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Modal composition of the central water in the North Atlantic subtropical gyre

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Abstract

The modal composition of the Central Water in the North Atlantic subtropical gyre is not clearly defined, as there are some uncertainties related to mode identification, as well as modes which are not well documented. This study shows that eastern North Atlantic Central Water (eastern NACW) in the subtropical gyre is composed of three modes: The North Atlantic Subpolar Mode Water (NASPMW σ_t=27.1 to 27.3), the Madeira Mode Water (MMW σ_t=26.4 to 26.6), and the mode water with a σ_t near 27.0, which is currently not well documented. We confirmed this mode based on the similarities found between it and the mode waters already reported. The similarities were determined from comparative analyses of the temperature/salinity standard curves and the gradients of the potential density anomalies of two concurrent data sets from two subtropical time-series stations (Bermuda Atlantic Time-series Study, BATS, in the west, and European Station for Time-series in the Ocean Canary Islands, ESTOC, in the east). In order to establish the outcropping regions, the corresponding pycnostads were determined using another climatologic data set (World Ocean Database, WOD2005). In this case, the pycnostads were located based on the presence of standard deviation minima from the average density anomalies. Finally, we confirmed that the pycnostads corresponded to the temperature values related to the modes by overlaying the characteristic modal isotherm of each of the modes in the geographic distribution of the pycnostads. Sea surface temperature data (SST) from the Ocean Pathfinder Program (OPP) were used to estimate the isotherms. The results showed a clear correspondence between the modal isotherms and the pycnostads, for both the modes that have already been documented and the mode confirmed in this study.

1 Background and objectives

The North Atlantic Central Water (NACW) is located at the main thermocline of the North Atlantic Ocean. This body of water could be defined as the result of the mix of several mode waters. As the name suggests, mode waters have been defined as layers that have vertical homogenous water properties and which are found over a relatively large geographical area (Hanawa and Talley, 2001). These waters are located well beyond the outcropping area as a result of advection, and are usually associated with wintertime convective mixing. The name was first used by Masuzawa (1969) and extended to a similar previous study (Worthington, 1959) as well as to successive studies related to similar water signals in other oceans (McCartney, 1977; Provost et al., 1999; Siedler et al., 1987).

Several mode waters have been described as being part of the NACW on the western and eastern boundaries of the subtropical North Atlantic Ocean. The North Atlantic Subtropical Mode Water (NASTMW) was the first mode water identified and is the only mode water on the west side of the subtropical North Atlantic Ocean. It was called 18° water (Worthington, 1959). It spreads throughout the northwestern side of the subtropical gyre, taking up a layer located between approximately 200 and 400 m depth. Its formation area is located southward of the Gulf Current Extension (Talley and Raymer, 1982). Its properties and characteristics have been extensively described by different authors (Schröeder et al., 1959; Worthington, 1976). On the eastern side, several mode waters have been identified, although there is still uncertainty concerning some of their characteristics.

Among the mode waters on the eastern subtropical side, the best documented mode is the Subpolar North Atlantic Mode Water (SPNAMW), which was identified by McCartney and Talley (1982). This mode water is formed by winter convection from a water flow which comes from the west and splits into two branches (south and north), with the southward branch flowing inside the subtropical gyre thermocline. The northward branch is the origin of other higher density mode waters, which are also formed by cooling (deep waters). These high density mode waters, together with the SPNAMW, are the four mode waters that constitute the water mass called Eastern North Atlantic Water (ENAW) described by Harvey (1982).

There have been several approaches used to explain the mode water structure or water types in the North Atlantic subtropical gyre. Fraga (1973) pointed out the presence of a homogeneous layer at 23° N, which he called "type A water", that originated further north. Later, Fiúza (1984) hypothesized that eastern NACW (named ACOAN in Portuguese) in the subtropical gyre was constituted by two mode waters: a mode water layer with subpolar origin and potential density range between 27.1 and 27.3 kg m^{-3} (SPNAMW essentially), and another mode water called Azores Front Mode Water, or Eastern North Atlantic Water in Harvey's nomenclature, with a subtropical origin ($ENAW_T$) (Fiúza, 1984; Ríos et al., 1992). This mode water is found in the upper level of the thermocline (<27.0–27.1 kg m^{-3}) and its outcropping region is located southward of the Azores Islands, along the subtropical front. A new approach emerged due to the identification of the similar density mode water called Madeira Mode Water (MMW) (Siedler et al., 1987). This mode water, which is clearly different from the NASTMW in the western subtropical gyre, also has a formation area and characteristics similar to the $ENAW_T$.

Although most water mass studies in the east have been centered on the ones mentioned above, there have been other studies which reported the presence of homogenous layers with a temperature around 14°C. For instance, a water mass study carried out on the Galician Coast reported a water flow near the coast (σ_t=27.0) during summertime which originated at about 40° N latitude (Fraga et al., 1982). Based on the abovementioned hydrographical results, Pérez et al. (2001) pointed to mesoscale eddies as the main mechanism for the downstream indirect ventilation of the upper NACW and noted the importance of a equatorward flow in the redistribution of the different modes of the eastern NACW. Finally, Oliveira et al. (2004) reported the presence of this flow at depths close to 400 m and located at 41° N latitude, inferred from the field data previously noted by Peliz et al. (2003) from the results of numerical model simulations.

Our objective was to show that the eastern NACW in the subtropical gyre is composed by three modes. Like the hypothesis proposed by Harvey (1982), in which the

ENAW from 4 to 12°C is constituted by four mode waters sorted by density, we propose in this study that the eastern NACW from 10 to 18°C is formed by three mode waters sorted by density. One of them would have a subpolar origin, whereas the other two would form in the subtropical region. The mode water with a subpolar origin is the SPNAMW (σ_t=27.1–27.3) and the subtropical modes are MMW (σ_t=26.4–26.6), which is the top of the eastern NACW layer, and the mode water with σ_t=27.0, which is currently not well documented. The characteristics of the already documented mode waters were visualized and a resemblance method was applied in order to identify the presence of the third mode. We describe the characteristics of this third mode on the eastern side.

2 Data

We used data from two in situ time-series stations "BATS and ESTOC", located on either side of the subtropical North Atlantic Ocean. These stations provide extensive hydrographic data sets. ESTOC (European Station for Time-Series in the Ocean, Canary Islands) is a Spanish-German time-series station located 100 km north of the Canary Islands and 450 km west of the NW African upwelling margin in the eastern boundary system of the subtropical North Atlantic gyre. It is a twin station to the older US-JGOFS BATS (Bermuda Atlantic Time-Series Station) located on the western side of the gyre. The positions of BATS and ESTOC in relation to the North Atlantic subtropical gyre can be seen in Fig. 1. Details on the sites can be found in the literature (Llinás et al., 1999; Llinás et al., 1997; Michaels, 1995; Michaels and Knap, 1996; Steinberg et al., 2001). We used time-series CTD data measured during the monthly cruises between 1994 and 2003.

The BATS data are available on the web site (http://www.bios.edu/research/bats.html), while the ESTOC data set was provided by the Instituto Canario de Ciencias Marinas (ICCM; http://www.estoc.es/). A total of 687 profiles were used; there were no major gaps in the BATS data, while the CTD time-series started continuously from

August 1995 at ESTOC. The previous TS data (from January 1994 to July 1995) were acquired by discrete sampling using reversing thermometers and salinity samples, which were analyzed on a Guideline salinometer. The CTD measurements were taken using different instruments at ESTOC during the survey period: a self-contained CTD probe from SIS, and CTD probes from IDRONAUT, Seabird and Neil-Brown. The TS-profiles were individually quality controlled following the WOCE protocols.

Another climatology data set taken from the World Ocean Database 2005 (WOD2005) was also used in order to supplement the analysis. These data, collected in 10° latitude × 10° longitude squares, were downloaded from the National Oceanography Data Center (NODC) (http://www.nodc.noaa.gov/OC5/WOD05/pr_wod05.html). The data set covers from 20° to 60° N latitude and 10° to 70° W longitude. A total of 215 288 standard temperature-salinity profiles were included. 654 was the minimum number of profiles used per square and 29 583 the maximum.

A satellite derived sea surface temperature set was used to establish the outcropping region. These data represent a long term consistent database for climatological studies (Kilpatrick et al., 2001) and are the fifth version of AVHRR Oceans Pathfinder (http://pathfinder.nodc.noaa.gov). They consist of a new reanalysis of the AVHRR data stream that has provided weekly averages of high resolution global SST records (4 km approx) since 1985. This time-series was used to obtain the SST annual distributions for the survey period. The data for the winter months (December to March) were processed for the period between 1994 and 2004. The values of the mean temperature, absolute minima, and temporal SST standard deviations were obtained for each winter, as well as the dates when the absolute minima were reached.

3 Discussion

3.1 TS diagram

Two standard curves for NACW were obtained by a third-order mean-square polynomial fit (Fig. 2a) from concurrent 10-year CTD time-series from BATS and ESTOC. The fit method also calculates the errors in the fitted salinity estimates. These errors are important because they provide information related to the ranges of lowest variability in both properties (temperature and salinity measurements) along the standard curves. In order to avoid the influence of seasonal variability, the values from the upper 100 m were removed.

ESTOC :

$$S = -762896 \times 10^{-5} \times T^{3} + 399681 \times 10^{-3} \times T^{2} - 519146 \times 10^{-2} \times T + 374461 \quad (1)$$

Standard deviation (STD) = 0.039; data number = 32153

BATS :

$$S = -96732 \times 10^{-5} \times T^{3} + 449738 \times 10^{-3} \times T^{2} - 526391 \times 10^{-2} \times T + 370687 \quad (2)$$

Standard deviation (STD) = 0.013; data number = 98997

The comparison of the two curves shows the actual differences between the NACW characteristics on the east compared to the west. In addition, it establishes the significance for both sites as representative of the NACW in the eastern and western regions of the North Atlantic subtropical gyre. The computed errors represent both the errors and uncertainties in the estimates and are obtained through the variance-covariance data matrix. Thus, the TS ranges in the curves whose error values were minima could be considered as the signals of the mode water cores.

The errors versus potential temperatures are shown in Fig. 2b. Several minima are visible on the plot and are located at different temperature ranges. The errors are

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higher at ESTOC than at BATS due to the higher variability in the area. The absolute minimum is at 11°C at ESTOC, while it is located around 18°C in the BATS curve. Thus, the absolute minima of the two curves coincide with those temperature values used in the literature to characterize the NASPMW in the east and the NASTMW in the west of the North Atlantic Ocean respectively (Hanawa and Talley, 2001). Two more relative minima are clearly visible at ESTOC; while only one more can be seen in the BATS curve. This relative minimum in the BATS curve is located near 11°C, the same temperature as the absolute minimum mentioned above for the ESTOC curve. The upper relative minimum found at ESTOC is located near 17°C, coinciding with the range of thermal features (16 to 18°C) which characterizes the MMW (Siedler et al., 1987). The lower relative minimum is located in a temperature range from 13° to 14°C. This relative minimum coincides with some previous studies which hypothesized a warmer type of SPNAMW (between 13°C and 14°C), subducted south of 40° N (Harvey and Arhan, 1988; Paillet and Arhan, 1996). Thus, the relative minimum observed in the ESTOC curve could be a consequence of this variety of SPNACW or mode water which is a result of cooling during winter (mixed layer depth around 200 m deep) and formed in the surrounding region of 42° N in the subtropical gyre.

3.2 Pycnostad analysis in the water column

The minimum in the vertical gradient of the potential density anomaly is considered a conservative tracer for the mode waters if we assume that mixing and relative vorticity are not considered (Hanawa and Talley, 2001). These minima, called pycnostads, are visible far from the outcropping regions (stability), which differentiates them from the surrounding waters. The geographical performances of these minima have been used in previous studies to identify water masses (Keffer, 1985; McDowell et al., 1982). In this study we attempted to identify the mode water signals (pycnostads) by using the time distributions related to this conservative tracer. The coincidence between the minima and the temperature ranges obtained in the TS diagram reinforces the results of this study. However, we are aware that making observations based on time-series results is very complex as there are no comparative data with the surrounding waters. In addition, the remoteness of the outcropping regions and the layer erosion as a consequence of the mixing processes add more uncertainty to the observation. This process mainly affects the shallower modes on the eastern side of the gyre, where the vertical mixing is seasonally strengthened after spring due to the reinforcement of the trade winds. In spite of this handicap, the possible presence of the minima or the expected identification of the corresponding cores can be considered as supplementary results in this analysis.

In Fig. 3, the upper plot, a layer of minimum values is visible in the vertical gradient distribution of the potential density anomaly at BATS. This layer, which is located between the 18 and 18.5°C isotherms, would correspond to the NASTMW signal. An inter-annual variation was observed in the layer thickness. This variation was noted by Palter et al. (2005) as being a consequence of the annual formation rate. In the ESTOC time-series there are no minimum gradient values associated with a specific layer. The vertical gradients of the potential density anomaly showed a vertical sequential decrease (Fig. 3, lower plot). A three layer structure was visible between the 11 and 18°C isotherms. The deeper layer with gradient values from 0.075 to 0.1 kg m^{-3} 100 m can be seen between 400 and 600 dbar and ranges between the 11 and 13°C isotherms. All of these characteristics suggest that this layer corresponds to the NASPMW. There may be a coincidence between these characteristics and the definition of the Mediterranean Outflow Water (MOW); however, the depth of the layer (MOW is located deeper than 600 m in this region) and the salinity values (higher than 35.8, not shown) dismiss the possibility that they are the same (Llinás et al., 2002). The shallowest layer with 0.15 to 0.2 kg m^{-3} 100 m was located between 100 and 200 dbar and delimited by the 16 and 18°C isotherms. These characteristics come close to the MMW definition. Finally, the intermediate layer located between 250 and 400 dbar with gradient values from 0.1 to 0.15 kg m^{-3} 100 m is delimited by the 13 to 16°C isotherms. This layer includes the thermal characteristics of the mode water core we are studying here (13 to 14°C).

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3.3 The outcropping region

Once the mode water cores had been identified, we needed to determine their formation areas. The mode waters documented in the literature have already had their characteristics and outcropping regions defined. These regions are characterized by the conservation of their thermohaline properties during each winter (pycnostad). Once again the outcropping regions of the mode waters already identified could be used as a similarity criterion to identify the outcropping region of the third mode (13 to 14°C).

With this aim, two different and independent climatologies were used: the WOD2005 and the Ocean Pathfinder Program (OPP) data sets. The analysis consisted in locating the pycnostads of the mode waters already documented in the literature and then, according to similarities, determining the existence of the pycnostads associated with the region where the third mode is formed. In order to locate the pycnostads, we estimated the average density anomaly and the standard deviation (STD) with 2° latitude × 2° longitude resolution from the WOD2005 data. The density anomaly value in each profile corresponded to the average density anomaly in the depth range estimated for the mixed layer depth (MLD) of that profile. This mixed layer was calculated by using a 0.5°C threshold method from 10 m. Thus, we obtained information about the geographical distribution of the average density anomalies in the MLD during winter (January to March; not shown) and the pycnostad locations (STD minima) from the standard deviations, which represented their temporal stability (Fig. 4). This period was selected because late winter has been suggested to when subduction into the pycnocline occurs (Stommel, 1979). The deep winter mixed layer and the annual subduction rates are controlled by the regional variation in the seasonal cycle of the mixed layer (Marshall et al., 1993). Figure 4 shows several pycnostads (STD minima in dark blue) located on both sides of the gyre and north of the line βsub=0 (Marshall et al., 1993, their Fig. 14). This line is supposedly the boundary from which the mode waters are subducted. The modes would be formed north of the line, and south of it they would be isolated from the atmosphere. This line, which is accurate to nearly 500 km, varies from year to year. The minima on the western side are located in the Sargasso Sea, which would correspond to the NASTMW outcropping region (Worthington, 1959). On the eastern side, three groups of minima are located north of the βsub=0 line, sorting in a north/south direction and arranged between 15° and 30° W longitude. From these minima, those located more to the north (near 50° N) would correspond to the outcropping region of the NASPMW (McCartney and Talley, 1982). Another two groups of minima are visible at 40° and 30° N latitude respectively. Those located more to the south would coincide with the formation region documented for MMW (Siedler et al., 1987), while the other minima would correspond to the latitude where homogeneous layers with a temperature of 14°C were observed in previous studies mentioned above (Harvey and Arhan, 1988; Paillet and Arhan, 1996).

Once the pycnostad regions had been located, we checked if the winter averages of the annual surface temperatures corresponded with the documented temperatures for the mode waters identified in the North Atlantic subtropical gyre. In order to do this, we used another independent climatology based on the sea surface temperature (SST) data from the Ocean Pathfinder Program (OPP). The survey period covered the wintertime (December to March) from 1994 to 2003. The data resolution was 1° latitude × 1° longitude and we obtained the annual mean temperatures, as well as the maxima, minima, the standard deviations and the occurrence dates. The aim of this statistical analysis was to determine the thermal variability linked to the pycnostads and the time of the year when the temperature minima occur, as it is at this temperature which the mode waters are probably subducted. The results showed low variability in the geographical distribution of the isotherms in relation to temperature minima or the time when they occurred (not shown). To conclude the study, we checked the correspondence between the SST annual isotherms from the OPP, using those documented as characteristic of the mode waters in the subtropical gyre, and the pycnostads found with the WOD2005 data set (Fig. 5). In this figure, the annual isotherms corresponding to 11, 13.7 and 18°C were plotted over the geographical distribution of the pycnostads obtained with the WOD2005 data set. The 11°C isotherms were mainly

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concentrated on the 50° N pycnostad, confirming the relationship with the NASPMW. The 18°C isotherms were concentrated both on the western and eastern sides and occupied the pycnostads related to the NASTMW in the west and the MMW in the east respectively. Finally, the 13.7°C isotherms, which are the temperature reference for the third mode found in the ESTOC time-series analysis, were concentrated at the pycnostad located near 40° N. This pycnostad, as mentioned above, would correspond to the homogeneous layers that we suggest here to the third mode water in this subtropical gyre.

4 Conclusions

The eastern NACW is composed of three modes in the subtropical gyre: NASPMW (σ_t=27.1 to 27.3), MMW (σ_t=26.4 to 26.6) and a mode with $\sigma_t \approx 27.0$ that we have called Azores Mode Water (AMW). This last mode, which is not well documented in the literature, has been identified based on similarities with the other already documented modes. The standard curve estimates of the NACW at the time-series stations BATS and ESTOC, using a least square polynomial fit, allowed us to observe the most stable temperature ranges in the curves. These temperatures mainly coincide with those used to identify the subtropical North Atlantic mode waters. In addition, the gradient analysis of the potential density anomaly showed a three layer structure in the temperature range from 10 to 18°C at the ESTOC site. The upper and lower layers correspond to NASPMW and MMW respectively, whereas the intermediate layer is centered near 14°C. Verification using two independent climatologies (WOD2005 and OPP) showed that a body of water with these characteristics has a pycnostad area located around 40° N, and the isotherm distribution related to the annual temperature minima overlays the picnostad. Like MMW, this mode will tend to disappear quickly at the end of summer due to an increase in vertical mixing caused by the trade wind re-forcing. This mode probably splits into two branches during its advection: one northward branch that contributes to the Portuguese Coastal Countercurrent, and an equatorward branch that follows the regional general circulation. At ESTOC it is observed with a potential temperature of 13.7°C, salinity of 35.88 and at a depth of around 350 m.

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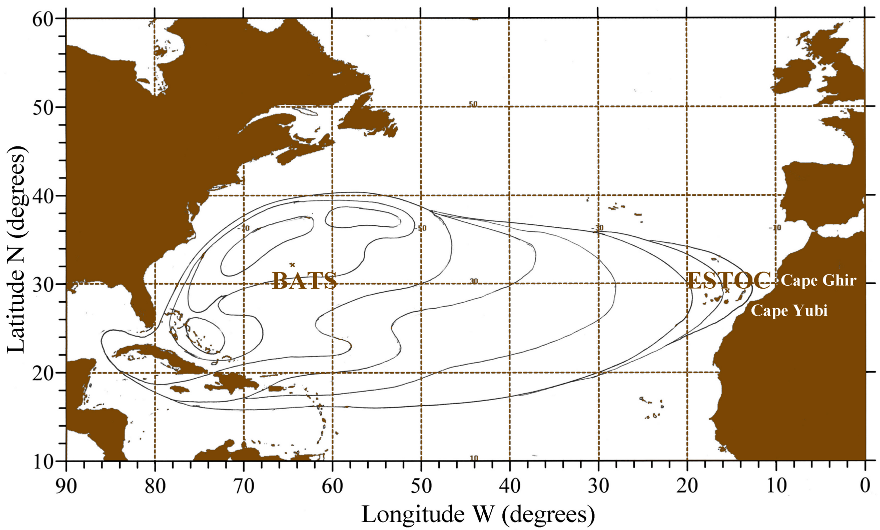

Fig. 1. BATS and ESTOC sites are located on the map. The solid lines characterize the subtropical gyre adapted from Schmitz and McCartney (1993).

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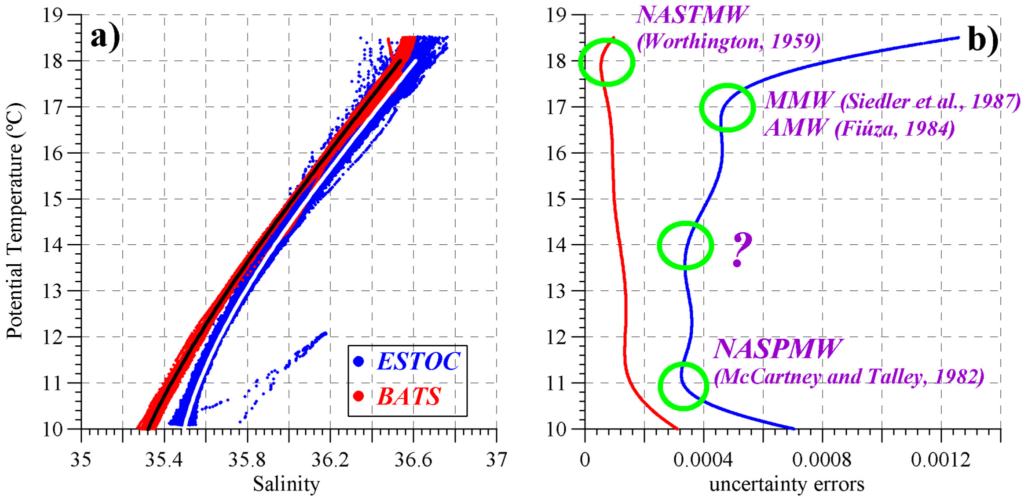

Fig. 2. (a) Temperature-salinity diagrams from time-series data at BATS and ESTOC TS. The respective standard curves are over-plotted as a white solid line for ESTOC and black for BATS. **(b)** Diagram of the resulting errors from the polynomial fit versus potential temperature of the two standard curve estimates.

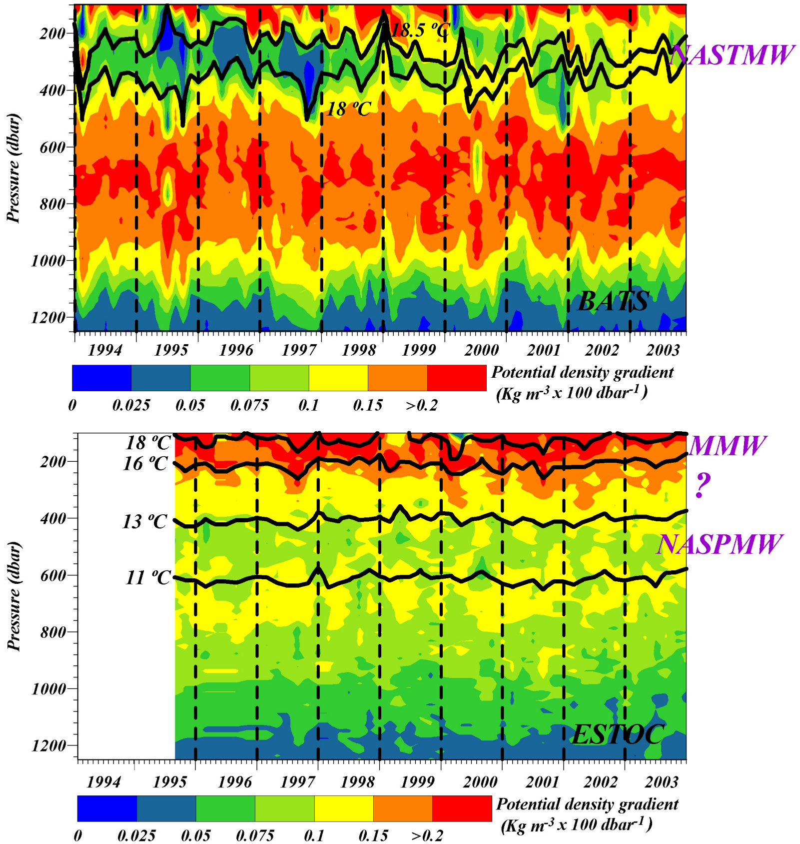

Fig. 3. Above: Gradient distribution of the potential density anomaly at BATS from 1994 to 2003. The 18 and 18.5°C isotherms were over-plotted to mark the NASTMW layer. Below: Similarly to ESTOC data. The 18 and 16°C isotherms mark the MMW layer, while 11 and 13°C delimit the NASPMW layer (11 and 13°C) and 13 and 16°C isotherms are over-plotted to show the likely third mode water on the North Atlantic eastern side.

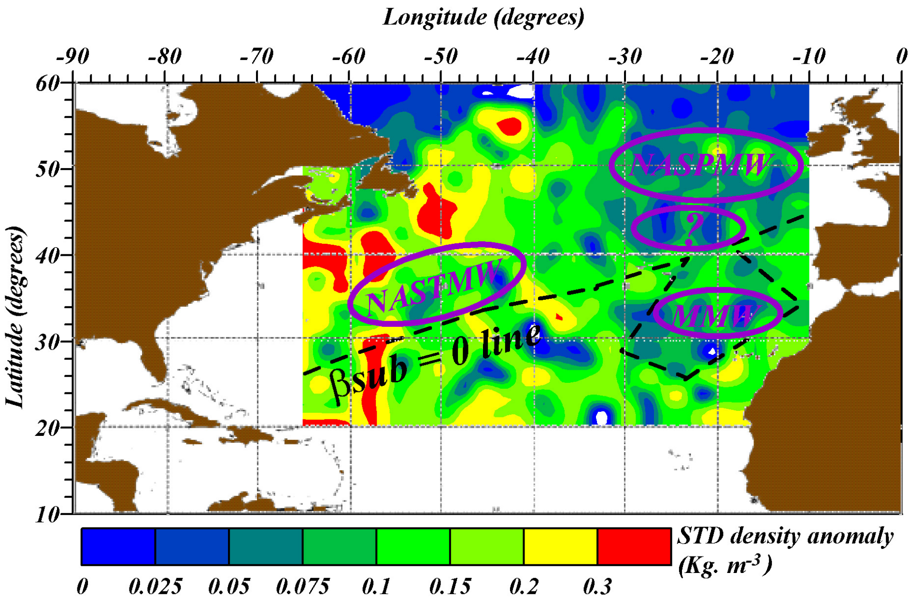

Fig. 4. Mode water pycnostads of the subtropical North Atlantic estimated from the WOD2005 data set. NASPMW (McCartney and Talley, 1982), NASTMW (Worthington, 1959) and MMW (Siedler et al., 1987) and the βsub=0 line (see text) adapted from Paillet and Arhan (1996).

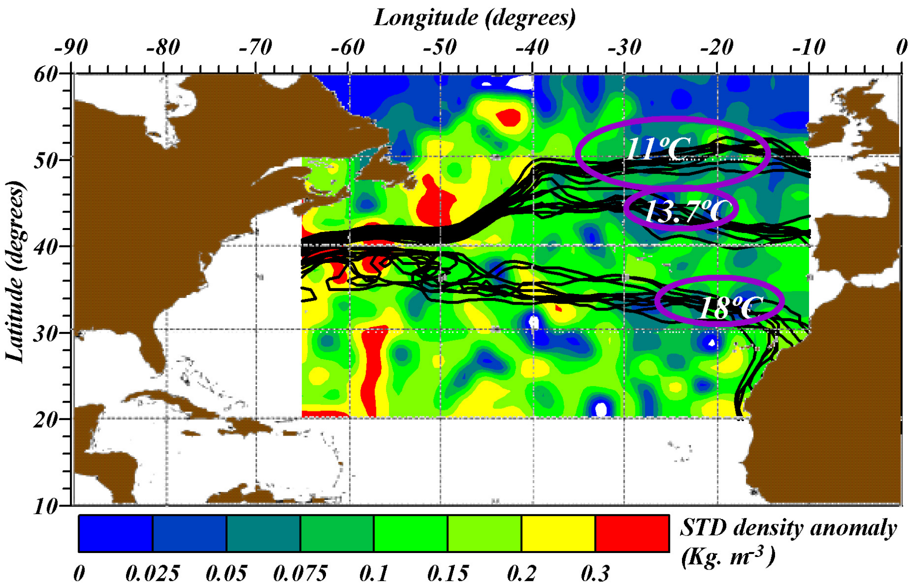

Fig. 5. The 11, 13.7 and 18°C annual isotherms (1994 to 2003) from the OPP data set which overlie the mode water pycnostads estimated from the WOD2005 data.