NOTES AND CORRESPONDENCE

Changes in Temperature and Salinity Tendencies of the Upper Subtropical North Atlantic Ocean at 24.5°N

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ABSTRACT

Strong interest in multidecadal changes in ocean temperature and heat transport has resulted in the occupation of the North Atlantic Ocean hydrographic transect along 24.5°N five times since 1957, more than any other transoceanic section in the world. This latitude is chosen because it is where the northward ocean transport of heat in the Atlantic reaches its maximum. An analysis of the five oceanographic cruises at this latitude shows that there has been a significant cooling of −0.15°C in the upper ocean (600–1800-dbar range) over the last 7 years, from 1998 to 2004, which is in contrast to the warming of 0.27°C observed from 1957 to 1998. Salinity shows a similar change in tendency, with freshening since 1998. For the upper ocean at 24.5°N, 1998 was the warmest and saltiest year since 1957. Data from the Argo network are used to corroborate the strong cooling and freshening since 1998, showing a −0.13°C cooling in the period between 1998 and 2006 and revealing interannual variability between 2005 and 2008 to be much smaller than the decadal variability estimated using the transect. The results also demonstrate that Argo is an invaluable tool for observing the oscillations in the tendencies of the ocean.

1. Introduction

The Atlantic Ocean meridional overturning circulation (MOC) contributes to the moderation of climate in Europe through the northward transport of 25% of the global heat flux, which is at maximum (1.5 PW) at around 24.5°N (Lavín et al. 2003). Consequently, transatlantic oceanographic sections at this latitude have become a benchmark for monitoring long-term changes in temperature in the Atlantic (Parrilla et al. 1994) and for studying the nature and causes of climate change (Bindoff et al. 2007).

The first oceanographic section across the North Atlantic subtropical gyre at 24.5°N was carried out during the 1957 International Geophysical Year (IGY; Fuglister 1960). Since then, four additional occupations have been carried out: one in 1981 (Roemmich and Wunsch 1985), two during the World Ocean Circulation Experiment (WOCE) in 1992 (Parrilla et al. 1994) and 1998 (Baringer and Molinari 1999), and then one in 2004 (Cunningham and Alderson 2007).

Examination of these hydrographic sections over the subtropical North Atlantic Ocean reveals that in 1992

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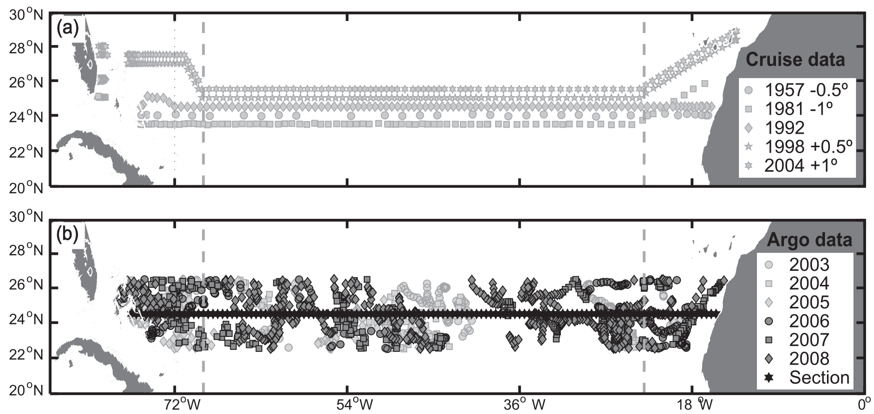


FIG. 1. (a) Positions of the CTD stations from the repeated hydrographic sections sampled across 24.5°N in 1957 (IGY), in 1981, during WOCE in 1992 (A05), and in 1998 (AR01), and finally in 2004. To avoid overlapping between each section, a latitude offset has been added to each section, as indicated in the legend. (b) Locations of each Argo profile in the period between January 2003 and December 2008 used in this study. The 2006 Argo zonal "synthetic" section obtained is also shown. The gray lines at 23° and 70°W bound the longitude range where the Atlantic was effectively sampled at 24.5°N during the five occupations.

the subtropical Atlantic along 24.5°N was warming at 0.65°C century^{-1}, with a maximum of 1°C century^{-1} in the intermediate waters at 1100 dbar between 1981 and 1992 (Parrilla et al. 1994). For the 2002−1992[1] period, this warming was higher (2.7°C century^{-1}) in the eastern basin thermocline (Vargas-Yáñez et al. 2004). According to Cunningham and Alderson (2007), who focused on the differences between the western (65°–75°W) and the eastern (25°–35°W) basins, the warming in the western Atlantic thermocline since 1957, at a rate of 1.11°C century^{-1}, dominated the transatlantic average, whereas deep water cooled and freshened. These authors concluded that waters shallower than 1750 dbar had been warming and becoming saltier since at least 1981 and that in 2004 they were significantly warmer and saltier than at any time since 1957.

From 1957 to 1981, the observed warming and increase in salinity was principally due to the downward heave of isopycnals, whereas from 1981 to 1992 it was dominated by changes in water mass characteristics (Bryden et al. 1996). The analyses of the 1992 and 2004 sections also indicated that upper-ocean changes dominate over deep ocean changes (Parrilla et al. 1994; Cunningham and Alderson 2007).

[1] The convention of using positive values to indicate a warming/increase in salinity has been followed throughout the text. By this convention, the older temperature/salinity section has to be subtracted from the most recent one when computations refer to time periods. Therefore, reverse-order year ranges are used to be consistent with figures and computed tendencies.

In addition to these five oceanographic sections, the global array of temperature–salinity free-drifting profiling floats, known as Argo, provides continuous monitoring of temperature and salinity in the upper 2000 dbar at regular 10-day intervals (Argo Science Team 1998). These data are made publicly available within hours of their collection. Argo has evolved to the point that the goal of 3000 free-drifting profiling floats has been recently achieved.

This paper reports that, on average, waters shallower than 2000 dbar across 24.5°N have cooled and freshened between 1998 and 2006. These results were obtained using two independent datasets: the repeated ocean cruises described above and the Argo network at its full capacity of large spatial and temporal coverage. The results also confirm the usefulness of the Argo network to study long-term variability in ocean properties and to permit basinwide views of the changes. The remainder of the paper is organized as follows: in section 2, the dataset and methods are described. Section 3 shows the results found in the comparison of the hydrographic sections and the Argo data. In section 4, the results are discussed and the conclusions are presented.

2. Data and methods

Each of the five hydrographic sections extends from the African continental shelf to the Bahamas. However, although the 1957 and 1992 sections follow the 24.5°N parallel over the entire Atlantic, the 1981, 1998, and 2004 sections angle southwestward from the African continental shelf at about 28°N to reach the target latitude at around 23°W and again angle northwestward at about 70°W to continue the section along 26.5°N (Fig. 1a). As a result, up to 2° differences in the latitudes of the sections may be found west of 70°W and east of 23°W.

The five transatlantic sections also differ in the details of their sampling scheme. The 1957 section consisted of 38 stations, with a mean distance between stations of 230 km, and was sampled with Nansen bottles at 25 depth levels; the 1981 section was carried out with continuous CTD measurements for 90 profiles with a mean spatial resolution of 79 km; and finally the 1992, 1998, and 2004 sections were carried out with continuous CTD measurements at a similar distance between stations, around 70 km.

To compare the five hydrographic sections in the longitude range at 24.5°N that was effectively sampled during the five occupations, only the CTD casts between 23° and 70°W are used. This avoids comparison of sampling at different latitudes over the African and Bahamian continental shelves, where there are up to a 2° difference in latitude between the different sections. Additionally, and given the different sampling grid for each transoceanic section, temperature and salinity data from each survey have been linearly interpolated to 101 pressure levels between the surface and 2000 dbar and bilinearly each 0.5° in longitude. The use of other interpolating yields the same results.

All available good quality Argo data in the North Atlantic between January 2003 and December 2008 are used. The Argo data system (Argo Data Management Team 2002) provides real-time quality control and delayed mode quality control when available. Additionally, the data passed a more stringent quality control procedure developed by the present authors. This quality control includes visual inspection of all the temperature and salinity profiles used, comparing them with their neighboring profiles by means of objective analysis. All floats with suspicious profiles either in temperature or salinity were inspected individually. Those profiles from floats with suspicious behavior, or on the Argo gray list (Argo Data Management Team 2002), have been excluded from the data. As a result, only 2048 from an initial set of 2411 profiles within the region of interest (20°–40°N, 80°–8°W) are used (Fig. 1b). The data were initially downloaded in May 2009, but similar results are obtained with data downloaded in March 2010, demonstrating the robustness of the method.

After our quality control step, the Argo data were objectively interpolated onto a hypothetical zonal "section" at 24.5°N, using an updated version of the method of optimal statistical interpolation employed previously by Fraile-Nuez and Hernández-Guerra (2006). This statistical approach is commonly used to obtain climatological fields, because it is designed to minimize the noise-to-signal ratio. Noise is defined as any nonresolved scale, and in transoceanic sections it is mainly attributed to eddies (Gomis and Pedder 2005; Pedder 1993). For the objectively interpolated temperature and salinity fields, the annual climatological temperature and salinity data from the *World Ocean Atlas 1994* (Levitus et al. 1994; Levitus and Boyer 1994) are used as a first guess to ensure that the anomaly field (data minus climatology) is a stationary, zero-mean random function of the location. A sensitivity study using the annual climatological temperature and salinity fields from the *World Ocean Atlas 2005* (Antonov et al. 2006; Locarnini et al. 2006) as a first guess yielded similar results, as described in section 3. However, the analysis carried out with the first guess obtained from the *World Ocean Atlas 1994*, which does not include the 2004 CTD data, ensures the independence of the Argo synthetic section from the 2004 CTD data.

The large amount of data and the 6-yr span of the observations allow the ocean "eddy" noise, always present in single hydrographic sections, to be greatly reduced. In this sense, the synthetic Argo section is less affected by eddy noise than the hydrographic sections at 24.5°N. This is demonstrated by the fact that the noise-to-signal ratio $\gamma = \langle \text{observational error} \rangle / \langle \text{observed anomalies} \rangle$ obtained during the objective analysis of the Argo section is an order of magnitude smaller than that for a single hydrographic section. In particular, the ratio is 0.08 for the Argo temperature section, but it is 1.27 and 0.68 for the WOCE A05 1992 and the WOCE AR01 1998 sections, respectively.

The resulting Argo synthetic zonal section is composed of temperature and salinity profiles every 0.5° between 23° and 70°W, at 101 pressure levels between the surface and 2000 dbar. The computed mean date is 2006; therefore, this synthetic Argo section would be considered as the sixth occupation of 24.5°N in 2006. This synthetic Argo section was used by Hernández-Guerra et al. (2009) to show that the transport estimates derived from Argo data have significantly less eddy noise than those estimated from individual hydrographic sections. Hernández-Guerra et al. (2009) have also shown that, within the estimation error, the upper limb of the Atlantic MOC has not changed significantly since 1957.

Synthetic sections with computed mean times for 2005, 2006, 2007 and 2008 are also obtained by objectively analyzing all the Argo data between January and December of the respective year, following the procedure described above. Similar results regarding the annual variability were obtained using yearly estimations based on data centered on the target year extending over a 2–3-yr time period.

The model proposed by Bindoff and McDougall (1994) is used to interpret temperature and salinity variations in the water column. Using a Taylor expansion and assuming that vertical gradients of temperature are constant in time, these authors showed that, for small displacements, temporal changes of potential temperature (θ) on isobars can be split into two components:

$$\left.\frac{d\theta}{dt}\right|_p = \left.\frac{d\theta}{dt}\right|_{\gamma_n} - \left.\frac{dp}{dt}\right|_{\gamma_n} \frac{\partial\theta}{\partial p},$$

where the subscript p denotes isobaric rates of change, the subscript γ_n denotes rates of change along neutral surfaces, $dp/dt|_{\gamma_n}$ denotes the isoneutral displacement, and $\partial\theta/\partial p$ denotes the vertical temperature gradient. The equation represents the observed changes of temperature along isobaric surfaces as the sum of two independent contributions: changes along neutral surfaces and changes due to vertical displacements of the isoneutral surface itself. The latter is referred to as heaving (Jackett and McDougall 1997). Two mechanisms can contribute to heaving: changes in isopycnal thickness by changing renewal rates and changes in the gyre circulation strength resulting from changes in wind stress curl. On the other hand, changes on isoneutral surfaces are representative of variability in the surface heat fluxes in the water formation area (Jackett and McDougall 1997; Arbic and Owens 2001). Salinity differences on isobars can be decomposed in a similar manner, but for the sake of brevity this decomposition is not presented here.

3. Results

a. Basinwide changes

Contoured sections of the temperature differences on isobaric surfaces for the periods 1998−57 (i.e., between 1957 and 1998), 2004−1957, 2004−1998, 2006(Argo)−1957 and 2006(Argo)−1998 are presented in Fig. 2. The temperature difference sections have been smoothed using a 300-km low-pass Gaussian filter to eliminate eddy variability from the cruise sections.

Temperature differences between the WOCE 1998 and IGY 1957 surveys (Fig. 2a) reveal that the subtropical North Atlantic at 24.5°N warmed during this 41-yr period at a similar rate, 0.65°C century^{-1}, as that found in 1992 (Parrilla et al. 1994). The warming occurred almost basinwide, with a maximum of up to 1°C found between 800 and 1000 dbar.

Temperature differences between the 2004 and 1957 sections (Fig. 2b) show that the Atlantic interior in 2004 was warmer than in 1957. However, the magnitude of the warming is lower than that in 1998, especially in waters deeper than 400 dbar, where the warming of up to 1°C found in 1998 was reduced to less than 0.5°C in 2004, and even lower in the eastern central Atlantic (20°–45°W). This recent cooling, reversing the previous long-term warming trend, is clearly observed in the temperature differences between the 2004 and the WOCE AR01 1998 sections (Fig. 2c). The cooling in the period 2004–1998 was basinwide, except for the central Atlantic (40°–55°W), where a 0.70°C warming in the upper levels (<200 dbar) is found. This warming extends to 1200 dbar but decreases to less than 0.05°C in the waters deeper than 1200 dbar. The observed 2004−1998 cooling had maximum values of −0.5°C at 800 dbar between 55° and 65°W in the western basin and at 350 dbar between 25° and 30°W in the eastern basin.

Temperature differences for 2006−1957 and 2006−1998 using the synthetic Argo section for 2006 (Figs. 2d,e) show changes similar to those found using the CTD data for the same periods. This confirms, using an independent dataset, the usefulness of the Argo data for long-term studies. In particular, the observed maximum cooling at 800 dbar between 55° and 65°W in the western basin, as well as the slight warming in the central Atlantic (40°–55°W), is clearly observed in the temperature difference section for the period between 1998 and 2006 (Argo).

Regarding salinity changes at 24.5°N, there was an increase between 1957 and 1998, with the larger changes occurring in the top 1200 dbar (Fig. 3a). Maximum values of up to 0.2 are found in the top 300 dbar, decreasing almost linearly to 0.02 at 1000 dbar. Salinity differences between the 2004 and IGY 1957 sections (Fig. 3b) show that the Atlantic interior in 2004 was saltier than in 1957, with a similar pattern to that found during 1998. However, the increase in salinity was lower than that found in 1998, especially in waters deeper than 300 dbar, because the waters in 2004 are just 0.05 saltier than in 1957. This recent freshening, reversing the previous long-term salt increase tendency, is clearly observed in the salinity differences between the 2004 and the WOCE AR01 1998 sections (Fig. 3c). During this period, the freshening was higher in the top 800 dbar, except for in the central Atlantic (40°–55°W), where a 0.05 salt increase in the upper levels (<300 dbar) and intermediate levels is found. Around 800 dbar, there is a relative maximum in the freshening with values of up to −0.1. Salinity differences for the periods 2006 (Argo)−1957 and 2006 (Argo)−1998 (Figs. 3d,e) show changes similar to those found using the CTD. This also confirms the observed freshening by means of an independent dataset.

b. Zonally averaged changes

Vertical profiles of zonally averaged temperature differences between 1957 and the five occupations (Fig. 4a)

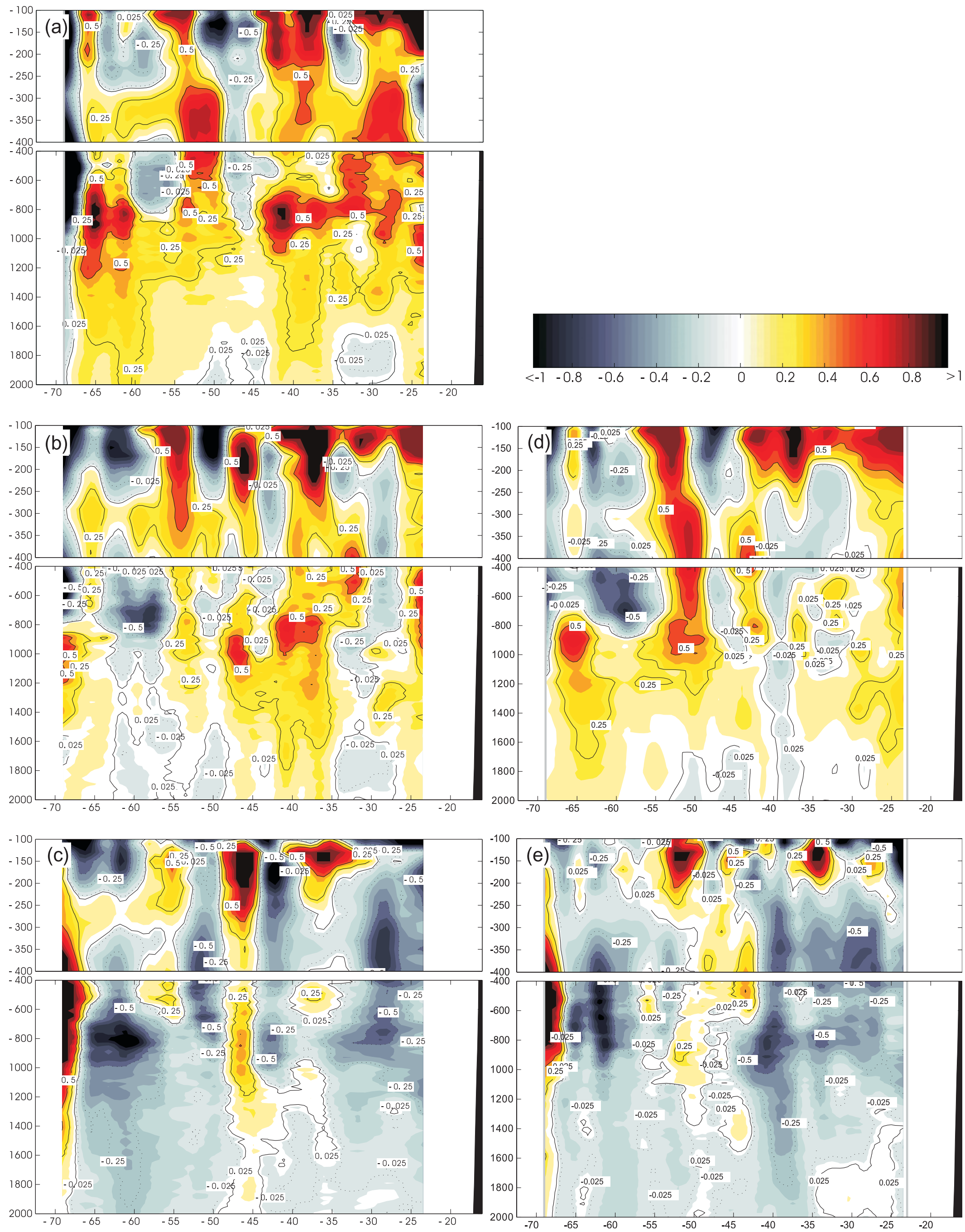


FIG. 2. Vertical zonal sections, on pressure surfaces, of potential temperature differences at 24.5°N in the Atlantic Ocean between the oceanographic sections carried out during (a) 1998−57 (i.e., between 1957 and 1998), (b) 2004−1957, (c) 2004−1998, (d) 2006 (Argo)−1957, and (e) 2006 (Argo)−1998. The gray lines at 23° and 70°W bound the longitude range where the Atlantic was effectively sampled at 24.5°N during the five occupations. Positive values indicate warming. This convention has been used throughout the text, subtracting the older temperature section from the most recent one when computations refer to time periods. The same color scale has been used for the five panels.

confirm and quantify the changes in the tendency observed in the basinwide sections. A warming between the first occupation in 1957 and the sections sampled in 1981, 1992, and 1998 is observed. The maximum warming shifted from 900 dbar in 1981 to 1000 dbar in 1992 and back to 900 dbar in 1998.

The maximum warming with respect to 1957 occurs in 1998, with an averaged warming of 0.27°C for the upper

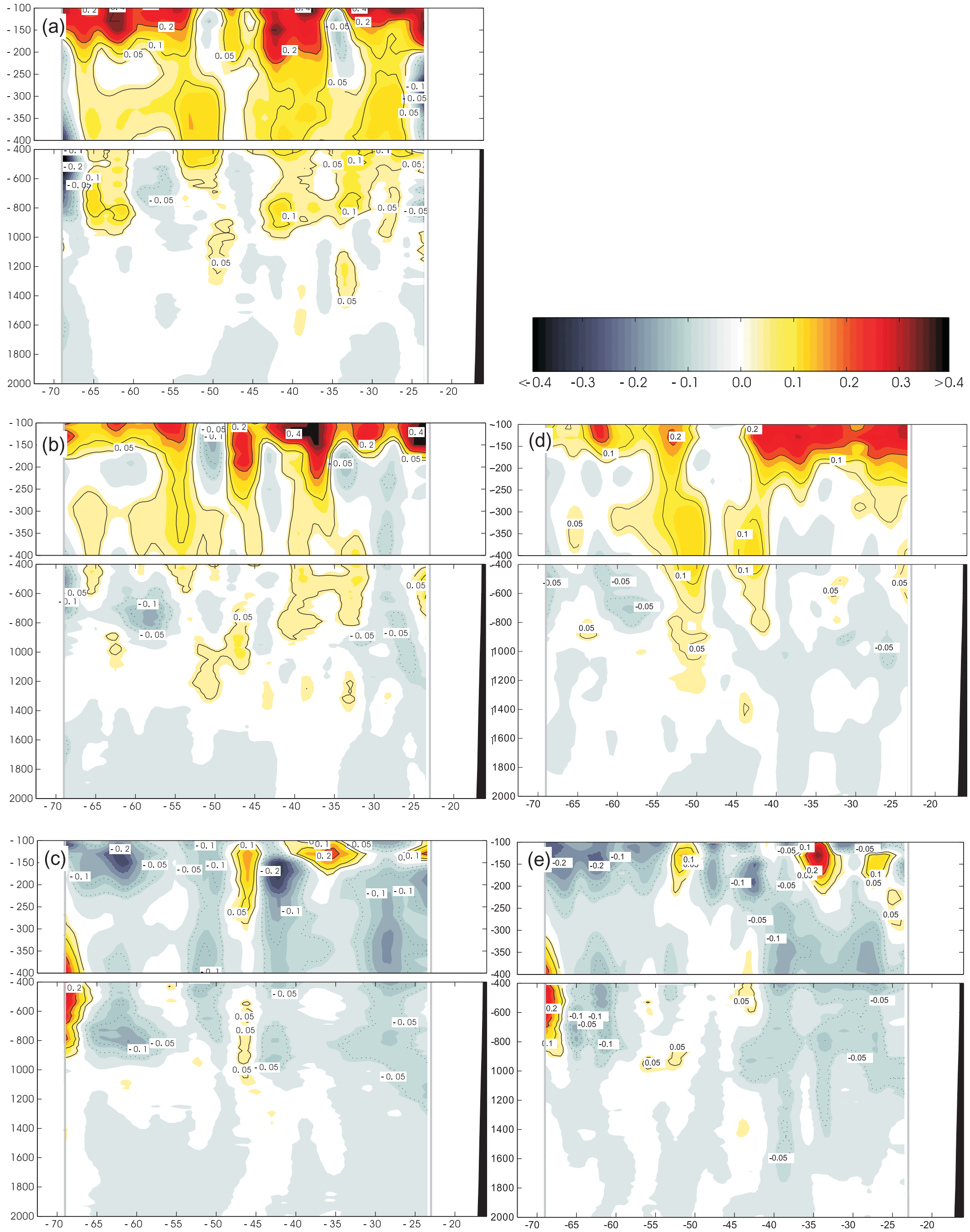


FIG. 3. As in Fig. 2, but for salinity differences. Positive values indicate increase in salinity. This convention has been used throughout the text, subtracting the older salinity section from the most recent one when computations refer to time periods. The same color scale has been used for the five panels.

ocean (600–1800 dbar), 0.24°C for the thermocline waters (300–800 dbar), and 0.27°C for the intermediate waters (800–1800 dbar; Table 1). From 1998 to 2004, the zonally averaged temperatures decreased, with the maximum cooling of −0.3°C found at 800 dbar. The thermocline waters cooled by −0.15°C, whereas the intermediate waters cooled by −0.13°C. The observed cooling between 1998 and 2004 is statistically significant and represents almost 50% of the warming found from 1957 to 1998. As a result, between 1957 and 2004 the thermocline waters warmed on average by 0.09°C, the intermediate waters by 0.14°C, and the upper-ocean layer by 0.12°C (Table 1).

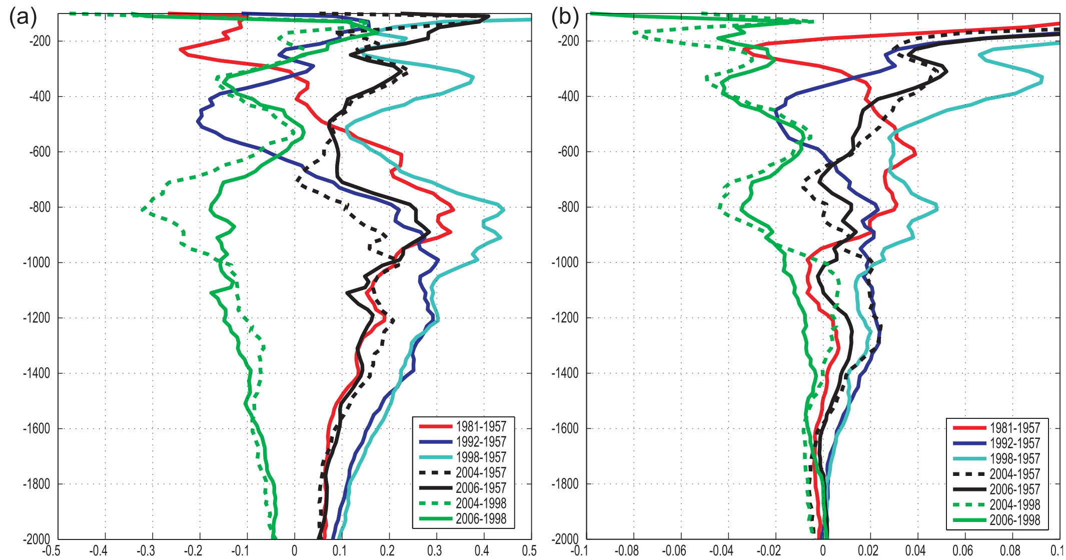


FIG. 4. Vertical profiles of zonally averaged (a) temperature and (b) salinity differences on pressure surfaces for the 1981−57, 1992−57, 1998−57, 2004−1957, 2006 (Argo)−1957, 2004−1998, and 2006(Argo)−1998 periods. The hydrographic sections have been compared only where CTD stations were sampled along 24.5°N (i.e., between 23° and 70°W). Positive values indicate warming and salt increase.

This statistically significant 0.12°C mean temperature increase since 1957 for the upper-ocean layer is less than half of that found during the 1998−57 period and is lower than the mean upper-ocean temperature increase observed in 1981. Once again, the results obtained using the synthetic Argo section are very similar to those obtained with CTD data. The differences between the mean temperature increases obtained with the 2006 Argo data and the 2004 CTD data in the three layers used are much smaller than the changes occurring between 1998 and 2004 and therefore confirm the robustness of the method and the validity of using the Argo network to observe long-term changes. Specifically, for the upper ocean the mean cooling between the 1998 and 2004 CTD sections was −0.15°C, whereas the difference between the 2004 CTD section and the 2006 Argo synthetic section was 0.02°C (Table 1).

Zonally averaged profiles of salinity differences (Fig. 4b) confirm the increase in salinity before 1998 and the decrease afterward. The CTD data show that 1998 was the saltiest year. Although the maximum values are found in the top 400 dbar, there is a subsurface maximum at 800 dbar, with values of up to 0.05 in 1998 but decreasing to almost zero in 2004. The freshening occurred between 1998 and 2004 also had a subsurface maximum of −0.04 at 800 dbar.

The Argo data show that the vertical profiles of the zonally averaged temperature and salinity differences for the periods 2006 (Argo)−1957 and 2006 (Argo)−1998 are very similar to those obtained using the 2004 CTD data. Moreover, the differences between the sections and the zonally averaged values for the 2004 and 2006 (Argo) datasets are much smaller than the changes that occurred in the period 2004–1998.

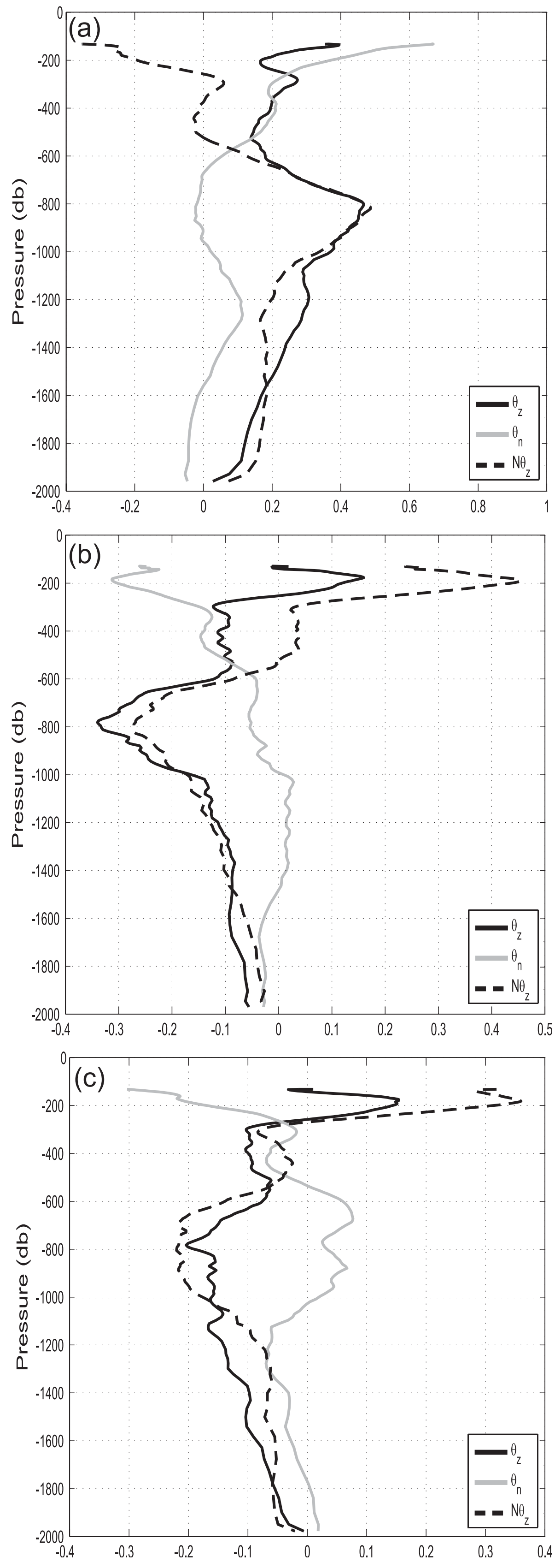
The associated changes in steric sea level since 1957 over the 800–1800-dbar interval reached a maximum of 3.3 cm in 1998 and then decreased, given the observed ocean cooling and freshening, to 1.8 cm in 2004.

c. *Isobaric change decomposition*

The decomposition of the temperature changes along isobaric surfaces as the sum of changes along neutral surfaces is shown in Fig. 5. Between 1957 and 1998 the main contribution to the warming in the upper ocean (600–1800 dbar) was due to a deepening of the isoneutral

TABLE 1. Mean temperature differences (°C) with respect to IGY 1957 between 23° and 70°W. In the last column (the one labeled "2006 Argo"), the value in the parentheses corresponds to the results obtained if annual climatological temperature and salinity data from the *World Ocean Atlas 2005* are used as a first guess for the objective analysis instead of data from the *World Ocean Atlas 1994*.

	1981	1992	1998	2004	2006 Argo
Upper ocean (600–1800 dbar)	0.16	0.20	0.27	0.12	0.14 (0.15)
Thermocline waters (300–800 dbar)	0.14	−0.05	0.24	0.09	0.05 (0.05)
Intermediate waters (800–1800 dbar)	0.14	0.22	0.27	0.14	0.16 (0.17)



surfaces (Fig. 5a). This deepening occurred during each individually observed period between 1957 and 1998, except in the period from 1981 to 1992 (not shown) that is dominated by changes in water masses.

Between 1998 and 2004, the main contribution to the cooling of the upper ocean came from shallowing of the isoneutral surfaces (Fig. 5b). Only the intermediate waters show some significant contribution from changes along neutral surfaces. This is consistent with the fact that in the eastern basin the intermediate waters are mainly Mediterranean Outflow Waters (1200 dbar), which have shorter time scales of variability and well-known mesoscale activity related to meddies. The decomposition of the temperature changes obtained from the 2006 Argo synthetic section is very similar to that obtained from the 2004 CTD section (Fig. 5c).

d. Annual and interannual variability

The coverage of the Argo network in 2005, 2006, 2007, and 2008 permits the estimation of yearly synthetic sections for each of these years, hence providing an estimate of interannual variability at 24.5°N. These estimates in turn give the first insight into the extent to which the observed changes at the 24.5°N transects may be related to decadal variability or to interannual variability aliased by the decadal sampling period.

Figure 6 shows the time evolution of the mean temperature and salinity between 70° and 23°W for the upper-ocean, thermocline, and intermediate waters for the five CTD occupations; the four yearly synthetic Argo sections; and the 2006 Argo synthetic section described in the previous paragraphs.

The interannual variability of the Argo synthetic sections between 2005 and 2008 is much smaller than the variability observed from the hydrographic sections. For instance, the standard deviation of the mean upper-ocean temperatures for the five hydrographic sections is 0.096, whereas this value decreases to 0.008 for the four Argo estimates. Similarly, the standard mean temperature of the thermocline (intermediate) waters is 0.106 (0.101) and 0.032 (0.013) for the Argo estimates.

The mean temperature and salinity for the synthetic section obtained with Argo data in the period 2003–08, equivalent to year 2006, is very similar to that obtained

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FIG. 5. Decomposition of the temperature changes along isobaric surfaces $d\theta/dt|_p$ (thick solid line) and as the sum of changes along neutral surfaces $d\theta/dt|_{\gamma_n}$ (gray line) and the changes due to vertical displacement of the isoneutral $-dp/dt|_{\gamma_n}\, d\theta/\partial p$ (thick dashed line) for (a) 1998−57, (b) 2004−1998, and (c) 2006(Argo)−1998. Positive values indicate warming.

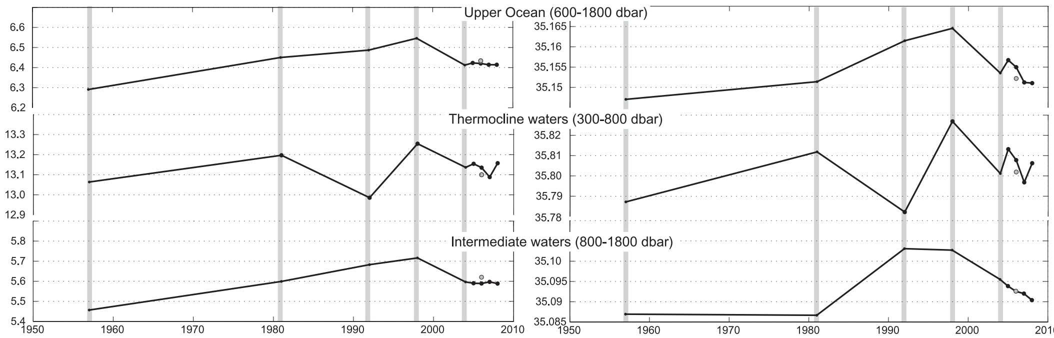

FIG. 6. Time evolution of averaged (left) temperature and (right) salinity between 70° and 23°W for the upper-ocean, thermocline, and intermediate waters. Vertical gray lines denote the CTD measurements (1957, 1981, 1992, 1998, and 2004), small black dots denote the annual Argo estimates (2005, 2006, 2007, and 2008), and gray dots denote the 2006 Argo synthetic section.

with data just for the year 2006, confirming the robustness of the Argo method.

4. Discussion and conclusions

In terms of century-scale tendencies, the subtropical North Atlantic along 24.5°N warmed until 2004 at a rate of 0.25°C century^{-1}. This tendency differs, significantly, from the 0.57°C century^{-1} observed with the data until 1992. Parrilla et al. (1994) also used data ending in 1992 to obtain a tendency of 0.65°C century^{-1}, the small difference resulting from the use of slightly different layers and zonal limits.

Our analysis of the temperature data from the most recent transatlantic section at 24.5°N (2004) reveals a mean cooling of the upper ocean of −0.15°C since between 1998 and 2004. Data from the Argo network, an independent dataset, also reveal a mean cooling of the upper ocean of −0.13°C for the same period. This observed cooling significantly reduces the post-IGY warming in the subtropical Atlantic. Between 1957 and 1998, the upper ocean warmed 0.27°C, whereas by 2004 this value decreased to 0.12°C (0.14°C as obtained using the Argo data).

These results clearly show, from the available hydrographic sections, that the upper ocean in 1998 was significantly warmer and saltier than in any transoceanic measurements at 24.5°N since 1957. Between 1957 and 1998, the warming in the upper ocean was mainly caused by deepening of the isoneutral surfaces, whereas the cooling found between 1998 and 2004 (2006 for the Argo synthetic section) was mainly due to shallowing of the isoneutral surfaces. The present dataset does not permit discrimination between the two mechanisms that contribute to heaving; therefore, the forcing for the observed changes since 1957 could be either wind-driven ocean forcing or changes in the renewal rates at the formation areas.

The interdecadal shifts from warming to cooling likely reflect intrinsic ocean–atmosphere variability that complicates the understanding of ocean climate change (Kerr 2008; Keenlyside et al. 2008). Such variability has been shown in a trans-Indian hydrographic section across 32°S (Bryden et al. 2003) and in the Mediterranean Sea (López-Jurado et al. 2005). Bryden et al. (2003) showed that salinity presented an increase that almost reversed the freshening of mode waters observed from 1960 to 1987, and López-Jurado et al. (2005) showed that 2005 presented a reversal of the long-term progressive warming observed from 1957 to 2005 in western Mediterranean Deep Waters.

Additionally, our Argo data show that the changes in the 24.5°N hydrographic zonal sections are a good proxy for decadal changes, because the interannual variability in the period with Argo synthetic sections (i.e., from 2005 to 2008) was small; therefore, the interannual variability aliased by the decadal sampling period is likely negligible. Without regular observations, oceanographers have little understanding of the scales of variability in water mass properties that can mask evidence of anthropogenic climate change. Sampling has been the central problem for all similar studies of decadal change based on repeated hydrographic transects anywhere in the global ocean, and our results highlight the invaluable contribution of the Argo system for understanding long-term variability of the ocean's interior.

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