung*, 2000] as well as model studies [*Häkkinen*, 1993] suggest that the first GSA originated from a major outflow of ice and fresh water from the Arctic during the latter half of the 1960s, in particular in 1968. The second GSA may have had its origin in the Canadian Archipelago or Labrador Sea [*Belkin et al.*, 1998]. The two GSAs occurred during different atmospheric conditions: the first corresponded to a period of low wind and fairly mild conditions in the Labrador Sea, whereas the second happened at a time of strong atmospheric forcing, which therefore resulted in deeper winter mixed layers with more erosion of the subsurface salinity maximum. We would therefore expect that the signature left in the surface layer should have been weaker for the second GSA, which is consistent with the smaller amplitude found in other areas after transport by the surface currents. This large influence of atmospheric forcing on vertical mixing through air-sea heat fluxes has recently been confirmed in the central Labrador Sea where, during 1996–1999, the air-sea heat fluxes and the subsurface haline stratification contributed five times more than the surface freshwater fluxes to changes in winter convection.

[6] Upper ocean salinity has been observed to evolve on interannual to interdecadal timescales in various parts of the North Atlantic subpolar gyre [*Levitus*, 1989; *Dickson et al.*, 1988; *Reverdin et al.*, 1997; *Belkin and Levitus*, 1996] (note that we use "upper ocean" in a loose sense, referring to the part of the water column above the level of the classical Labrador Seawater that can be within the late winter mixed layer). The data most commonly investigated are from repeated sections, located very often near the edges of the subpolar gyre adjacent to the continental slopes and from a limited number of hydrographic stations. Repeated hydrographic surveys provide regional salinity fields useful for examining scales of the salinity variations [*Belkin and Levitus*, 1996; *Bersch et al.*, 1999; *Koltermann et al.*, 1999]. Upper layer salinity at stations in the subpolar gyre indicates a progression of anomalies along the branches of the North Atlantic Current and around the gyre on decadal timescale [*Taylor and Stephens*, 1980; *Reverdin et al.*, 1997]. In the eastern part of the gyre, these are reminiscent of the SST decadal signal described by *Hansen and Bezdek* [1996] and *Sutton and Allen* [1997]. Upper ocean salinity and temperature vary in phase in this region [*Reverdin et al.*, 1997], which is also observed to a lesser degree in the deep convective areas (*Lazier* [1980], for the central Labrador Sea]). However, the correlation between temperature and salinity does not always hold on a year-to-year basis. For instance, in 1996, the upper layer waters between Ireland and Greenland were found to have warmed with respect to previous years, but salinity had increased only in the eastern part of the section [*Bersch et al.*, 1999]. The cause of such T-S variability is intriguing: is it related to atmospheric forcing or to changes in oceanic circulation; is it an isolated event or is it part of a significant pattern? There are, however, strong limitations to interpreting the hydrographic data because of the limited spatial and time coverage, even though the annual repeat of some sections is of enormous value. The same is true for observations in other parts of the subpolar gyre.

[7] In the North Atlantic subpolar gyre, there is considerably more surface salinity data than ocean salinity profiles with better spatial coverage and over a longer period, albeit with a seasonal bias favoring summer over winter. Are these data useful for the climate investigations that usually require knowing the upper ocean salinity variability? A major issue is whether salinity stratification near the surface is so large as to prevent the identification from surface data of the low frequency signals in upper ocean salinity. This issue is likely to depend on the season during which the surface data are collected.

1. During winter, salinity is weakly stratified in the upper layer of the subpolar gyre: a consequence of convective vertical mixing. Wintertime surface salinity is therefore indicative of the often-thick layer of upper water, which is mixed at least once during the winter (this is what we will refer as upper ocean). For example, a correlation coefficient of 0.84 was found between time series of winter averaged salinity at 0m and 100m for sites India-Lima in the eastern subpolar gyre (most data collected near 59°N/20°W) [*Reverdin et al.*, 1997].
2. During summer, there is often a near-surface stratification in salinity. This results from a seasonal cycle in SSS already noticed by *Knudsen* [1905], whereas seasonal salinity variability is considerably less below the summer seasonal pycnocline (usually located above 50m). SSS seasonal variability is larger along the shelves of North America and Greenland and in the western subpolar gyre than further east [*Smed*, 1943; *Levitus*, 1986]. In the western subpolar gyre near 50–55°N, the seasonal (summer) surface salinity reduction relative to the upper ocean values can reach 1.00 (salinity has no unit, but is often referred to as practical salinity unit: psu) due to advection of fresh water from the North American shelves and from the slope currents [*Bauer et al.*, 1991] in particular near the subarctic front. Year-to-year variability in summer SSS may therefore differ strongly from the upper ocean layer variability. At all sites investigated in the eastern part of the subpolar gyre [*Reverdin et al.*, 1997], the correlation between surface and subsurface was weakest in summer.

[8] This suggests that winter surface data will be more useful for oceanographic investigations than data from other seasons. However, we are often faced with less surface data in winter than in the other seasons, and therefore a secondary objective of this study is to assess to which extent nonwinter surface salinity data can be used as indicative of

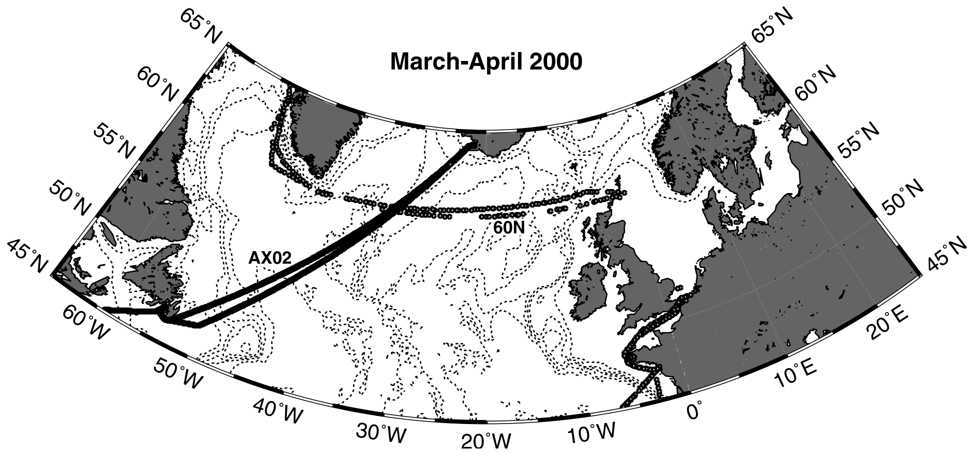

Figure 1. Salinity sampling from the Nuka Arctica (east-west close to 60°N) and the Skogafoss (Iceland to Newfoundland) in March–April 2000. The data from the Nuka Arctica are from real-time transmission to the GOOS center at AOML (Miami).

upper ocean changes. This is investigated here rather indirectly by assessing where deviations from the seasonal cycle are correlated in successive seasons. There are already hints at some sites in the eastern subpolar gyre with subseasonal sampling that there is significant correlation of SSS between successive seasons [*Reverdin et al.*, 1997]. There was less correlation at site Mike (66°N/2°E), which is closer to a water mass front.

[9] The period 1996–2000 was chosen for this investigation because of particularly good near-surface ocean sampling. Data are available from a variety of sources, including thermosalinograph salinities from two merchant vessels that frequently transited the North Atlantic subpolar gyre as well as during the important hydrographic surveys that were carried out under the international programs WOCE (World Ocean Circulation Experiment), VEINS (Ventilation of the Nordic Seas), and under various national programs. Profiling floats have also been deployed in the subpolar North Atlantic [*Lavender et al.*, 2000; *Bacon et al.*, 2001], and part of this data set is used here. The thermosalinograph data provide time series with nearly monthly resolution in limited parts of the gyre that can be used to establish the seasonal time evolution of salinity. These are, however, of short duration (5 and 8 years, respectively). We will also consider a much longer time series of seasonally averaged salinity along 60°N (winter not sampled) from 1896 to 2000.

2. Data Sources and Methods

2.1. Data

2.1.1. Surface Samples

[10] Sea surface salinity (SSS) measurements have been made routinely in portions of the North Atlantic subpolar gyre from water samples collected from merchant vessels since 1896 [*Knudsen*, 1905; *Smed*, 1943; *Reverdin et al.*, 1994], and from the ocean weather ships that occupied an array of sites since 1948 (only one at 66°N/2°E, "Mike" is still in service) [*Gammelsrød et al.*, 1984, 1992]. As these programs returned data over a much longer period than what is available from hydrographic surveys, surface samples are a major source of information about subpolar gyre variability on multidecadal timescales. However, these surface data are of variable accuracy, provide only partial spatial coverage and have long interruptions in the sampling, in particular during the two World Wars and in the 1970s and 1980s [*Reverdin et al.*, 1994]. Here, we will be particularly interested with the data collected between Denmark and southwest Greenland, whose accuracy is fairly well documented between 1896 and 1960 [*Knudsen*, 1905; *Reverdin et al.*, 1994]. In addition, we incorporate hydrographic station (available from the NODC archives) at the shallowest reported level, and a few recent surface data in the ICES archives.

2.1.2. Thermosalinograph Data

[11] Salinity data are also provided by thermosalinographs (TSG) with water typically pumped from a depth of 4–6 m. A TSG was installed in early 1994 on a merchant vessel of the company EIMSKIP that regularly travels between Newfoundland and Iceland (the sampling in this area was maintained through three changes of ships) [*Reverdin et al.*, 1999]. This effort yielded a nearly 8-yearlong time series. In 1997, another TSG was installed on the Nuka Arctica, a vessel of the Royal Arctic line that usually travels between Denmark and southwest Greenland except between January and early April. The two lines are illustrated on Figure 1. Discrete water samples are collected regularly on these vessels for later analysis and calibration of the TSG conductivity cell. Because the TSG is not cleaned regularly, large drifts occur, in particular during port calls, and the correction that must be applied can be large. When not enough samples were available to correct the drifts (this happened mostly for the Nuka Arctica), we estimate the drift by comparison with other data (the two TSG lines intersect west of the Reykjanes Ridge). The drifts have an effect on the final accuracy of the data, in particular during late summer to early autumn when the data quality was often lower. We estimate that the overall salinity accuracy of these TSG data sets is around ±0.02 (the comparison between the water samples and the corrected TSG salinity usually presents an RMS difference of 0.02 or less, but can degrade to 0.05 in the summer-early autumn). There is also considerable data loss due to system failures (e.g., inadequate pumping in the water circuit of the Nuka Arctica, loss of position data or system malfunctioning on

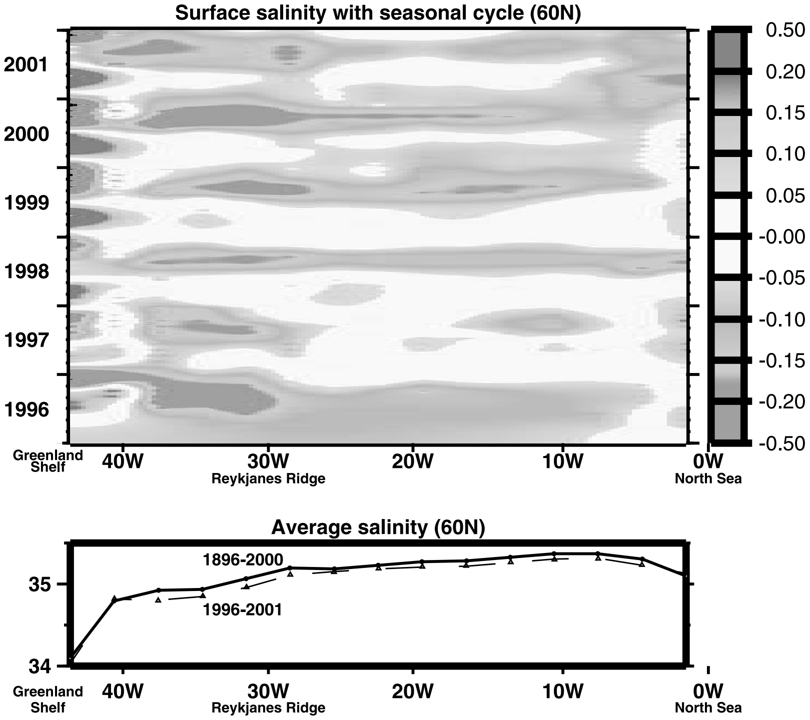

Figure 2. Hövmüller diagram of salinity along 60°N between Greenland and the Shetlands (with seasonal cycle, but after removing the climatological long-term average). The first six months of 1996 usually have insufficient data, and there is rarely data from mid-January to mid-April which is filled on the plot by combining the average seasonal cycle with deviations from it interpolate linearly between January and April. The lower panel compares the 1896–2000 average with the average for 1996–2001. See color version of this figure at back of this issue.

the Skogafoss from August 2000 to October 2001). All the TSG data are available through ICES.

[12] In addition, we have used TSG data in this area from a few research cruises (the most important ones being the CATCH cruise in the western Atlantic in early 1997 [*Caniaux et al.*, 2001]; the Interpole cruise on the R/V Marion Dufresne in summer 1999; the Marathon cruise on the R/V Polarstern in October 1996; and various cruises conducted by the German (IFM Kiel) Sonderforschungbereich (SFB) 460 in 1996–1999. We also use data from one surface drifter with a salinity sensor deployed in the eastern Irminger Sea in 1996, which appears to have worked well for more than a year. Data from two other drifters deployed at the same time are not usable.

2.1.3. CTD Data

[13] All the CTD profiles collected during WOCE and VEINS and publicly available are used, as well as profiles from regular Canadian surveys off Labrador and in the Labrador Sea. Collection of the WOCE data peaked between mid 1996 and the autumn of 1997, and for VEINS between 1997 and 1999 (mostly off East Greenland). In addition, we included Icelandic surveys in the Irminger Sea carried between 1996 and 1999 (Calanus, Redfish and Redfish2 cruises). Salinity data were usually selected at a depth of 5 m (alternatively, we used the average of salinity in the upper 15 m with very similar results), and are usually of a higher quality than the other data.

2.1.4. PALACE Floats

[14] Data from three PALACE floats communicated by Sheldon Bacon and John Gould from IOS (Southampton, UK) and carefully calibrated based on comparisons with CTD surveys were used for the period 11/1996 to 11/1998. Although the data at depth are close to what is expected based on local CTD data [*Bacon et al.*, 2002], the accuracy near the surface is less reliable, so that we select the salinity at the first reported subsurface level (usually near 15 m).

2.2. Methods

[15] We will first discuss SSS data along 60°N between Cape Farewell and the Shetland Islands, then between Iceland and Newfoundland (AX02), and finally SSS fields in 1996–2000.

2.2.1. 60°N

[16] The best sampling along 60°N is since July 1997 when observations were made at least monthly, except from mid-January to mid-April. These data are from TSGs so that the mesoscale spatial variability is well sampled. Close to Cape Farewell (southern tip of Greenland), because of weather and the occasional presence of ice, the ship's route can vary considerably with respect to the bathymetry, and the data are therefore more difficult to interpret. We bin the data by monthly 3° longitude boxes (155 km) with usually little noise resulting from mesoscale variability except in the vicinity of the slope fronts and shelves, in particular, near the east Greenland Current. We also fill some gaps by data collected at nearby latitudes (59°N or 61°N) with a correction for the differences in average salinity.

[17] The seasonal cycle and the long-term mean along 60°N are well documented based on the data collected between 1896 and 1993, and therefore we also construct

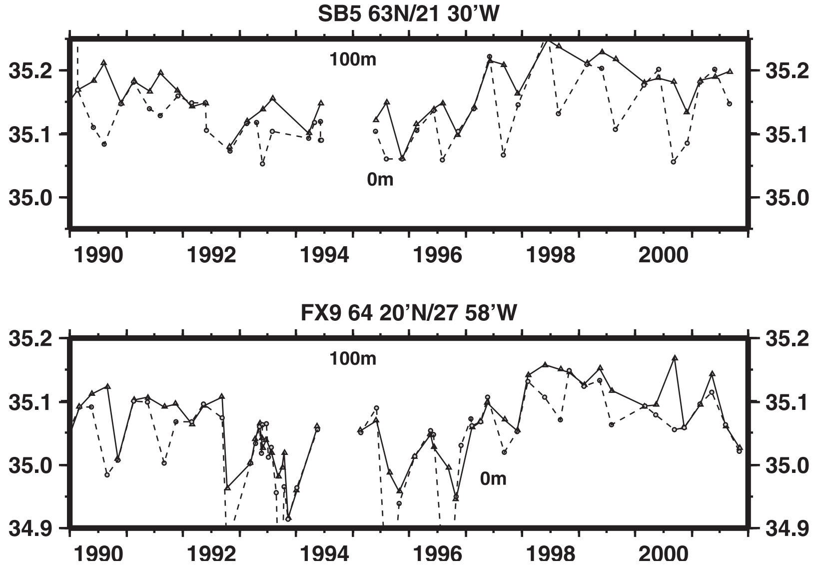

Figure 3. Salinity variability at 100m (full line) and 0m (dashed line) at two seasonally visited hydrographic stations off Iceland: station Selvogsbanki 5 south of Iceland (63°N/21°30′W) and station Faxafloi 9 west of Iceland (64°20′N/27°58′W). The large ticks correspond to 1 January of each year.

longer time series of deviations with respect to the seasonal cycle. For earlier periods, the sampling is often much coarser, and so data were grouped in 3-months*3-degrees longitude bins after removing the average seasonal cycle for the period 1896–1993 (January to March, April to June,. . ., with the January to March bin often holding no data). Many gaps were interpolated spatially for the plot, either along the 60°N track or from data at nearby latitudes between 58°N and 62°N (taking into account the latitudinal gradient in average SSS). Nonetheless, there is no data in 1916–1920, and very little data in 1940–1946. Corrections of some of the surface data were adopted based on work by *Reverdin et al.* [1994]. In 1960, the ship-of-opportunity program stopped, and we rely on cruise data to construct the time series. Data are particularly sparse in the early 1970s, when individual seasons are not always sampled (this is worst for the area close to the Reykjanes Ridge). However, the resulting time series do not show a sudden jump in 1960, which suggests that the transition between ships-of-opportunity data and the hydrographic cruise data is not a major issue.

2.2.2. AX02

[18] The area between Iceland and Newfoundland has been monitored since June 1993 along WOCE line AX02 (Figure 1). Earlier data are rare, so an independent seasonal cycle is not as reliable as it was along 60°N. In this area, except close to the shelves of Newfoundland and Iceland, the *Levitus* [1986] climatology is strongly weighed by the observations of the 1950s and 1960s, which correspond to a low NAO index period and higher SST than normal for that part of the subpolar gyre [*Kushnir*, 1994]. We therefore preferred to construct a seasonal cycle for the recent, better-sampled period (June 1993 to December 2001). At 60°N/32°W, the salinity anomaly time series has a similar character to that from the 60°N section at 30–33°W (section 3.1; Figure 2) referred to the 1896–1993 average seasonal cycle, albeit shifted to more positive values.

2.2.3. SSS Fields

[19] To map SSS, we use an objective mapping routine [*Bretherton et al.*, 1976] applied to the deviations of individual data from the average seasonal cycle constructed from a mix of surface data from hydrographic stations and from the various ships-of-opportunity from the turn of the century until 1993. (An average instrumental bias in the early surface data is corrected, based on a comparison between surface and first subsurface data in hydrographic stations). The signal is assumed Gaussian-correlated over 200 km, and the noise is assumed small (10% variance) compared to the signal (Therefore the mapping produces a smoothed version of the data). Data within 350 km of the analyzed point are incorporated, and if no data are present within this radius, no analysis is produced. The correlation scale (200 km) is set to avoid having too many gaps in the fields and is usually less than the scale of the SSS signal along the two recent ship-of-opportunity lines. Once grouped by 2 or 3 months, satisfactory data coverage is obtained for a large share of the subpolar gyre during the late spring and summer seasons as well as during the autumns of 1996 and 1997. Surface data coverage has been less during other seasons, resulting in uncertain analyses.

3. Sea Surface Salinity

3.1. The 60°N Section Between Greenland and the North Sea

[20] The Hövmüller diagram (Figure 2) for the period 1996–2001 includes the seasonal cycle, but excludes the long time mean. The salinity is typically highest in late winter-early spring, and lowest in late summer-early autumn, with a seasonal range which always exceeds 0.1 and reaches 0.2 or more west of 30°W in the Irminger Sea. The seasonal cycle is much larger on the Greenland shelf near Cape Farewell, but with significant high-frequency variability indicated by large month-to-month variability.

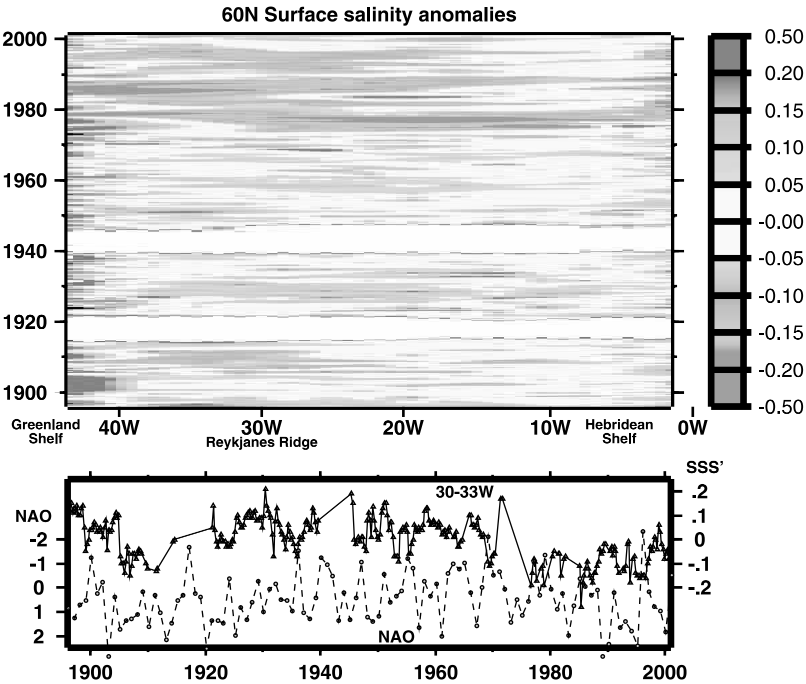

Figure 4. SSS′ along 60°N. Upper panel: Hövmüller diagram of salinity deviations from the long-term climatological seasonal cycle (the ticks on the vertical axis correspond to 1 January of the year indicated). The normalized NAO DJFM winter index based on Iceland and Gibraltar SLP data is also shown (inverted scale on the left) with salinity at 30–33°W (scale on the right) (lower panel). See color version of this figure at back of this issue.

[21] In nearly all seasons (there is little data in mid-January to mid-April), the data are fresher than the long-term mean, in particular near 10–20°W and 28–38°W. Near 10–20°W, this is more pronounced from mid 1999 to early 2001, a period clearly fresher than the previous years. The average salinity is lower (typically by 0.1) for 1996–2001 than for the longer period 1896–2000, a magnitude much larger than the uncertainty of the averages (for the long-term average, error results mostly from uncertainties in the corrections applied to the early data, but should be less than 0.02). This difference is found in all seasons.

[22] During the recent period, the highest salinity in the Irminger Sea (30–40°W) (not presented) occurred in late 1998–1999, whereas in the Iceland Basin (east of the Reykjanes Ridge 20–30°W), the maximum was reached in 1997–early 1998. A difference between east and west was also found by *Bersch et al.* [1999] along the repeated section located a little further south. They showed that in 1996 the salinity of the upper water had increased compared to earlier surveys in the Iceland Basin, but not yet in the Irminger Sea. The time series spanning just 1996–2001 is too short to characterize east-west differences in the phase of the variability.

[23] The difference between east and west in recent years is also visible close to Iceland between two repeated hydrography stations, one south of Iceland in the Iceland Basin (Selvogsbanki 5 located at 63°N/21°30′W) and one west of Iceland in the Irminger Sea (Faxafloi 9 at 64°20′N/28°W). At the first station, the salinity increase occurs in 1996–1998 and a decrease starts in 1999, whereas for the second station the salinity increase is in 1997–1998 and the decrease begins in early 2000 (Figure 3). Note that at both stations, the variability is most clearly visible subsurface (at 100m, there is still a residual seasonal cycle with lowest values in the autumn), but that the surface data roughly portray the interannual changes in all seasons and are very similar to the subsurface data in winter-early spring. These seasonally resolved time series (Figure 3) are longer than the ones in Figure 2. They suggest that the recent years experienced a high salinity compared to the period 1992–1996. However, as we already commented, even these high recent salinities are not particularly high compared to the long-time mean, suggesting the presence of multidecadal SSS variability.

[24] This can be investigated further based on the seasonal time series of deviations from the seasonal cycle along 60°N (Figure 4). In these time series, to first order, the major changes appear almost coherent across the basin (except on the Greenland shelf). Very fresh water appeared in the mid to late 1970s (by 0.2), and again in the late 1980s and mid 1990s (but more so in the western part of the section, where SSS′ values exceed 0.1, less in the east). These episodes fit with the description of *Reverdin et al.* [1997] and *Belkin et al.* [1998]. They also correspond in recent years to what is observed near Iceland (Figure 3). There are salty episodes around 1930 and 1960 (by 0.1), and a fresh period near 1908–1911 (better defined in the west) (see also *Dickson et al.* [1988]). This roughly corresponds to what is observed in sea surface temperatures (SST) [*Kushnir*, 1994], although the low SST found in the 1920s [*Kushnir*, 1994] is apparently not associated with low salinity.

[25] The spatial correlation of SSS′ at 0 lag is large across the section for spring or summer time series (correlation

coefficient on the order of 0.5 between the Irminger Sea and the eastern Atlantic near 6–8°W). Lagged correlations suggest that the Irminger Sea lags the Iceland Basin near 20°W by nearly 1 year. There is a statistically less reliable lag of the eastern end of the section (1 year or less) with respect to the Iceland Basin. To a large extent, the correlation results from the large decadal signal (low-frequencies correspond to a significant portion of the signal in particular in the western part of the section with correlation from one year to the next in the same season reaching 0.5). When filtering out the multidecadal variability (by removing a 10-year running-mean), the correlation drops to a low-significance level, so that the phase relationships cannot be ascertained. The lags suggested in these seasonally binned data along 60°N are, however, coherent with what we observed in 1996–2001 (hydrography along 56–60°N also suggest different phasing of the salinity variability in the Iceland Basin and the Irminger Sea) [*Bersch et al.*, 1999].

[26] There is no strong indication in this region for seasonal modulation of interannual variability. The different seasons in this seasonally binned data set present a similar interannual RMS variability, typically on the order of 0.06 to 0.08, increasing from east to west for the deep ocean (much larger values are found on the shelves, in particular close to Greenland). Correlation from one season to the next is largest between spring and summer and smallest between summer and autumn (there is not enough winter data to estimate the correlation with this season). However, when spring or summer is taken as the origin of the lag correlation, the autocorrelation function usually decreases regularly with increasing lag, with an exception at one-year lag when there is no decrease between spring and summer. It is not clear how these results are influenced by the sampling, which is less dense in spring than in summer. However, they suggest that in those areas, the processes controlling summer SSS interannual variability similarly affect the other seasons.

3.2. AX02 Section Between Iceland and Newfoundland

[27] The recent seasonal cycle used to construct the time series is usually fresher than the climatology from hydrographic data (not shown). However, it presents comparable phase and amplitude (dashed curve on the lower panel of Figure 5) with amplitude less to the north, increasing south of 55°N with a further large increase south of 50°N where the fresher water of the Labrador Current is found along the continental slope. Near the shelf break, however, the *Levitus* [1986] climatology has a smoother transition in amplitude due to the analysis method adopted to construct it.

[28] The deviations from the average cycle in 1993–2001 present larger RMS values near 52°N/45°30′W (0.15) and over the continental slope (0.24) south of 50°N than at 51°N/47°W (0.09) or at 54°N/42°10′W–55°N/40°40′W (lower panel of Figure 5). Variance increases slightly near 56°N/38°40′W–58°N/35°10′W, where the front associated with the Irminger Current is crossed, and decreases to 0.05 near Iceland. The area near 52°N is straddled by the northwest extension of the North Atlantic Current (NAC) and the Labrador Current flows along the continental slope off the Grand Banks. In the Labrador Current, there is a strong seasonal modulation in RMS variability that is larger in summer and early autumn than in winter-early spring (0.37 versus 0.16 at 49°N/49°W). This was also observed at the 47°N/47°W site in the Flemish Pass in the continuation of this current [*Reverdin et al.*, 1997]. The seasonal modulation of the RMS variability is not statistically significant elsewhere.

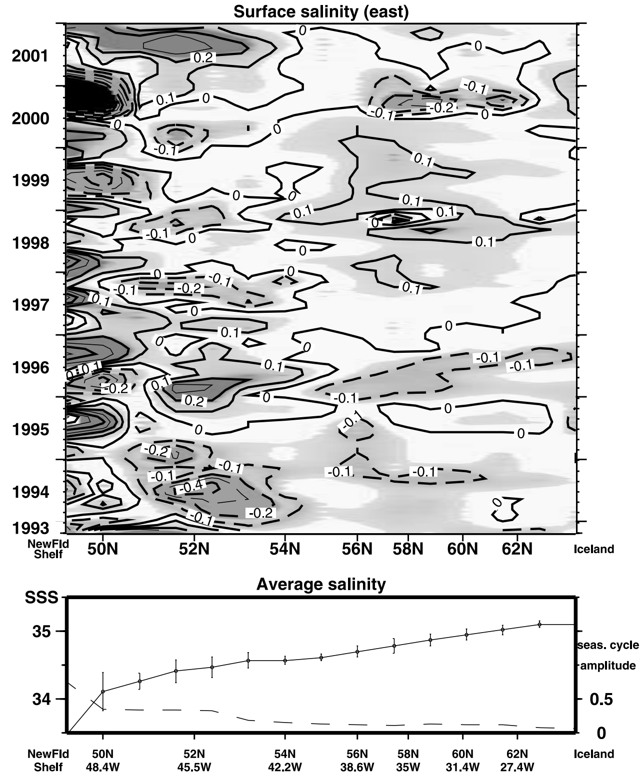

Figure 5. Hövmüller diagram of salinity deviations from the June 1993 to December 2001 average seasonal cycle between Iceland and Newfoundland (line AX02 of Figure 1). The horizontal coordinate is latitude, stretched near the southern end of the section. The lower panel shows the average salinity (full line) with the bars giving two RMS variability of the deviations from the average seasonal cycle. The dashed line is the amplitude of the average seasonal cycle (scale on the right). See color version of this figure at back of this issue.

[29] In the northwest Atlantic extension area of the NAC (near 52°N on Figure 5), SSS anomalies with respect to the 1993–2000 period are negative before mid 1995, after which large positive anomalies are experienced until mid 1997. Altimetric data suggest a weaker subpolar gyre circulation after 1996 [*Verbrugge and Reverdin*, 2002]. However, in 1996, these data also indicate increased northward flow in this area. This could be associated with the penetration of saltier and warmer NAC water. Subsurface temperature measured in this area confirms the presence of warmer NAC water at the end of 1995-early 1996, but this does not last as long as the positive SSS anomaly [*Reverdin et al.*, 1997]. It is difficult to draw significant conclusions on this difference, as the subsurface temperature sampling is only marginal in this area that is characterized by large mesoscale eddy variability.

[30] North of 54°N toward Iceland (54°N–64°N), SSS presents negative anomalies until early 1997 and positive anomalies in 1998–1999, changes coherent with those observed along 60°N with no evidence for seasonal mod-

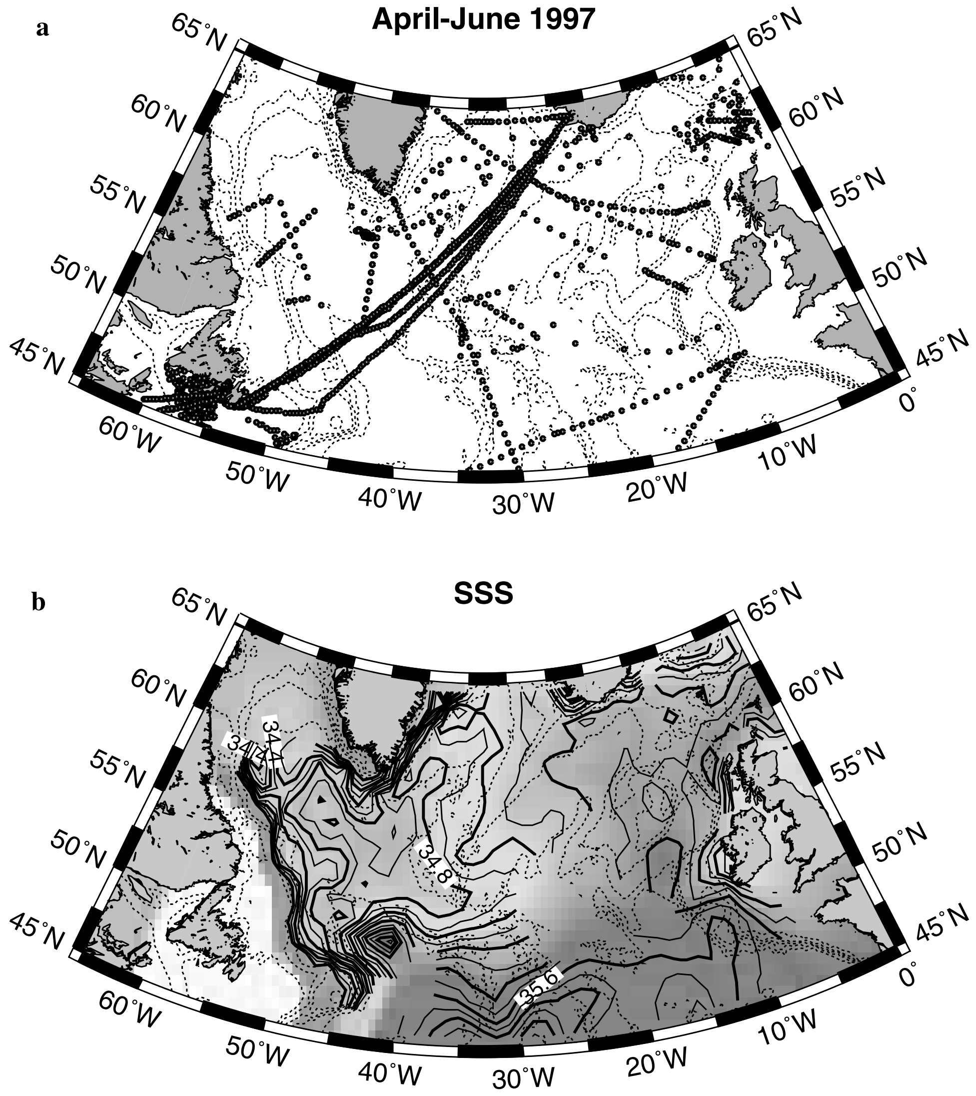

Figure 6. Data distribution (6a) and salinity field (6b) in April–June 1997. See color version of this figure at back of this issue.

ulation of the anomalies. Part of the subsurface temperature variability in this region was interpreted by *Reverdin et al.* [1999] as relating to displacements of the front associated with the cyclonic circulation along the rim of the Irminger Sea. However, the lack of large changes along 60°N across the mean position of the front suggests that this is not the main cause of SSS variability along AX02.

3.3. SSS Fields

[31] A typical reconstructed SSS field is presented for April–June 1997 (Figure 6). Not surprisingly, it shows the typical features of the climatology (the deviations from the climatology are smaller than the spatial variability). We observe the meridional salinity gradient across the NAC in the western Atlantic south of the subarctic front (in particular near 46–47°N and 50–52°N, as described by *Belkin and Levitus* [1996]) with a fresh (34.7–35.0) tongue north of it penetrating eastward to the mid-Atlantic ridge. The pool of fresh water also extends northward in the central Irminger Sea, separated from the east Greenland Current by slightly saltier water. There is a tongue of fresher (34.0–34.7) surface water north of 55°N originating from the east Greenland Current south of Greenland. North of 55°N, the largest salinities are in the Rockall Trough (15°W) extending toward the southern part of the Faroe-Shetland Channel along the Scotland shelf-break side (60°N/5°W). Zonal salinity gradients are rather weak in the Iceland Basin, and a little stronger close to the Reykjanes ridge (southwest of Iceland), with a salinity maximum on the eastern flank of the ridge.

[32] Some periods are not as well covered with the worst coverage in April–June 2000 (Figure 7a). Even for this poorly covered season, the analysis produces a consistent pattern of negative anomalies with respect to the climatology (Figure 7b) in large parts of the domain, but with the occasional bull's-eyes related to the insufficient coverage. The RMS variability in time portrayed by these fields is highly variable spatially (Figure 8). Within the interior of the subpolar gyre it is usually between 0.05 and 0.1 (with lowest values in the east). Temporal variability is larger in the southern Labrador Sea and within the NAC west of 20W near 48N and 51–53N (the vicinity of the subarctic front). Large values are found near shelves and the northwest

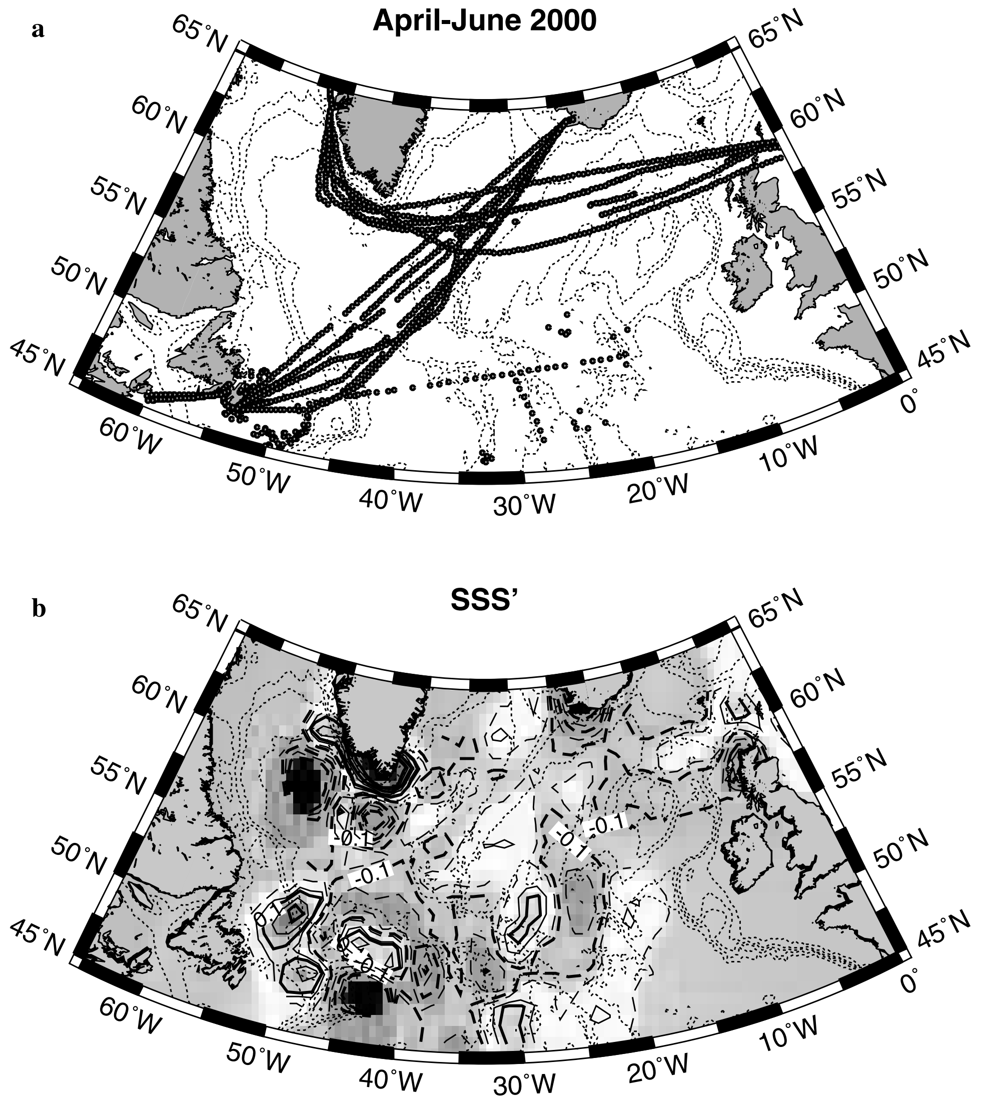

Figure 7. Data distribution (7a) and salinity deviations from climatology (7b) in April–June 2000. See color version of this figure at back of this issue.

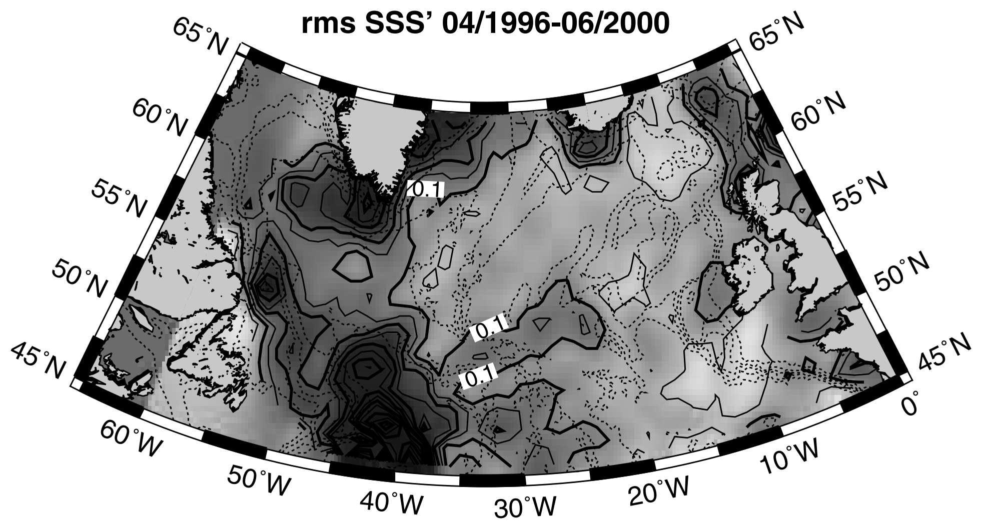

Figure 8. Rms variability in the analyses of SSS (18 fields between April 1996 and June 2000).

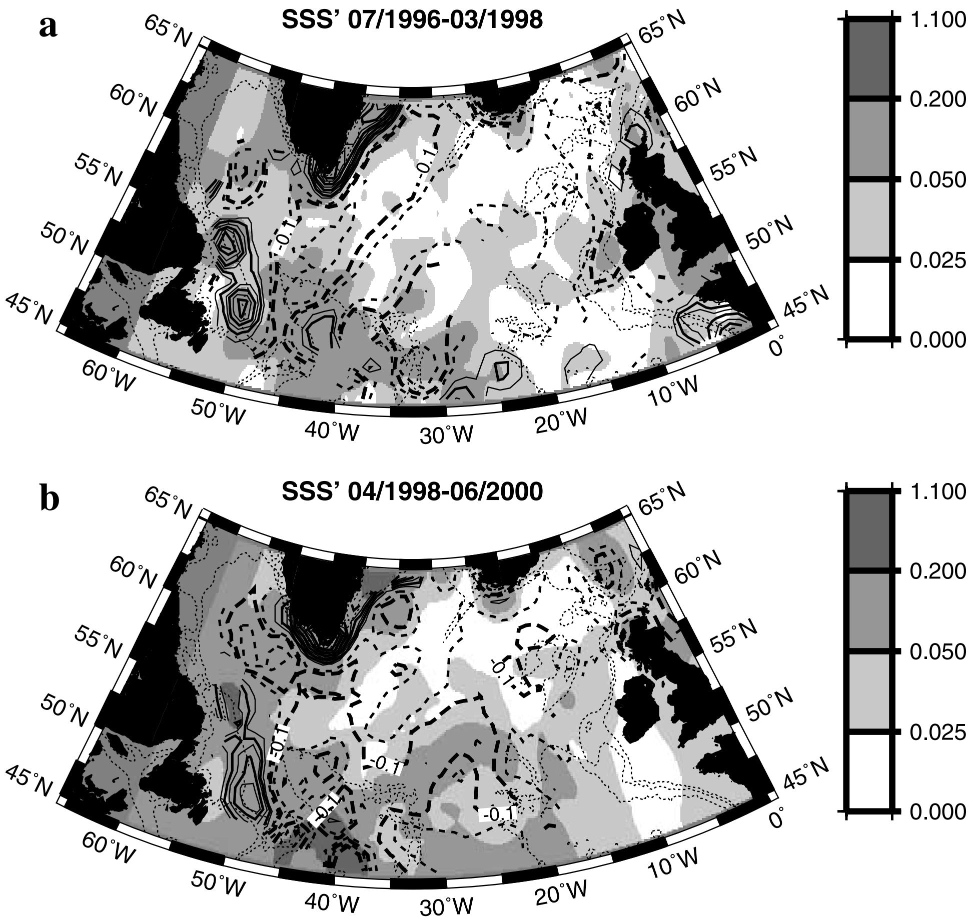

Figure 9. Average deviations from climatology for (9a) July 1996 to March 1998, and (9b) April 1998 to June 2000. The 90% confidence domain are indicated in a gray scale (scale on the right).

corner extension of the NAC in the western Atlantic. What part of this variability is large-scale low frequency, and what part is caused by errors resulting from insufficient sampling of mesoscale variability?

[33] The anomaly fields present large uncertainties where sampling is insufficient to reduce mesoscale noise, in particular near the shelf breaks and in the NAC, where the circulation is variable [*Ducet et al.*, 2000]. Without an adequate knowledge of signal and noise, an upper bound for the uncertainty on the SSS fields assuming that deviations of the anomaly fields between successive seasons results from errors. This assumes that the "signal" is correlated between successive seasons. However, winter and summer surface anomalies are not correlated at OWS C (52.7°N/35°W), and this is likely to be also true for the whole NAC and the fresh tongue area to its north. In this domain with a large seasonal cycle of surface salinity and surface fresh water content [*Smed*, 1943; *Levitus*, 1986], variability in summer is related to seasonal advection and surface trapping of freshwater [*Bauer et al.*, 1991], and this contributes largely to the variability between seasons. Therefore in those regions, the estimated error will be overestimated. On the other hand, SSS anomalies in successive seasons are better correlated farther north away from shelves. In those regions, an error estimate based on seasonal differences will be closer to reality.

[34] To reduce errors, we rather arbitrarily divided the whole record (1996–2000) into two periods in which we composite the anomaly fields: before and after 31 March 1998 (Figure 9). In many areas, data are missing in some seasons and consequently the average is more weighed toward summer. The positive anomalies near shelf breaks are suspicious, in particular near East Greenland, which might not have been properly sampled in the climatological field (the same difficulty was noticed with the 60°N time series, Figure 2). Both composites show widespread negative SSS anomalies with respect to climatology, often exceeding −0.10, across the interior subpolar gyre. These average values are usually significant at the 90% confidence level (notice, however, that the fields are not complete in the southeastern part of the domain with the limited data set used here, although the data suggest positive SSS anomalies at least for the first composite). Similar anomalies with respect to climatology are also observed at subsurface (not shown). The negative anomalies are larger in the Irminger Sea during the first period. They are larger in the Labrador Sea, the Iceland Basin north of 55°N (excluding the Rockall Trough) and the northwest corner of the NAC (45°W/50°N) during the second period.

[35] Between Iceland and Newfoundland (line AX02) and along 60°N, the evolution suggested by these anomaly composites with respect to the average seasonal cycle based

on all the available hydrographic and ships-of-opportunity data collected between 1896 and 1993 is coherent with the evolution described in the previous sections with typically O(0.05 to 0.10) changes between the two periods of Figure 9 (July 1996 to March 1998, and April 1998 to June 2000).

4. Discussion

[36] SSS in the subpolar N. Atlantic has been sampled regularly for sufficient time to resolve seasonal variability in two areas: along 60°N since 1896 (albeit with usually no data from mid-December to mid-April, and with gaps during the two world wars and in the early 1970s), and along WOCE line AX02 between Iceland and Newfoundland since 1993. In other areas of the subpolar domain, we investigated SSS variability since 1996, based mostly on irregularly distributed hydrographic cruises. In the parts of the North Atlantic subpolar gyre presenting a weak SSS seasonal cycle, the analyses indicate comparable interannual to decadal SSS variability in the different seasons. On interannual timescales, the data we have investigated suggest that this does not hold in the parts of the subpolar gyre which experience large seasonal variability (near the slope currents off Greenland and North America and near 48–53°N in the western Atlantic (northern branches of the NAC)) [see *Levitus*, 1986]. This is not surprising as the seasonal changes in these regions result to a large extent from advective processes [*Bauer et al.*, 1991], which have large year-to-year changes. It would be even more interesting to have three-dimensional fields to gain a better idea of the vertical trapping scale of the surface anomalies. The sparseness of the data often prevents this analysis on a seasonal timescale. In the absence of such information, it is difficult to make use of SSS during the stratified seasons from late spring to early autumn. In those areas, composites that mix data from different seasons should be considered with caution.

[37] During recent years, most of the subpolar gyre has been anomalously fresh, but with noticeable differences between the different basins. This is best illustrated along 60°N, where the multiyear evolution of SSS is quite similar between Greenland and the Shetlands, albeit with an indication of a one-year lag in the Irminger Sea compared to the Iceland Basin (near 15–25°W) (more clearly illustrated by *Reverdin et al.* [1997] for a few time series stations). Within the period 1996–2000, there was a salinity maximum that propagated around the subpolar gyre, and was replaced in its wake by anomalously fresh waters in the Iceland Basin.

[38] Previous studies suggested a link between SSS variability and atmospheric variability (mostly NAO; cf. section 1). The lower panel of Figure 4 presents the winter NAO index together with a SSS typical time series west of Reykjanes ridge. The correlation at 0 lag is not correlated with the NAO, but there is a significant (at 95% confidence level) negative correlation (−0.3) when salinity lags the NAO by 3 to 4 years (low salinity after high NAO index). The large-scale freshening since the early 1970s is coincident with the increase in the westerlies at 50–60°N [*Kushnir*, 1994]. However, the earlier period with large westerlies in the early 1920s at these latitudes is associated with only moderate negative anomalies. The low frequency relationship between salinity and the wind pattern was also shown by *Reverdin et al.* [1997] for the post-war years, but was clearer for time series in the western part of the subpolar gyre than in the eastern part, which includes the 60°N section. *Reverdin et al.*'s [1997] analysis indicated that the SSS variability was not identical through the region, even when lags between different sites were taken into account. Therefore the low correlation with NAO we find here is not completely unexpected.

[39] The association of low salinity with the large westerly winds of recent decades is not completely straightforward. There are some indications from model simulations and surface data suggesting that the higher NAO indices in these recent decades should be associated with an increase in the meridional circulation, and therefore of the cross-gyre transports [*Eden and Jung*, 2001; *Kushnir*, 1994] that would contribute to higher SSS. However, this reinforcement of the meridional circulation does not seem to be fully supported by hydrographic data [*Koltermann et al.*, 1999]. There should also be a reinforcement of the subpolar gyre circulation [*Eden and Willebrand*, 2001], expected lag with respect to the wind change. This seems to be observed in hydrographic data [*Curry and McCartney*, 2001] and could contribute to a negative salinity anomaly, in particular if it relates to more surface Arctic fresh water transported into the interior of the subpolar gyre. The observed salinity changes suggest a contribution of the second process. This was the hypothesis for the propagating salinity anomalies observed from a few time series by *Reverdin et al.* [1997]. Studies of ice export from the Arctic indicate that since the late 1970s, high NAO indices are favorable to an increase in fresh water export from the Arctic to the Nordic seas [*Vinje et al.*, 1998; *Kwok and Rothrock*, 1999] and probably also through Denmark Strait between Iceland and Greenland to the Irminger Sea [*Hilmer and Jung*, 2000]. This may not always be the case: for instance, the largest freshening south of Denmark Strait might have resulted from the large ice export in the late 1960s, in particular 1968, a year with average NAO index [*Dickson et al.*, 1988; *Häkkinen*, 1993; *Hilmer and Jung*, 2000].

[40] The response on an interannual timescale of SSS to the variability in the winds and heat flux forcing might be somewhat different from the one at the lower frequencies just discussed. Numerical simulations [*Häkkinen*, 2001; *Eden and Willebrand*, 2001] indicate changes both in the subpolar gyre strength and in the meridional circulation: high NAO corresponding to enhanced gyre strength and meridional circulation. *Eden and Willebrand* [2001] also discuss different timescales involved with an initial step after a change in wind stress curl involving changes in cross-gyre transport (an NAO increase associated with less poleward flow in the central part of the basin). In recent years, there was at least one sudden change (decrease) of NAO index in the autumn 1995 and the following winter. Both altimetric data [*Esselborn and Eden*, 2001; *Verbrugge and Reverdin*, 2002] and in situ observations [*Bersch et al.*, 1999] indicate a significant weakening of the subpolar gyre circulation following this weakening of the zonal wind stress. There is also some evidence in the altimetric data for an initial increase of poleward velocity in the northwest extension region of the North Atlantic Current, which could contribute to an increase of salinity in this region. How the weakening of the subpolar gyre would result in a salinity increase in the

interior of the subpolar gyre is not clear from the data (T and S variability in the Irminger Sea are not in phase). There is some suggestions that it might first happen in the southwest part of the gyre, from there to the Iceland Basin, then by advection to other areas of the subpolar gyre. Changes in E-P will also contribute, although the E-P pattern associated with NAO [*Bojariu and Reverdin*, 2002] is rather uncertain in the subpolar gyre because of insufficient data and the uncertainties in model reanalyses, but tends to indicate a dipole between east and west in the subpolar gyre (high NAO with a positive E-P in the west, and negative in the east, so that the weakening of the winds would contribute to a salinity increase in the eastern part of the subpolar gyre).

[41] For understanding further what controls upper ocean salinity variations in the North Atlantic subpolar gyre, two-dimensional maps of the salinity evolution and salt advection are required over a longer period that what are presented here. It would be best to have also the information on the vertical trapping scale of the SSS anomalies. Profiling floats deployed in the subpolar gyre, mainly since the autumn 1996 [*Lavender et al.*, 2000; *Bacon et al.*, 2001] will provide a comprehensive data set of temperature and salinity profiles starting mostly 15 m from the sea surface with a relatively low vertical resolution. The data set will resolve the seasonal cycle of salinity stratification from late 1996 to at least early 1998. New instrument deployments are taking place in 2001/2002 within the international ARGO program that will better resolve the surface layer. Assessment of the usefulness of these data for study of surface salinity variability has been initiated by comparison with nearby surface TSG data. Remaining errors in the data are found to be less than the long-term variability in the subpolar gyre which we have found to be always larger than 0.1, so that the profiling floats will certainly contribute to monitoring the low-frequency upper ocean salinity in the subpolar gyre. This, together with satellite-derived SSS estimates and surveys along dedicated ships-of-opportunity routes should provide the adequate data sets for further investigation of climate variability in the North Atlantic.

[42] **Acknowledgments.** We are very grateful to the numerous oceanographers that got involved in the collection of surface data in the North Atlantic during the last 105 years. It is also wonderful that ICES in Copenhagen (Denmark) has coordinated these activities and archived the data during most of that period. We are highly indebted to the company EIMSKIP based in Reykjavik (Iceland) and to the company Royal Arctic Line based in Nuuk (Greenland) and Aalborg (Denmark) to have been so cooperative with the scientific programs that were carried from their ships, The crews of these ships have greatly contributed to the success of the program. We are quite thankful for the technical support from various institutions (in particular, NOAA and IRD). It is a pleasure to acknowledge the speediness with which the WOCE and VEINS hydrographic data were made public, and for the communication of data from three PALACE floats (Sheldon Bacon, Luca Centurioni and John Gould at SOC, Southampton, UK). This is a contribution to the French Programme National d'Etude du Climat with financial support from Institut National des Sciences de l'Univers and from Institut Français de Recherche des Territoires Polaires. Finally, we are grateful to John Toole for numerous editorial comments and questions. The data that we used are available through a variety of sources, in particular, http://www.ices.dk, http://www.wocediu.org/WHP/index.htm, http://www.ices.dk/ocean/project/veins, http://www.mar.dfo-mpo.gc.ca/science/ocean/database/data_query.html.

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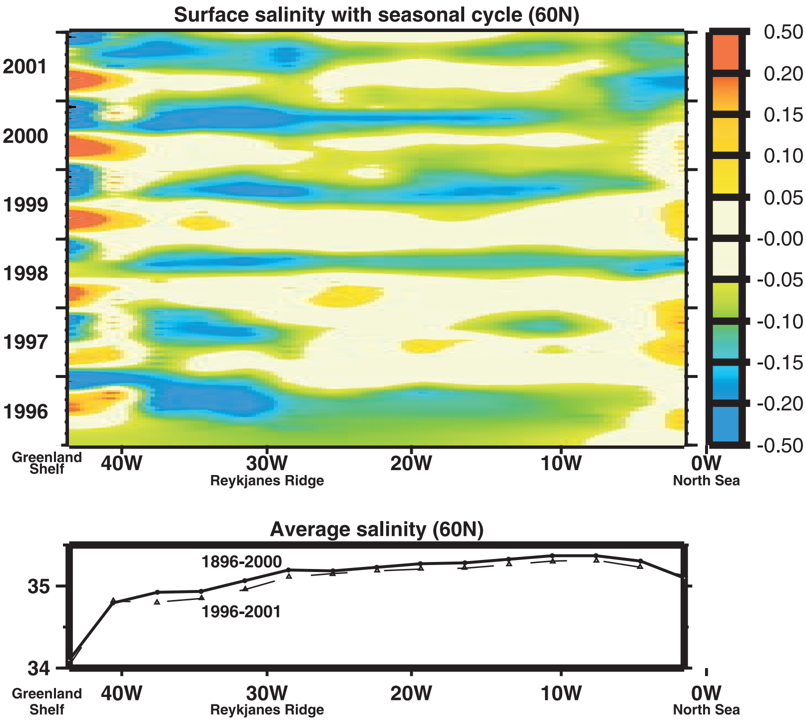

Figure 2. Hövmüller diagram of salinity along 60°N between Greenland and the Shetlands (with seasonal cycle, but after removing the climatological long-term average). The first six months of 1996 usually have insufficient data, and there is rarely data from mid-January to mid-April which is filled on the plot by combining the average seasonal cycle with deviations from it interpolate linearly between January and April. The lower panel compares the 1896–2000 average with the average for 1996–2001.

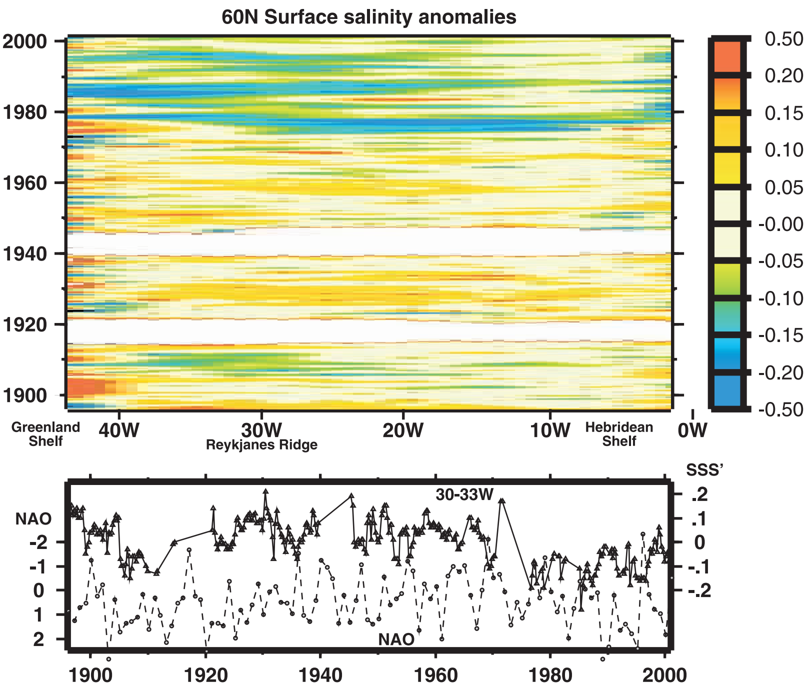

Figure 4. SSS′ along 60°N. Upper panel: Hövmüller diagram of salinity deviations from the long-term climatological seasonal cycle (the ticks on the vertical axis correspond to 1 January of the year indicated). The normalized NAO DJFM winter index based on Iceland and Gibraltar SLP data is also shown (inverted scale on the left) with salinity at 30–33°W (scale on the right) (lower panel).

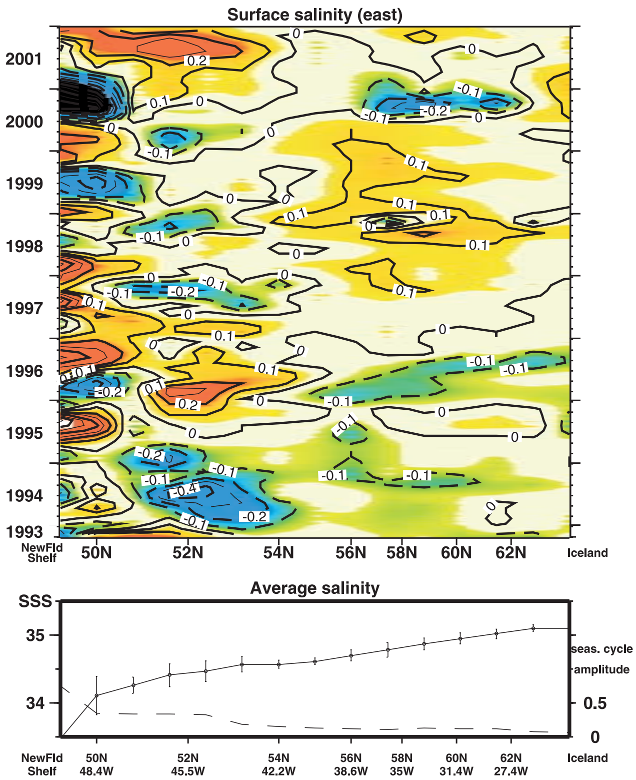

Figure 5. Hövmüller diagram of salinity deviations from the June 1993 to December 2001 average seasonal cycle between Iceland and Newfoundland (line AX02 of Figure 1). The horizontal coordinate is latitude, stretched near the southern end of the section. The lower panel shows the average salinity (full line) with the bars giving two RMS variability of the deviations from the average seasonal cycle. The dashed line is the amplitude of the average seasonal cycle (scale on the right).

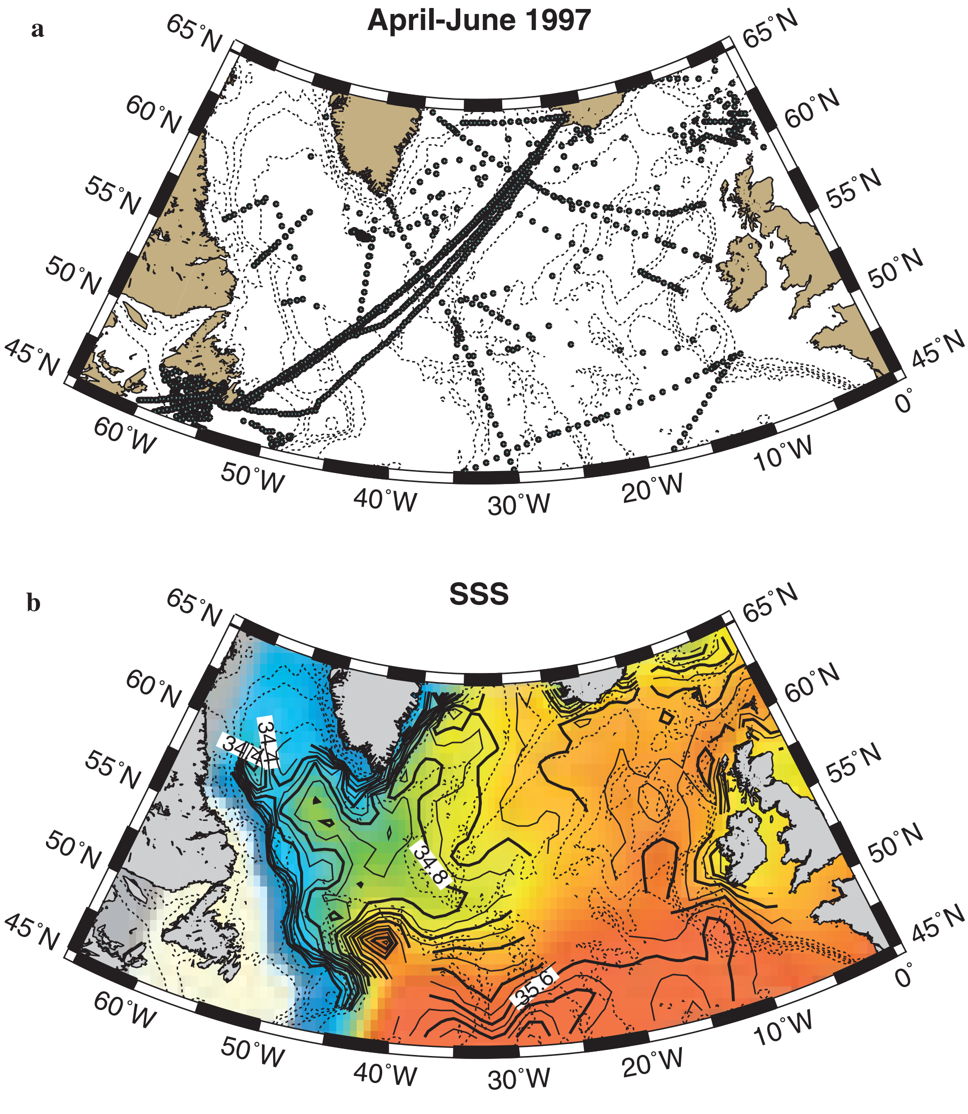

Figure 6. Data distribution (6a) and salinity field (6b) in April–June 1997.

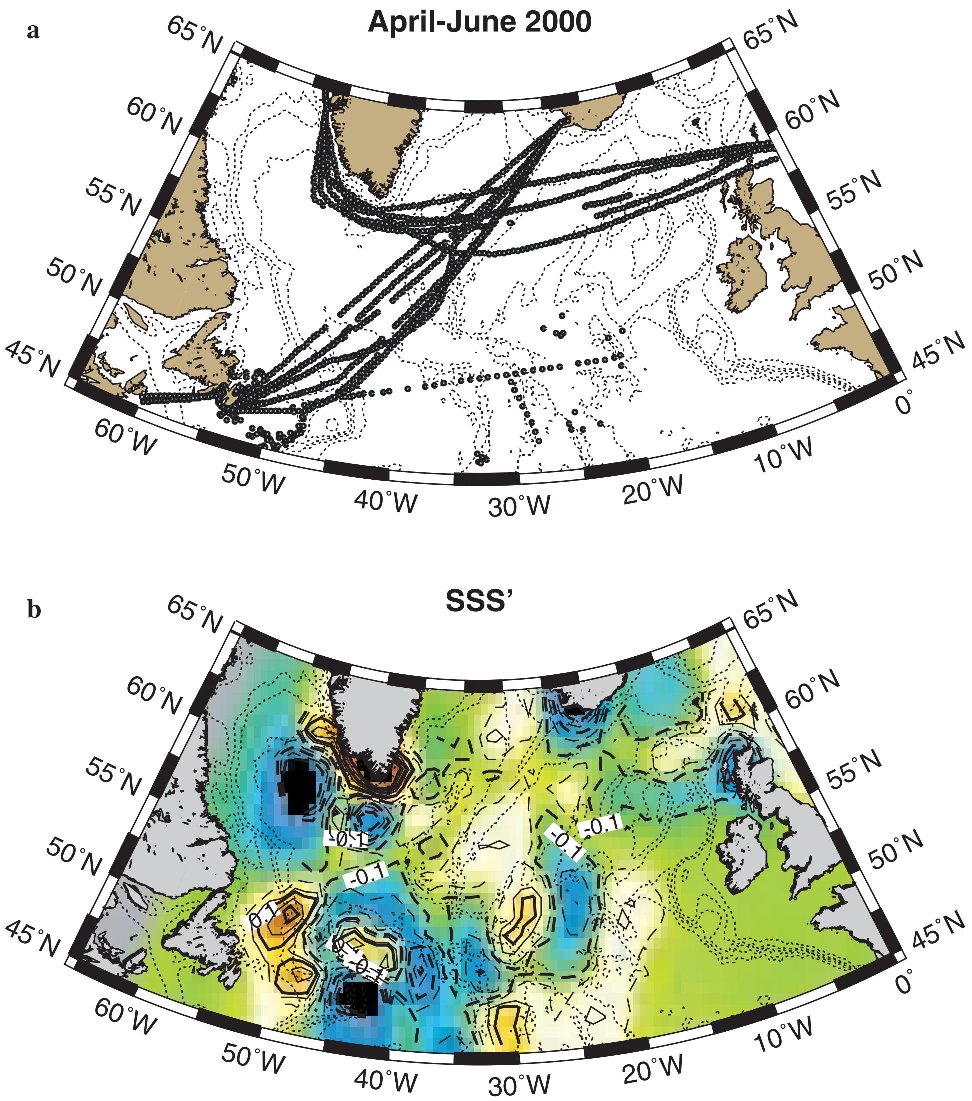

Figure 7. Data distribution (7a) and salinity deviations from climatology (7b) in April–June 2000.