WATER MASSES IN UPPER AND MIDDLE NORTH ATLANTIC OCEAN EAST OF AZORES

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SUMMARY

During the "ANA" cruise in November 1988, Western North Atlantic Water (WNAW) was found linked to the Azores Current (AC) at 23° W, where according to various authors Eastern North Atlantic Water (ENAW) forms a boundary with WNAW east of the Mid-Atlantic Ridge (MAR). This boundary changes position during the year. The vein of Mediterranean Water (MW) moving towards the MAR seems to be connected with the AC, and restricts the penetration of ENAW of subpolar origin (ENAWP).A subsurface front has been found along 42° N, separating ENAW of subtropical origin (ENAWT) that moves northeastwards generating a cyclonic eddy that is confined between the lower limit of surface layer and approximately isopycnal 27.06, and modified ENAWP that moves southwards forming various anticyclonic eddies.

INTRODUCTION

The central water masses in the Northeast Atlantic are characterized by weak circulation and little marked structure in contrast with the northwestern Atlantic where Western North Atlantic Central Water (WNAW, Iselin 1936) dominates and characterizes the main thermocline. The North Atlantic Current (NAC) crosses the Mid-Atlantic Ridge (MAR) at 48° N, and the Azores Current (AC) crosses the ridge between 32° and 36° N (Harvey and Arhan, 1988, Stramma and Müller, 1989). Klein and Siedler (1989) found and described a strong seasonal variability in the flow of AC. As these currents spread eastwards, characteristic changes are produced in the thermocline by winter ventilation and by mixing with surface waters (Pollard and Pu, 1985).

The first studies in this area were mainly concerned with Mediterranean Water (MW) (Lacombe and Tchernia, 1960; Parrilla and Moron,1971; Madelain,1972). This water is characterized by a strong salinity maximum that extends northwards close to the continental slope of the Iberian Peninsula, and also westwards. Recently, the MW distribution has been found to be connected with meddies formation whose presence north of 36° N off Portugal have been demonstrated by Käse et al. (1989). With regard to the NACW, the most commonly described characteristic of this region (Maillard, 1986; Saunders, 1982) is a weak easterly current without clear continuity. The thermocline of NACW is defined in different ways and with different nomenclatures. The introduction of subpolar mode water formed in the northeastern cyclonic gyre (McCartney and Talley, 1982) produces Eastern North Atlantic Central Water (ENAW) defined by Harvey (1982) for the large volumes of Central Water formed north of 46°N, with temperatures and salinities between (4°C, 34.96 and 12°C, 35.66). We call this water ENAWP (for subpolar). The introduction of these mode waters is an improvement in the T/S relationships given for NACW by Sverdrup et al (1942), since it differenciates between two different water bodies of NACW in this area. As these mode waters advance or diffuse to the south-southeast they form a front with the MW that restricts its presence in the southeast North Atlantic (Pollard and Pu, 1985, Fig. 3; Coste et al. 1986)

In contrast, the coast of the Iberian Peninsula is characterized by upwelling between April and September (Wooster et al, 1976). Fiuza (1984) found that this upwelled water originates in a front in the Azores area (about 36°N and 22°W) the preceding winter. Fiuza (1984) defined ENAW from a T-S segment delimited by 10.00°C, 35.40 and 12.20°C, 35.66 (Le Group Tourbillon, 1983) and another T-S segment between 13.15°C, 35.80 and 18.50°C, 36.75 (Fiuza and Halpern, 1982). These two segments are linked to a curve that coincides, between 12.50°C, 35.70 and 12.825°C, 35.75, with NACW defined by Helland-Hansen and Nansen (1926). Emery and Meincke (1986) call this water ENACW, but they define it with a greater range (8-23°C and 35.2-36.7). Nevertheless it does not correspond with the observational data (Fig.1). The segment of Tourbillon Group included in the ENAW definition of Fiuza (1984) coincides in part with those defined by Harvey (1982). We call H (12.2° C, 35.66) the limit between ENAWP and ENAWT (for subtropical origin). So, this point corresponds to the upper limit of ENAWP.

In the area of Finisterre, Fraga et al. (1982) found a quasi-permanent upwelling in summer due to the presence of a subsurface front between central water of distinct origins. The water to the south of the front is similar to that defined by Fiuza (1984) as ENAW, while that to the north is ENAW modified by surface mixing, and whose origin is at 47°N (Fraga et al. 1982). Collins et al (1983) also found fronts in the same area (44°N, 14°W). Fiuza (1984) regarded this front as the northern limit of ENAWT.

The aim of the present work is to determine the origin and thermohaline characteristics of the waters with temperatures greater than 5°C that flow along or to the western coast of the Iberian Peninsula. Special reference is made to the distribution and displacement of different bodies of central water present in close areas, which generate distinct frontal and upwelling processes near Cape Finisterre.

MATERIAL

During the "ANA" cruise of the "Biomass-IV" expedition on R/V "Profesor Siedlecki" in November 1988, 20 stations were occupied between 42° 53'N - 9° 28.5'W and 23° 29'N - 23° 40.1'W. Nine stations lay on a transect perpendicular to the NW coast of Galicia (Spain); the other eleven stations lay on a meridional transect perpendicular to the first. (The positions of stations are shown in Figure 12, later.)

At each station, salinity, temperature and pressure were measured with a "Neil Brown" CTD model S-N01/1132. Samples for salinity determination were collected at 0, 50, 100, 150, 200, 250, 300, 400, 500, 600, 700, 800, 1000 and 1100 m depth with Nansen bottles, of which four (at 150, 300, 700 and 1100 m) had three thermometers, two protected and one unprotected, to check the CTD calibration. The salinities were measured with an induction salinometer (Plessey Environmental Systems Model 6230N).

WATER MASS DEFINITIONS

Figure 1 shows a T-S diagram with the data from all the stations. The water column between 150 and 600 db that corresponds approximately with 26.5 and 27.2 isopycnals is dominated by central water, but the thermohaline characteristics are those of either ENAW or WNAW according to the depth and/or geographical position. The central water with S<35.66 lies closer to ENAW as defined by Harvey (1982), and shows that waters of subpolar origin best characterize the deeper levels of central water in the whole area. Furthermore, this water mass mixes with MW in different ratios.

In the transect along the 42°N zonal section, the surface water has higher temperatures due to heating. The salinity on the surface is determined by the salinity of the winter mixing layer. On the other hand in the meridional transect there is a clear north-south thermal gradient, and high salinity surface water of tropical origin is present in the form of a wedge (Worthington, 1976).

All T-S diagrams on the zonal section (42°N) indicate a segment of central water corresponding to ENAW as defined by Fiuza (1984), except at stations 8 and 9 (Figs. 2 and 3) where the salinity maximum at 100 db has a temperature higher than that corresponding to ENAW. The maximum salinity values of ENAW are found in coastal stations 1 and 2, and in stations 5 and 8. In stations 3, 4 and 7 there are marked changes where the maximum salinity values decrease to similar values to H, which corresponds with the upper saline limit of ENAWP.

The T-S diagrams of the meridional stations (Figs. 3, 4 and 5) show a clear increase of maximum salinity in the segment corresponding to the central water according to how the stations are situated towards the south. This increase is due to a greater contribution of the more saline component of WNAW, although ENAWP is present at all stations at Gamma-q>26.9 (Gamma-q =density-10-3 at q° of potential temperature. UNESCO, 1985). Exactly at station 14 the T/S relationship (Gamma-q<26.9) is coincident with WNAW, whereas south of 32°N (station 15) we note: i) the increase in the less saline component of central water due to the presence of intermediate water of subpolar origin (Emery and Meincke (1986) have shown that the northern limit of the distribution of AAIW is about 20°N), ii) the saline edge of subtropical origin in the surface layer and, iii) the presence of saline subsurface water (S>36.4). Fraga (1973) also found a saline wedge at 23°N, 23°W, that he calls A with salinity 36.84 and 18.5°C and the origin of which he locates further to the north. A water with similar characteristics has been described by Siedler et al (1987) as Madeira Mode Water spreading to the southwest. The MMW probably makes up the component of maximum salinity of ENAWT which differentiates it from WNAW and which is similar to the ENAWT found by Käse and Rathlev (1982).

The tongue of MW is characterized by a salinity maximum at depths between 1000 and 1300 db. The maximum value observed corresponds to a salinity of 36.220 at 10.91°C at a level of 1276 db at station 2 (Fig. 2). The highest percentages of MW are close to the slope of the Iberian Peninsula (Fig. 2), due to the Coriolis efect as the MW moves northwards (Madelain, 1967). The influence of MW diminishes to the west and the presence of ENAW increases. Nevertheless, higher salinity values have been observed at station 12 (Fig. 3), at 36°N, 22°W.

SUBSURFACE FRONT IN THE AZORES ZONE

The distribution of isopycnals (Fig. 6) shows a surface layer of seasonal warming,that reaches a depth of 150 to 170 db. This layer varies latitudinally with greater vertical gradients to the south. Although the isopycnals gradually reach the surface, a divergent zone associated to the AC is observed between stations 12 and 15 (see below). The thermohaline characteristics of surface water in stations 13 and 14 are similar. However, those of subsurface water are clearly different. The surface water of station 13 is substituted for surface water of station 14, and therefore a displacement of surface water to the north is situated in the divergent zone.

The outstanding dynamic characteristic is the marked elevation of the subsurface isopycnals from stations 13 to 14 which affects the entire water column. This elevation at 33°N is associated with the Azores Current (AC), which produces (by the Coriolis effect) an accumulation of water on its southern edge (station 14) and elevated isopycnals at its northern edge (station 13) as it moves eastwards through the MAR and subsequently towards the southeast. The core of AC is centered at about 200 m, in the same position that the maximum divergence between 26.6 and 26.7 isopycnals has been found (Fig. 6). This fact is shown in Fig. 7 where the calculated geostrophic velocity is represented, taking as reference layer 1400 db given by Sy (1988) for the Azores region. The accumulation of water on the southern border of the AC (33°N) produces a slight sinking of the isopycnals with values greater than 26.7, and a slight elevation of the isopycnals with values of less than 26.5, which in the most superficial layer causes the lateral displacement described above.

The salinity distribution of central water mainly coincides with the isopycnals represented by horizontal lines in Fig. 8. However between stations 13 and 14 there is an important elevation of the isohalines towards the surface layer, which clearly shows an important horizontal frontal process of mixing between WNAW and subsurface water. The TS diagrams in Figure 4 also show a marked change in the 26.6 and 26.7 isopycnals between stations 13 and 14 in contrast to the close proximity of the salinity maximum at stations 10-13 in the 26.7 isopycnal (Figs. 3 and 4), and which also can be by the horizontal homogeneity of WNAW included between 36 and 36.1 isohalines (Fig 8b).

To the north of station 10 (Fig. 3), between 26.7 and 26.8 isopycnal, an important subsurface gradient in the salinity maximum exists, which corresponds with WNAW. This feature also can be observed in Figure 8. This frontal process is similar to that described in the same area by Käse and Siedler (1982) and Fiuza (1984, in his Figure 1.9).

To the north of station 13, between 200 and 600 db (Fig. 6) the greater separation of the 26.9 and 27.2 isopycnals shows an increase of vertical homogeneity of central water which is predominantly ENAWP (S<35.66). Located between these same levels, just to the north of AC, is a westward current core (Fig. 7). Also in November, Stramma and Müller (1989) found a current system very similar to that shown in Fig. 7 in a vertical section projected onto 26°30'W. To the north and south of the MW tongue, opposite currents, separated by about 200 Km, suggest the possibility of an anticyclonic gyre, like a meddy. Käse et al (1989) found meddies with similar diameters at 36°N, 17°W.

We do not have meridional transects located farther west, but taking into account the Topogulf 1 and Topogulf 2 profiles (Harvey and Arhan,1988, their figs. 3 and 4) located on both sides of MAR, the MW tongue and the AC are related in such a way that the MW tongue lies slightly farther north than the AC. Furthermore, in the case where the AC has two branches, the two tongues of MW are situated farther north. Also, Sy (1988) shows the spreading of MW limited by the current system of AC and NAC.

SUBSURFACE FRONTS OF ENAW

In contrast to the meridional section, the zonal section shows a much weaker salinity gradient. At the surface the thermal gradient determines the isopycnal distribution, creating a pycnocline at about 50-75 db (Fig. 9), and several frontal features exist due to lateral displacements (station 2, Fig. 2).

In the zonal section, two groups of T-S diagrams that repeat the same dynamic processes, have been separated (Fig. 2). Thus, the thermohaline characteristics of stations 5, 1, 2 and 3 are similar to those of the stations 8, 5, 6 and 7. The stations 3 and 5 are repeated in order to facilitate the comparison. On the other hand, the isopycnal distribution (Fig. 9) also shows repeated dynamic processes. The stations 3, 4 and 7 have high values of Gamma-q, with salinity maxima close to 35.66 that correspond to the absence or weak influence of ENAWT. However, the presence of ENAWT is notable at stations 1, 2, 5 and 8 where there are various convergences. Taking into account the subtropical origin of this water and the form of the isopycnal gradients between 26.8 and 27.0, Figure 9 shows the currents that must correspond with two cyclonic gyres centered on 12°W and 19°W (see Fig. 10), coinciding with the current vectors given by Swallow et al (1977) in their Figure 1, for January-February. The T-S diagrams of station 6, 1 and 2, situated near the frontal zone, show the total or partial loss of the most saline parts of ENAWT by mixing with subsurface water in its evolution towards the north.

The maintenance of ENAWT in latitudes higher than that of its formation and the higher isopycnal elevation of the eastern part of the zonal section are probably due to the geostrophic adjustment of the eastward oceanic flow driven by the large-scale meridional baroclinic pressure gradient in the eastern North Atlantic as the flow reaches the continental slope of the western Iberian Peninsula (Frouin et al, 1990). The maximum salinity values of ENAWT during the year at points close to the continental slope (42°N, 9°W) (Table 1). The continuous increase since the preceding winter indicates the progressive course of central water of southern origin during the year. The maximum values of ENAWT at the end of the year are higher than those at 40°N, 10°W in February.

A strong current of ENAWT, at the most easterly edge, occurs close to the slope of the Iberian Peninsula (Fig 10). Using infrared satellite images, Frouin et al (1990) found a similar salty surface current flowing along the Iberian Peninsula to Biscay Bay during late November and early December 1983. Pérez et al. (1985) found ENAWT further to the north at 47°N, 10°W. Between 15° and 18°W (Fig. 10) a weak and wide ENAWT displacement towards the north also exists. On the other hand, in the PHYGAS cruises in the Bay of Biscay there is a general tendency for an anticyclonic gyre although cyclonic and anticyclonic gyres occur on a smaller scale (Fruchaud-Laparra et al 1976a; Fruchaud-Laparra et al 1976b). These authors showed that the presence of ENAWT is restricted to the southern part of the Bay of Biscay.

The isopycnal distribution of salinity (Fig. 11) indicates that the northerly penetrations of a ENAWT layer are confined between the lower limit of the surface layer and approximately the 27.06 isopycnal, whit its maximum thickness at station 8 between 100 and 270 db (Fig. 9). The existence of zero current between 250 and 400 m depth (Madelain, 1967) corresponds with the 27 and 27.1 isopycnals that define the vertical boundary between ENAWP and ENAWT proceeding from the north and south, respectively. Below this level there is clear evidence of a front between ENAWP and MW, with maximum values of ENAWP at station 9 (salinity minimum less than 35.4) and a maximum of MW at station 2 with 36.1 PSU.

Under the 27.2 isopycnal (Fig. 9) the shape of the isopycnals changes in response to the presence of the MW core. In this way, there is a slight sinking of the isopycnals close to 27.4 at stations 4, 6 and 9, giving rise to 3 minima coincident with the increased presence of ENAWP detected by lower salinities. The most important constriction of MW is situated at 15°W and associated with a strong horizontal salty gradient (Fig. 11); an important geostrophic current southwards is located exactly at this position (Fig. 10) in contrast to the core of maximum salinity which shows a northward current. It is interesting to note that in this frontal zone, the calculated geostrophic current keep the salty edge to its left, separating two tongues of MW. This important front at 15°W also was observed by Harvey (1982) at 16°W along 46°N. Thus, the frontal edge of the MW tongue together with ENAWP indicates a strong current in the opposite direction to the normal spread of MW.

Another constriction of the tongue of MW at 13°W can observed. Harvey (1982) in a section in 46°N also found this constriction at 12° W with a detached core of MW at 18°W. This pattern of MW distribution, on the same latitude, coincides with Madelain (1967) who showed the separation of two tongues as a consequence of the topographical influence of the Galicia Bank (42°45'N, 11°40'W). The MW distribution further to the west is limited by ENAWP.

CONCLUSION

Like Fiuza, we have found ENAW with salinity values greater than 35.66 to the east of 18°W near the Iberian coast. But during the "ANA" cruise (November 1988) WNAW was found linked to AC along the 23rd meridian, where, at the end of winter the presence of ENAW is indicated by various authors (Käse and Rathlev, 1982; Pollard and Pu, 1985). Thus the boundary between WNAW and ENAW east of the MAR varies during the year with its maximum penetration to the northeast in December.

The position of the tongue of MW that moves towards the MAR seems to be linked to the AC and limits the penetration of ENAWP. Near Finisterre, the spread of MW produces a strong salty gradient. The current established keeps the salty edge to its left.

According to Maillard (1986), after crossing the MAR, the AC and NAC produce an area of divergence west of Cape Finisterre where the circulation is very poorly defined. On the southern margin of NAC, ENAWP moves southwards generating the various anticyclonic eddies that have been described by various authors (47°N and 18°W in Harvey and Glynn,1985; and in the Biscay Bay by Fruchaud-Laparra et al., 1976). On the other hand, ENAWT is formed at the northern margin of the AC and moves partly northeastwards towards the Iberian coast, generating meanders or probably, as have been described above, various cyclonic eddies (see Fig. 12). There is an area of subsurface convergence between 43° and 44°N where ENAWP, modified by summer warming, can mix with ENAWT between 26.9 and 27.1 isopycnals. In this way, the presence of ENAWT is strongly reduced north of Finisterre. Furthermore this convergence is well marked at Finisterre (Fraga et al, 1982), where there is a permanent subsurface front responsible for the intense upwelling which takes place in spring and summer (Fraga, 1980; Mouriño et al, 1985; Fraga et al, 1987).

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References

Collins, D.S., R.T. Pollard & S. Pu (1983) Long SeaSoar CTD sections in the North East Atlantic Ocean collected during RRS Discovery cruise 116. Institute of Oceanographic Sciences, Report, 148, 77 pp.

Coste B., A.F.G. Fiuza & H.J. Minas (1986) Conditions hydrologiques et chimiques associées à l'upwelling côtier du portugal en fin d'été. Oceanologica Acta, 9, 149-158.

Emery, W.J. & J. Meincke (1986) Global water masses: summary and review. Oceanologica Acta, 9, 383-391.

Fiuza, A.F.G. & Halpern (1982) Hidrographic observations of the Canary Current between 21°N and 25.5°N in March/April 1974. Rapport et Procès-verbaux of Réunions. Conseil International de l'Exploration de la Mer, 180, 58-64.

Fiuza A.F.G. (1984) Hidrologia e dinamica das aguas costeiras de Portugal, These Doctoral Science, Univiversity. Lisbonne, Portugal 294 p.

Fraga, F. (1973) Oceanografía química de la región de afloramiento del noroeste de Africa I. Resultados Expediciones Científicas B/O Cornide, 2, 13-52.

Fraga, F. (1980) Upwelling off the Galician coast, Northwest Spain. en Coastal Upwelling. American Geophysical Union Washington, 176-182.

Fraga, F., C. Mouriño & M. Manriquez (1982) Las masas de agua en la costa de Galicia: junio-octubre. Resultados Expediciones Científicas, 10, 51-77.

Fraga, F., C. Mouriño, F.F. Pérez & A.F. Ríos (1984) Datos hidrográficos de la estación fija "OD". Datos Informativos Instituto Investigaciones Pesqueras, 10, 1-25.

Fraga, F., C. Mouriño, F.F. Pérez, A.F. Ríos & C. Marrasé (1985) Campaña "Galicia VII". Datos básicos. Datos Informativos Instituto Investigaciones Pesqueras, 12, 1-50.

Fraga, F., F.G. Figueiras, R. Prego, F.F. Pérez & A.F. Ríos (1987) Campaña "Galicia IX". Oceánica. Datos Informativos Instituto Investigaciones Marinas, 20, 1-148.

Frouin, R., A.F.G. Fiúza, I.Ambar & T.J. Boyd (1990) Observations of a poleward surface current off the coasts of Portugal and Spain during winter. Journal of Geophisical Research, 95, 679-691.

Fruchaud-Laparra, B., J. Le Floch, J.Y. Le Tareau & A. Tanguy (1976a) Etude hydrologique et variations saisonnières dans le proche Atlantique en 1973. Rapport Scientifique et Technique CNEXO, 26, 111 pp.

Fruchaud-Laparra, B., J. Le Floch, C. Le Roy, J.Y. Le Tareau & F. Madelain (1976b) Etude hydrologique et variations saisonnières dans le proche Atlantique en 1974. Rapport Scientifique et Technique CNEXO, 30, 108 pp.

Harvey, J. (1982) Θ-S relationship and water masses in the Eastern North Atlantic. Deep-Sea Research, 29, 1021-1033.

Harvey J & J. Glynn (1985) Water Mass Estructure and transport in the Tourbillon eddy. Deep-Sea Research, 32, 675-695.

Harvey J. & M. Arhan (1988) The water masses of the Central North Atlantic in 1983-84. Journal of Physical Oceanography, 18, 1855-1875.

Helland-Hansen, B. & F. Nansen (1926) The eastern North Atlantic. Geophysiske Publicajoner, 4, 1-76.

Iselin, C.O'D. (1936) A study of the circulation of the Western North Atlantic. Papers in Physical Oceanography and Meteorology, 4, 101 pp.

Käse, R.H. & J. Ratlev (1982) CTD-data from the North Canary Basin, Poseidon cruise 86/2, 26 March - 13 April, 1982. Berichte aus dem Institut für Meereskunde Kiel, 103, 130 pp.

Käse, R.H. & G. Siedler (1982) Meandering of the subtropical front south-east of Azores. Nature, 300, 245-246.

Käse, R.H., A. Beckmann & H.H. Hinrichsen (1989) Observational evidence of salt lens formation in the Iberian Basin. Journal of Geophysical Research, 94, 4905-4912.

Klein, B. & G. Siedler (1989) On the origin of the Azores Current. Journal of Geophysical Research, 94, 6159-6168.

Lacombe, H. & P. Tchernia (1960) Quelques traits généraux de l'hydrologie Méditerranéene. Cahiers Océanographiques, 12, 527-547.

LE GOUPE TOURBILLON (1983) The tourbillon experiment, a study of mesoscale eddy in the eastern North Atlantic. Deep-Sea Research, 30, 475-511.

Madelain, F. (1967). Calculs dynamiques au large de la Peninsule Ibérique. Cahiers Océanographiques, 19, 13 pp.

Madelain, F. (1972) Données sur la circulation d'eaux d'origine méditerranéenne au niveau du cap Finisterre. Rapport. Scientifique et Technique. CNEXO, 11, 18 pp.

Maillard, C. (1986) Atlas Hydroligique de L'Atlantique Nord-Est. Institut Français de Recherche pour L'Exploitation de la Mer. (IFREMER), 199 pp.

McCartney, M.S. (1982) The subtropical recirculation of Mode Waters. Journal of Marine Research, 40(Suppl.),427-464.

McCartney, M.S. & L.D.Talley (1982) The Subpolar Mode Water of the North Atlantic Ocean. Journal of Physical Oceanography, 12, 1169-1188.

Mouriño, C., F.F. Pérez, A.F. Ríos, M. Manríquez, M. Estrada, C. Marrasé, R. Prego & F. Fraga (1985) Campaña "Galicia VIII". Datos básicos. Datos Informativos Instituto Investigaciones Pesqueras, 13, 1-108.

Parrilla, G. & J.Mª G. Morón (1971) Contribución al estudio de la vena de agua mediterránea en la costa occidental de la Península Ibérica. Boletín del Instituto Español de Oceanografía, 145, 23 pp.

Pérez, F.F., A.F. Ríos, F.F. Fraga & C. Mouriño (1985) Campaña "Galicia VII". Datos básicos. Datos Informativos Instituto Investigaciones Pesqueras, 11, 1-38.

Pollard R.T. & S. Pu (1985) Structure and ventillation of the upper Atlantic Ocean norteast of the Azores", Progress in Oceanography, 14, 443-462.

Saunders, P.M. (1982) Circulation in the eastern North Atlantic. Journal of Marine Research, 40 (suppl)., 641-657.

Siedler, G., A. Kuhl & W. Zenk (1987) The Madeira Mode Water. Journal of Physical Oceanography, 17, 1561-1570.

Stramma, L. & T.J. Müller (1989) Some observations of the Azores Current and the North Equatorial Current. Journal of Geophysical Research, 94, 3181-3186.

Sverdrup, H.U., M.W. Johnson & R.H. Fleming (1942) The Oceans. Their Physics, Chemistry and General Biology. Prentice-Hall. Inc., 1087 pp.

Sy, Alexander (1988) Investigacion a large-scale circulation patterns in the central North Atlantic: the North Atlantic Current, the Azores Current, and the Mediterranean Water plume in the area of the Mid-Atlantic Ridge. Deep-Sea Research, 35, 383-413.

Swallow, J.C., W.J. Gould & P.M. Saunders (1977) Evidence for a poleward eastern boundary current in the North Atlantic Ocean. ICES C.M. 1977/C:32, 20 pp.

UNESCO (1985) The International System of Units (SI) in Oceanography. Unesco Technical papers in Marine Science, 45: 124 pp.

Wooster, WS., A. Bakun & D.R. McLain (1976) The seasonal upwelling cycle along the eastern boundary of the North Atlantic. Journal of Marine Research, 34, 131-141.

Worthington L.V. (1976) On the north Atlantic circulation. Oceanographics Studies, Vol. 6, Johns Hopkins University Press, 110 pp.

Wüst, G. & A. Defant (1936) Schichtung und zirculation des atlantischer ozean. Meteor Werk-Berlin.

FIGURE CAPTIONS

Fig. 1. T-S diagram for all stations; locations shown in Fig. 12. H is the limit between ENAWp and ENAW x. WNAW, ENAW and ENACW curves according to]SELIN (1936), FIUZA (1984) and EMERY and MEINCKE (1986), respectively. MW is Mediterranean Water according to WOST and DEFANT (1936).

Fig. 2. T-S diagrams for Stas 1-8.

Fig. 3. T-S diagrams for Stas 9-12.

Fig. 4. T-S diagrams for Stas 12-15.

Fig. 5. T-S diagrams for Stas 17-20. A according to FRAGA (1973). MMW (Madeira Mode Water) according to SIEDLER *et al.* (1987).

Fig. 6. Distribution of isopycna]s (7o) in a vertical section along 23°W. (7o = density-]03 at *O°C* of potential temperature; UNESCO,]985). Dot represents AC to the east.

Fig. 7. Geostrophic velocity in cm s -1 (positive to the west) in a vertical section along 23°W. The reference layer is 1400 db given by Sv (1988) for the Azores region.

Fig. 8. Vertical section of salinity distribution along 23°W from 24 ° to 40°N. SW, surface water. (a) Salinity vs pressure (0-200 db); (b) salinity vs Y0. The thick line represents the lower |imit of the surface water.

Fig. 9.Distribution of isopycnals (70) in a vertical section along 42°N. Dots represent water moving to the south and crosses water moving to the north.

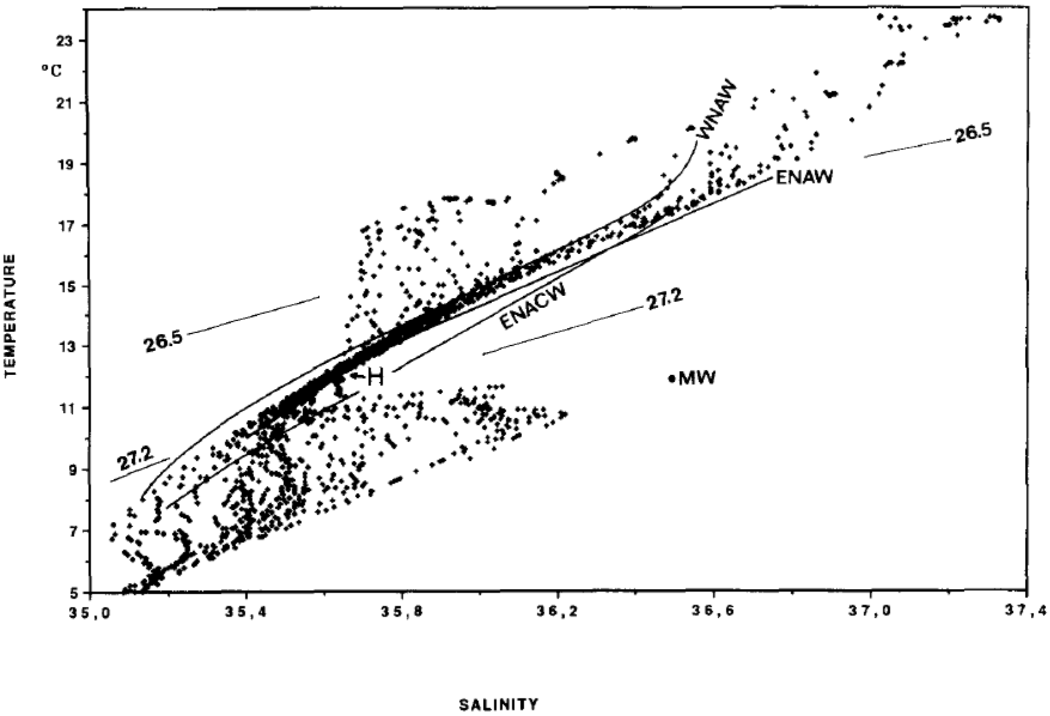
Fig. 10. Geostrophic velocity in cm s i (positive to the north) Ln a vertical section along 42°N. The reference layer is 700 db. This level corresponds with the intermediate layer between MW and ENAWp which move in opposite directions (McCARTNEY and TALLEY, 1982).

Fig. lI. Vertical section of salinity distribution along 42°N from 23 ° to the coast. SW, surface water. (a) Salinity vs pressure (0-150 db); (b) salinity vs Y0. The thick line represents the lower limit of surface water. The dashed line corresponds to the upper limit of ENAWp.

Fig. 12.Schematic coarse view of ENAW distribution in the North Atlantic Ocean and positions of CTD stations.

Table 1. Maximum salinity values of ENAW

Position	Date	Cruise	S	Reference
42°N				
42°00'N, 9°46'W	Feb. 84	G-VII	35.552	FRAGA *et al.*(1985)
42°08'N, 8°59'W	May 82	ONDA-D	35.735	FRAGA *et al.* (1984)
41°54'N, 9°41'W	Jul. 84	G-VIII	35.775	MOURIÑO*et al.* (1985)
41°52'N, 9°39'W	Sep. 86	G-IX	35.789	FRAGA *et al.* (1987)
42°05'N, 9°42'W	Nov. 88	ANA	35.918	This paper
41°54'N, 9°39'W	Dec. 83	G-VI	35.962	Pérez *et al.* (1985)
40°N				
40°00'N, 9°55'W	Feb. 84	G-VII	35.812	FRAGA *et al.* (1985)



TEMPERATURE
°C
23
21
19
17
15
13
11
9
7
5
SALINITY
35,0
35,4
35,8
36,2
36,6
37,0
37,4
WNAW
ENAW
ENACW
26.5
26.5
27.2
27.2
H
•MW

Figure 1

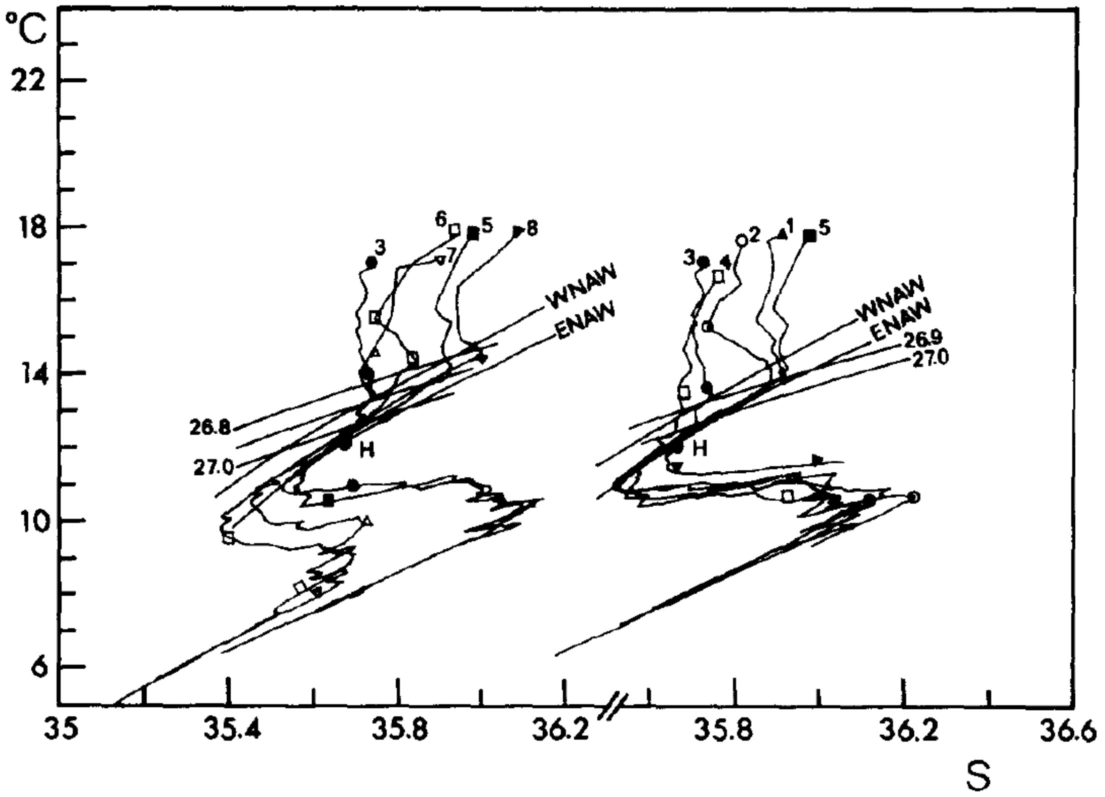

°C
22
18
14
10
6
35
35.4
35.8
36.2
35.8
36.2
36.6
S
WNAW
ENAW
26.8
27.0
26.9
H
3
6
5
8
7
4
2
1

Figure 2

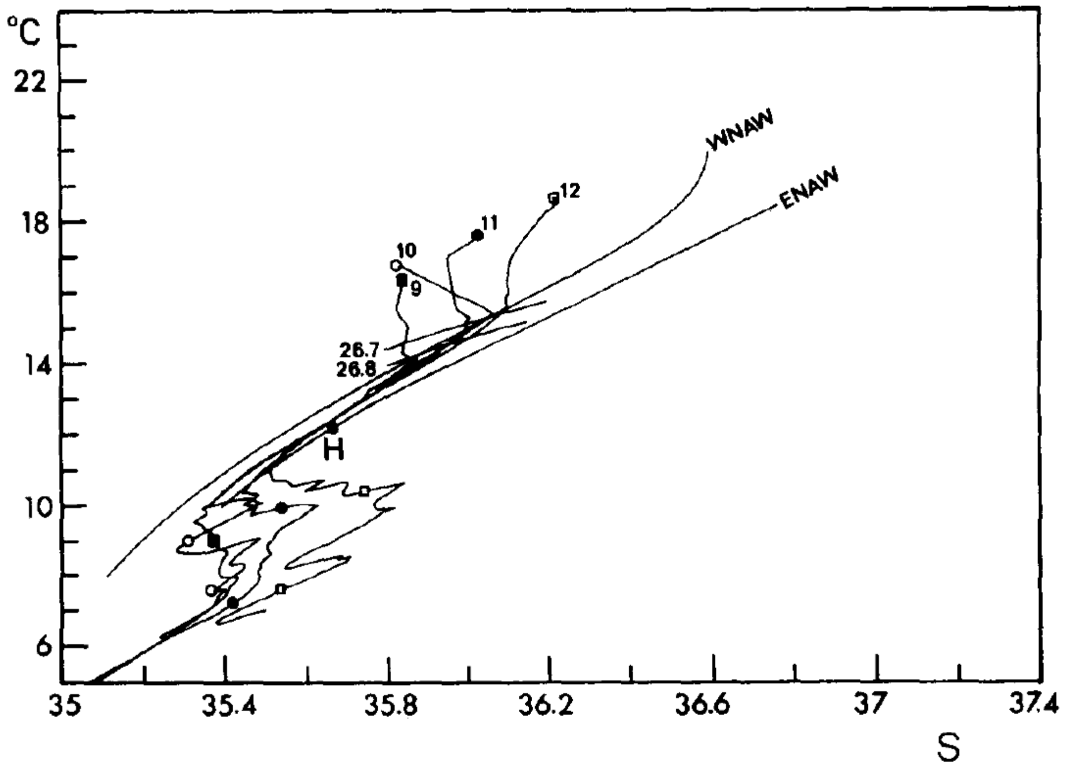
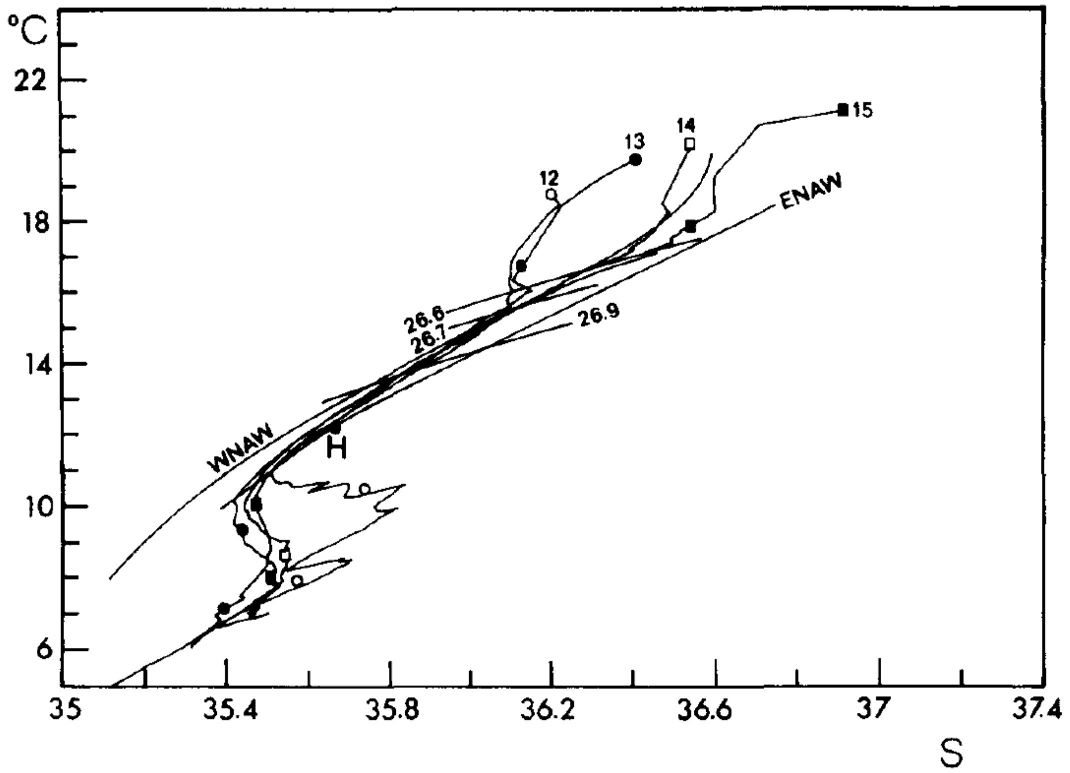

°C
22
18
14
10
6
35
35.4
35.8
36.2
36.6
37
37.4
S
WNAW
ENAW
12
11
10
9
26.7
26.8
H

Figure 3



°C
22
18
14
10
6
35
35.4
35.8
36.2
36.6
37
37.4
S
12
13
14
15
ENAW
WNAW
26.6
26.7
26.9
H

Figure 4

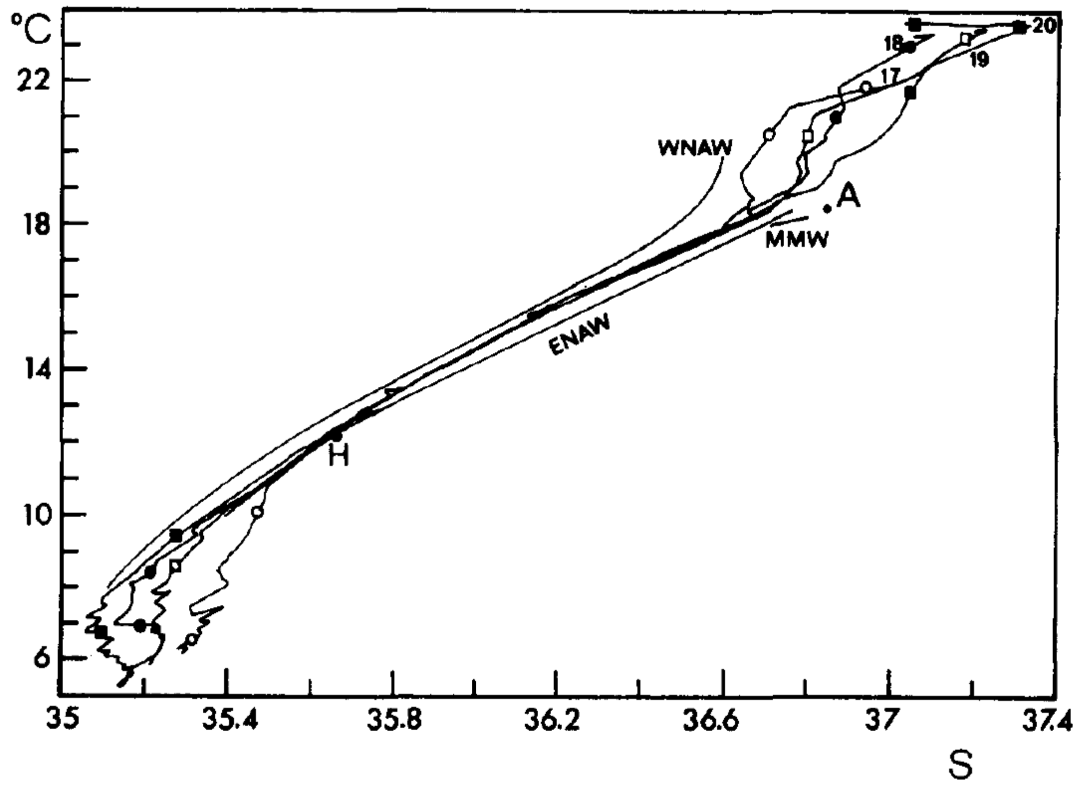

°C
22
18
14
10
6
35
35.4
35.8
36.2
36.6
37
37.4
S
WNAW
ENAW
MMW
A
H
17
18
19
20

Figure 5

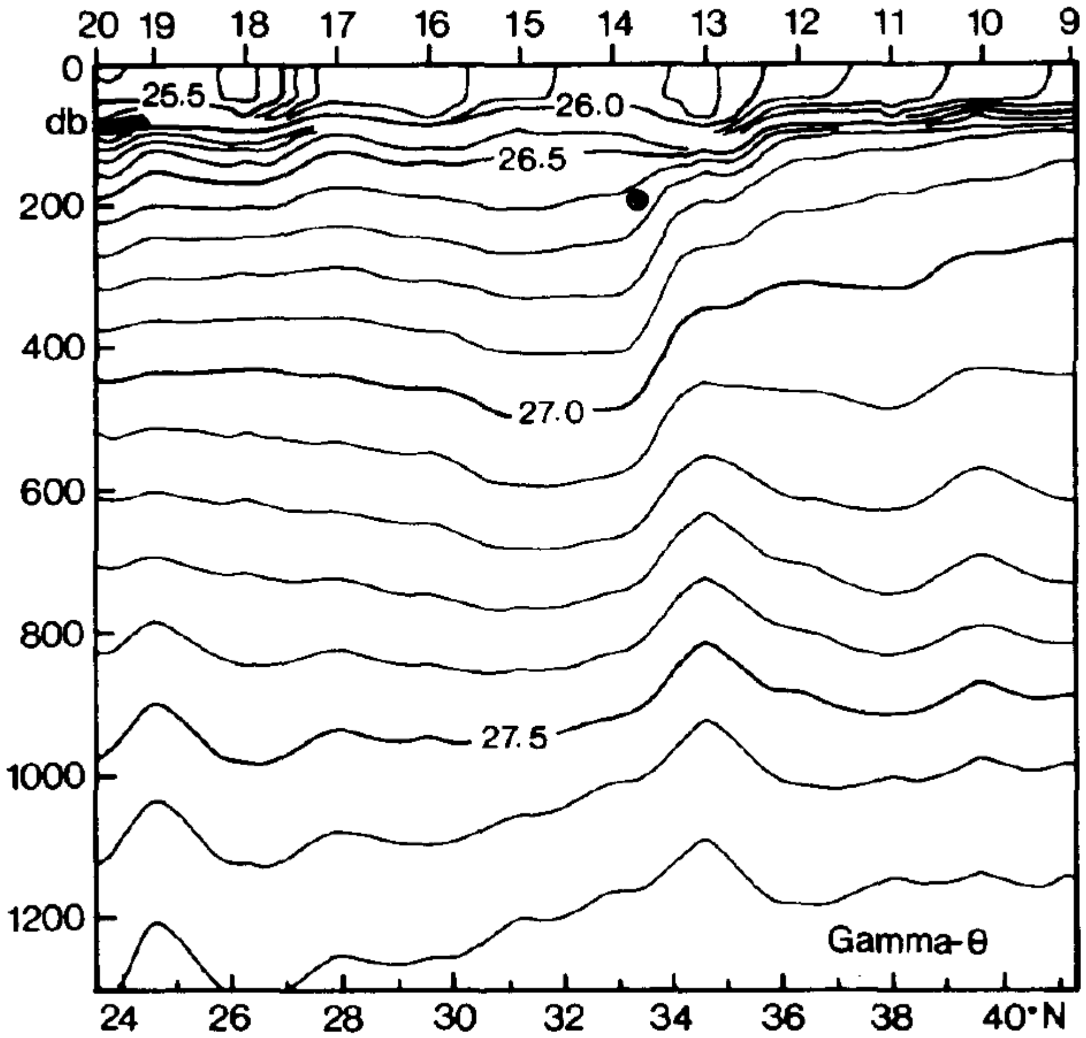

20
19
18
17
16
15
14
13
12
11
10
9
0
db
200
400
600
800
1000
1200
25.5
26.0
26.5
27.0
27.5
Gamma-θ
24
26
28
30
32
34
36
38
40°N

Figure 6

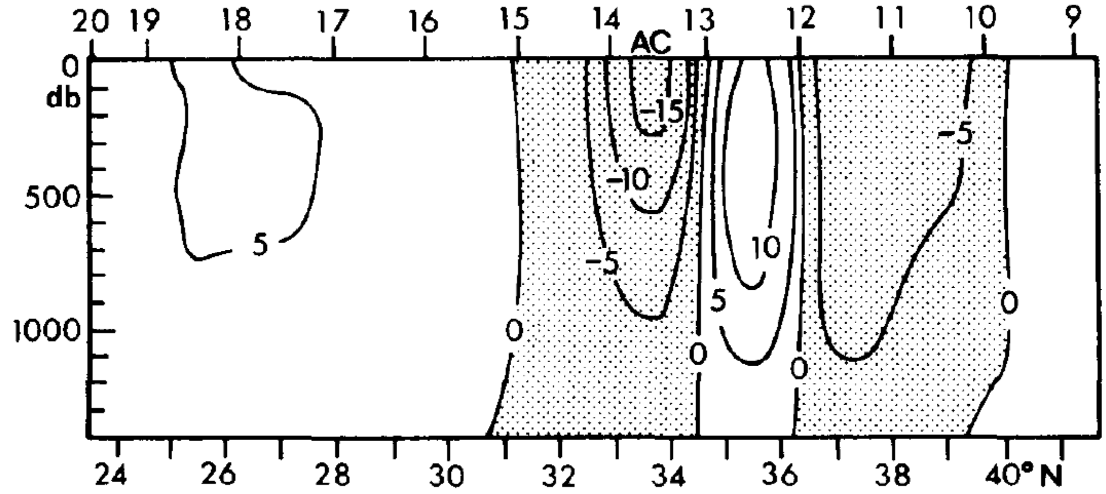

20
19
18
17
16
15
14
AC
13
12
11
10
9
0
db
500
1000
5
0
-15
-10
-5
10
5
0
0
-5
0
24
26
28
30
32
34
36
38
40° N

Figure 7

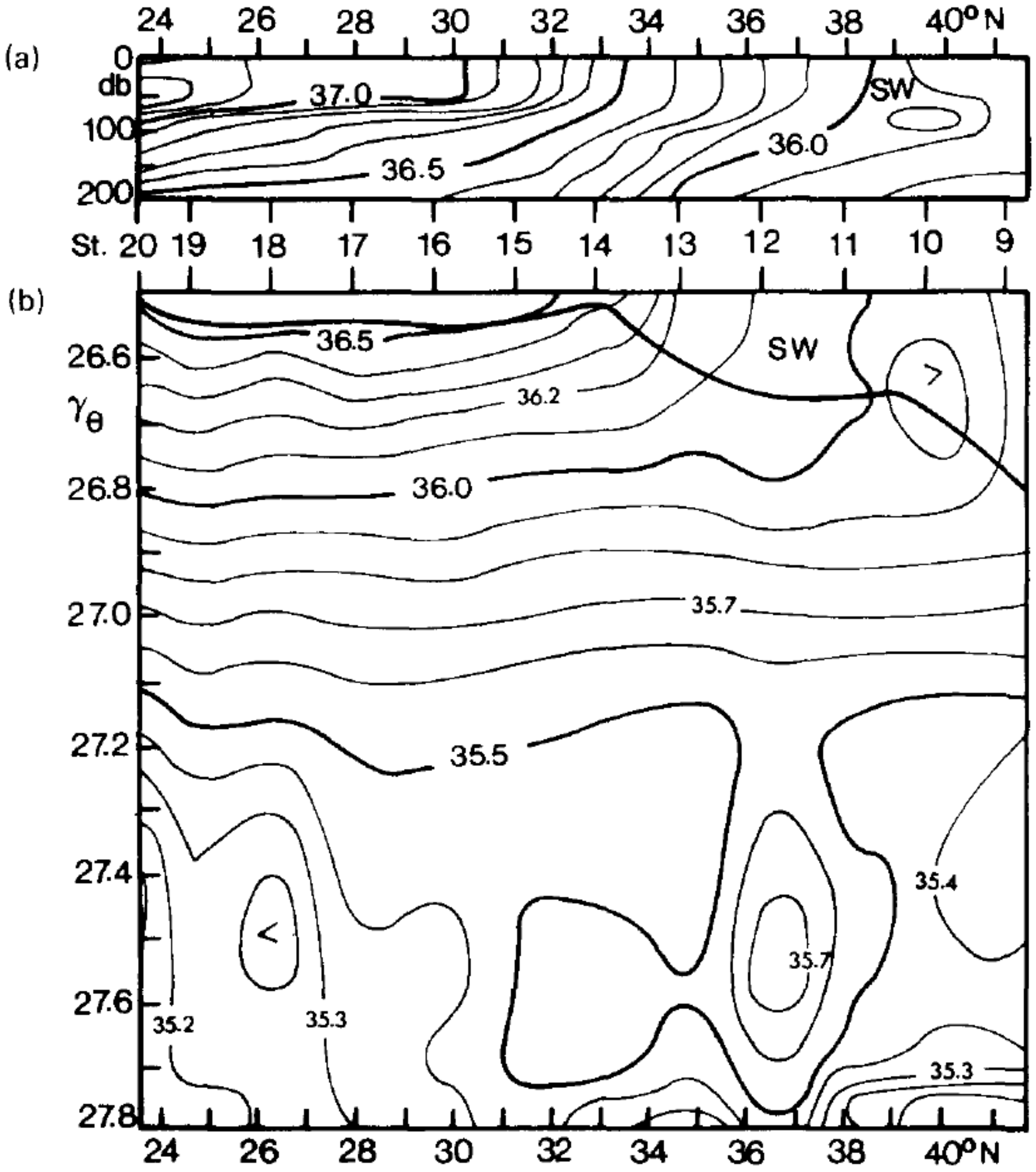

(a)
24
26
28
30
32
34
36
38
40° N
0
db
100
200
37.0
36.5
36.0
SW
St. 20
19
18
17
16
15
14
13
12
11
10
9
(b)
26.6
γθ
26.8
27.0
27.2
27.4
27.6
27.8
36.5
36.2
SW
>
36.0
35.7
35.5
35.4
<
35.7
35.2
35.3
35.3
24
26
28
30
32
34
36
38
40° N

Figure 8

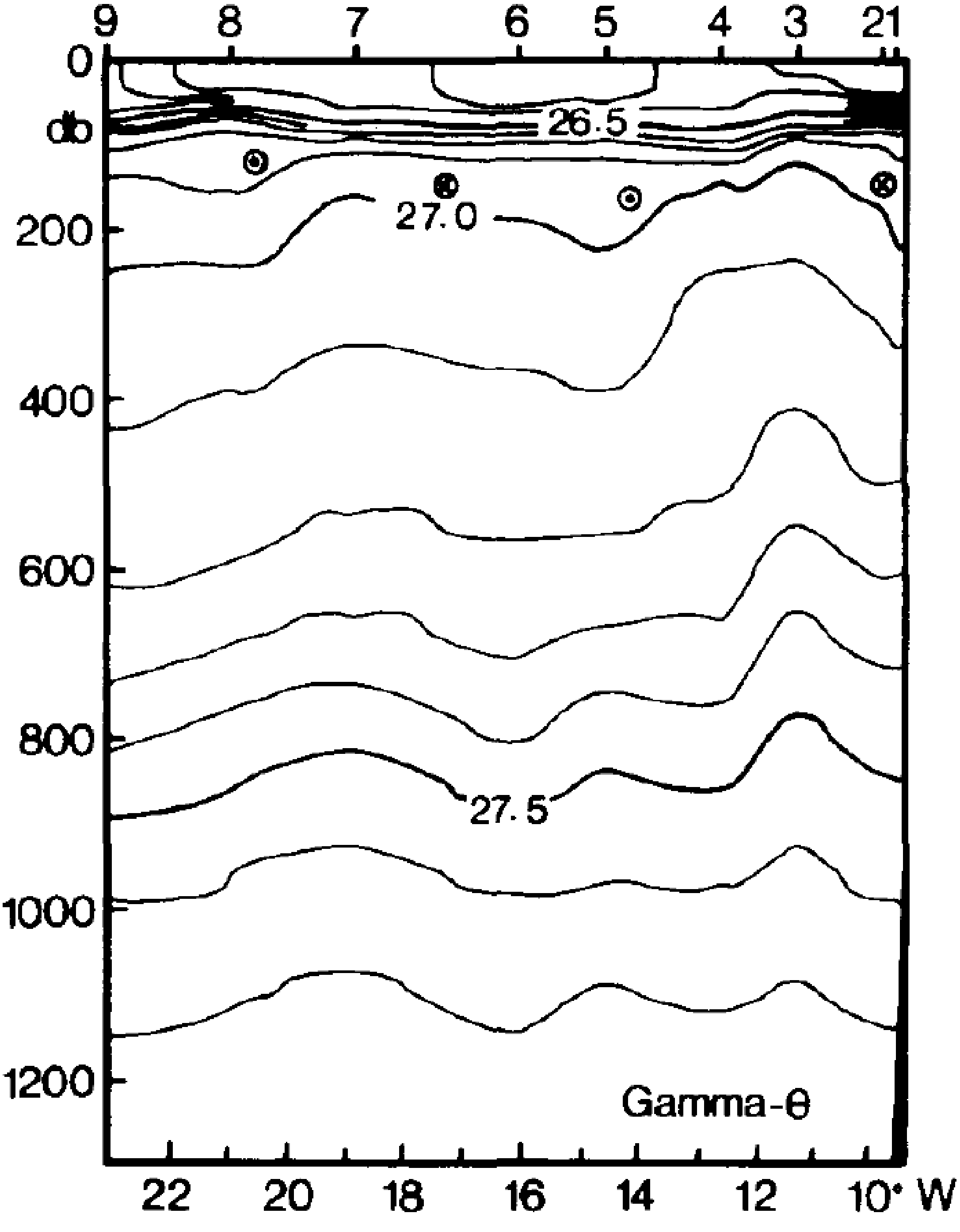

9
8
7
6
5
4
3
21
0
db
200
400
600
800
1000
1200
26.5
27.0
27.5
Gamma-θ
22
20
18
16
14
12
10° W

Figure 9

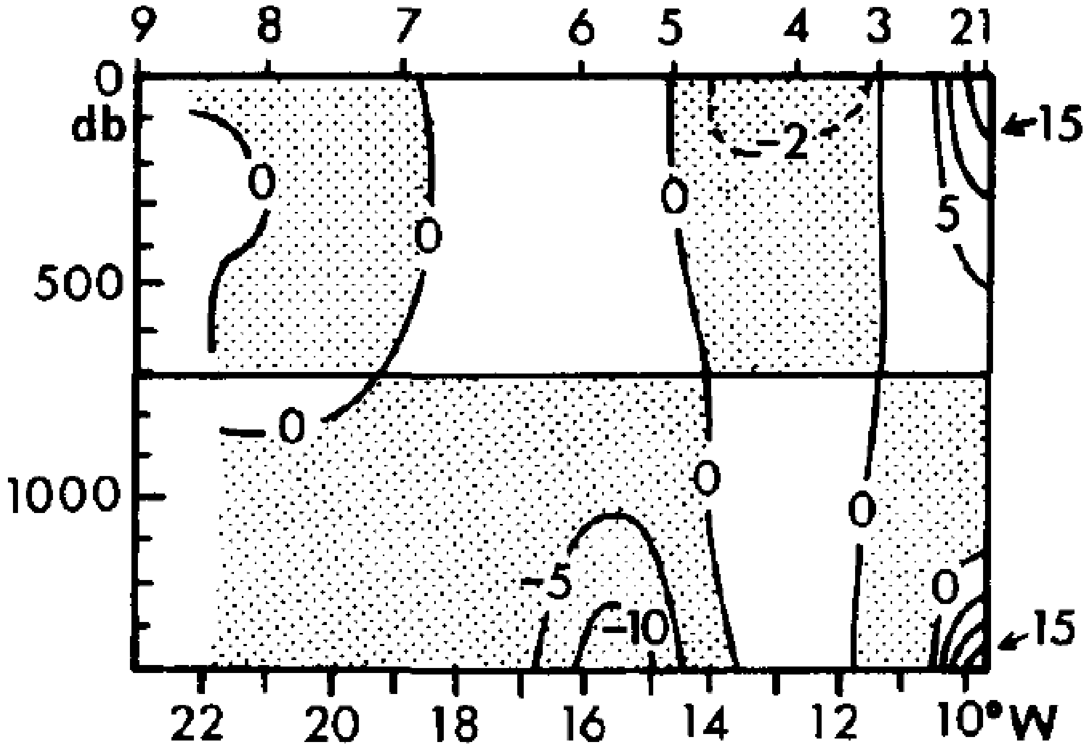

9
8
7
6
5
4
3
21
0
db
500
1000
0
0
0
-2
5
←15
-0
0
0
-5
-10
0
←15
22
20
18
16
14
12
10°W

Figure 10

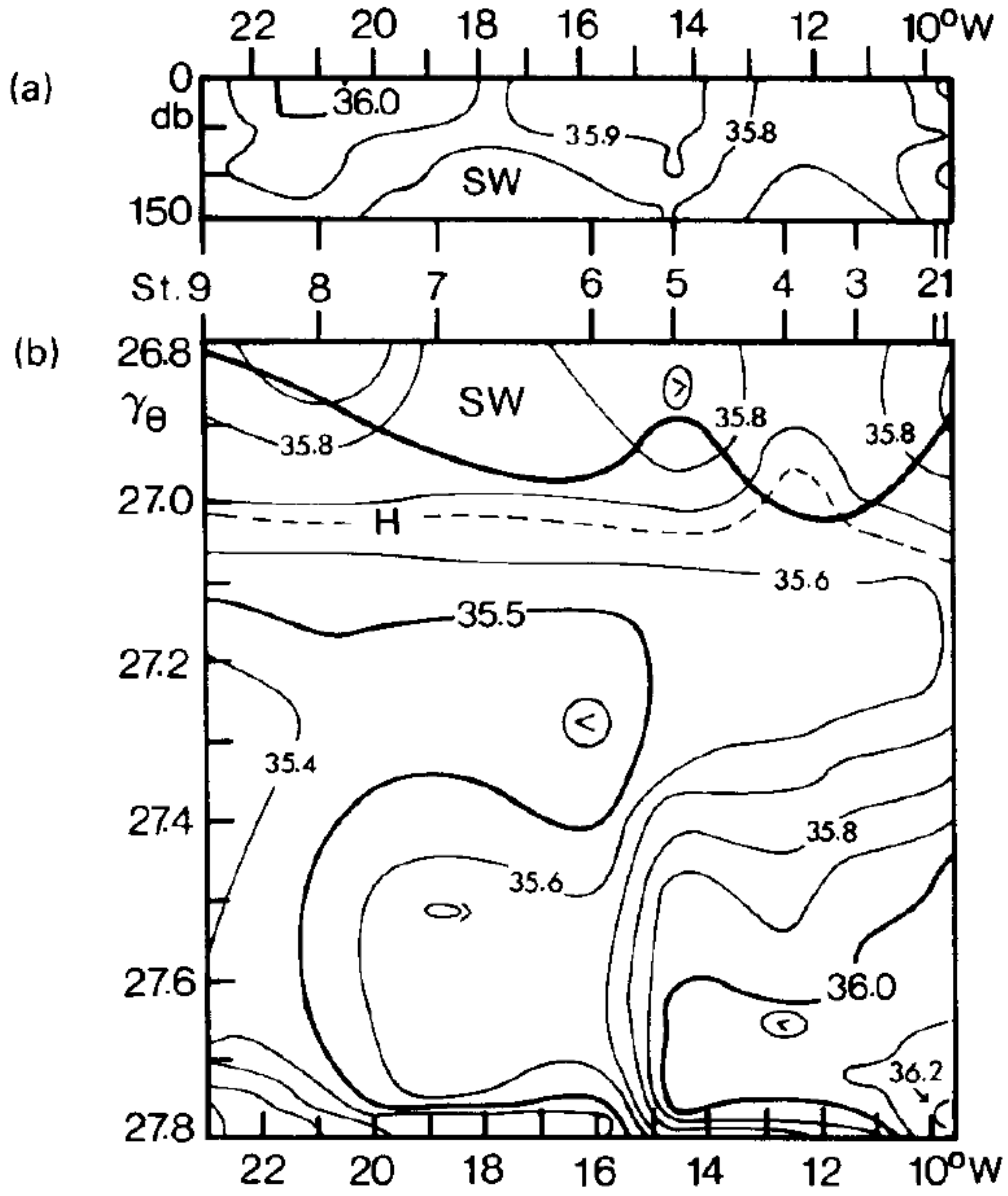

(a)
(b)
22
20
18
16
14
12
10°W
0
db
150
36.0
35.9
35.8
SW
St. 9
8
7
6
5
4
3
21
26.8
γ_θ
27.0
27.2
27.4
27.6
27.8
SW
35.8
35.8
35.8
H
35.6
35.5
35.4
35.6
35.8
36.0
36.2
22
20
18
16
14
12
10°W

Figure 11

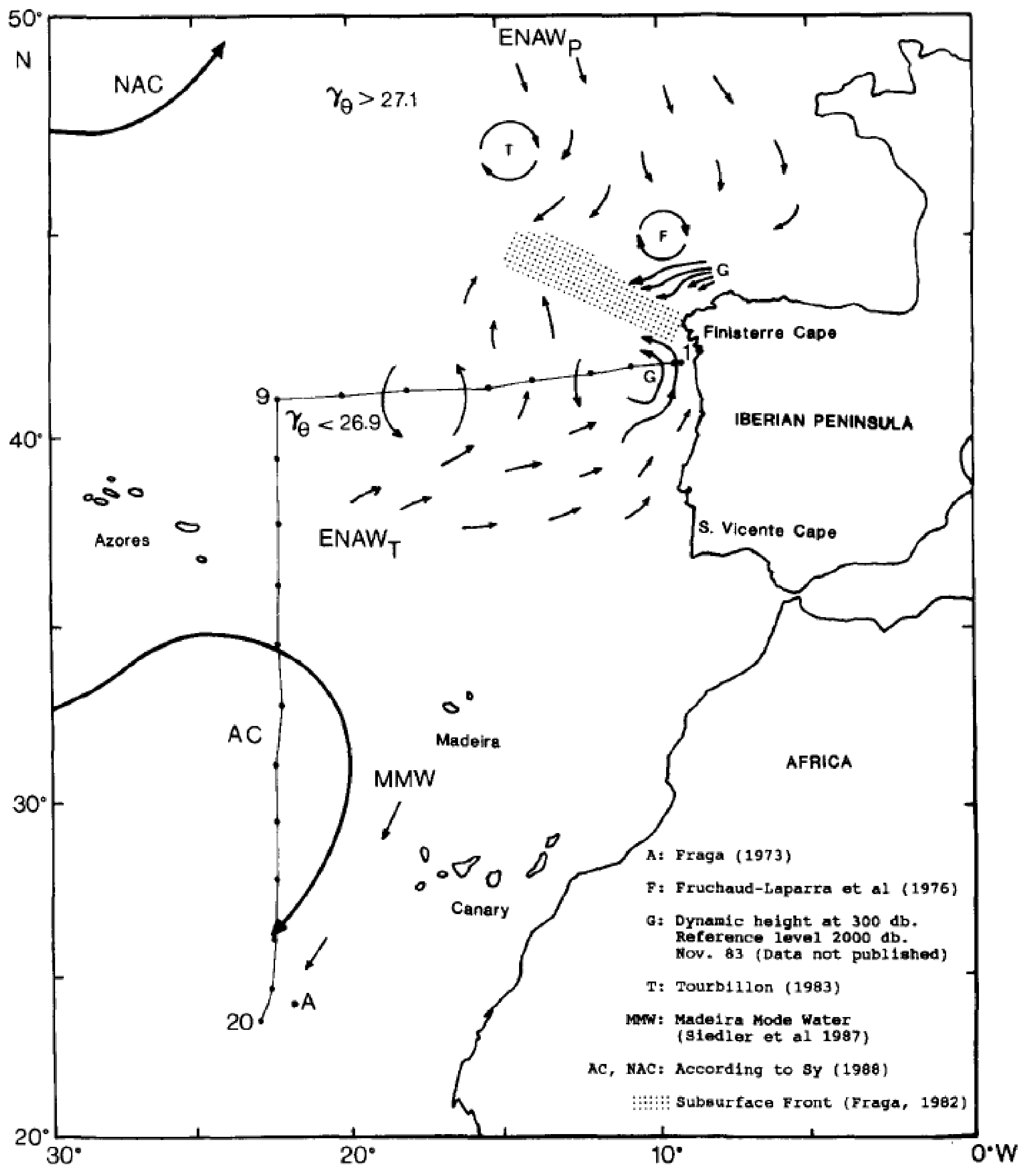

50°
N
NAC
ENAW$_P$
$\gamma_\theta > 27.1$
T
F
G
Finisterre Cape
1
G
9
$\gamma_\theta < 26.9$
IBERIAN PENINSULA
40°
Azores
ENAW$_T$
S. Vicente Cape
AC
Madeira
AFRICA
MMW
30°
Canary
A
20
A: Fraga (1973)
F: Fruchaud-Laparra et al (1976)
G: Dynamic height at 300 db. Reference level 2000 db. Nov. 83 (Data not published)
T: Tourbillon (1983)
MMW: Madeira Mode Water (Siedler et al 1987)
AC, NAC: According to Sy (1988)
Subsurface Front (Fraga, 1982)
20°
30°
20°
10°
0°W

Figure 12