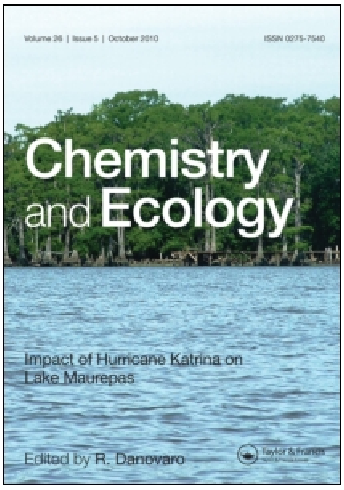

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Distribution of nutrients and AOU in the Mediterranean Water (North Atlantic Ocean)

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Water samples were collected in the Northeast Atlantic Ocean (33–37° N and 11–16° W) in May 1983, and vertical profiles of chemical and physical parameters allowed us to identify the different water masses. A significant difference in salinity and its maximum can be found at different places and depths, as a consequence of the spreading of the Mediterranean Water (MW) from the Strait of Gibraltar. The apparent oxygen utilization shows a correlation with nutrients in North Atlantic Central Water. The relative percentages of water masses were assessed in order to examine the depth of maximum influence of MW as a function of latitude and to apply this knowledge to the black scabbard fish long-line strategy. The long-line fishing depth location was adapted to the specific MW distribution of the different banks with improvements in the mean catch efficiency. The thickness of the MW prevalence layer has a pronounced decrease to the south. MW influence clearly sinks and decrease to south-west. The highest percentage of the MW was found in the Gorringe Bank area and the lowest in the Madeira area.

Keywords: Apparent oxygen utilization (AOU); Water masses; Nutrients; Northeast Atlantic Ocean

1. Introduction

Gorringe, Lion, Ampère, Seine banks, and Archipelago of Madeira are important deep fishing grounds in the Portuguese Economic Exclusive Zone (EEZ).

Within the framework of the 'Madeira fishing and oceanography support programme', ten cruises took place during 7 years (1980–1987). As the cruise of May 1983 surveyed all the selected areas, a detailed analysis of these oceanographic data was undertaken.

The main objective of the cruises was to gather oceanographic data for comparison with data obtained from fishing experiences. The long-line fishing method was used, and the main species studied was *Aphanopus carbo* Lowe, 1839 (black scabbard fish) [1–4], which inhabits the slopes of the banks, in one layer localized at 600–1200 m. Thus, the sampling was more concentrated within these depth limits.

Mediterranean Water (MW) in the North Atlantic is generally accepted as being the result of mixing between North Atlantic Central Water (NACW) and the Gibraltar outflow. The depth

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and the thickness of the MW layer and their characteristics are very important in determining the location of fishing gear.

Some studies of the dynamic topography and salinity fields at mid-depths (900–3000 m) showed that the vertical salinity profile exhibits a pronounced maximum layer between 800 and 1500 m [5], and that the direct injection of MW stops at about 1600 m [6].

The oceanographic data collected provided further knowledge of the vertical distribution of MW in one area where only a few studies had been conducted previously.

Correlations between apparent oxygen utilization (AOU) and nutrients within each water mass suggest the occurrence of different processes of oxygen consumption. The distribution trends from north to south were studied.

The aim of this paper is to produce an overview of this area of the Northeast Atlantic, to describe the vertical distribution of percentage of MW, AOU and nutrients at five locations, and to determine correlations among these parameters.

2. Material and methods

The zone of the North Atlantic around these banks can be characterized as oligotrophic with a euphotic zone down to 50–60 m and a deep chlorophyll *a* maximum, normally close to the top of the nitracline [7].

The Portuguese ship RV *Noruega* was used to collect data from oceanographic stations (figure 1) in the fishing grounds: Gorringe (one station), Ampère (two stations), Lion (three stations), Seine (three stations) and North-east Madeira (one station).

At each station, 28 sea-water samples were collected for salinity, dissolved oxygen, and nutrients. The samples were taken at standard depths, from the surface to 1800 m, using Nansen bottles equipped with reverse thermometers (protected and unprotected); between 400 and 1300 m, the vertical sampling had a resolution of 50 m. Temperatures were obtained after readings of main and auxiliary thermometer considering their calibration certificates.

For the nutrient determinations, water samples were drawn off in 25-ml polyethylene vials with screw caps. The vials were washed with acid, rinsed with the sample, and immediately

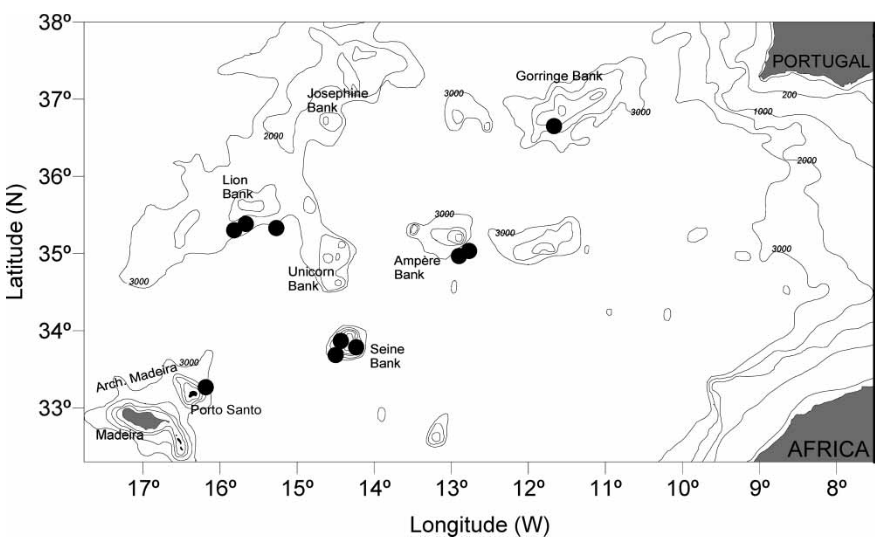

Figure 1. Location of sampling stations.

deep-frozen. No filtration of water was performed. The analyses were carried out using a three-channel Technicon AAII autoanalyser, according to the methods of Technicon Industrial Systems [8–10]. Samples were always analysed from surface to bottom to minimize the risk of contamination. The accuracy for five repeated readings is $\pm 0.08\ \mu mol\ kg^{-1}$ for nitrates, $\pm 0.07\ \mu mol\ kg^{-1}$ for silicates, and $\pm 0.02\ \mu mol\ kg^{-1}$ for phosphates. 'Sagami' standards were used to check the precision of the calibrations.

Dissolved oxygen was measured by titration (Methröm-Herisau) using the Winkler method, following modifications by [11]. The accuracy for five repeated readings is $\pm 1.2\ \mu mol\ kg^{-1}$. Salinity was determined from conductivity measurements [12] undertaken with a Beckman RS9 salinometer. The accuracy for five repeated readings is ± 0.005.

The percentage of different water masses in the North East Atlantic was computed by the method proposed by [13] for analysis of water masses with a T/S diagram, as applied by [14]. This method includes the techniques of the mixing triangle with no assumption of isopycnal mixing.

3. Results and discussion

The hydrographic data set for this region was obtained during 10 cruises, which took place between 1980 and 1987, and are available in the literature [1–4]. Graphs in this paper relate only to data from the cruise conducted from 11 to 27 May 1983 comprising 10 oceanographic stations from the fishing grounds; Gorringe (one station), Ampère (two stations average), Lion (three stations average), Seine (three stations average) and North-east Madeira (one station), (figure 1).

Inspection of the hydrographic data set led to the conclusion that there are no significant temporal variations in the studied parameters below the seasonal thermocline [1–4], so the results obtained using the data collected during the cruise conducted in Spring 1983, to survey the five above mentioned banks, are representative.

The global analysis of the T/S diagram (figure 2) allows identification of the main hydrographic structures and water masses; the NACW and the NADW (North Atlantic Deep

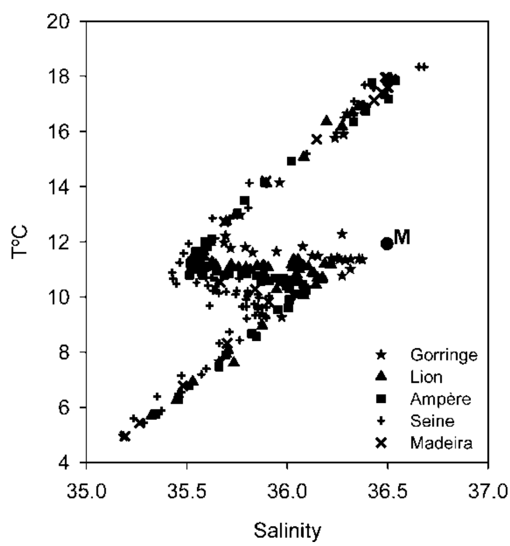

Figure 2. Global T/S diagram.

Water) are represented by straight lines, and the point 'M', as referred by [5], defines the core of undiluted MW which corresponds to a salinity of 36.5 and a temperature of 11.9 °C.

The vertical distribution of salinity (figure 3) shows a strong negative gradient at the NACW, from a subsurface salinity maximum at 50–75 m to a salinity minimum at 450–600 m.

This superficial salinity maximum, very pronounced at Ampère and Madeira, represents the upper limit of the NACW (table 1), where the nutrients begin to increase, as a result of the remineralization of organic matter (figure 4).

The layer from 450–600 m to 1300–1400 m is characterized by the presence of a salinity maximum (36.37–35.89) localized at 1100–1200 m, highlighting the presence of the MW, and a minimum value of dissolved oxygen (DO), approximately 196–189 μmol kg^{-1}. These

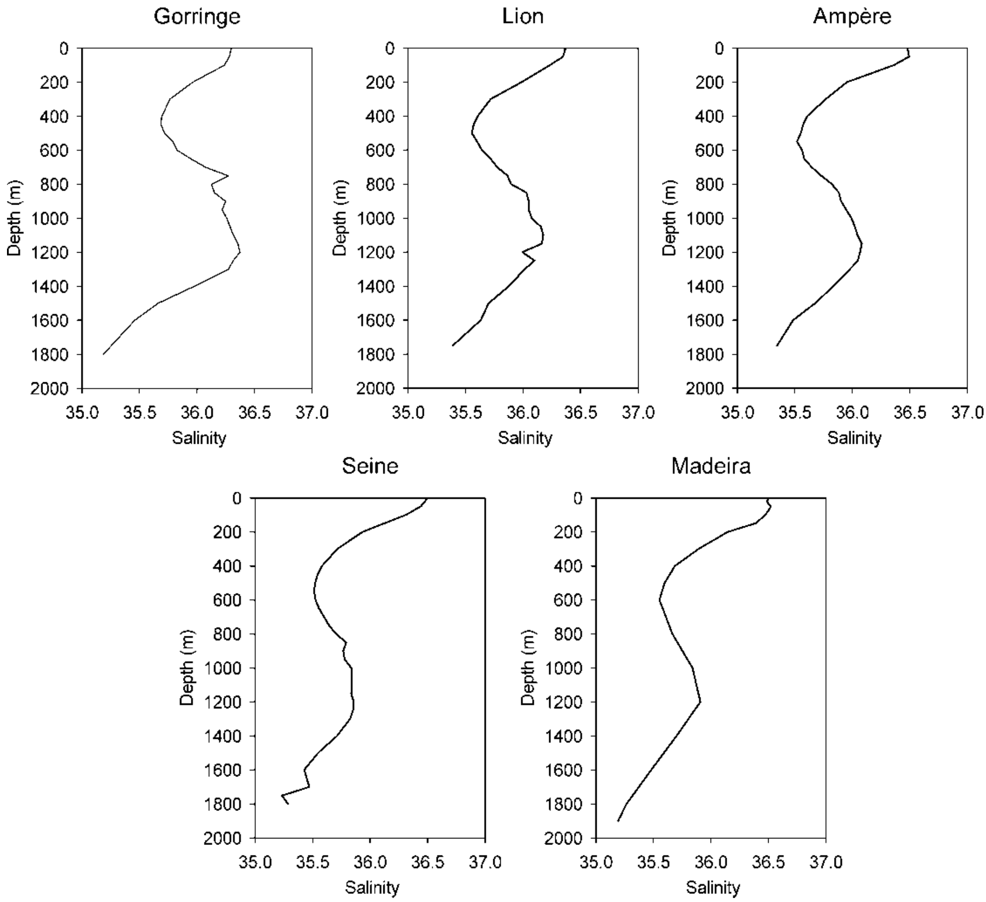

Figure 3. Vertical distribution of salinity.

Table 1. Limit values of NACW salinity.

	Upper	Lower
Gorringe	36.24 (100 m)	35.69 (450 m)
Lion	36.35 (50 m)	35.56 (500 m)
Ampère	36.49 (50 m)	35.52 (550 m)
Seine	36.44 (50 m)	35.51 (550 m)
Madeira	36.52 (50 m)	35.55 (600 m)

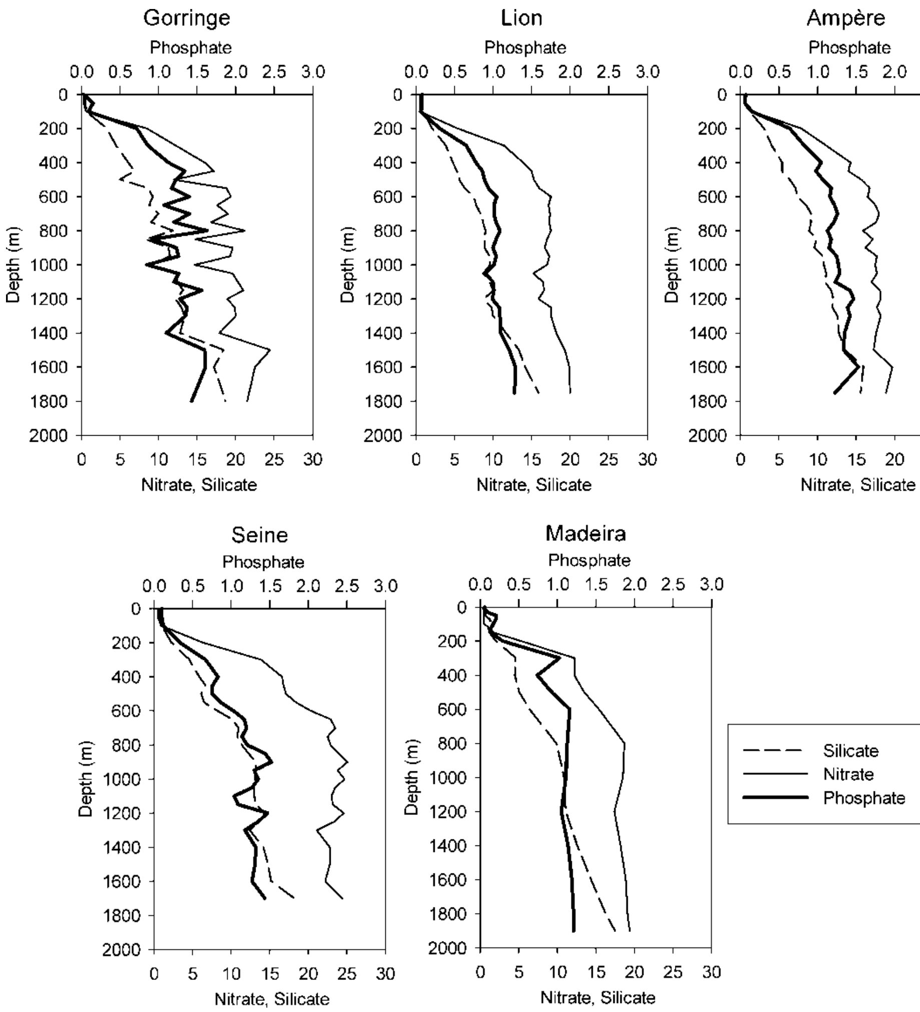

Figure 4. Vertical distribution of nutrients (μmol kg^{-1}).

values are in accordance with those presented by [15]. The influence of latitude on the depth at which the minimum value of DO occurs is remarkable (table 2).

The great spatial variability of salinity, with almost constant temperature, is a characteristic of MW. This stretch of high salinity water extends deep into the ocean, although its strength decreases below 1200 m [16]. The MW layer in the North Atlantic is generally accepted as being the result of mixing between NACW and the Gibraltar outflow [5].

Table 2. Values of DO minimum and respective depth.

	DO (μmol kg^{-1})	Depth (m)
Gorringe	196	1000
Lion	196	750
Seine	192	925
Ampère	192	950
Madeira	189	800

The maximum salinity values recorded were 36.37 at Gorringe and 35.91 at Madeira with temperatures close to 11.4 °C and 9.8 °C, respectively (figure 2); there is a clear decrease in salinity with latitude. Nutrients attain their maximum in this layer. The influence of the NADW is most pronounced below 1200 m.

Nutrients were almost depleted in the upper layer, and their concentration increases rapidly with depth through the NACW, as the result of the remineralization of organic matter. Maximum values recorded were 15.3–18.4 μmol kg^{-1} for nitrates, 0.86–1.34 μmol kg^{-1} for phosphates and 5.7–7.2 μmol kg^{-1} for silicates.

In the MW layer, nutrient concentrations attain higher values of 17.5–25.1 μmol kg^{-1} for nitrates, 1. 05–1.52 μmol kg^{-1} for phosphates and 9. 1–13.2 μmol kg^{-1} for silicates (figure 4).

Apparent oxygen utilization (AOU) indicates biologically induced consumption that has taken place after water has ceased to be in direct exchange with the atmosphere. It is defined as the difference between saturated oxygen concentration at the water's potential temperature and salinity, and the observed oxygen concentration. The negative surface values down to depths of approximately 100 m indicate that productivity related changes in oxygen concentration are more pronounced in these layers [17], which make the measured oxygen values higher than the theoretical saturated values.

Data analysis shows an AOU maximum value of 84–98 μmol kg^{-1} in the layer of MW (figure 5), and a gradual decrease with depth down to 1800 m. The value of 90 μmol kg^{-1} has been indicated by [18] in this core of the North East Atlantic.

Relationships between nutrients and AOU within each water mass were investigated, and a significant correlation between AOU and nutrients was found only within the NACW (table 3), similar to that reported [18] for nitrates and silicates.

A linear relationship between fluorescent intensity and AOU and correlations with the nutrients in the Central Pacific middle layer were also indicated by [19]. This means that the oxidative remineralization of organic particulate matter produces inorganic nutrients in the water column, so that the vertical distribution of AOU is similar to that of nitrates, phosphates, and silicates. In the MW layer, values of nutrients and AOU were high and almost constant.

In order to study the possible relationship between long-line fishing depth yields and MW distribution, water masses in the MW layer were quantified applying the following linear equations obtained by [14].

$$\%\text{MW} = 117.34 \times S - 9.14 \times T - 4074.2$$
$$\%\text{CW} = -118.71 \times S + 20.88 \times T + 4084.4$$
$$\%\text{DW} = 1.36 \times S - 11.73 \times T + 89.8.$$

where MW is the Mediterranean Water, CW is the North Atlantic Central Water, and DW is the North Atlantic Deep Water. T and S are the values of temperature and salinity.

The application of these algorithms enables the profile of the percentage of MW at the different sampling sites to be described (figure 6).

The most significant influence of the MW can be observed below 500–700 m, and its maximum percentage values were localized at depths of about 1200 m.

The highest percentage of MW was found in the Gorringe area (90%), and the lowest in the Madeira area (about 50%). The thickness of the MW prevalence layer has a pronounced decrease to the south, as also indicated by [14]. The MW influence clearly deepens and decreases to the south-west, as also highlighted by [20]; the highest percentages of MW are

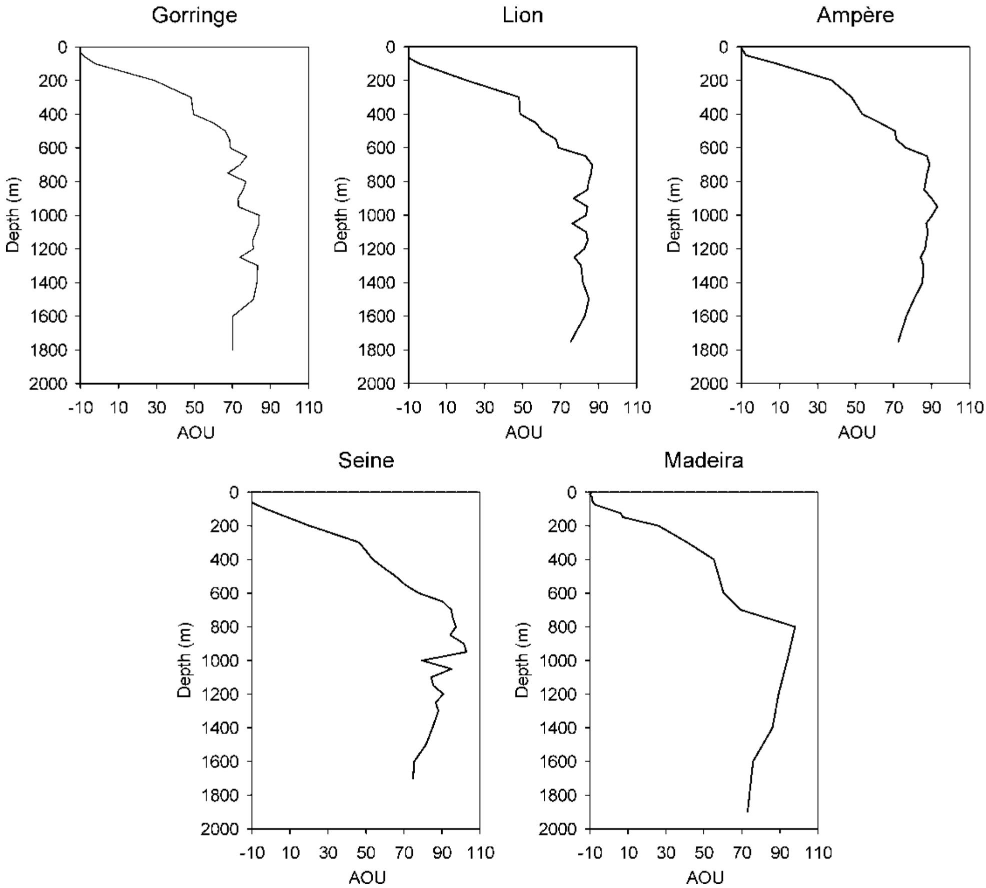

Figure 5. Vertical distribution of apparent oxygen utilization (µmol kg^{-1}).

found close to the slope of the south-west Iberian Peninsula, and its influence diminishes to the West and South.

These results have contributed to the improvement of the black scabbard fishing strategy. Higher fishing yields have been observed near the depth of the highest prevalence of MW (1100–1300 m) and experiments with horizontal long lines set in the maximum MW layer have obtained higher fishing yields than the respective vertical long lines located between 800 and 1300 m. As a result, the long-line depth location has been adapted to the specific oceanographic conditions of the different banks, and a greater mean catch efficiency has been achieved.

Table 3. AOU vs. nutrients linear regression.

	AOU/N	r^2	n	AOU/P	r^2	n	AOU/Si	r^2	n
Gorringe	4.1	0.919	11	65.55	0.758	11	8.3	0.828	11
Lion	5.9	0.857	10	69.06	0.966	7	9.6	0.959	11
Ampère	5.0	0.946	11	74.99	0.931	10	9.3	0.957	14
Seine	5.0	0.968	11	89.35	0.963	11	7.6	0.934	14
Madeira	5.0	0.949	8	85.21	0.957	6	11.0	0.961	8

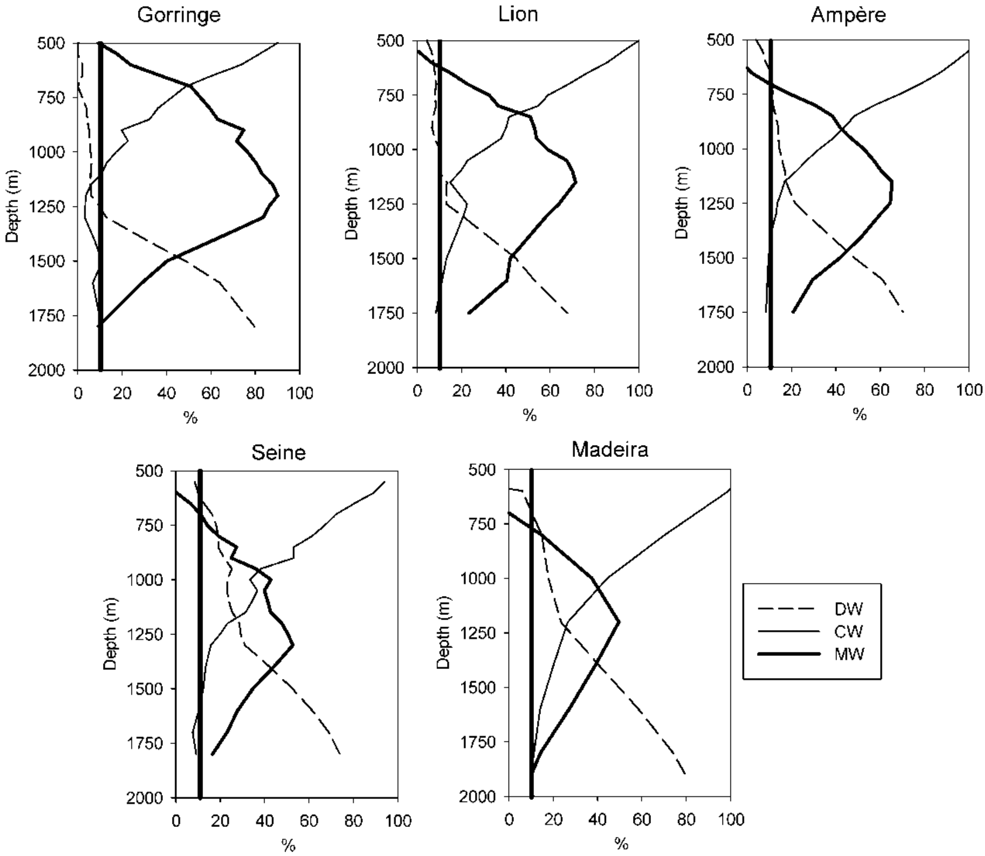

Figure 6. Vertical distribution of the percentages for different water masses.

4. Conclusions

- MW spreads significantly as far as Madeira, and its major observed influence in this region is at Gorringe Bank (table 4);
- surface salinity increases to the south;
- the lower depth limit of the NACW deepens to the south;
- the minimum value of DO decreases, and is found at shallower depths, the lower the latitude;
- AOU maximum values increase to the south.

Table 4. Depth range and values of maximum influence of MW.

	Depth (m) 10% MW	Depth (m) % Max MW	%Max MW
Gorringe	504	1200	90.0
Lion	625	1150	71.4
Ampère	702	1150	65.3
Seine	687	1300	52.8
Madeira	754	1200	49.6

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