Impact of Combining Temperature Profiles from Different Instruments on an Analysis of Mixed Layer Properties

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ABSTRACT

For a joint analysis of temperature profiles from floats, expendable bathythermographs (XBTs), and other instruments (e.g., thermistor chains) the consistency of the profiles from the different sources needs to be ensured to avoid results with systematic errors. In this study profiles from the different instrument types are compared after they passed through a series of quality control tests. The different methods for quality control are presented. After ensuring that only high-quality profiles remain in the dataset, a statistical analysis of the temperature differences between adjacent profiles (in space and time) is performed. Potential regional differences as well as possible differences between the various float types are addressed. Finally, the impact of combining the profiles from floats with those from other instruments on gridded fields of the mixed layer temperature, thickness, and heat budget is discussed. It is found that the joint analysis yields more reliable results for the gridded fields and the heat storage rate. A large part of this improvement is a result of the reduced seasonal bias.

1. Introduction

Profiling floats have been used to observe upper-ocean temperature, and frequently salinity also, for more than a decade. The international Argo project began in 2000 (information available online at http://www-argo.ucsd.edu). The target of Argo is to deploy and maintain an array of 3000 profiling floats in the World Ocean. Approximately 1200 floats were operational in May 2004.

Adding new measurement technologies to an observing system can have an impact on the results of data analysis. In particular, the deployment of profiling floats has the potential for affecting estimates of climatologies of temperature and salinity, estimates of the heat budget in the upper ocean, and the derivation of the modes of variability of these parameters. It has to be ensured that no systematic differences between temperature profiles from profiling floats and expendable bathythermographs (XBTs) or other instruments exist. This is especially important if long-term climate changes are studied.

The rapidly increasing number of profiling floats in the oceans now allows a comparison of their temperature profiles with those from XBTs and other instruments. In this study, the comparison will be restricted regionally to the tropical Atlantic and North Atlantic. Some studies on related topics have already been published. For example, Wong et al. (2003) analyzed the drift of salinity sensors of the profiling floats and developed a method to correct the drift. Oka and Ando (2004) reported on the stability of temperature and conductivity sensors of three profiling floats that were recovered after 4–9 months in the ocean. Over this period of time the temperature sensor was stable, because the recalibration resulted in an offset that was smaller than the precision of the calibration method.

However, no studies have been completed yet that directly compare temperature profiles from floats with those from XBTs or other instruments. In this study, the statistics of the difference between adjacent profiles from floats and XBTs, from floats and other instruments (excluding floats), as well as from different floats will be analyzed. Section 2 describes the quality control procedures that are applied to the datasets and gives additional details about the way the comparisons are performed; section 3 analyzes the results of the profile comparisons; and section 4 gives an example showing the impact of combining the datasets on the heat budget of the mixed layer.

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2. Data and methods

Data from profiling floats, XBTs, and other instruments (e.g., thermistor chains or occasionally CTDs) that are collected in the tropical Atlantic (30°S–30°N) and North Atlantic (30°–55°N) during the years from 1997 through 2003 are used in this study. The primary source of the XBT and other temperature observations in the upper ocean is the Global Telecommunication System (GTS) that is used by the meteorological and oceanographic community. Oceanographic (and other) datasets are retrieved from the GTS by the Marine Environmental Data Services [MEDS; available as delayed-mode data via the Web-based environmental data server at the Atlantic Oceanographic and Meteorological Laboratory (AOML)] and the National Oceanographic Data Center (NODC; for real-time data). The profiling float data are available from GTS and from the Argo Global Data Assembly Centers (GDAC; information online at http://www.usgodae.org/argo/argo.html, www.ifremer.fr/coriolis/cdc/argo.htm). The data from the Argo GDAC, using the U.S. Global Ocean Data Assimilation Experiment (GODAE) server, were used whenever available. Because all XBT profiles, as well as all profiles received through GTS, contain the profile data on depth levels, the depth was converted to pressure to allow for comparisons with the float profiles.

The most commonly used XBTs measure the temperature profile down to 460 (T4, T6) or 760 (T7, Deep Blue) m. XBTs record the time relative to the time at the start of the profile and the resistance of the thermistor. The depth is derived by applying a fall rate to the recorded time, and the resistance is converted to temperature. According to Sippican,[1] the accuracy of the temperature measurements of their XBTs is ±0.1°C, and the probe depth is determined to have an accuracy of 2%. Full-resolution XBT profiles have a vertical resolution that is smaller than 1 m. Because most XBT profiles were distributed through GTS, the vertical resolution is reduced (typically only inflection points are available in this case).

Three types of floats were deployed in the region studied here: autonomous profiling explorer (APEX), flotteur profileur français (PROVOR), and Sounding Oceanographic Lagrangian Observer (SOLO) floats.[2] The floats mostly use FSI or SBE sensors.[3] For the SBE sensors the accuracies are ±0.002°C for the temperature and ±2.4 db for the pressure. For the FSI sensor the accuracies are ±0.002°C for the temperature and ±0.02% of the full scale for the pressure (i.e., about ±0.4 db for a 2000-m float), according to the manufacturer. Some floats that are used in deployments prior to the Argo project had a Micron pressure transducer and YSI thermistor, or the SeaScan TD module.

Duplications of XBT profiles exist as a result of the combination of datasets from different sources. They are eliminated on the basis of 1) matches or near matches of the position, time, and profile, and 2) identical profiles regardless of the time and location (in this case both are removed from the dataset). Duplications of float profiles are much easier to identify because they are marked by a unique identifier [provided by the World Meteorological Organization (WMO)]. The identifier remains with the float profile for GTS transmissions, distribution via the Argo Global Data Centers, and archiving at NODC.

To eliminate or correct (see below) bad profiles, the data passed through automatic quality control tests. Profiles that failed the test were inspected visually. The automatic quality control of float profiles follows the standard procedures that are approved by the international Argo data management team. (A document describing the Argo quality control tests is available online at www.ifremer.fr/coriolis/cdc/argo_rfc.htm; the main tests are a speed check, gross range tests, spike tests, pressure increasing test, and a vertical gradient test.) In addition, the profiles were compared with the Levitus climatology [Conkright et al. 1998, hereafter World Ocean Atlas (WOA) 1998, and, more recently, Conkright et al. 2002, hereafter WOA 2001] and the National Centers for Environmental Prediction (NCEP) ocean reanalysis [D. Behringer, Global Ocean Data Assimilation System (GODAS), 2004, personal communication], which helps in the detection of sensor drifts or offsets. A similar quality control procedure is applied to all profiles that were collected with XBTs or other instruments.

Corrections of profiles can be applied to the following two different cases. 1) For pre-Argo floats with Micron pressure transducers, a hysteresis of the pressure sensor needs to be taken into account (no other floats used in this study showed signs of a hysteresis of the pressure sensor). The hysteresis is removed by subtracting the pressure recorded at the surface, after the pro-

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[1] Sippican manufactured 90%–95% of the XBTs deployed in the Atlantic Ocean in 1997–2004. The other 5%–10% are mostly Sparton XBTs, and occasionally were Tsurumi-Seiki Co. (TSK) XBTs.

[2] APEX floats are manufactured by Webb Research Corporation; PROVOR floats are manufactured by METOCEAN or MARTEC; SOLO floats are manufactured by the Scripps Institution of Oceanography or Woods Hole Oceanographic Institution.

[3] FSI sensors are manufactured by Falmouth Scientific, Inc.; SBE sensors are manufactured by Sea-Bird Electronics, Inc.

file has been measured, from the pressure recorded during the ascent. The offset of the pressure at the surface is mostly less than 20 db and is frequently less than 10 db. Only two floats had occasional offsets of the surface pressure of 50 db or more. 2) Comparisons of float profiles with nearby (in space and time) profiles from other floats or other instruments are performed to identify floats with temperature calibration problems. It is required that the temperature differences are verified by several independent observations. In this way one float (with the WMO number 13859) with a consistent temperature offset of 0.6°C was identified. In both cases the quality control tests described above were applied to the corrected profiles again.

Differences between temperature profiles are derived if the zonal (meridional) distance between two profiles is smaller than 0.5° (0.2°) and the time difference does not exceed 5 (used in the tropical Atlantic and North Atlantic) or 10 (used in the North Atlantic, because fewer profile pairs are available there) days. In the North Atlantic the impact of increasing the permitted time difference is analyzed. The difference between two profiles is derived in the following way: First, the vertical resolution of the nonfloat profile is checked. If the mean pressure increment of this profile is larger than 10 db,[4] then the float profile is interpolated linearly to the depths of the profile with coarse resolution. If this is not the case, then both profiles are interpolated to 10-db intervals. The latter is also done if both profiles were measured by floats. The profiles of the temperature differences can be used to determine if systematic differences between the data collected with the two different measurement techniques (floats and XBTs) exist.

The statistics of the temperature differences are studied on the basis of box-and-whisker plots (Mosteller and Tukey 1977; e.g., Fig. 1b), as well as distributions and the statistical quantities in two layers. The box-and-whisker plots have been generated in three steps. First, the temperature differences are linearly interpolated to regular pressure increments for all profile comparisons (for better visibility 20 db was chosen here). In the second step the median and the upper and lower quartiles are derived for each pressure level. The quartiles are used to enclose a box and the median is drawn as an additional line in the box. The quartiles and the interquartile range (the difference between the upper and the lower quartile) are multiplied by 1.5 to give the maximum length of the whiskers (see below), which is used to identify outliers (shown as dots).[5] The whiskers, which indicate the expected range of values, are lines that extend outward from the upper and lower quartiles. It has to be noted that the whiskers do not always have the same length at a level because they never extend beyond the outermost data point. In the third step the values that are outside of the expected range (the outliers) are removed from the dataset and the median value, the quartiles, and the lengths of the whiskers are derived again. In this process some values that were in the whiskers before become outliers because the interquartile range and the length of the whiskers is reduced. To further analyze the temperature differences the distributions and basic statistical properties for two different layers are derived. For this purpose an interpolation to 10-db pressure increments was used to achieve more robust statistical estimates.

To analyze the impact of combining the profiles from floats and other instruments on gridded fields, the data are grouped into 1° latitude × 5° longitude boxes. Then, the mixed layer thickness and temperature are derived for each profile. Herein, the bottom of the mixed layer was defined as the depth where the temperature decreases to a value that is smaller than the maximum temperature that is observed in the profile minus 1°C. This definition was chosen because the surface temperature can be less than the temperature just below the surface. Gridded fields are derived in two steps. First, the data and positions within each box are averaged over the time period of interest. Second, an objective analysis is performed with a grid resolution of 1° × 1°. The correlation length scales were set to 20° in the zonal and 4° in the meridional direction. The error of the observations was assumed to be 0.01°C, 0.01 psu, and 10 m for temperature, salinity, and mixed-layer thickness, respectively. The error of the climatological field was assumed to be 1°C, 1 psu, and 10 m. The rms error from the objective analysis is used to exclude regions with insufficient data coverage from the contour maps and from further analysis. The limits chosen for this purpose are 0.03°C, 0.03 psu, and 5 m for the three parameters. Maps of the mixed layer properties are derived for the full dataset and for a subset containing no data from profiling floats. To identify regions where the temporal distribution of the data are likely to give rise to errors in the resulting fields, the bias of the temporal data distribution is derived according to $B = \overline{\exp(i\mathbf{M}/12 \times 2 \times \pi)}$, where **M** is a vector containing the months with observations in the box.

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[4] Large pressure increments are especially common among XBTs if profiles from GTS are used.

[5] The value of 1.5 was found to be the most efficient for data of normal or nearly normal distributions (Mosteller and Tukey 1977).

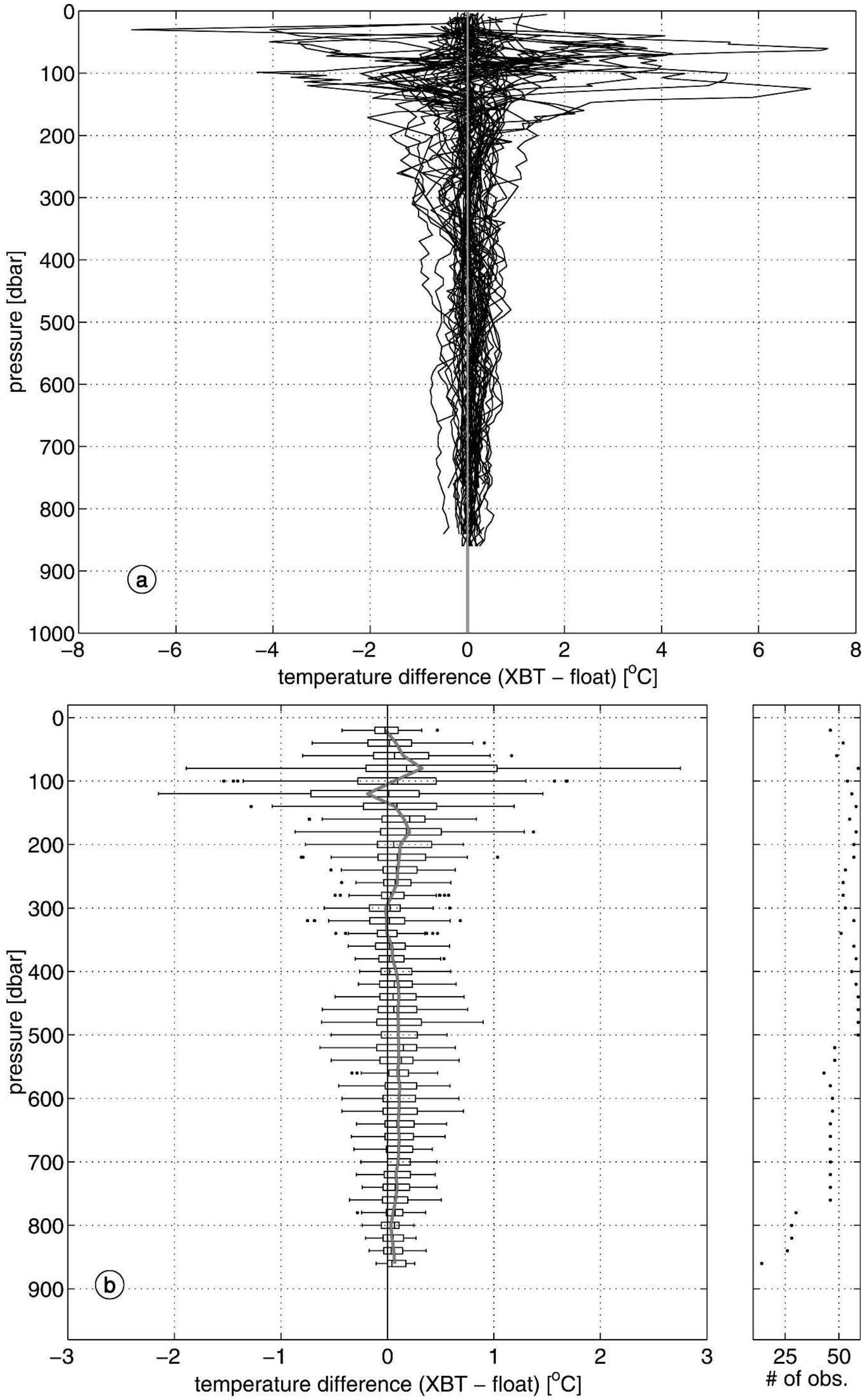

FIG. 1. Temperature difference in the tropical Atlantic (30°S–30°N) between XBT and float profiles located within a 0.2° latitude × 0.5° longitude box that were obtained within 5 days of each other: (a) all profiles and (b) box-and-whisker plot after the exclusion of large outliers (see section 2). The box has lines at the lower, median, and upper quartile values. The whiskers are lines extending from each end of the box to show the extent of the data that are not considered outliers. The remaining outliers are marked with dots. The gray line follows the means. The panel to the right is part of (b) and shows the number of data points that are available for the statistical estimates at each level.

The value for B has to be derived for each box. The amplitude is given by $A = \sqrt{B_r^2 + B_i^2}$, and the phase is given by the imaginary part of $P = \log_n(B)$, where B_r (B_i) is the real (imaginary) part of B, and $\log_n$ is the natural logarithm.

The mean monthly heat budget of the mixed layer is derived in a simplified form to further analyze the impact of combining the float with XBT and other data. Herein, only the surface flux and the heat storage rate are considered. Four years of data (2000–03) are used for this calculation. The heat storage rate is derived as $\rho c_p z_{\mathrm{ml}} dTdt^{-1}$, where ρ is density, c_p is the specific heat of seawater, z_{ml} is the mixed layer thickness, T is the mixed layer temperature, and t is time. The surface flux is derived from the NCEP–National Center for Atmospheric Research (NCAR) reanalysis product (Kalnay et al. 1996). It is the sum of the incoming shortwave radiation, the outgoing longwave radiation, and the latent and sensible heat flux.

3. Profile comparisons

In the first part of this section an extensive comparison of float profiles with XBT profiles is performed. This is followed by a comparison of all available profiles that are not from profiling floats with those that are from profiling floats. Finally, the impact on the mixed layer thickness is derived for both cases.

The differences between XBT and float profiles, obtained within 5 days of each other, are shown in Figs. 1 and 2. The maximum difference of more than 7°C is found within the thermocline (Fig. 1a), which is centered near 100 db (Fig. 3). This is to be expected, because small differences of the thickness of the mixed layer have a large impact on the temperature differences within the depth range that is covered by the thermocline. Basically, in the profile with the thicker mixed layer the thermocline starts, and may end, at a greater depth than in the profile with the thinner mixed layer. The latter, obviously, depends on the slopes of the thermoclines in the two profiles.

Figure 1b (discussed below) shows the box-and-whisker plot after the removal of large outliers (the identification of outliers is described in section 2). These data are used to derive the histograms of the distributions of the temperature differences and the associated Gaussian curves for depths above and below 250 db (Figs. 2a and 2b). This depth was chosen because it prevents an influence of the thermocline on the lower layer (Fig. 3). In both panels the Gauss curve was derived from the standard deviation and the mean of the data distribution. The maximum was normalized to match the second-highest number of measurements, as is visible in the corresponding histogram. Typical for Gaussian distributions both histograms are centered at 0°C, and they are basically symmetric with respect to about 0°C. This indicates that the distributions are indeed Gaussian. If the outliers were included in the graph for the shallow layer (Fig. 2a), then the histogram and the Gaussian curve would have larger values in the tails, because the standard deviation is larger than when outliers are excluded (Table 1). Below 250 db (Fig. 2b) the distribution is narrower than above 250 db because the thermocline is not part of this deeper layer. This is reflected in the fact that 95% of the differences between the observations are within 0.5°C from 0°C below 250 db, whereas only 72% of the differences between the observations are within that range in the upper 250 db. According to Table 1, the magnitudes of the mean and median values of the temperature differences do not exceed 0.09°C if outliers are excluded, unless a 10-day time difference between the observations is permitted. The mean and median values of the temperature differences mostly depend only slightly on the inclusion or exclusion of outliers. Only in the upper 250 db, where the outliers can be large, can the exclusion of the outliers reduce the mean and the median values of the temperature differences significantly.

Figure 1b shows that the median value of the temperature difference is small and positive at most depths. Between 500 and 800 db the median values are larger than between 300 and 500 db, but they remain smaller than 0.1°C. It can be seen that the number of samples drops by one-quarter near 500 db (Fig. 1b).[6] If profiles obtained within 10 days of each other are considered (not shown), the difference between the median values in the two layers is much smaller, and the number of samples drops by only 10% near 500 db. Several possible explanations come to mind: 1) the change of the number of samples near 500 db; 2) XBTs that extend to a depth of about 500 m may have a slightly different temperature calibration than XBTs going to greater depths; or 3) the depth-dependent error of the depth derived for XBTs, which is about ±2% of the depth (e.g., ±10 m at 500 m). Possibility 3 is unlikely, because it would cause a more gradual change of the median temperature difference near 500 db, rather than a quite abrupt change. Possibility 2 seems unlikely, because in this case the change of the permitted time difference between two observations should not have an impact.

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[6] The drop in the number of samples may be a result of the fact that many XBTs are designed to step profiling near 460 m. They often continue measuring below their maximum vertical range to ensure that they meet the specifications.

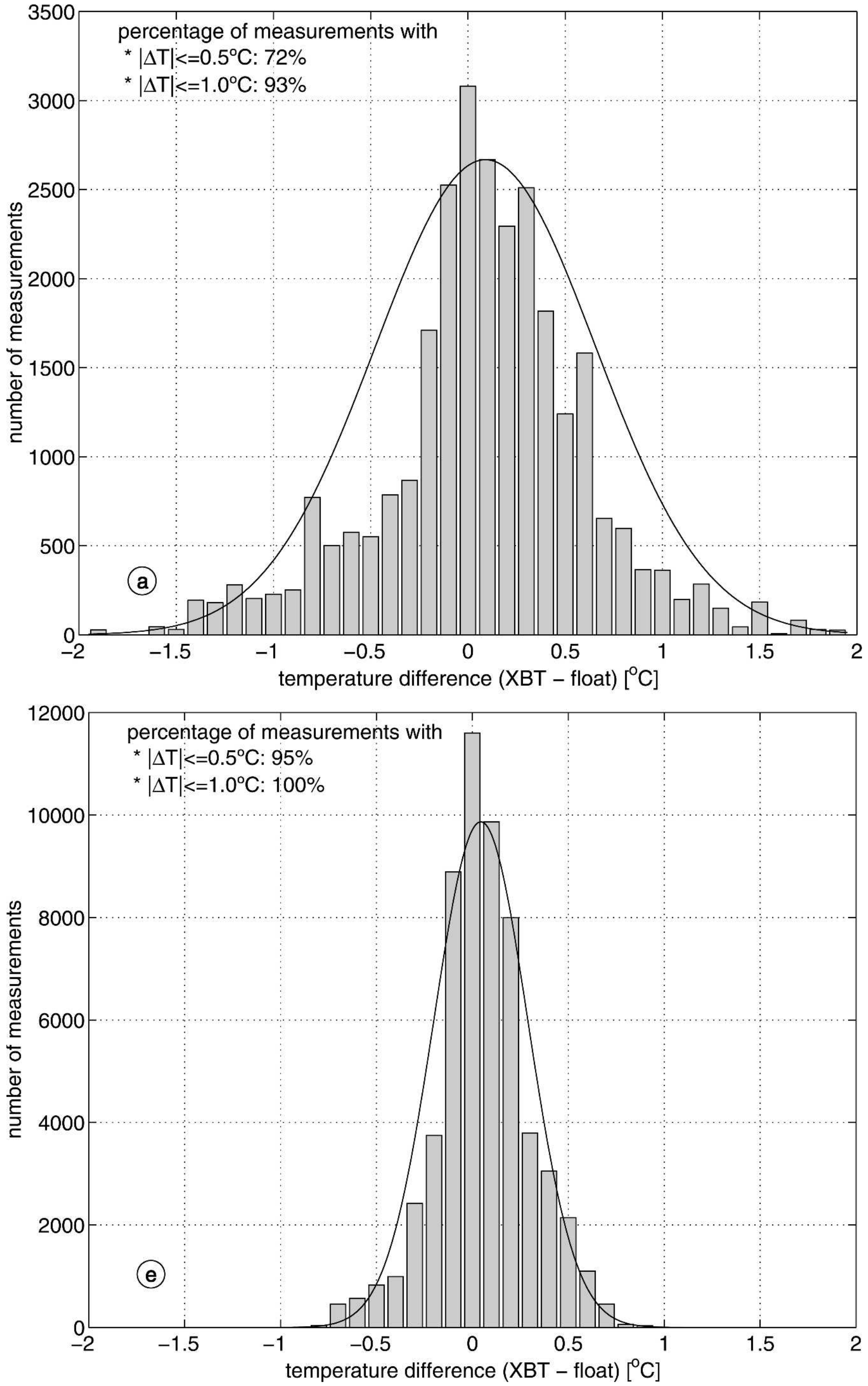

FIG. 2. Histograms and Gaussian curves of the distributions for the data shown in Fig. 1 obtained, after exclusion of outliers, for the layer (a) above 250 db (3000 measurements correspond to about 10% of all measurements) and (b) below 250 db (10 000 measurements correspond to about 19% of all measurements).

Possibility 1 seems more likely, because statistical properties tend to depend more strongly on the number of samples if that number is small. Also, a larger jump in the number of samples near 500 db, as is found for the 5-day time difference, will result in different statistical properties in the two layers.

To summarize the results of the comparison for the tropical Atlantic, it can be said that (Table 1) 1) the

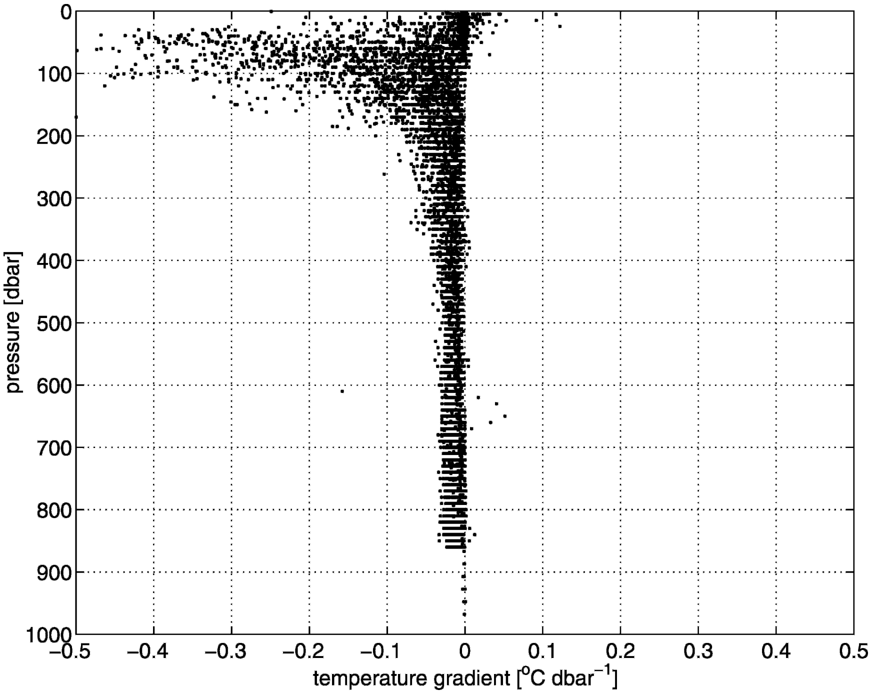

FIG. 3. The vertical temperature gradient $[dT(dp)^{-1}$, with temperature T and pressure $p]$ in the tropical Atlantic from profiling floats.

median values are always smaller than the measurement error of XBTs (0.1°C), and 2) if outliers are excluded, then the mean values are mostly smaller than the measurement error of XBTs (the only exception is the upper ocean when the 10-day time interval is used).

The comparison of temperature profiles obtained from adjacent floats in the tropical Atlantic (Table 2) yields similar results as the comparison of XBT profiles with float profiles for the 5-day period. As before, the median values are always smaller 0.1°C. In addition, the mean values do not exceed 0.1°C. If the outliers are excluded, then the differences between the tabulated values from the float–XBT and the float–float profile comparisons are insignificant. Figures 1b and 4 reveal quite similar patterns of the profile differences. However, a few small differences can be detected: 1) the larger median values, which were found below about 500 db in the XBT–float comparison, cannot be found in the float–float comparison; 2) the mean and median

TABLE 1. Statistics of the temperature differences between XBT and adjacent float profiles (XBT minus float temperature, Figs. 1 and 2) in the tropical Atlantic (30°S–30°N). All profiles are within a 0.2° latitude × 0.5° longitude box. The statistics are derived for the full dataset and after elimination of outliers (see section 2 for the method used for the identification of outliers).

	Temperature difference (°C)				
Pressure (db)	Median	Mean	Std dev	Minimum	Maximum
For 62 profile pairs obtained within 5 days					
>250	0.04	0.05	0.27	−1.42	1.11
≤250	0.08	0.17	1.00	−6.91	7.32
Excluding outliers, 62 profile pairs					
>250	0.04	0.05	0.25	−0.76	0.90
≤250	0.08	0.08	0.58	−2.15	2.75
For 218 profile pairs obtained within 10 days					
>250	0.09	0.09	0.29	−1.42	1.39
≤250	0.09	0.20	1.09	−6.91	8.33
Excluding outliers, 218 profile pairs					
>250	0.09	0.09	0.28	−0.89	1.04
≤250	0.09	0.14	0.69	−2.42	2.85

TABLE 2. Statistics of the temperature differences between adjacent float profiles in the tropical Atlantic (30°S–30°N). All profiles are within a 0.2° latitude × 0.5° longitude box. The statistics are derived for the full dataset and after elimination of outliers (see section 2 for the method used for the identification of outliers).

	Temperature difference (°C)				
Pressure (db)	Median	Mean	Std dev	Minimum	Maximum
For 57 profile pairs obtained within 5 days					
>250	0.03	0.04	0.24	−1.05	1.39
≤250	0.07	0.10	0.97	−6.13	6.02
Excluding outliers, 57 profile pairs					
>250	0.03	0.04	0.23	−0.85	0.98
≤250	0.08	0.10	0.53	−1.75	2.43

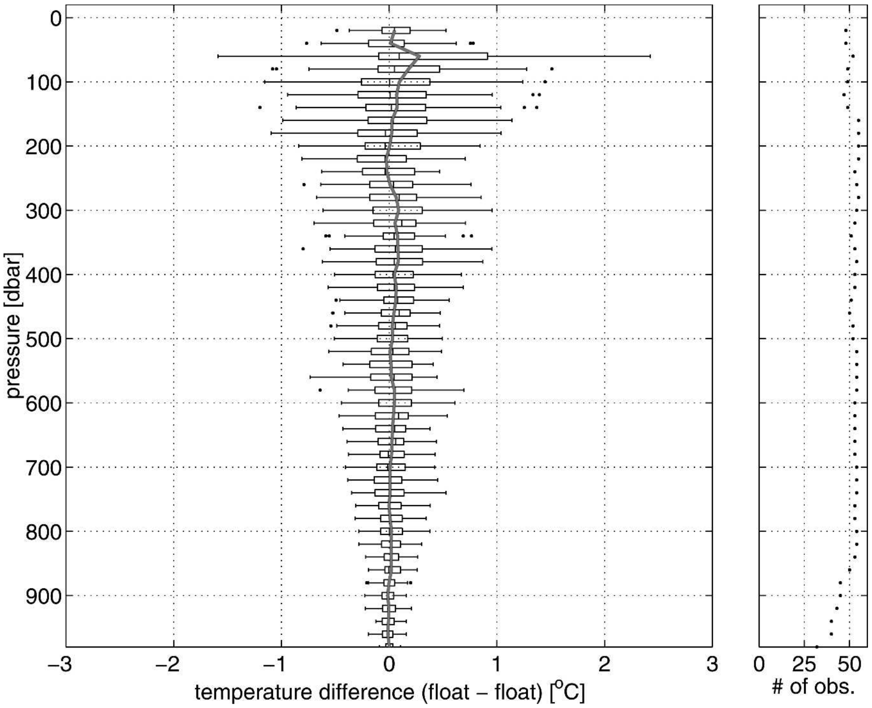

FIG. 4. Box-and-whisker plots (as in Fig. 1) of the temperature difference for adjacent float profiles in the tropical Atlantic (30°S–30°N), after exclusion of outliers. All considered profiles are within a 0.2° latitude × 0.5° longitude box, and were obtained within 5 days of each other.

values in the float–float comparison are significantly smaller than those in the XBT–float comparison; and 3) relatively large positive means can be seen at 60–120 db in the float–float comparison. In the XBT–float comparison the mean is smaller and changes sign between 100 and 120 db. This seems to be of minor importance because of the high variability of the temperature in the thermocline layer, and because the median value remains positive.

In the subtropical North Atlantic, below 250 db, comparisons of float profiles with XBT profiles (Table 3) yield, partly, larger mean and median values of the temperature differences than the comparisons in the tropical Atlantic (Table 1). This is reflected in the preference for significant positive temperature differences below 250 db in the North Atlantic (Fig. 5a). Contrary to this, the mean and median values for the layer above 250 db are insignificant. Figure 5b reveals that the median values depend significantly on the depth. Below 20 db, the median values of the temperature differences increase to about 0.2°C at 40 db before they decrease to almost 0°C in 100–180 db. From 180 to 860 db they increase again, but more gradually, to 0.2°C. Below 860 db, the number of samples is too small to derive sound statistical estimates, because too few XBT measurements are available.

Several possible causes for these statistical differences between the tropical Atlantic and North Atlantic come to mind: 1) instrument- or sensor-dependent measurement errors, 2) regional differences of the variability, and 3) the small number of samples. Most float profiles in the subtropical North Atlantic were obtained

TABLE 3. Statistical comparison of temperature profiles from XBTs with adjacent float profiles in the subtropical North Atlantic (30°–55°N). All profiles are within a 0.2° latitude × 0.5° longitude box. The statistics are derived for the full dataset and after elimination of outliers (see section 2 for the method used for the identification of outliers).

	Temperature difference (°C)				
Pressure (db)	Median	Mean	Std dev	Minimum	Maximum
For 56 profile pairs obtained within 5 days					
>250	0.13	0.16	0.29	−0.72	1.23
≤250	0.00	0.05	0.63	−3.56	3.17
Excluding outliers, 56 profile pairs					
>250	0.13	0.16	0.28	−0.63	1.00
≤250	0.00	0.03	0.46	−1.32	1.69
For 171 profile pairs obtained within 10 days					
>250	0.12	0.14	0.32	−1.30	1.28
≤250	0.02	0.04	0.72	−11.30	4.28
Excluding outliers, 171 profile pairs					
>250	0.12	0.14	0.31	−0.76	1.02
≤250	0.02	0.05	0.54	−1.46	1.99

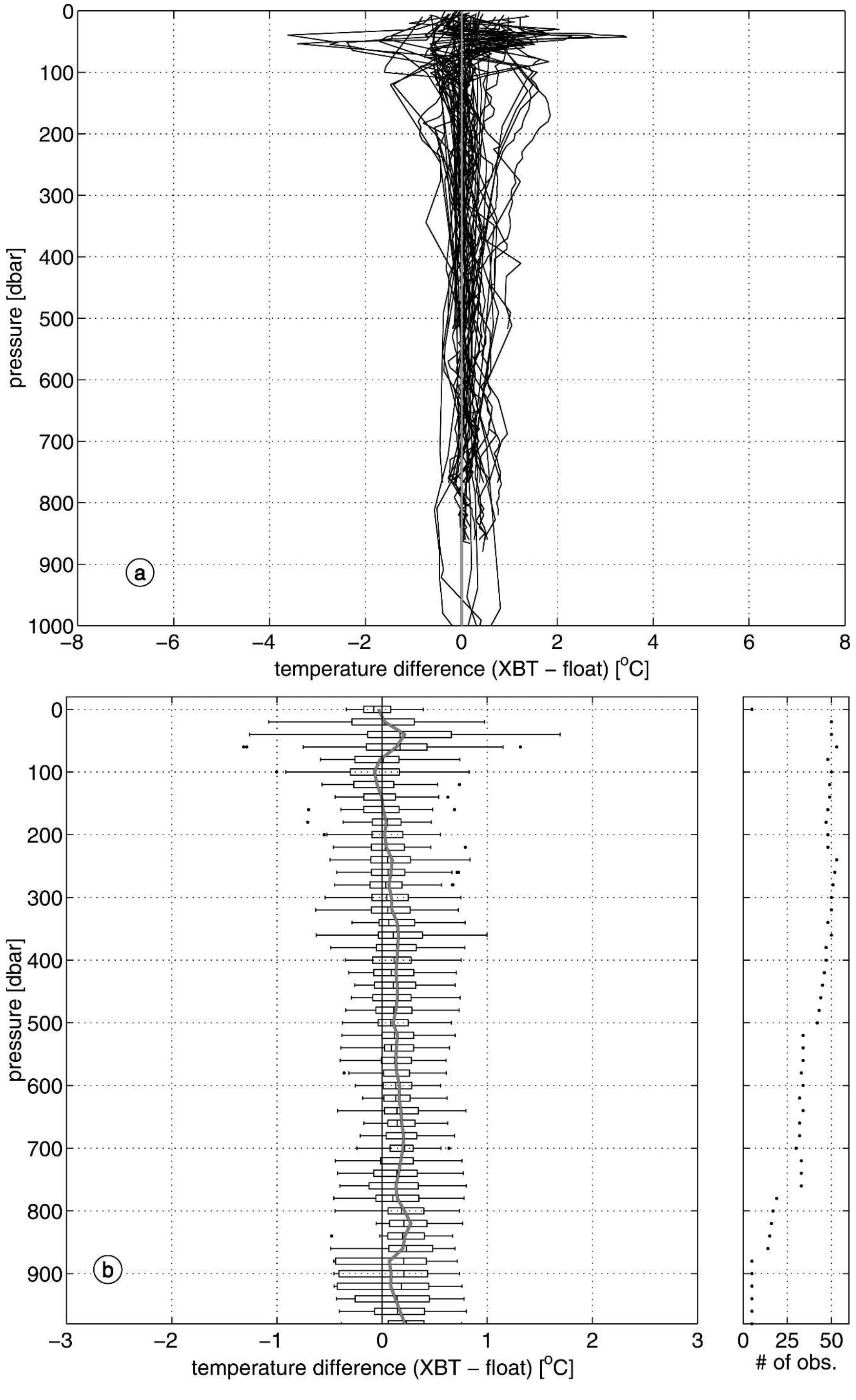

FIG. 5. Temperature difference in the North Atlantic (30°–55°N) between adjacent XBT and float profiles obtained within 5 days of each other. All considered profiles are within a 0.2° latitude × 0.5° longitude box: (a) all profiles and (b) box-and-whisker plot after exclusion of outliers (as in Fig. 1).

with PROVOR, SOLO, and APEX floats with temperature and salinity sensors. Many instruments of the same kind were also deployed in the tropical Atlantic. Table 4 shows the statistics for these float types in the two regions. For the APEX floats, and to a lesser extent for the SOLO floats, the median and mean temperature differences in the North Atlantic are larger than in the tropical Atlantic. For the PROVOR floats the same is

TABLE 4. Statistical comparison of temperature profiles from XBTs with adjacent float profiles by float type (note: _TS indicates that the floats have a temperature and salinity sensor). All profiles are within a 0.2° latitude × 0.5° longitude box. The statistics are derived for the full dataset and after elimination of outliers (see section 2 for the method used for the identification of outliers).

		Temperature difference (°C)				
Type	Median	Mean	Std dev	Minimum	Maximum	Samples
		North Atlantic (30°–55°N), above 250 db				
SOLO_TS	0.17	0.15	0.23	−0.46	0.55	9
APEX_TS	0.11	0.14	0.22	−0.25	0.58	8
PROVOR_TS	0.07	0.08	0.27	−0.45	0.57	36
		Tropical Atlantic (30°S–30°N), above 250 db				
SOLO_TS	0.14	0.12	0.26	−0.51	0.71	19
APEX_TS	−0.01	0.00	0.31	−0.77	0.78	10
PROVOR_TS	0.10	0.14	0.29	−0.46	1.11	7
		North Atlantic (30°–55°N), below 250 db				
SOLO_TS	0.16	0.17	0.17	−0.13	0.45	9
APEX_TS	0.18	0.17	0.16	−0.10	0.42	8
PROVOR_TS	0.10	0.11	0.13	−0.09	0.30	34
		Tropical Atlantic (30°S–30°N), below 250 db				
SOLO_TS	0.14	0.13	0.16	−0.18	0.42	19
APEX_TS	0.00	0.00	0.20	−0.39	0.37	10
PROVOR_TS	0.06	0.08	0.13	−0.14	0.32	7

the case, but only below 250 db. The fact that the same float type has a different statistic in the two regions makes it unlikely that float-type-dependent measurement errors (possibility 1) are the cause for the differences between the two regions. A similar categorization by temperature sensor type does not reveal any significant difference between the statistics for the various sensor types (not shown). However, it has to be cautioned that this result is less robust then the result by float type. This is the case because the information about the installed temperature sensor is only available for about 30% of the float profiles that are available for the comparisons in the North Atlantic. For the tropical Atlantic the corresponding percentage is 50%. For the float types the percentages are significantly higher, with 100% and 70% for the North Atlantic and tropical Atlantic, respectively.

Problems with the XBT measurements (also possibility 1) seem unlikely as well. First of all, if there were depth equation problems (e.g., using the wrong depth equation when generating the profile), one would expect a clear depth dependence of the temperature difference. Whenever the raw XBT data were available it has been verified that the profiles that are used in the comparison were derived with the correct depth equation. At the same time, it was verified that the correct resistance to temperature conversion was applied.

Regional differences (possibility 2) could potentially explain the differences. Table 5 shows the percentages of temperature differences below 250 db that are found in different intervals of temperature differences for all profiles and for the profiles in the subregions (tropical Atlantic and North Atlantic). Two main differences between the tropical Atlantic and North Atlantic are as follows, and can be seen in the table: (a) in the tropical Atlantic the percentage in the range 0.0°–0.1°C is larger than in the North Atlantic (20% versus 17%); and (b) the percentage in the North Atlantic in the tail toward negative (positive) temperature differences are smaller (larger) than in the tropical Atlantic. For example, only 27% of the temperature differences in the tropical At-

TABLE 5. Statistical comparison of temperature profiles from XBTs with adjacent float profiles by region. Percentages are given for the occurrence of temperature differences within several intervals. Only the layer below 250 db is considered. All indicates that the whole region was considered (30°S–55°N). TA stands for Tropical Atlantic (30°S–30°N) and NA stands for North Atlantic (30°–55°N). All profiles are within a 0.2° latitude × 0.5° longitude box and were obtained within 5 days of each other.

Interval (°C)				
Min temp	Max temp	All	TA	NA
−10.0	−1.0	0%	0%	0%
−1.0	−0.5	3%	3%	1%
−0.5	−0.2	8%	8%	8%
−0.2	0.0	25%	25%	20%
0.0	0.2	35%	36%	32%
0.2	0.5	23%	23%	25%
0.5	1.0	5%	4%	13%
1.0	10.0	0%	0%	1%
−0.2	−0.1	10%	9%	8%
−0.1	0.0	15%	16%	12%
0.0	0.1	20%	20%	17%
0.1	0.2	15%	16%	15%

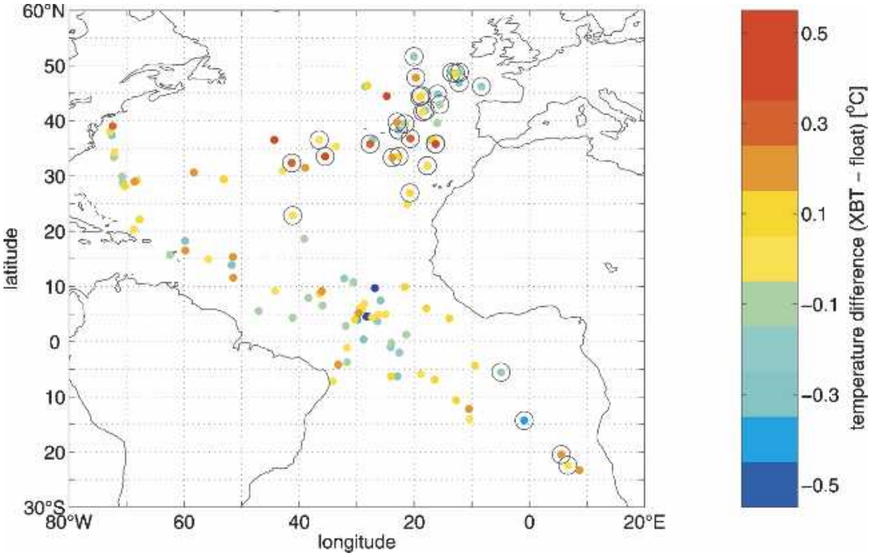

FIG. 6. Map showing mean temperature differences between adjacent XBT and float profiles obtained within 5 days of each other. The means were obtained for the layer below 250 db. All considered profiles are within a 0.2° latitude × 0.5° longitude box. Highlighted by circles are temperature differences associated with profiles from PROVOR floats, because they have the highest data density in the eastern North Atlantic.

lantic exceed 0.2°C, whereas 39% do this in the North Atlantic.

Another way of looking at the regional differences in conjunction with the float type is given in Fig. 6. It is apparent that the larger positive temperature differences are concentrated in the eastern subtropical North Atlantic, in 30°–45°N, 50°–10°W. The points in the map have been linked to the associated float type. For example, the PROVOR observations are highlighted by black circles. In the northeastern Atlantic, five points, indicating temperature differences exceeding 0.4°C, are associated with PROVOR floats (the other two points with such a large temperature difference are also in the northeastern Atlantic, and they are associated with an APEX and a SOLO float, respectively), but there are also many points with negative temperature differences for PROVORs in the same area. In the southeastern Atlantic, the four temperature differences from PROVOR–XBT comparisons are all small and nicely grouped around 0°C. This, again, indicates that the float type is not likely to be responsible for the relatively large temperature differences in the North Atlantic, and that regional differences may play a role (see above). It is noted that the region where the largest temperature differences occur coincides quite well with the region where "meddies" (Mediterranean salt lenses), carrying the relatively salty and warm water originating in the Mediterranean Sea, are found (e.g., Armi and Zenk 1984; Käse and Zenk 1987; Sparrow et al. 2002). This gives rise to relatively large horizontal gradients in this region. The Mediterranean outflow water is heavier than the surface and thermocline water of the North Atlantic. In the region of interest it has its largest signal at intermediate depths (around 1000 m), with a typical maximum of the temperature anomaly of 2.5°C, and a vertical extent of almost 1000 m. It is noted that the temperature differences in the upper 250 db are similar for the tropical Atlantic and the North Atlantic (Tables 1–3 and 6), and that the differences below the thermocline increase with increasing depth (Fig. 5b). This pattern would be likely if the sampling of the Mediterranean outflow water was not performed with the same regularity with the two different measurement technologies. It could be, for example, that a significant number of XBTs were purposefully deployed at locations with the largest signals associated with Mediterranean outflow water, which would cause the observed depth dependence of the temperature differences. The floats are deployed randomly and are, therefore, more likely to sample the different water masses at intermediate depths in a random manner.

It can be concluded that the most likely cause for the larger mean temperature difference in the North Atlantic is the smaller number of samples, in conjunction with the high variability with large horizontal gradients that are typical for the Mediterranean outflow region (possibilities 2 and 3), because that allows a bias resulting from the regional and temporal distribution of

TABLE 6. Statistics of the temperature differences between adjacent float profiles in the North Atlantic (30°–55°N). All profiles are within a 0.2° latitude × 0.5° longitude box. The statistics are derived for the full dataset and after elimination of outliers (see section 2 for the method used for the identification of outliers).

	Temperature difference (°C)				
Pressure (db)	Median	Mean	Std dev	Minimum	Maximum
For 68 profile pairs obtained within 5 days					
>250	0.01	0.01	0.26	−1.43	1.30
≤250	0.07	0.00	0.61	−3.52	5.35
Excluding outliers, 68 profile pairs					
>250	0.01	0.01	0.24	−0.85	0.86
≤250	0.07	0.04	0.37	−1.53	1.23

TABLE 7. Statistics of the temperature differences between float and adjacent other profiles (all instrument types except floats) in the tropical Atlantic (30°S–30°N). All profiles are within a 0.2° latitude × 0.5° longitude box. The statistics are derived for the full dataset and after elimination of outliers (see section 2 for the method used for the identification of outliers). As before the temperature measured by the float has been subtracted from the temperature measured by the other instrument.

	Temperature difference (°C)				
Pressure (db)	Median	Mean	Std dev	Minimum	Maximum
For 156 profile pairs obtained within 5 days					
>250	0.03	0.02	0.28	−1.42	1.26
≤250	−0.01	−0.02	0.94	−6.91	7.32
Excluding outliers, 156 profile pairs					
>250	0.03	0.02	0.27	−1.06	0.85
≤250	−0.02	−0.05	0.59	−2.44	2.26

samples to become important. In support of this possibility, SOLO and APEX floats have a quite strong anticorrelation between the number of samples and the mean and median values of the temperature difference. Mostly fewer samples result in larger mean and median temperature differences. Only for the PROVOR floats does this anticorrelation not hold below 250 db.

Table 7 shows statistical results for the differences between float and nonfloat profiles in the tropical Atlantic. The number of profile pairs is almost tripled if profiles from other instruments, in addition to the XBTs, are considered. The mean and median values in Table 7 are always smaller than in Table 1 (both tables are for the tropical Atlantic, but the latter is based strictly on float–XBT comparisons). This difference is especially large in the layer above 250 db when the outliers have not been excluded. The primary cause for the smaller mean and median values if all nonfloat profiles are considered is likely to be the larger number of available profile pairs.

Aside from the temperature differences, it is important to know if the mixed layer thicknesses that are derived from float and other profiles are consistent, for example, if the heat budget of the mixed layer is to be studied. For this comparison the lower boundary of the mixed layer is defined as the depth where the temperature is 1°C less than the mixed layer temperature. In the tropical Atlantic the range of the mixed layer thicknesses is 10–140 db. The mean difference of the mixed-layer thicknesses from the float–XBT comparison is only 6 db, with a standard deviation of 14 db (62 samples). In the North Atlantic the mean difference of the mixed layer thicknesses is only −1 db, with a standard deviation of 27 db (56 samples). If float profiles are compared with nonfloat profiles, then the mean difference of the mixed layer thicknesses is only 1 db with a standard deviation of 13 db (156 samples) in the tropical Atlantic.[7]

4. Impact of combination of float profiles with other profiles on gridded fields

Figure 7 shows the gridded (1° × 1°, see section 2 for details) mixed layer temperature for the year 2002 derived (a) from nonfloat profiles only, and (b) from a combination of nonfloat and float profiles. Most of the large-scale features of the temperature field are similar in both figures. The larger amount of data in Fig. 7b (almost twice as many profiles and 20% more boxes with data) yields more reliable temperatures in several regions, see, for example, the following.

1) The tongue of water that is colder than 11°C, extending from the western boundary to 30°W near 48°N, and the maximum of 17°C to the north of it (Fig. 7a), are absent in Fig. 7b, which is consistent with the climatology (WOA 2001; Fig. 7c).[8] It is noted that the minimum in Fig. 7a is not supported by observations, that is, an area without data can be seen in Fig. 8a. The maximum in Fig. 7a is supported by a few data points, where the data coverage is biased toward the summer (Fig. 8a, where red lines indicate large biases with amplitudes exceeding 0.5

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[7] For the North Atlantic no profile pairs between floats and other instruments that are not XBTs were available. Note: Other instruments can be thermistor chains, CTDs, or of unknown type.

[8] Using a climatology to identify unrealistic features in the gridded fields can be problematic because of the interannual variability and because of the use of different horizontal scales during the mapping process. However, if these limitations are kept in mind, the climatology can help in the identification of problems.

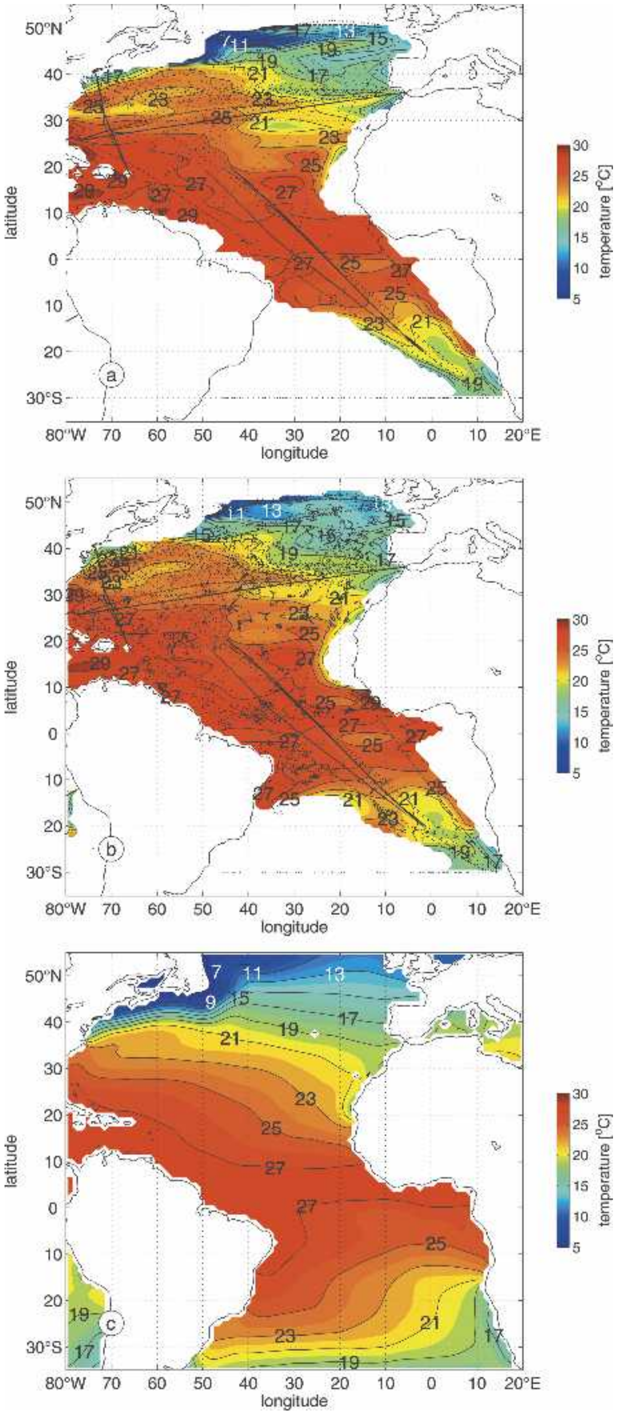

FIG. 7. (a) Annual mean of the mixed layer temperature in the year 2002 for nonfloat profiles, based on 6346 profiles in 567 boxes. (b) Annual mean of the mixed layer temperature in the year 2002 for all profiles, based on 11 886 profiles in 667 boxes. (c) Climatology of the surface temperature from WOA 2001.

on a scale from 0 to 1; see section 2 for details on the bias calculation).

2) The cell of water that is colder than 21°C around 30°N, 31°W (Fig. 7a) has disappeared in Fig. 7b and does not exist in the climatological mean either (Fig. 7c). When float observations are excluded, a bias toward winter/spring can be seen in Fig. 8a at this location.
3) The area with colder water around 32°N, 65°W (Fig. 7a) is smaller and warmer in Fig. 7b and is absent in the climatological field (Fig. 7c). A bias toward winter (Fig. 8a) gives rise to this cold anomaly in Fig. 7a.

To summarize: in all of these cases the seasonal bias is larger for the map based only on nonfloat data (Fig. 8). In the Tropics the seasonal bias is also often larger when float profiles are excluded from the analysis, but the impact is smaller than in the North Atlantic because of the smaller temperature variations that are associated with the seasonal cycle.

For the mixed layer thickness (Fig. 9) the seasonal bias (Fig. 8) plays a significant role, both outside and inside the tropical band. Features in Fig. 9a (based on nonfloat observations only) that are absent or different in Fig. 9b (based on combined nonfloat and float observations) include the following: 1) the maximum at 48°N (Fig. 9a) is significantly farther west and slightly farther north in Fig. 9b; 2) the minimum at 42°N, 50°W (Fig. 9b) is absent in Fig. 9a; 3) the maximum at 28°N, 34°W (Fig. 9a) is much weaker in Fig. 9b and can be seen as an eastward extension of the maximum around 50°W; 4) the maximum around 3°N in Fig. 9a is much larger than that in Fig. 9b because it is based on data that are collected primarily during the second half of the year [during this period the North Equatorial Countercurrent has the largest eastward velocities (e.g., Garzoli and Katz 1983), which is reflected in the large gradient of the mixed layer thickness north of 3°N]; and 5) two strong maxima that exist in Fig. 9a between 5° and 25°S, while Fig. 9b shows only one significant maximum in this area (centered at 10°S). In general, the features in Fig. 9b are much closer to the climatology (Fig. 9c) than those in Fig. 9a.

The change of the heat storage rate is derived both from nonfloat observations only, and from float and nonfloat observations (Fig. 10). For both cases the magnitude and the seasonal cycle are comparable, that is, the heat storage rate increases from about -75 W m^{-2} in the winter to more than 50 W m^{-2} in the summer. However, the time series that is derived from nonfloat observations has a relative minimum at day 90, followed by the largest value of almost 80 W m^{-2} at day 120 (Fig. 10a). The surface flux does not reveal a similar

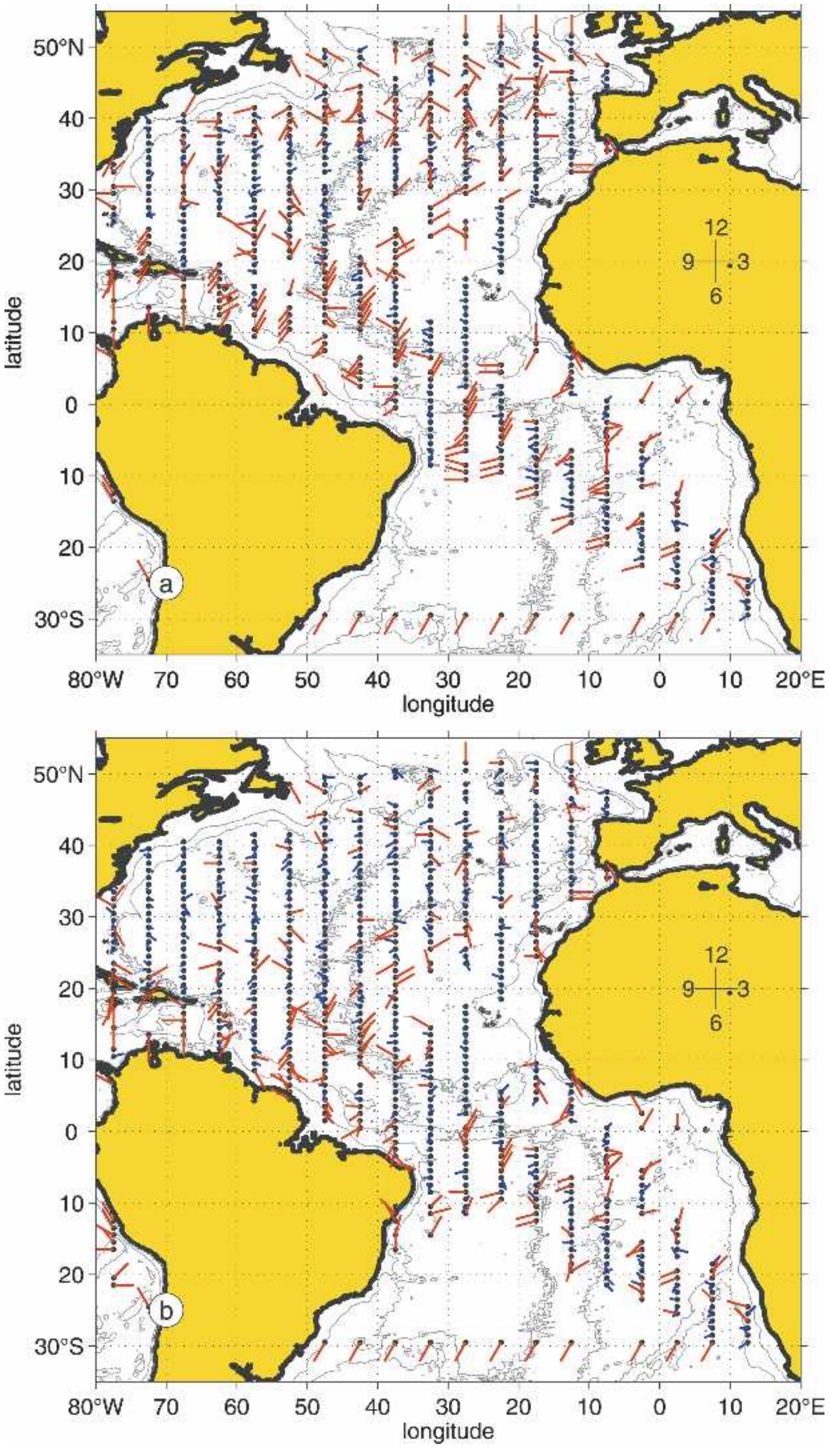

FIG. 8. Seasonal bias for the profiles obtained in the year 2002. The direction of the lines gives the phase (months 1–12) and the length gives the amplitude (0–1) of the bias. The inset crosshair represents an amplitude of 1 for four different months. If the amplitude is less (more) than 0.5 the lines are blue (red): (a) for nonfloat profiles, based on 6346 profiles in 567 boxes; and (b) for all profiles, based on 11 886 profiles in 667 boxes.

pattern. Once the float data are added to the calculation the feature disappears (Fig. 10b). The remaining differences between the surface flux and the heat storage rate are not unrealistic. They could, for example, be the result of the horizontal advection of heat. An analysis of the full heat budget is beyond the scope of this paper.

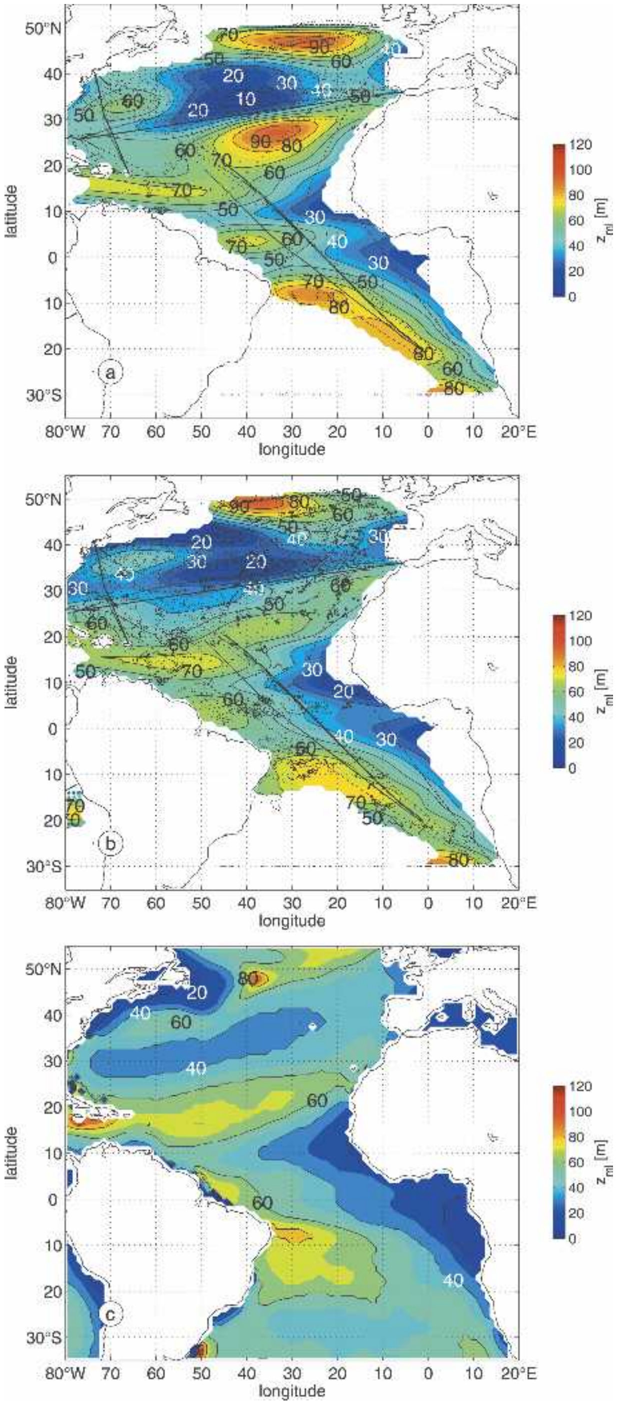

FIG. 9. (a) Annual mean of the mixed layer thickness in the year 2002 for nonfloat profiles, based on 6346 profiles in 567 boxes. (b) Annual mean of the mixed layer thickness in the year 2002 for all profiles, based on 11 886 profiles in 667 boxes. (c) Climatology of the mixed layer thickness from WOA 2001.

5. Conclusions

The comparison of temperature profiles from floats and XBTs shows that, in the tropical Atlantic, the data that are collected with these two instrument types are consistent with each other within the measurement error associated with XBT temperatures, if outliers are excluded (Table 1). A statistical comparison of float profiles with nonfloat profiles (including those from XBTs) in the tropical Atlantic indicates that no significant differences exist, even if the outliers are not excluded (Table 7).

In the North Atlantic, significant temperature differences were found below 250 db, with mean and median values exceeding 0.1°C (Table 3). Different possible causes were discussed in section 3. No link between a float type or sensor type and the temperature differences could be found. Regional differences indicate that a likely explanation is that a different sampling pattern for floats and XBTs exists in the region where the many meddies containing Mediterranean outflow are found (e.g., Armi and Zenk 1984; Käse and Zenk 1987; Sparrow et al. 2002). This relatively warm and salty outflow water is centered at about 1000 db. It may be that a significant number of XBTs were deliberately launched into meddies, while the floats sample the different water masses more randomly. This scenario is consistent with the fact that the temperature difference in the North Atlantic gradually increases with increasing depth below 250 db (Fig. 5).

A comparison of mixed layer depths that are derived from combined float and XBT profiles results in 6 db with a standard deviation of 14 db in the tropical Atlantic (62 samples), and 1 db with a standard deviation of 26 db in the North Atlantic (56 samples). If instruments other than XBTs are included in the tropical Atlantic, then the mean difference is 1 db, with a standard deviation of 13 db (156 samples).[9]

Gridded maps of the mixed layer properties for 2002 (Figs. 7 and 9) reveal significant differences between those generated with float data and those generated without float data. These differences are primarily a

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[9] See note 8.

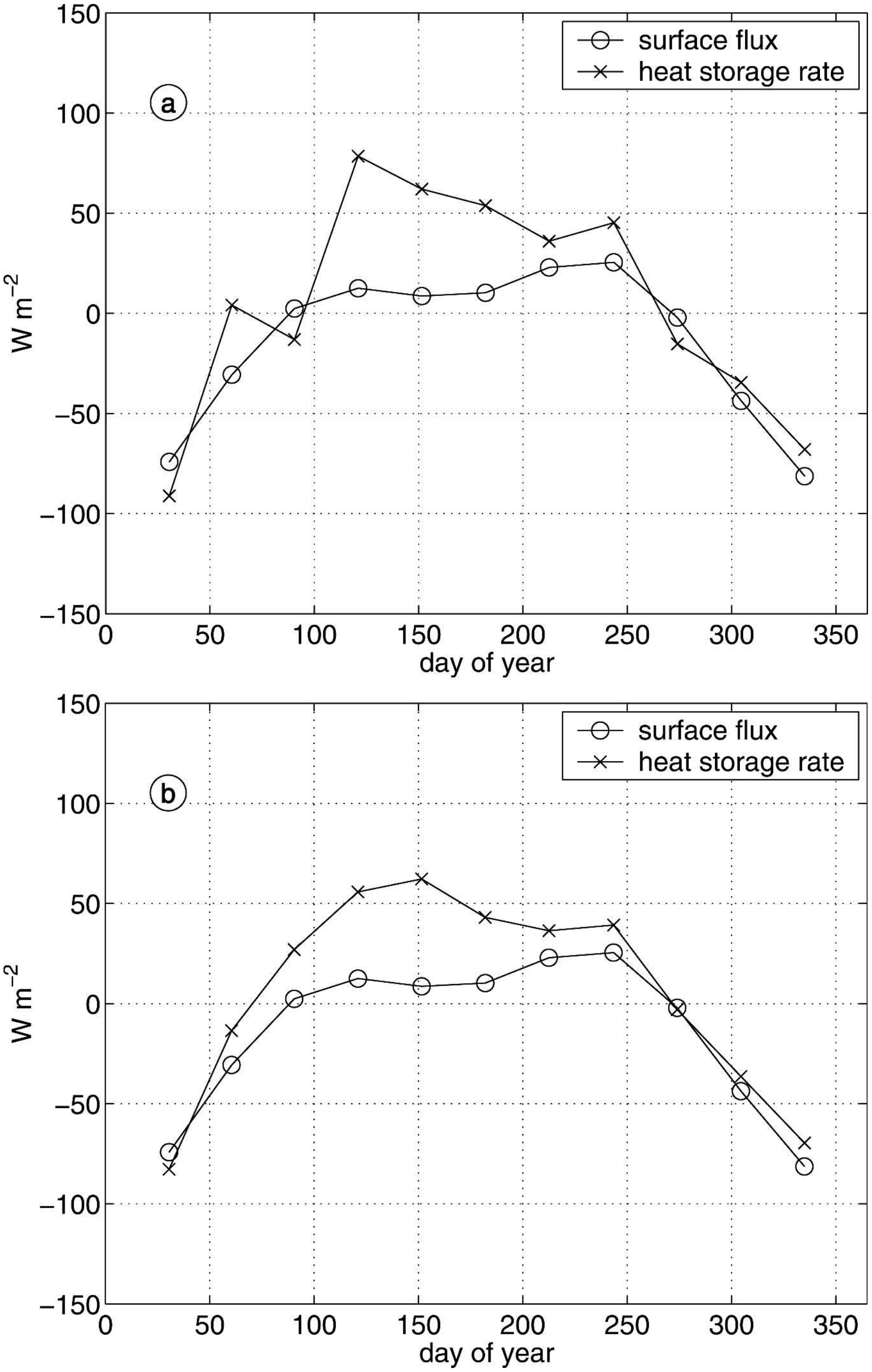

FIG. 10. The mean annual cycle of the surface flux and the heat storage rate based on observations collected in the tropical North Atlantic (5°–25°N, 60°–30°W) in the years 2000–03: (a) from nonfloat profiles, and (b) from all profiles.

result of the larger number of samples after the float profiles were added, which significantly reduces the seasonal bias. The maps based on all data deliver a better representation of oceanic features such as the North Equatorial Countercurrent, and they are in better agreement with the climatology (WOA 2001; Figs. 7c and 9c).

The mean annual cycle of the heat storage rate, derived from data collected in 2000–03, follows the surface flux more closely if data from the floats are added to the data from the other instruments (Fig. 10). The remaining differences are the result of the exclusion of all terms except for the surface flux and the change of the heat storage rate from the heat budget.

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