The Evaluation of Salinity Measurements from PALACE Floats

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ABSTRACT

Seven PALACE (Profiling Autonomous Lagrangian Circulation Explorer) floats were deployed in October 1996 in the Irminger Basin of the Atlantic Ocean as a U.K. contribution to the World Ocean Circulation Experiment. Of these floats, four were fitted with a conductivity–temperature–depth package. The floats were ballasted to drift at a depth of about 1500 m, above the Labrador Sea Water (LSW) cold and fresh extreme, and programmed to surface every 14 days. The floats made a profile during each ascent to the surface. The authors present a method to evaluate the performance of the conductivity sensors and to calibrate the float salinity data. Since the LSW appears to be relatively stable over a timescale of ~1–2 months and a length scale of ~50–100 km, the authors were able to make direct comparisons between the first year of float data and accurate ship-based measurements and, therefore, were able to correct for errors of the conductivity sensors. A correction was applied in all cases. The conductivity sensors were all stable within, or very close to, the manufacturer's specification, with a maximum drift for salinity of (0.0009 ± 0.0004) month^{-1}.

1. Introduction

The Autonomous Lagrangian Circulation Explorer, or ALACE, float was designed as an expendable subsurface float independent of acoustic tracking networks. Before deployment, the floats are ballasted to dive to a preset depth and programmed to surface after a fixed time interval. The floats rise to the surface by changing their buoyancy, that is, by increasing their volume via an external bladder into which hydraulic fluid from an internal reservoir is pumped. The process is reversed for descent. The position of the float is measured at the sea surface by Système Argos satellites. More details on float technology can be found in Davis et al. (1992). It was soon realized that this instrument made a useful platform for other measurements, which led to the addition of temperature and then conductivity probes to make profiles during the ascent of the float to the surface; those floats are called PALACE (Profiling ALACE).

The deployment of ALACE and PALACE floats has proven to be an effective way to sample low-frequency motions in the oceans (Davis 1998b) together with the hydrological characteristics of the upper 2000 m of the water column. The conductivity–temperature–depth (CTD) profiles obtained with PALACE floats, although not yet able to achieve the standard of more accurate CTD measurements from ships, represent a very cost-effective way to monitor the upper ocean (Davis 1998a,b). In addition, floats allow access to remote parts of the ocean and provide data from areas of severe winter weather conditions rarely sampled by ships. At the moment some restrictions are imposed by the Argos communication system: the quantity of data that can be transmitted is low and two-way communication is not possible.

The implementation of international programs like ARGO (ARGO Science Team 1998) will aim to provide float CTD data in near–real time. This implies that tools to perform data quality control and to correct for possible sensor errors must be available. The aim of this paper is to provide an example of how the error for salinity (derived from float temperature and conductivity measurements) can be estimated.

It is difficult to obtain accurate conductivity measurements from floats deployed for long periods. Biofouling on the conductivity cell is regarded as one of the main causes of drift toward lower salinity (Freeland 1997; Davis 1998a). Sudden jumps in salinity of order $\Delta S = 0.1$ have also been reported and these may be difficult to correct (Davis 1998a). Since water samples are not available for calibration, we need an alternative method to check the salinity data. One possibility is to compare the float observations with climatological databases; this method has the advantage of guaranteeing a satisfactory space–time coverage, thus permitting estimation of errors for most of the float profiles, but since the comparison is made with averaged profiles, it may be hard to separate the natural variability of properties as measured by the floats from sensor-induced errors.

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The other possibility is to use accurate CTD measurements from ships, made into water masses with stable and well defined θ–S relationships (where θ is the potential temperature), for direct comparison with float data (Freeland 1997; Davis 1998a; Bacon et al. 1998, 1999). Floats calibrated in this way can also be used for float–float intercomparisons when ship data are not available. The main disadvantage of this approach is that it relies on occasional matches (in space and time) between ship and float data, which may result in relatively long periods during which the float salinity performance cannot be monitored. In this paper we use the second approach to evaluate the performance of the float conductivity cells.

2. The operational area

a. The Irminger Basin

The circulation in the Irminger Basin is generally cyclonic at all depths. The dominant features are the surface western boundary current flowing south down the east coast of Greenland, comprising the East Greenland Current, a fresh cold current of polar origin, and the Irminger Current, a saline recirculating component of the North Atlantic Current; the deep Iceland–Scotland Overflow water (ISOW, also referred to as Charlie–Gibbs Fracture Zone water in the western part of the basin) heading north up the western flank of the Reykjanes Ridge and then southward down the continental slope off east Greenland; and the Deep Western Boundary Current, comprising the Denmark Strait Overflow, overlain by ISOW. Between the surface and deep flows lies the Labrador Sea Water (LSW). The cold and fresh extreme marking the core of the LSW was at about $S = 34.85$, temperature $T = 3.0°C$ in 1992 (Sy et al. 1997), although it is climatologically variable (Dickson et al. 1996). Above and below are more saline water masses of Atlantic origin, some locally recirculated in the Irminger Current (above LSW) from the North Atlantic Current, others more distantly related, as in the overflows (below LSW, see e.g., Schmitz and McCartney 1993). The data used for comparing the float-derived salinity measurements cover depths immediately above the LSW cold and fresh extreme.

CTD data collected from ships during several cruises made between October 1996 (when the floats described here were launched) and October 1997 show that the salinity below 900–1000 db was stable over that period of time. As an example the envelope of salinity profiles, between 600 and 1600 db and measured in autumn 1996 during two cruises that were 16 days apart, is shown in Fig. 1a. The location of the stations is shown in Fig. 1b. Below 1200 db, the maximum width of the envelope is less than 0.014 in salinity. Figure 1a also shows the average salinity profile and its standard deviation that, below 1200 db, is less than 0.005. The small spread of the salinity profiles over 16 days in an

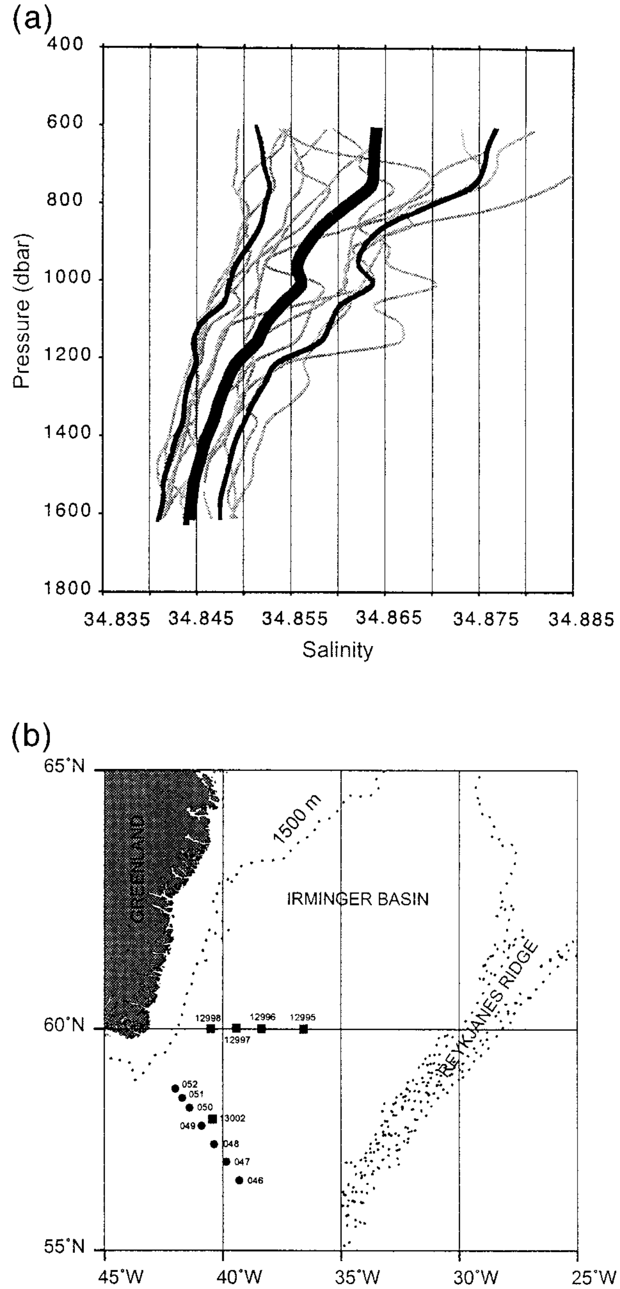

FIG. 1. (a) Profiles of salinity measured at the stations with ship deployed CTD. The data have been averaged over intervals of 50 db, corresponding to the vertical resolution of our PALACE floats for pressures greater than 555 db. The width of the envelope below 1200 db is less than 0.014. The thick black curve is the average profile and the lateral black curves represent ±1 std dev. (b) Position of CTD stations used for the θ–S plots in (a). Squares are for RRS *Discover* cruise 233 (Oct 1996) and dots are for R/V *Knorr* cruise 147 (Nov 1996). The two sets of stations were occupied 16 days apart from each other.

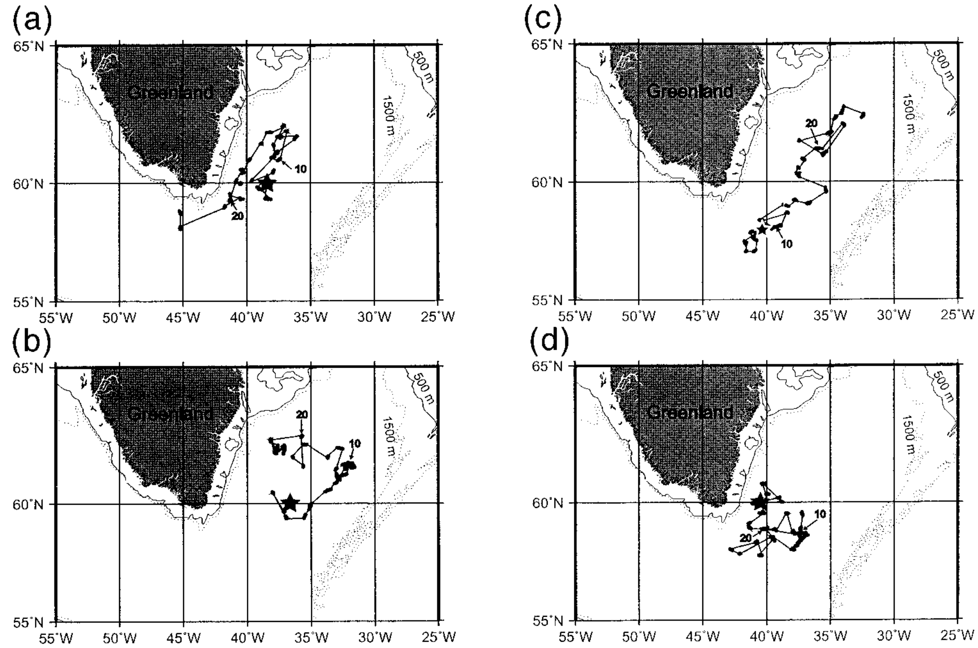

FIG. 2. Trajectories followed by the four CTD floats during the first year: (a) float 1, from Oct 1996 to Sep 1997; (b), (c), (d) floats 2, 3, and 4, respectively, from Oct 1996 to Nov 1997. The dots represent the position of the float at the surface. The lines join the last position fix at the surface with the first position fix at the surface of the following surfacing event. The star symbols denote the launch positions. The numbers denote the sequential profile number as received by the satellite. The floats were programmed to surface every 14 days.

area encompassing a significant portion of the Irminger Basin suggests that the LSW can be used to compare the salinity measured by the float CTD with ship-based observations.

b. Float operation

Seven PALACE floats were deployed in October 1996 from RRS *Discovery* in the Irminger Basin as a U.K. contribution to the World Ocean Circulation Experiment (WOCE) and following previous U.K. interest in the area (Gould 1992; Read and Gould 1992; Bacon 1997). Of these floats, four were fitted with a CTD package using the High Accuracy Conductivity Sensor (HACC), manufactured by Falmouth Scientific Inc. (FSI), and a Yellow Spring Instruments epoxy encapsulated precision thermistor, No. 44016, in the tip of a stainless steel needle probe. The conductivity and temperature sensors have respectively a nominal stability of $\pm 1 \times 10^{-3}$ mohm^{-1} cm^{-1} month^{-1} (equivalent in salinity to ± 0.0008 month^{-1} at $p = 1450$ db and $T = 2.9$°C) and in temperature to ± 0.0001°C month^{-1}. Each CTD float was launched immediately after a CTD profile had been made by the ship.

The target depth of the floats was set to ~1500 m, a little shallower that the core of the LSW layer. Using measurements from RRS *Charles Darwin* cruise 62 in 1991, local conditions at the target depth were approximated by $T = 3.21$°C and $S = 34.88$ resulting in density at 1500 db of $\rho = 1034.674$ kg m^{-3}. The manufacturer provided the floats ballasted accordingly.

The floats were programmed to return to the surface every 2 weeks. Of the 336 h forming the repeat cycle, 289.9 h were used to gather measurements at the cruising depth, leaving the extra time for ascent/descent of the float and transmission of data to the satellite. Figures 2a–d show the paths followed by the four CTD floats during their first year of operation.

TABLE 1. List of cruises used for comparison with float data.

Cruise	Principal Scientist	Date
RRS *Discovery* cruise 223, leg 2	Raymond Pollard, SOC	Oct 1996
R/V *Knorr* cruise 147	Mike McCartney, WHOI	Nov 1996
R/V *Knorr* cruise 151	Lynne Talley, SIO	Jun 1997
F/S *Meteor* cruise 39, leg 4	Fritz Schott, IfM Kiel	Jul 1997
RRS *Discovery* cruise 230	Sheldon Bacon, SOC	Aug 1997
R/V *Knorr* cruise 154	Ruth Curry, WHOI	Oct 1997

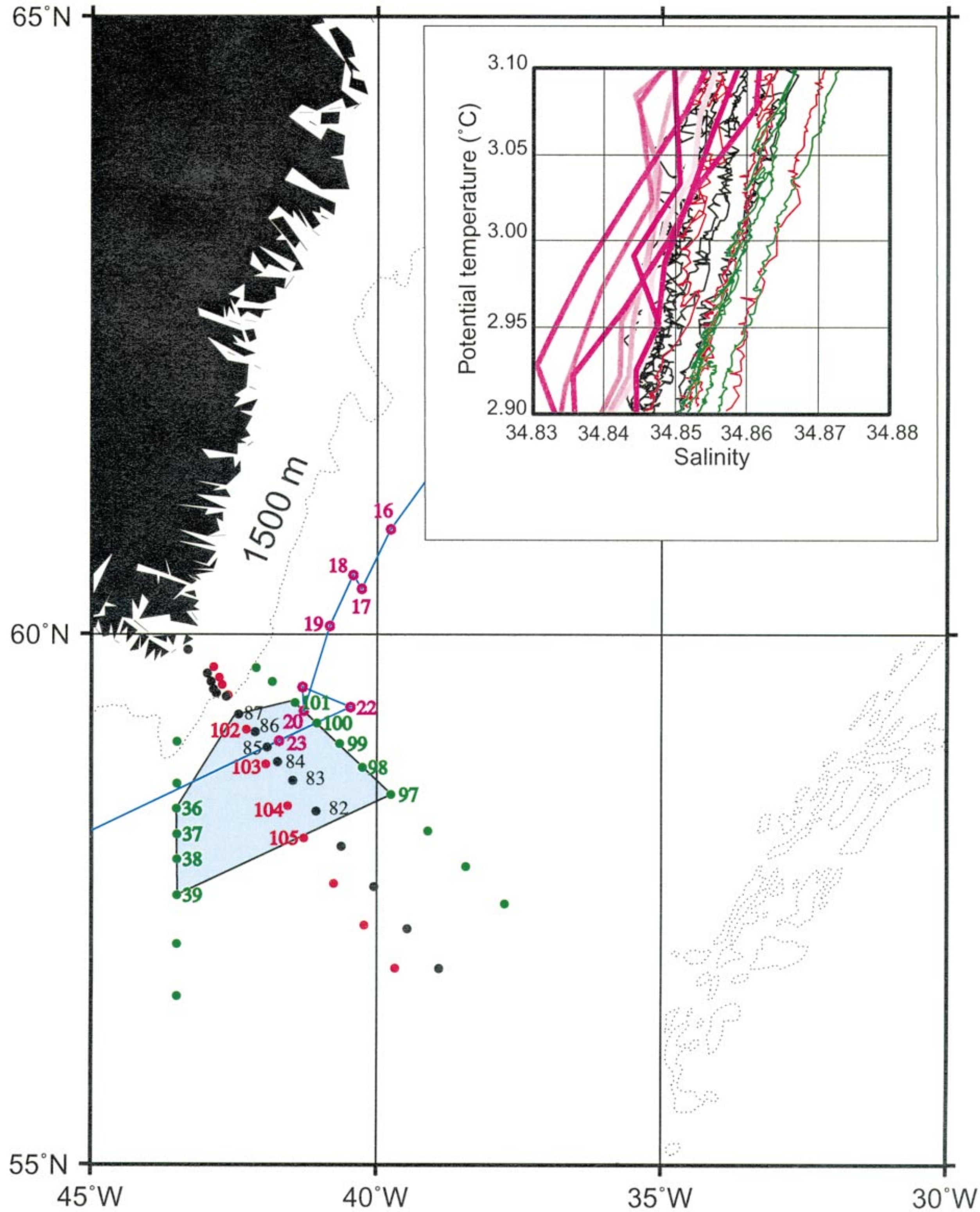

FIG. 3. The ship CTD data from the stations included in the shaded pentagon were used to plot the θ–S diagram shown in the upper-right corner. Red is for R/V *Knorr* cruise 151 (Jun 1997), black for RRS *Discovery* cruise 230 (Aug 1997), and green for F/S *Meteor* cruise, 39 leg 4 (Jul 1997). The path followed by float 1 is also shown in light blue. The purple dots mark the position at which the CTD float profiles were taken. The purple curves in the θ–S diagram were obtained from float data gathered during the same period in which the cruise measurements were done, i.e., from profile 16 to 22. Light purple corresponds to profile 16, dark purple to 22. The float salinity shows a spread of the same order of the spread of salinity measured during the three cruises. The float salinities also appear shifted toward lower values, thus suggesting that a positive correction should be added to them.

TABLE 2a. Time and space separation between profiles measured by the CTD mounted on float 1, indicated by its sequential number in the first cell, and profiles measured by CTD casts from ships. A negative time means that the float profile has been made after the CTD ship profile. Cruise abbreviations are derived from Table 1.

01 v D223	02 v D223	19 v M39-4	20 v M39-4	20 v D230	22 v M39-4
−14 day (71 km)$^{-1}$	−28 day (41 km)$^{-1}$	19 day (103 km)$^{-1}$	5 day (87 km)$^{-1}$	28 day (57 km)$^{-1}$	−23 day (57 km)$^{-1}$
−14 day (87 km)$^{-1}$	***	19 day (89 km)$^{-1}$	5 day (53 km)$^{-1}$	28 day (67 km)$^{-1}$	−22 day (83 km)$^{-1}$
***	***	***	5 day (22 km)$^{-1}$	***	−22 day (103 km)$^{-1}$
***	***	***	5 day (9 km)$^{-1}$	***	***

The profile data collected by the floats during their ascent were averaged prior to transmission as follows: 10-db steps between 5 and 195 db, 20-db steps between 207 and 527 db, and 50-db steps between 555 and 1455 db. The coarse resolution in the vertical is a restriction imposed by the Argos message regime and not by float technology.

3. Conductivity sensor calibration

Here we focus attention on data from pressures greater than 600 db in order to exploit the stability of water masses with stable θ–S relationships. The float salinity was calculated from conductivity and temperature using the calibration coefficients provided by the float manufacturer.

We consider the errors of float salinity as time varying offsets that are applicable to the profile for pressures greater than 600 db. As an example, we show θ–S plots obtained from ship CTD stations taken on three different cruises spanning a period of 2 months (Fig. 3, top right corner), and from float profiles taken in the same area. The figure illustrates the combined magnitude of the temporal and spatial variability within the shaded area south of Greenland (see also Fig. 1b). The width of the CTD profile envelope is about 0.02 in salinity on potential temperature surfaces between 2.9° and 3.1°C. The width of the salinity envelope of float profiles, all recorded with the same instrument and spanning the same time interval, is about 0.016 in amplitude (the casts made with the float are generally located northeast of the ship CTD stations and this may introduce some bias). The two envelopes have very similar amplitudes and slopes. The float data appears shifted toward lower salinities, thus suggesting that a positive correction should be added to them.

The availability of a large quantity of high quality WOCE hydrographic data from the subpolar gyre in 1996 and 1997 makes possible a systematic evaluation of the quality of the float salinity data. There are two approaches in comparing the float data with the hydrographic data: we can compare float salinity profiles with individual or small groups of ship CTD profiles whose positions are closely adjacent (in space and time), or, alternatively, we can take a statistical approach by using background θ/S distributions. The first approach has the advantage minimising the effect of eddy noise, seasonal–interannual variability, and spatial variations.

Throughout this work we will assume that the temperature measured by the floats is correct within the manufacturers specifications. Using a linear fit to the deep θ–S curves for several float profiles, we calculated that an error in potential temperature of 0.001°C (the possible drift in 1 yr) will result in a difference in salinity of about 0.00015, which is not significant.

We now outline the method used to the identify pairs of profiles. We used data from six cruises. These are listed in Table 1. The first is the launch cruise itself in October 1996. We began with the simple assumption that two CTD profiles that are close in space and time, whether made by a float or a ship-deployed CTD, are

TABLE 2b. As in Table 2a, but for float 2.

01 v D223	16 v KN151	22 v D230
−13 day (33 km)$^{-1}$	8 day (118 km)$^{-1}$	3 day (76 km)$^{-1}$
−13 day (78 km)$^{-1}$	***	3 day (22 km)$^{-1}$
***	***	4 day (41 km)$^{-1}$
***	***	4 day (96 km)$^{-1}$

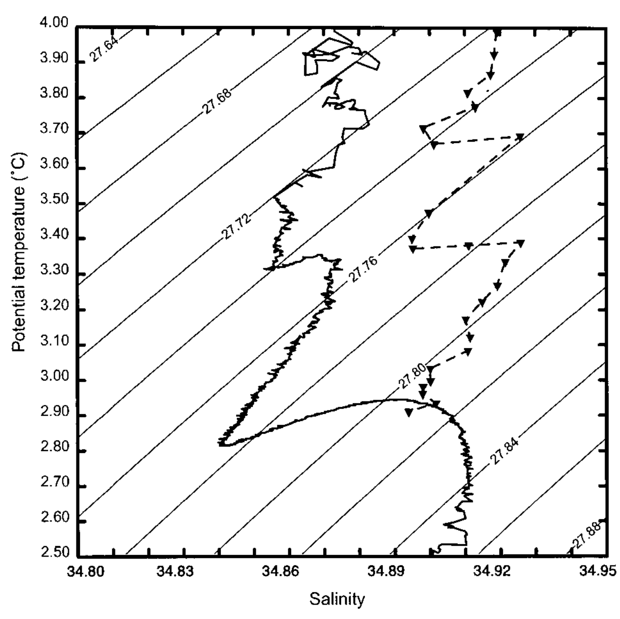

FIG. 4. Comparison, in θ–S space, of the uncorrected profile number 22 (2 Sep 1997) from float 3 with a ship CTD profile from *Discovery* cruise 230. The two stations are about 39 km apart. The ship CTD profile was made 24 h before the float profile. The two curves have similar slopes below 3.4°C and the salinity measured by the float appears to have an offset of ~0.04. Curves of constant σ_0 are also superimposed.

TABLE 2c. As in Table 2a, but for float 3.

01 v D223	01 v KN147	22 v D230	26 v KN154	27 v KN154
−14 day (55 km)$^{-1}$	0 day (24 km)$^{-1}$	1 day (39 km)$^{-1}$	0 day (114 km)$^{-1}$	−14 day (169 km)$^{-1}$
***	***	***	0 day (74 km)$^{-1}$	−14 day (113 km)$^{-1}$
***	***	***	0 day (65 km)$^{-1}$	−14 day (55 km)$^{-1}$
***	***	***	0 day (95 km)$^{-1}$	−14 day (11 km)$^{-1}$

likely to be independent measurements of the same water mass. For each position of the float profile, given by the first satellite fix at the surface, we calculated the separation, in space and time, from ship CTD stations. We selected pairs of float and ship CTD profiles that occurred within 50 days and 100 km of each other. The shape and the slope of float and ship θ–S diagrams, for water with potential temperature lower than 3.1°–3.2°C, were then inspected to decide whether a ship/float profile pair were within the same hydrographic regime. Figure 4 shows an example of a pair of float and ship CTD observations. The two stations, in the middle of the Irminger Basin, are 1 day apart and separated by about 38 km. Below 3.4°C the slopes of the two curves are similar and the salinity measured by the float appears to have an offset of 0.04. Tables 2a–d contain the spatial and temporal separations of the pairs of stations selected for the comparison for each float.

The error in salinity was calculated on potential temperature surfaces rather than on pressure surfaces in order to remove the apparent variation in salinity caused by the vertical displacement of the same water mass. The vertical displacement varied in space and time and was observed to be up to ~250 db. Once a pair of float and CTD profiles was selected as satisfying the comparison criteria, the data were treated as follows. If more than one ship CTD station was chosen for comparison with a particular float profile, a mean ship θ–S curve was calculated by averaging on potential temperature surfaces. Performing the comparison of salinity on θ surfaces meant that much of the processing was directed at avoiding inversions in potential temperature (in the θ–S space). Some of the inversions in the CTD ship θ–S diagrams were eliminated by averaging the data into 50-db intervals in the vertical (the same resolution used by floats at the deepest levels). The restriction to potential temperatures below 3.2°C and a further average of salinity data into potential temperature intervals ≥0.025°C led, in the majority of cases, to θ–S profiles free of inversions. When inversions were still present, the potential temperature interval used to calculate the offset was reduced to exclude the inversion points. CTD data from floats were processed in the same way.

The salinity error ΔS is given by $\Delta S = S_{\text{ref}} - S_f + \epsilon$, where S_{ref} is the salinity measured from the ship, S_f is the salinity measured by the float, and ϵ represents the natural variability associated with the time and space scales used for the comparison. Using potential tem-

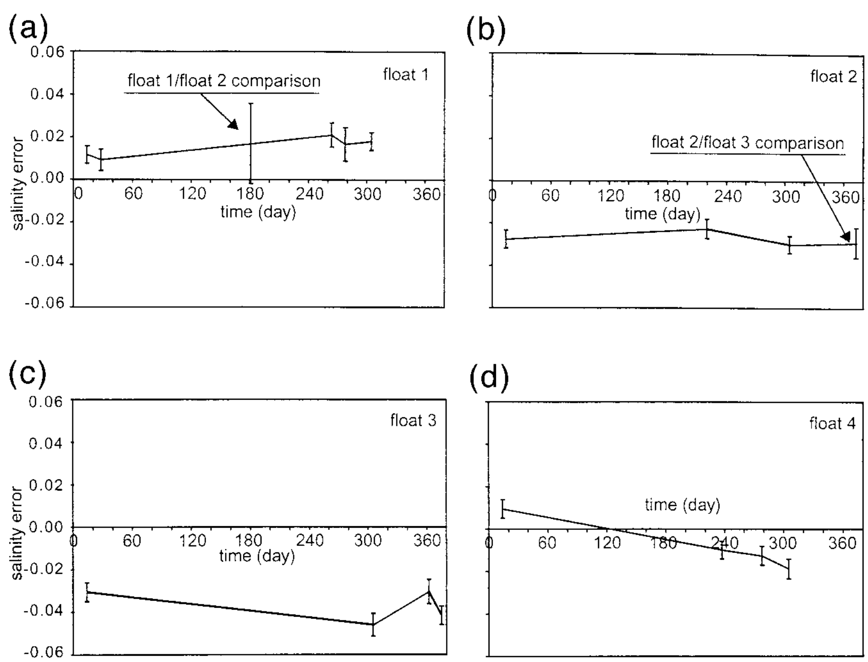

FIG. 5. Time series of the salinity error for the four floats. Time is expressed in days since the deployment of float 1 (27 Oct 1996).

TABLE 2d. As in Table 2a, but for float 4.

01 v D223	17 v KN151	20 v M39-4	22 v D230
−14 day (50 km)$^{-1}$	−3 day (102 km)$^{-1}$	4 day (38 km)$^{-1}$	−2 day (119 km)$^{-1}$
−14 day (24 km)$^{-1}$	−3 day (84 km)$^{-1}$	5 day (15 km)$^{-1}$	−1 day (113 km)$^{-1}$
−13 day (77 km)$^{-1}$	−3 day (87 km)$^{-1}$	5 day (56 km)$^{-1}$	***

perature as a common independent variable, the differences between float and ship salinities were computed for each pair of profiles. This error was calculated as the average of the salinity differences for different temperatures values. The results are shown, for each float, in Fig. 5. The θ–S diagrams obtained after calibrating the salinity using a piece-wise linear fit to the estimated errors are shown in Fig. 6.

Assuming that $\langle \epsilon \rangle = 0$, which is equivalent to assuming that we are comparing two independent measurements of the same salinity distribution, we need an estimate of its error, σ_ϵ. We estimated σ_ϵ as the averaged standard deviation of salinity on θ surfaces between 2.85° and 3.2°C using profiles from the two most stable floats (1 and 2, as can be seen from Figs. 5a,b and Figs. 6a,b). The standard deviations have been calculated from the first 23 profiles of float 1, since it subsequently entered the Labrador Sea, and for the first 27 profiles of float 2, that is, until November 1997. The two standard deviations, averaged on θ surfaces, are equal and amount to 0.004.

Despite the high spatial and temporal density of ship CTD data in the same region as the floats, our comparison of salinity measurements leaves quite large gaps between estimated correction points. To improve the time series of the correction points we have also used float–float comparisons. Float salinity data, calibrated with the corrections derived from CTD measurements

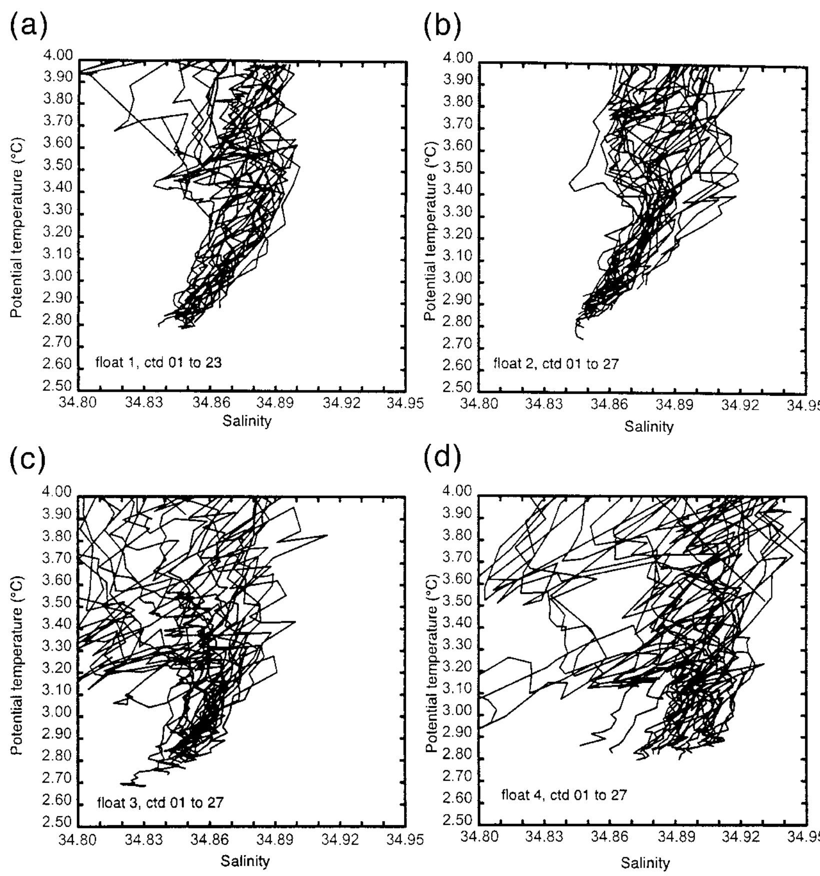

FIG. 6. θ–S diagrams from float CTD data calibrated using a piece-wise linear fit to the calculated errors (shown in Fig. 5). For floats 2, 3, and 4 we used data up to Nov 1997. (a) The curves for float 1 are plotted until Aug 97, after which the float left the Irminger Basin and entered the Labrador Sea. The envelope of profiles for water with potential temperature lower than 3.0°–3.1°C is narrow for floats (a) 1, (b) 2, and (c) 3, and (d) shows a bigger spread for float 4, thus suggesting that the applied calibration is incorrect.

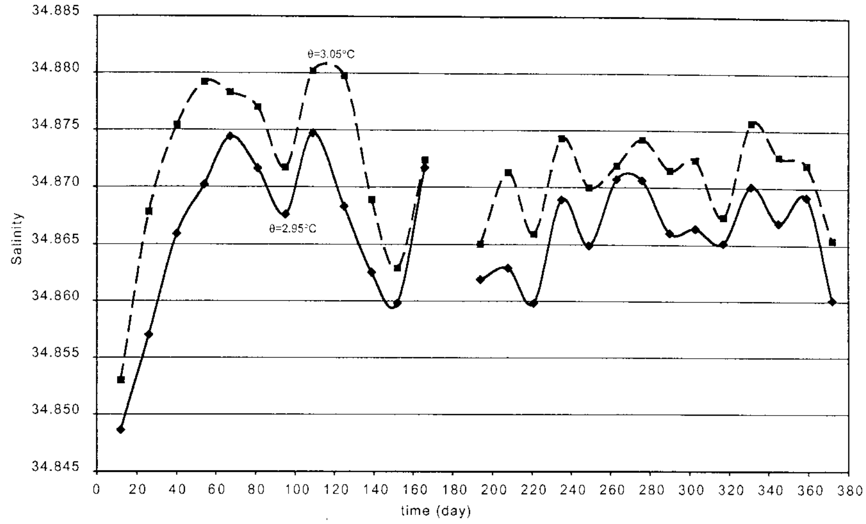

FIG. 7. Time series of salinity obtained from the CTD package mounted on float 4. The solid curve is the salinity observed at $\theta = 2.95°C$, the dashed curved at $\theta = 3.05°C$. The low salinity values recorded at day 15 and day 29 (first two points) suggest that the conductivity sensor has undergone two consecutive jumps (or fast drift episodes) each of about 0.01 in salinity. The time is expressed in number of days since the deployment of float 1 (27 Oct 1996).

from ships were used to calculate the corrections for other float data using the same selection criteria already described for float/ship CTD comparison. This has added two extra calibration points as shown in Fig. 5a (day 181) and Fig. 5b (day 373).

The drift of the conductivity cell was taken as the slope of the linear regression curve fitted to the calculated errors.

4. Discussion

The salinity data from floats 1 and 2 show respectively a slow drift [$(0.9 \pm 0.4) \times 10^{-3}$ month^{-1}, Fig. 5a; $(-0.2 \pm 0.3) \times 10^{-3}$ month^{-1}, Fig. 5b] and an almost constant offset. Also, the θ–S diagrams for these two floats (Figs. 6a,b) show, for potential temperature lower than 3.1°C, that the envelope is tight in salinity (amplitude ~0.02), thus confirming that the error is slowly increasing with time.

The calibration curve calculated for float 3 has two points (Fig. 5c; day 305, 1 September 1997, and day 362, 28 October 1997) that do not lie on the linear fit (not shown in figure). The comparison of consecutive θ–S diagrams for float 3 between August 97 and October 97 does not show any obvious anomaly in the salinity data. We therefore rule out the hypothesis of mismatches induced by the conductivity sensor and we attribute the anomalous salinity errors to noncorrect comparison with salinity measured from ships. As before, the θ–S envelope made with the profiles measured during the first year is narrow for $\theta < 3.0°C$, with an amplitude of ~0.03 in salinity. The estimated drift of salinity for this conductivity cell is $(-0.6 \pm 0.6) \times 10^{-3}$ month^{-1}.

The linear fit to the salinity errors (Fig. 5d) calculated for float 4 shows a drift of $\sim(-2.7 \pm 0.2) \times 10^{-3}$ month^{-1}, which is large compared to the others. The θ–S diagram of the calibrated data (Fig. 6d) suggests that this choice is incorrect since the spread of the curves is too large (if compared with Figs. 6a–c) to be attributed with confidence only to natural variability. Time series of salinity for float 4, for $\theta = 2.95°C$ and $\theta = 3.05°C$, are shown in Fig. 7. It appears that a sudden transition has taken place during the first two profiles (day 15, day 29). The salinity offset between the first and the fourth profile (both measured by the same conductivity cell, the offset being calculated in the same way explained in the previous section for float/ship CTD comparison) is (0.021 ± 0.003). This figure is very similar to the difference between the initial offset (Fig. 5d; day 14) and the offset calculated in June 1997 (day 237, samefigure) from ship CTD data, therefore suggesting that two consecutive salinity jumps each of ~0.01 have taken place during the first two months of operation. The new calibration curve is shown in Fig. 8a and the θ–S envelope of the calibrated data in Fig. 8b. The comparison with Fig. 6d shows that with the new calibration the scatter of the θ–S curves for $\theta < 3.0°C$ is reduced and the amplitude of the new envelope is now ~0.02 in salinity. The drift of the salinity calculated with this conductivity sensor, calculated from the linear fit after day 40 is $(-0.5 \pm 0.4) \times 10^{-3}$ month^{-1}.

5. Conclusions

We have investigated the salinity data measured by four FSI HACC probes mounted on our PALACE floats in the attempt to calculate their errors and to isolate evidence of systematic drift. The comparison was made

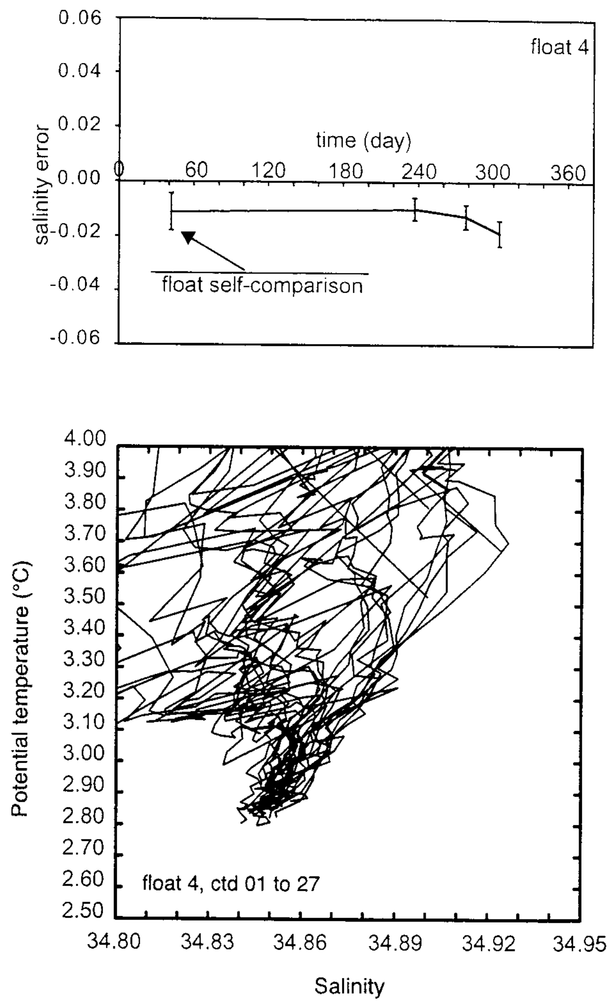

FIG. 8. A new calibration curve calculated by adding the offset computed by comparing the first and the second salinity profiles measured by the CTD package mounted on float 4 with (a) the fourth profile measured with the same instrument. (b) The θ–S diagram made with this new calibration curve. The spread of the envelope is reduced if compared with the similar diagrams shown in Fig. 6d.

with accurate CTD measurements made from ships. Using the stability of the physical properties of Labrador Sea Water over a time scale of 1–2 months and a dense space–time coverage of cruise data, we were able to identify CTD casts suitable for calibration purposes.

All sensors have a time dependent error in salinity. Three of them, 1, 2 and 3, are stable over 1 yr and show drifts that are within, or very close to, the manufacturer's specification. We conclude that the apparent variations in the offset of float 3 (day 305 and day 362) were due to an incorrect choice of ship CTD casts used for comparison. For the remaining float, 4, the conductivity cell still shows stability and an acceptable drift, but underwent two consecutive jumps in salinity (or fast drift events), each with amplitude ~0.01, during the first month of operation.

The method that we have described, combined with the use of data from climatological databases, should provide an effective method to check salinity data on large numbers of floats. New generation of sensors are progressively becoming available and they may perform better than the ones we have examined here. However, until such time as conductivity sensors are developed which report accurately and without errors, a global ARGO float array will require data quality control on the lines employed here. Ship CTD data, penetrating into relatively stable intermediate/deep waters, will be used opportunistically for float salinity calibration, and with a sufficiently high density of floats, corrections may be propagated throughout the float fleet by float–float calibration.

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