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Geostrophic Transports across the Mid-Atlantic Ridge between 24°N and 53°N

by

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ABSTRACT

In the frame of the TOPOGULF experiment 5 hydrographic boxes were designed to allow a better approach to a realistic reference-level for classical geostrophic calculation. By means of both the inverse method of WUNSCH (1978) and the empirical search method of FIADEIRO and VERONIS (1982), respectively, geostrophic currents and associated transports across the total length of the MAR between 24°N and 53°N were estimated. As a reference-level a deep "level of no (slow) motion" was found in terms of σ_2 = 36.97 - 37.035 (1500 - 2900 dbar) in good agreement with hydrographic features. The total transport above this level is calculated as 37 Sv to the east. The transport occurs in two principal currents, the Azores Current (12 Sv) and two branches of the North Atlantic Current (17 Sv). The meridional extent of the Mediterranian Water ouflow is found to be restricted by the Azores Current in the south and the southern branch of the North Atlantic Current in the north and the zonal distribution is influenced by the Mid-Atlantic Ridge.

INTRODUCTION

The synoptic data base for the investigation of large scale processes in the North Atlantic is only fragmentary and by far most statements were deduced from zonal sections. Especially in the central and eastern parts of the North Atlantic long meridional sections were scarce. Not only ISELIN´S (1936) classical monograph about the North Atlantic circulation was affected by this problem, but also more recent circulation studies were influenced by the lack of synoptic datasets with long meridional sections (STOMMEL, NIILER and ANATI (1978), WUNSCH and GRANT (1982)). As a contribution to close this gap a section along the Mid-Atlantic Ridge (MAR) is obvious for several reasons:

- The MAR is the dominating meridional topographic structure in the Atlantic Ocean.
- It crosses the North Atlantic subtropical gyre.

- It devides the North Atlantic in two approximately equally sized basins with to some extend clearly different water masses.
- Possibly it influences the progress of the currents of the Gulf Stream extension.

The TOPOGULF experiment, carried out by groups from COB Brest, France, with RV LE SUROIT and IfM Kiel, F.R.Germany, with RV POSEIDON and RV METEOR (TOPOGULF GROUP, 1986), was projected in order to obtain a synoptic estimate of the zonal transport in the central North Atlantic by means of hydrographic sections along either side of the MAR from the subtropical gyre up to the subpolar front. Additionally the area was planned to be devided in 5 mesoscale boxes by 6 normal-ridge sections connecting the parallel-ridge sections, to get a more realistic approach for a level of no (slow) motion (hereafter referred to as LONM) as reference-level for classical geostrophic calculation by means of some kind of conservation equation rather than by ad hoc assumptions as usual. Unfortunately during the field phase 1983 in the northern boxes extremely bad weather governed the schedule of RV POSEIDON. Thus only 4 quasi synoptic boxes could be worked in that year (fig. 1). Finally, the northern most box was finished a year later, in summer 1984 with RV METEOR (fig. 1), demonstrating as a nonestimated result the spot-light character of our hydrographic measurements concerning the North Atlantic circulation.

The Method

For calculating geostrophic currents by means of the dynamic method (DIETRICH, KALLE, KRAUSS and SIEDLER, 1975) a classical ad hoc reference-level model with a LONM in an intermediate depth, say at 2000 dbar in the North Atlantic, seems reasonable. Obviously this can be in serious contrast to the corresponding transports since according to $T = D_0\int^R c\,dz$ with D station distance, R LONM and c geostrophic current velocity the transport T is influenced twice by a wrong choice of the LONM. This relatively large error in the estimation of mass transports, viz caused by the unknown barotropic component, is the limiting factor in all heatflow calculations. To solve this problem in the past, several methods were suggested - with more or less successful results. At least the somewhat frustrating discussion was reopened in the late ´70s and early ´80s by the beta spiral method (STOMMEL and SCHOTT, 1977; SCHOTT and STOMMEL, 1978), the inverse Method (WUNSCH, 1977; 1978) and the empirical search method (FIADEIRO and VERONIS, 1982). Due to the limited ship time the TOPOGULF large scale field programme was restricted to the application of the two methods last mentioned.

The inverse method (IM), applied on oceanographic problems by WUNSCH (1977), is based on the solution of the equation system $A_{(M\times N)} b_{(N\times 1)} = -\Gamma_{(M\times 1)}$ which is derived from an ocean of M transport conserving layers and N hydrographic station pairs describing a closed volume. The geometry of the boundary is given by the M x N matrix A, the residuum of the baroclinic transport balance by the column vector Γ. As the solution of this underdetermined equation system one receives the column vector $\underline{b}$ as an estimate for the barotropic correction to satisfy the condition of a balanced geostrophic transport, which consists of a baroclinic and a barotropic component. A powerful practical method to solve this problem, the singular value decomposition (SVD) of the matrix A, contains implicitly the minimum norm condition, i.e. $\underline{b}^T\underline{b}$ = min, which represents a minimum energy solution.

The empirical search method (ESM) of FIADEIRO and VERONIS (1982) is a straightforward procedure for the best reference-level and practical oceanographers are influenced in favour of its easy application on real hydrographic data. The starting point is the same as for the IM: The definition of several conservative layers, usually based on some hydrographic criteria, is followed by the calculation of a transport balance T_l for each layer l. As a best approach to a LONM the least square criterion $T^2 = \sum_{l=1} T^2(R) = \min$ is defined assuming that larger mass imbalances are due to a wrong ad hoc choice of the LONM.

The procedure applied on the TOPOGULF data is as follows: First, the conservative layers as defined by the hydrography of the 5 boxes is classified, followed by the calculation of the LONM according to the dynamic method and the ESM. Finally, this LONM is used as an initial condition for the IM, which serves as a quasi fine adjustment or 2nd order solution.

Since the order of underdetermination for the IM remains large for the TOPOGULF boxes one should expect that a large deviation of the initially assumed reference-level from a real existing LONM cannot be corrected sufficiently, hence the result of the calculation will be contaminated extremely by the totally wrong chosen starting condition. A well estimated initial condition should produce a smaller inverse correction and, of course, a smaller remaining error. For extented ocean areas the existence of a single constant pressure level cannot be assumed as a LONM. It seems reasonable to choose any other parameter as reference variable except pressure. For the TOPOGULF data σ_2 proved to be appropriate, for the poorly structured southern box as well as for the hydrographical most complex METEOR box (TOPOGULF GROUP, 1986).

Taken the ocean levels as defined by WÜST (1936) as a basis one obtains 4 potential conservative layers in the central North Atantic:
1. The Warmwatersphere (WW), limited by the 50 dbar pressure interface to shield this layer at the top from influences from the sea surface, and by the 8°C isotherm or the O_2 minimum as a lower boundary.
2. The Upper North Atlantic Deep Water (UNADW), characterised by the salinity maximum of the Mediterranian Water (MW).
3. The Middle North Atlantic Deep Water (MNADW), marked by the salinity minimum of the Labrador Sea Water (LSW) or in modern terms by the minimum of the large scale potential vorticity q. A further indication is the relative high oxygen content associated with the LSW.
4. The deepest two layers, the Lower North Atlantic Deep Water and Bottom Water, here combined to one (LNADBW), are characterised by increasing silicate content towards the bottom in the eastern basins due to the influence of the Antarctic Bottom Water (AABW).

Only 4 layers as defined above seem not to be sufficient. It appears that the degree of underdetermination was too high for the IM, and for the ESM the 2 deepest layers (MNADW and LNADBW) dominated the imbalance T^2, notwithstanding the uppermost layer containing the strongest currents. After a further subdivision of the layers in a way that the thickness was better equalized without breaking hydrographic conditions, the results were satisfactory. The final definitions of the layers used are displayed exemplarily for section 1 in fig. 2. The lower boundary of the WW is given by the $\sigma_2 = 36.3$ isopycnal in good conformity with the oxygen minimum. No layer boundary intersects the cores of MW, SAAIW or LSW. In the north one and in the south two additional layers are situated between MW and LSW. In the region between these two watermasses only conservative layers are expected due to the small advection. In the area north of the Azores the POSEIDON and METEOR (not shown) boxes contain only 7 layers due to shallower profiles or modified hydrography respectively, but the two SUROIT boxes and the SUROIT-POSEIDON triangle contain 8 layers each.

The result for the reference variable $R = \sigma_2$ for the ESM approach is displayed in fig. 3a. The development of the ESM functions for the Suroit boxes shows clear results and the significant minima are summarised in the table below. The results for the boxes north of the Azores are not as clear since a second minimum appears. However, this minimum is rather flat (P = 699 - 1394 dbar) and less stable due to a variable number of layers and is not believed to be very realistic. Additionally, an ESM approach using the mean square inverse correction to find the minimum of all minimum norm solutions does not show this second flat minimum (fig. 3b) for the IM solutions of rank $\gg 6$. Further arguments against the significance of the flat second minimum are based upon current meter measurements which show no LONM here (FAHRBACH, KRAUSS, MEINCKE and Sy, 1985) and upon the fact that it would cross the MW tongue. Thus the accepted ESM values are those of the deep minima as listed in the table. The ESM result for the SUROIT-POSEIDON triangle is far from being clear, showing two less distinctly marked minima. Principal doubts are reasonable because the triangle encloses the Azores, hence topographic effects may influence the shape of the ESM curve. Additionally, the data here consist of two independent data sets with a systematic discrepancy in salinity of about 0.005 (TOPOGULF GROUP, 1986).

Independent of the arguments brought forward, it is obvious that except for the triangle all boxes give indications of the existence of a deep LONM. Fundamentally, as an initial reference-level for the area north of 40°N $R = \sigma_2 = 36.970$ and south of 40°N $R = \sigma_2 = 37.035$ was chosen (the dotted line in fig. 2). It is located in the south at 2500 dbar or deeper; in the north significantly below 2000 dbar. For the METEOR box only the LONM approaches at 1500 dbar at the north western corner (not shown).

The reference-level as defined above is incompatible with values DEFANT (1961) found for the North Atlantic assuming a vanishing current in vertically extented layers with parallel isobaths. After DEFANT, the LONM should deepen from about 1000 dbar in the south to 1600 dbar in the north of the TOPOGULF boxes, i.e. with an opposed slope. STRAMMA (1984) applied the ESM to 3° x 3° boxes with historical data in addition to the method of DEFANT (1961). He shows significant differences compared with the values discussed above. For the area of the TOPOGULF boxes STRAMMA received a LONM between 1200 and 1300 dbar, thus intersecting the MW salinity maximum, which seems not supporting his choice. On the contrary, as observations show, the North Atlantic Current (NAC) has a limiting influence on the spreading of the MW pointing to a LONM below the MW level. The same argument holds for the Azores Current (AC) as well (see section 4). SIEDLER, ZENK and EMERY (1985) stated from mooring data a reference-level as deep as 3000 dbar or even deeper, and SAUNDERS (1982) as well argued in his East Atlantic circulation study for a deep LONM. Finally, as stated already above, the obtained minimum from the calculation of $\sum_j b_j^2(R,L)$ similar to the ESM (fig. 3b) implies a further indication for the existence of a deep reference-level. That is, as FIADEIRO and VERONIS (1982) pointed out, the minimum of all minimum norm solutions of the IM. Of course, the results are dependent from the number M of layers and especially from the number L of eigenvalues used. All together, however, it reveals a clear indication for a deep reference-level. To summarize the reference-level discussion it is concluded that there is every reason to believe that the LONM as defined above is a good choice.

3. Transports across the MAR

Referring to the 1983 data in fig. 4 a,b the geostrophic currents and cumulative transports calculated by means of ESM and IM are displayed as two long quasi synoptic sections following the MAR along its western and eastern side. In order to get an idea of the size of the inverse correction applied the transport calculated from each b_j is displayed in this figure separately.

As a first result it was surprising to find no significant differences in the total section transports between an ad hoc 2000 dbar overall constant LONM model and this ESM-IM model. The first model showed a transport (in brackets the values for the ESM-IM model) above the LONM and west of the MAR of 23 Sv (23 Sv) and below the LONM of 11 Sv (9 Sv). East of the MAR the values are 32 Sv (31 Sv) and 5 Sv (3 Sv), respectively. The same holds true for the velocities because the calculated velocities do not depend critically on the choice of the LONM as the shear below the main thermocline becomes small compared to that near the sea surface. Obviously this should be in serious contrast to the corresponding transports, which was the argument for more efforts on the choice of a LONM. However, there are local differences which hopefully justify the powerful machinery used. In the following description all results refer to the ESM-IM model.

Section 1 extends along the eastern slope of the MAR from 24°N to 52°N (close to the Gibbs-Fracture-Zone (GFZ)) and is about 1000 km longer than the western section 2, which does not proceed beyond 47°N. Thus the eastward net transport above the reference-level of 31 Sv exceeds the net transport of the western section of 23 Sv significantly. As section 1 extends further to the north it includes a larger part of the NAC despite the fact that this section does not touch the subpolar front. An error of about 5 Sv might occure at its southern end, caused by a possibly cyclonic eddy leading to some kind of aliasing effect.

The cross-ridge net transport occurs in two main current branches:
1. The Azores Current (AC) is located east of the ridge between 32°N and 32.5°N, and west of the ridge between 35°N and 36°N. Here it has a maximum velocity of 47 cm/sec. With a water mass analysis and transports obtained from the trans-ridge section 4 (see fig. 1) the current path is traceable easily, and it seems to be clear that this strong current velocity is the cumulative result of both the current branch and an eddy. The meandering flow (fig. 5) can be identified as the southern branch of the Gulf Stream extension defined as a strong current fixing the north-eastern limits of the 18°C water (MANN, 1967) or as the AC (GOULD, 1985), respectively. However, its net volume transport of 12 - 13 Sv through the total width of box II is less than the 1/2 value reported by MANN (1967) and CLARKE, HILL, REINIGER and WARREN (1980) but fits surprisingly well with the results GOULD (1985) received from his frontal survey during april 1981 and KÄSE and SIEDLER (1982) from a box study in spring 1982 eastwards of section 1.
2. A branch of the North Atlantic Current (NAC), which crosses the MAR just at the location of normal-ridge section 7 (fig. 6) as water mass analysis show. Its transport is about 12 - 13 Sv. Unfortunately, this POSEIDON sections could not be completed beyond the GFZ, which seems to be the stationary location of the subpolar front with an expected transport of about 6 Sv (MEINCKE, SY and FAHRBACH, in prep.).

The estimated transport below the reference-level showed an eastward flow as well, 9 Sv through the western and 3 Sv through the eastern section, respectively. It is evident that no reversion of the general eastward flow can be observed in the sense SAUNDERS (1982) and MAILLARD (1984) found. Both authors used a generally deeper reference-level. However, the different results in deep flow calculations are not really significant rather than a result of different choices of layer depth and width, the sensitivity of the assumed LONM and finally the inverse correction with a total contribution of 5 Sv for the western and 1.5 Sv for the eastern section.

Comparisons of the values reported here with those from the appropriate literature should not be overemphasized and thus are omitted in this report. All investigations in the North Atlantic reveal a highly variable system with different energetic scales in time and space. As an example, BARYSHEVSKAYA (1985) analysed 57 hydrographic sections from OWS ´C´ to Gibraltar carried out from 1975 through 1983, and she found for the NAC a mean transport of 18.8 Sv with single realisations varying from 29.1 Sv (may 1978) to 4.2 Sv (september 1980). Thus, the quasi synoptic TOPOGULF data set representing a spot picture is not the adequate basis to be compared with a more or less averaged data set, not to mention the different reference-levels, integration depths, methods, etc..

To give an example of this spot like character of the TOPOGULF survey the result of the transport calculation of the 1984 METEOR sections is displayed in fig. 7. The METEOR box enclosures the GFZ and thus showing a current of about 6 - 7 Sv associated with the subpolar front. The other main feature belongs to a southern branch of the NAC of about 10 - 12 Sv similar to the branch in the 1983 POSEIDON box. However, both current branches cross the MAR on different paths demonstrating the high variability of the NAC system as to be seen in the summed-up display in fig. 8.

4. The Mediterranian Water plume

Following DEFANT (1955), one sees the MW spreads continuously far beyond the MAR with its core-salinity decreasing from 36.4 to about 35.1. Consequently he interpreted this spreading as mainly dominated by diffusion. Later, KATZ (1970) found evidence that this decrease was not continuously over the whole area of the MW plume. Re-examining data from the Fuglister Atlas he found serious indications for a stronger change of the MW salinity decrease over the MAR. This supports the idea that the MAR, as a topographic barrier between the western and eastern basins, represents a boundary for the MW spreading; not as a physical divider but as an area of excessive mixing. JOYCE (1981) reported a similar topographic influence on the MW spreading observed by means of CTD and XBT data from RV KNORR Cruise 66 (1977) in the vicinity of Oceanographer-Fracture Zone. Frontal structures are clearly visible in a map WORTHINGTON (1970) prepared for the MW plume. The great saline wedge of MW finally led WORTHINGTON (1976) to argue that the large anticyclonic gyre in the North Atlantic could not exist without destroying this wedge. However, significant differences in θ/S diagrams of sections across the MAR, an example is displayed in fig. 9, support the findings of KATZ (1970). The influence of the topography is indicated by the steplike decrease of the MW portion in the UNADW.

As can be followed from the θ/S analysis, the NAC is clearly traceable by watermass distribution alone. That is feasible for the dynamically relevent main thermocline as well as for the dynamically neutral MW in the layer below (fig. 10). Obviously similar to the MAR topography, the current field of the NAC acts upon the spreading of the MW as a boundary. This observation was confirmed by all 5 cruises in that area from 1981 through 1984. Always the most southern branch of the NAC was found as the northern boundary of the MW tongue (MEINCKE, SY and FAHRBACH, in prep.). A feasible explanation might be seen in the lateral erosion of the salinity wedge by means of the strong advection of the NAC. In the domain of the AC similar θ/S features can be found (fig. 10).

5. Summary and Conclusion

The hydrographic measurements of the TOPOGULF experiment produced a set of results which are listed below as a final overview before the construction of a coherent picture is attempted:

1) The main part of the volume transport across the MAR between 24°N and 53°N takes place in 2 current systems, the North Atlantic Current and the Azores Current. Both are clearly separated from the mesoscale eddy field. It appears from our data that the part of the NAC on the total transport exceeds that of the AC.
2) The structure of these current systems is dominated by meanders and their paths relative to the MAR are highly variable.
3) A reversal of the current field in great depths is not observed.
4) Hydrographic as well as methodic arguments suggest a deep level of no (slow) motion.
5) In intermediate depths the MW tongue spreads to the west between the two current systems as its northern and southern boundaries respectively. The topography of the MAR influences the zonal and the current systems the meridional spreading of the MW, respectively.

Thus, deviating from the classical conception of DIETRICH, KALLE, KRAUSS and SIEDLER (1975) in some parts (fig. 11), following the gross features of MAILLARD (1984), SAUNDERS (1982) and KRAUSS (1986) and additionally including our results from zonal XBT sections in the eastern North Atlantic (FAHRBACH, KRAUSS, MEINCKE and SY, 1983 a,b), the scheme of the Northeast Atlantic circulation reveals as follows (fig. 12):

South-east of the Newfoundland Banks the Gulf Stream separates into two branches, the AC directed to the south-east and the NAC proceeding to the north towards the Newfoundland Basin. Further to the east but still in front of the MAR the NAC divides into a part which traverses the MAR as the permanent subpolar front, topographically fixed to the GFZ and into a regime attached to the south. The latter consists of one or more transient current branches between the subpolar front and 45°N. After crossing the MAR the NAC system changes its general direction towards the north. There exists no significant part beyond the MAR directed to the south which can be interpreted as consisting of the Gulf Stream recirculation. This view is supported by results from extented drifter experiments during the years from 1981 through 1984 (KRAUSS, 1986). KRAUSS found no indication for a current from Flemish Cap towards the Azores or the Canary branch as postulated in the scheme of fig. 11. Further, he observed a systematic northward drift east of the MAR which agrees well with results deduced from XBT sections. A part of the subpolar front feeds the subarctic cyclonic gyre. The southern Gulf Stream extension presumably crosses the MAR in the vicinity of the Oceanographer-Fracture Zone or the area adjoined to the south. Thus, the AC is the northern and eastern boundary of the subtropical gyre with the 18°C water as its typical water mass in its core. In the east the AC extends to the Canary Basin. In the triangle between the NAC and AC the MW tongue slides westwards at intermediate depths, not disturbed by any meridional circulation but by some kind of influence due to the topography of the MAR. Finally, concerning

WORTHINGON´S (1962, 1976) scheme of the disconnected Gulf Stream and NAC the author agrees with the opinion of CLARKE, HILL, REINIGER and WARREN (1980) who were able to disprove some key arguments of his hypothesis in a convincing discussion on the basis of their extented synoptic data set. Thus, coming to a final remark, it is the author´s impression that our knowledge concerning the North Atlantic circulation did not proceed far beyond since the time of STOMMEL´S (1958) classical scheme (fig. 13).

6. References

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Table: The level-of-no-motion (LONM) obtained by ESM in terms of σ_2 and corresponding pressure P averaged over the box.

	SUROIT south	SUROIT central	SUR/POS triangle	POSEIDON box	METEOR south	METEOR north	
σ_2	37.009	37.034	(36.826)	36.976	36.986	36.974	kg/m**3
$\bar{P}$	2254	2498	(1400)	2205	2202	2114	dbar

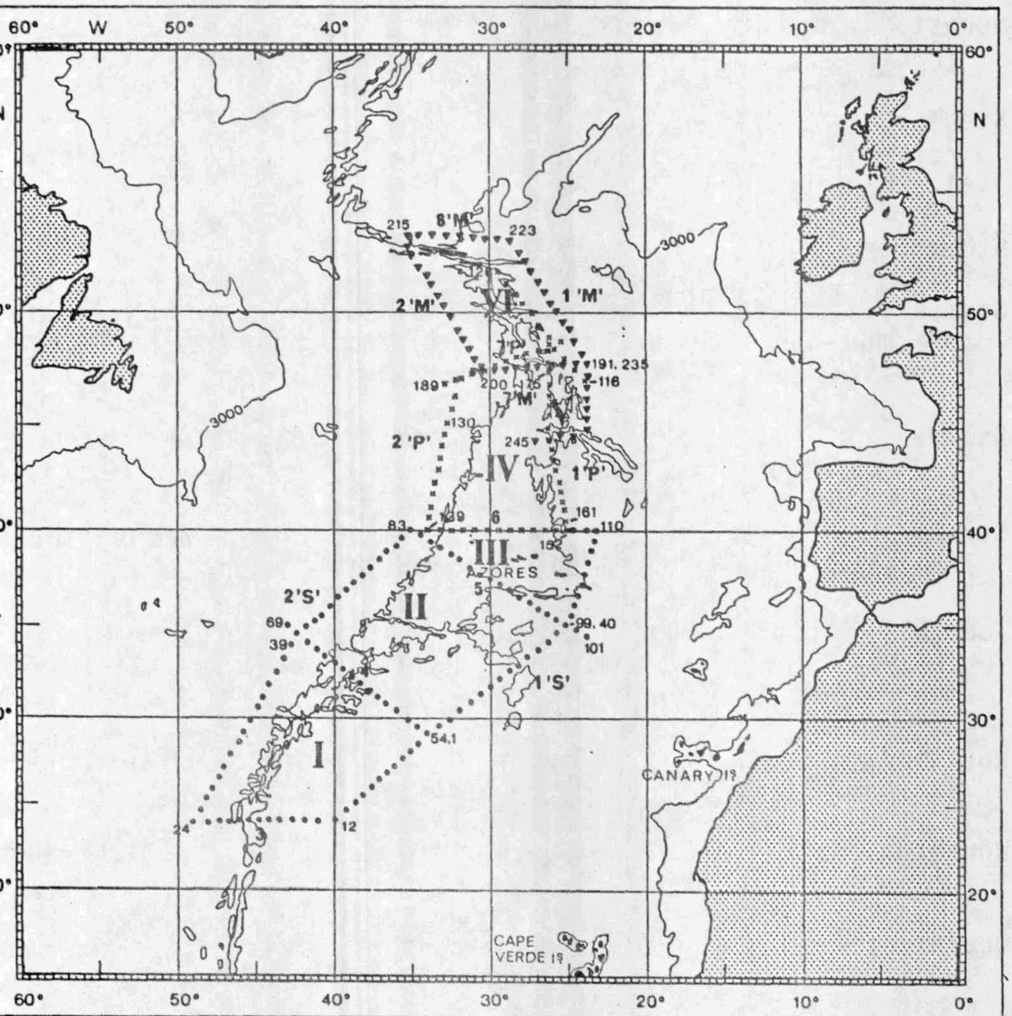


Fig. 1: Location of the TOPOGULF boxes used for the inverse analysis

The boxes are designed as I: SUROIT south
II: SUROIT central
III: POSEIDON/SUROIT triangle
IV: POSEIDON box
V: METEOR south (not complete)
VI: METEOR north

The sections are designed by arabic numbers

• hydrographic stations RV "Suroit"
x " " RV "Poseidon"
▶ " " RV "Meteor"

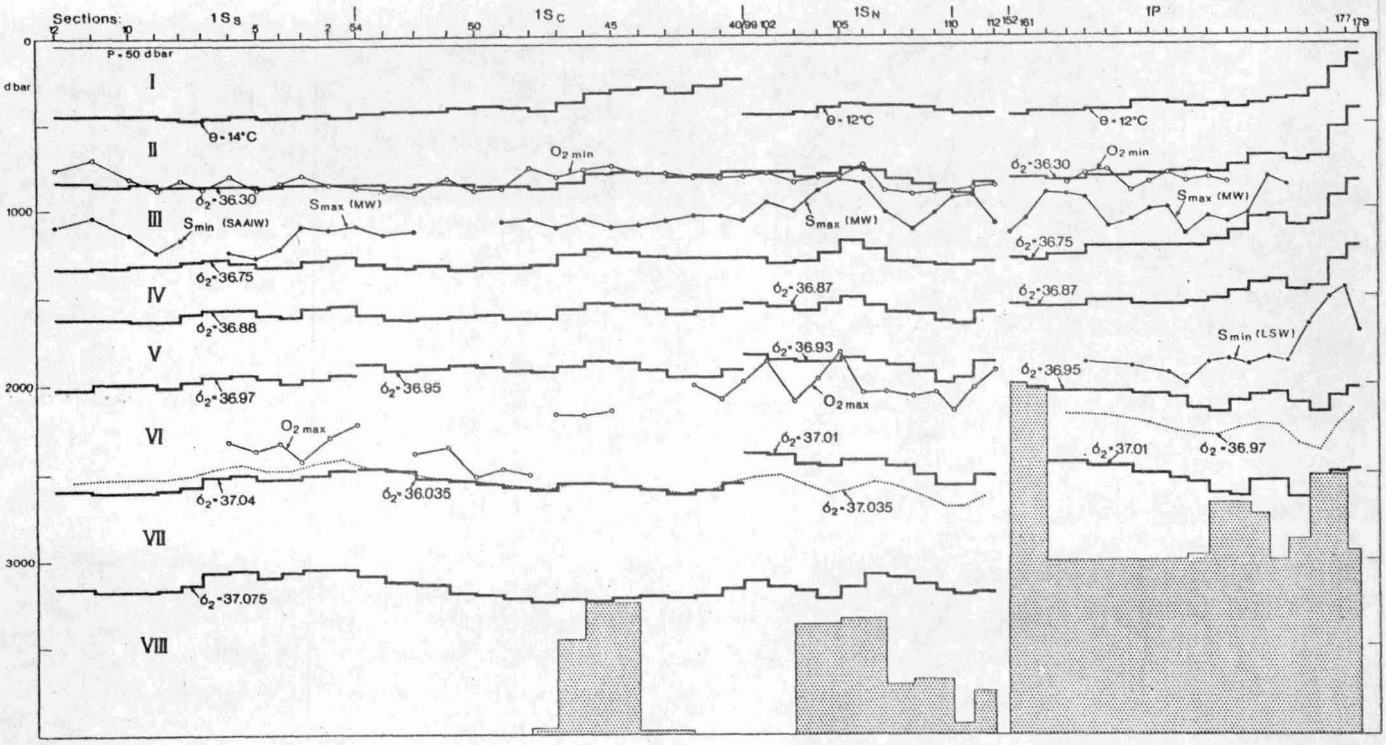


Fig. 2: The definition of the layers along the eastern section chosen for the box analysis for the "inverse method" as well as for the "empirical search method". The dotted line marks the reference-level finally used for the geostrophic calculations. Additionally, the main hydrographic features as obtained from the data are displayed.

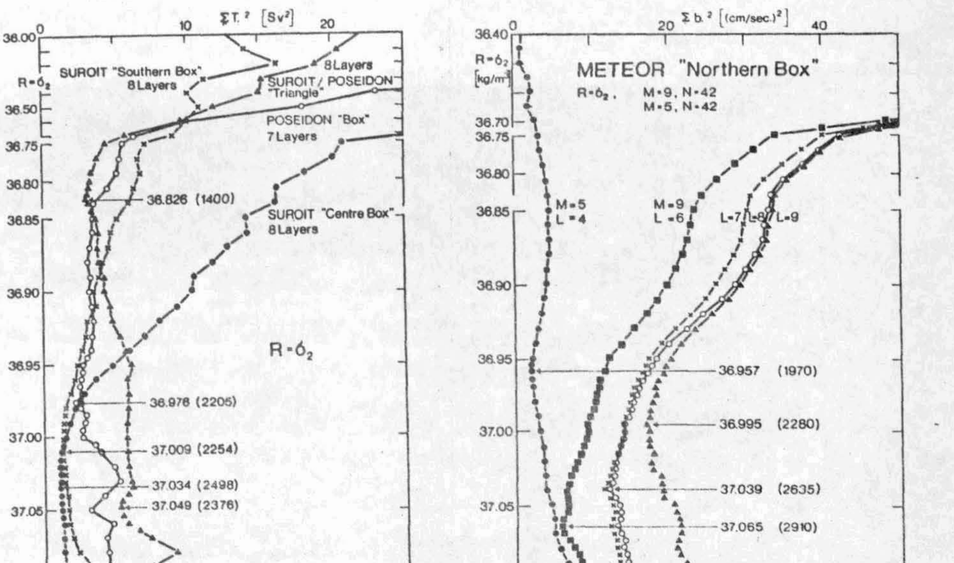
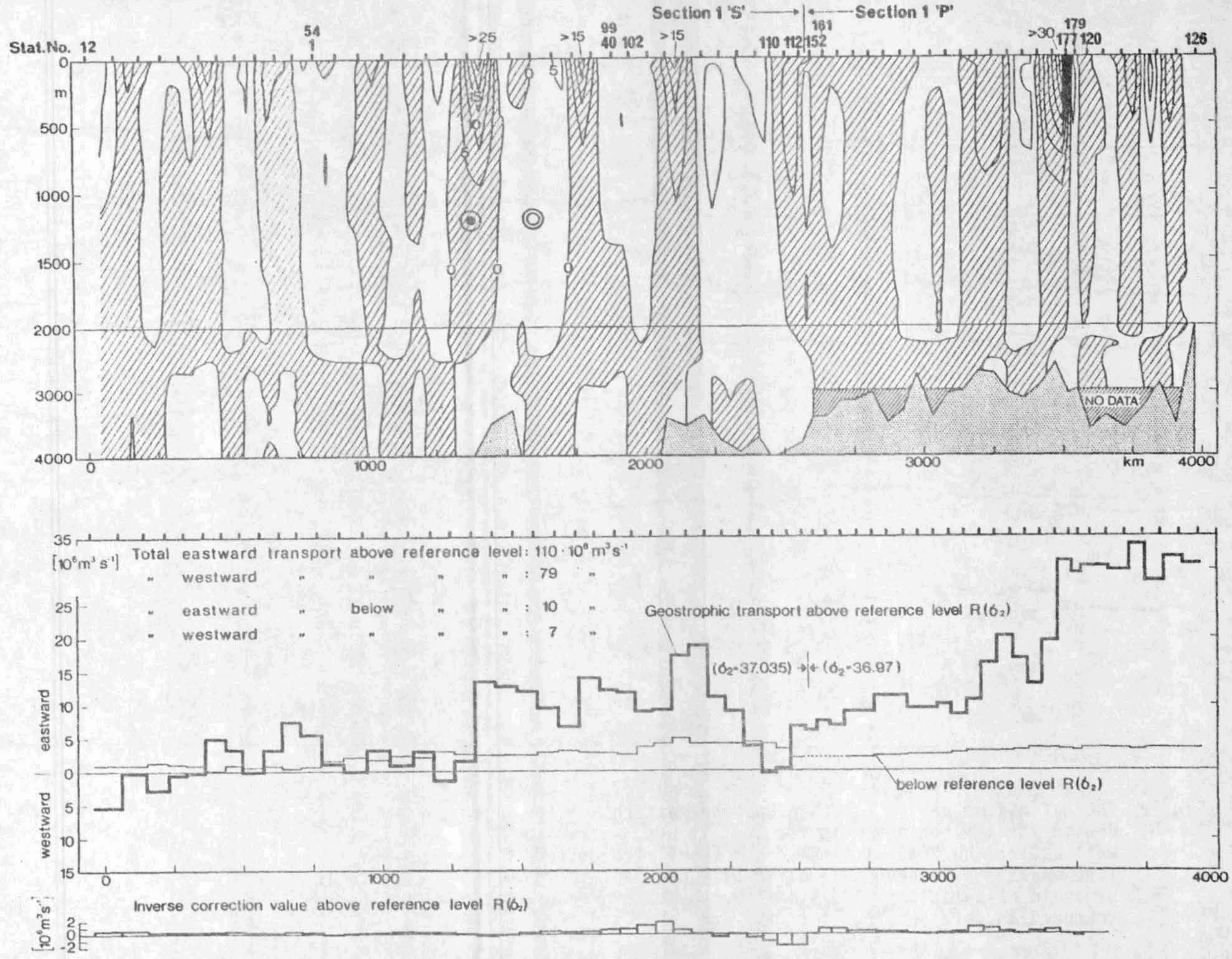


Fig. 3: a) Mean square transport imbalances $\sum_\ell T_\ell^2$ as a function of the reference-variable σ_2 for the four synoptic boxes of 1983 with l the layer.

b) Mean square inverse correction $\sum_j b_j^2$ as a function of reference-variable σ_2 and for various numbers of eigenvalues for the METEOR north box with j the stationpair.

a)



b)

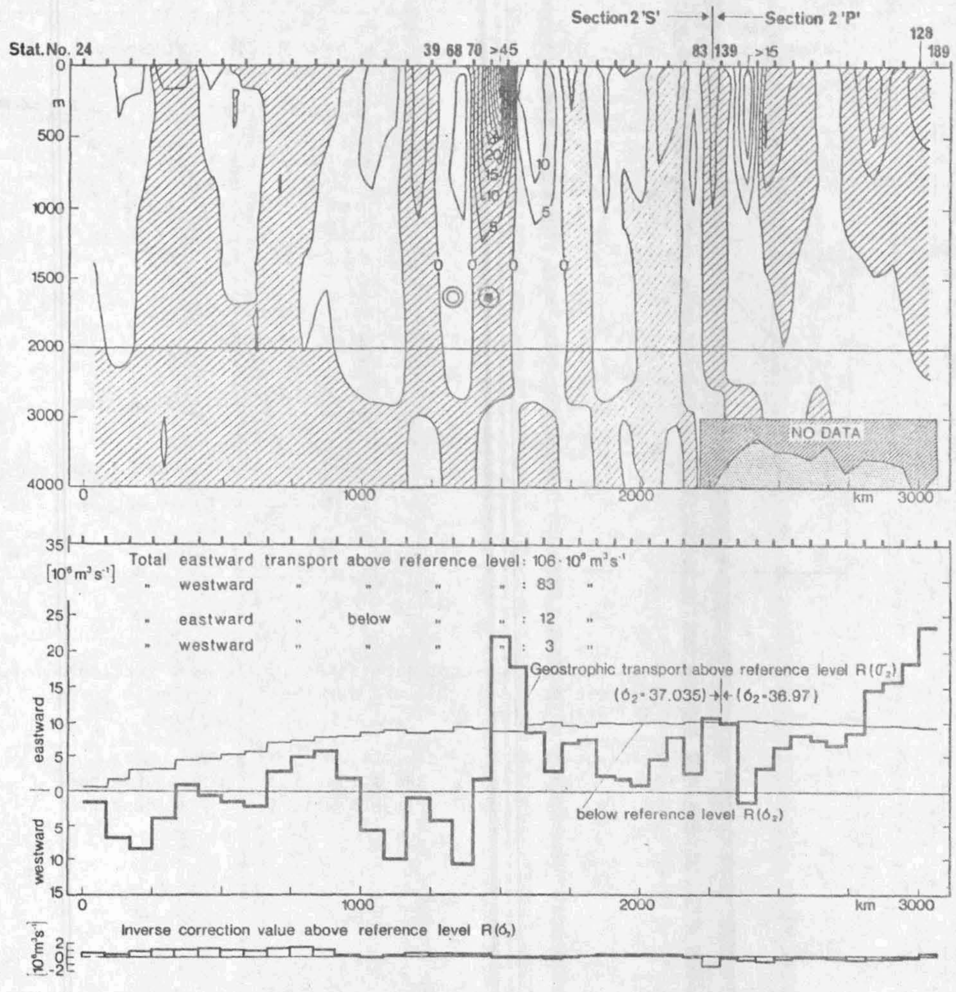


Fig. 4: a) The geostrophic currents, mass transports (cumulative from south to north) along the eastern section and the portion of the transport which is due to the applied inverse correction.

b) Same as fig. 4a, but for the western section.

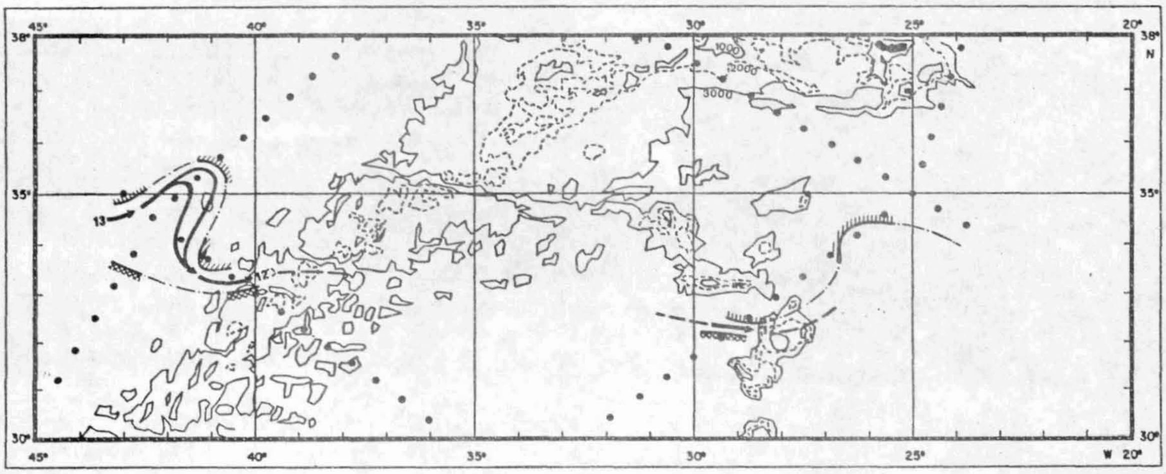


Fig. 5: The AC as found in the SUROIT central box.

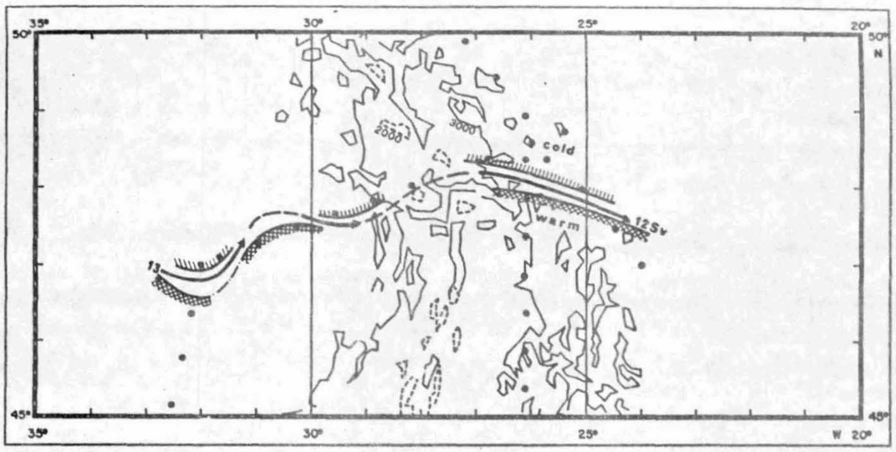


Fig. 6: The NAC as found in the POSEIDON box.

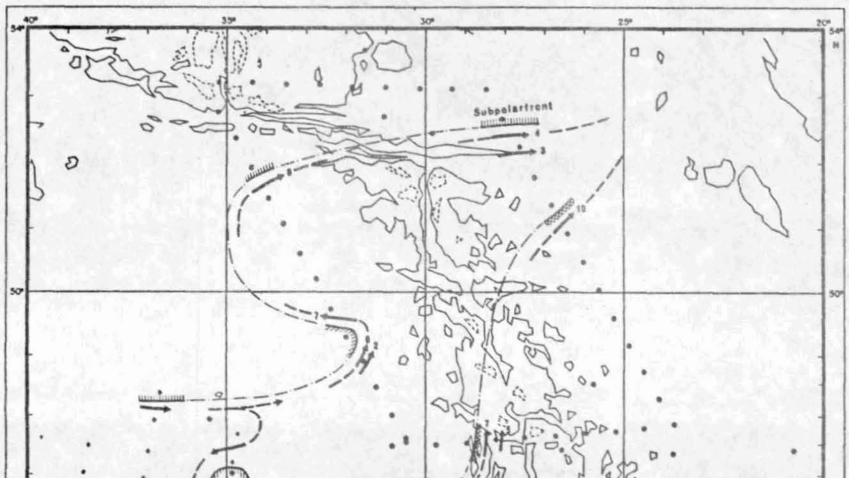


Fig. 7: The NAC as found in the METEOR boxes (•) and from a POSEIDON survey in the western North Atlantic at the same time (•).

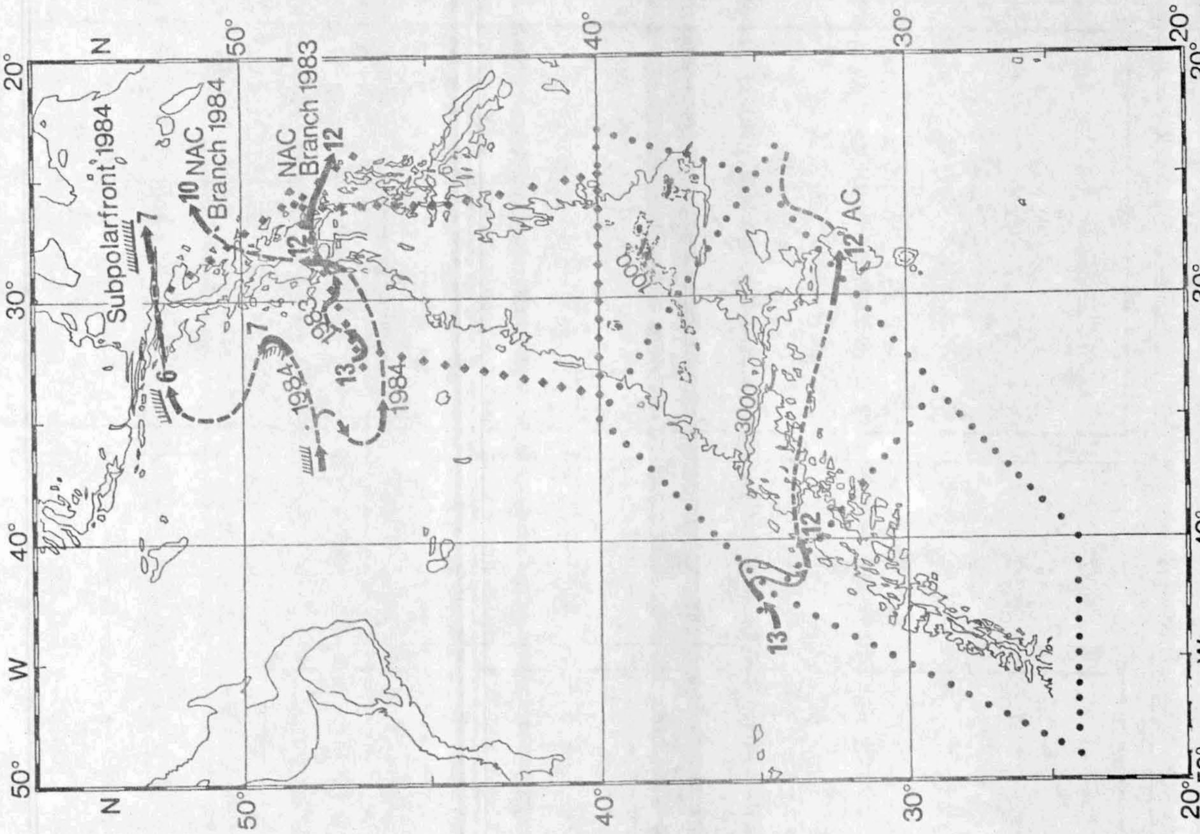


Fig. 8: Summarized overview of the main geostrophic currents as calculated from the TOPOGULF data.

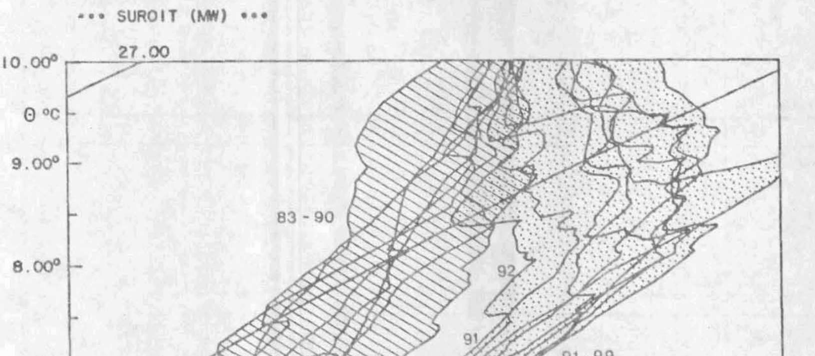
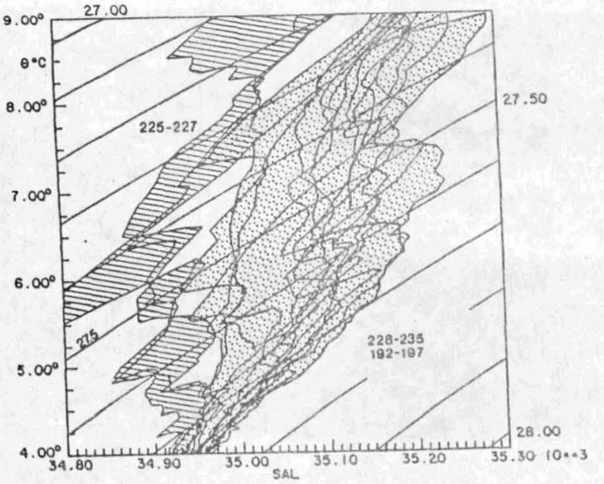
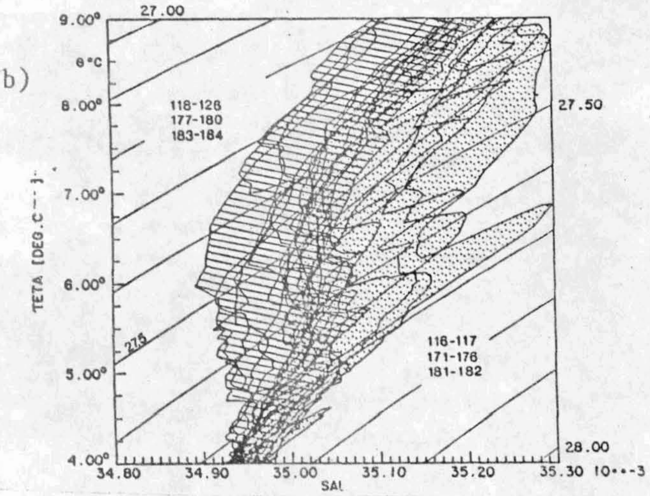


Fig. 9: The influence of the MAR on the spreading of the MW shown by θ/S diagrams across the MAR along section 6. The stippled area contains strong MW influenced water masses (all from the eastern part of section 6), the hatched area contains weak or no MW influenced water masses (all from the western part of section 6). Station 150 contains both characteristics.





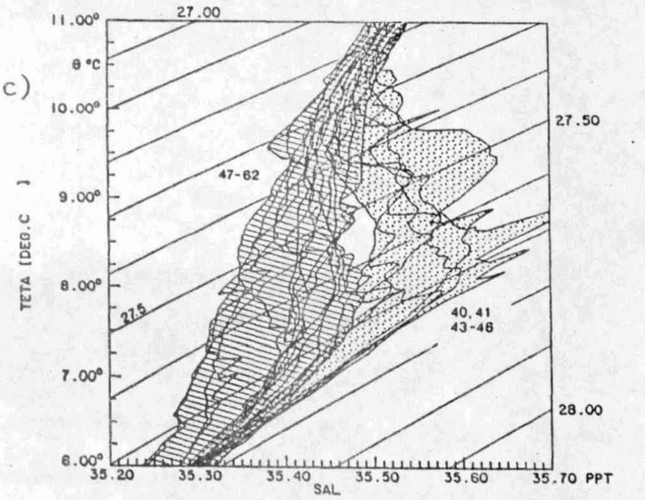


Fig.10: The influence of the NAC (a,b) and AC (c) on the MW spreading shown by θ/S diagrams. The stippled area contains profiles south of the NAC branch (a,b) and north of the AC (c).

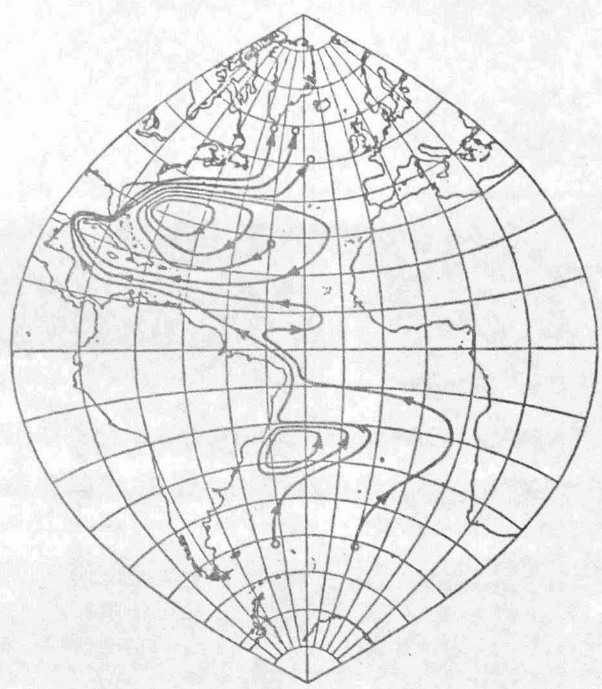


Fig.13: Scheme of the upper ocean circulation in the Atlantic after STOMMEL (1958, fig. 82a).

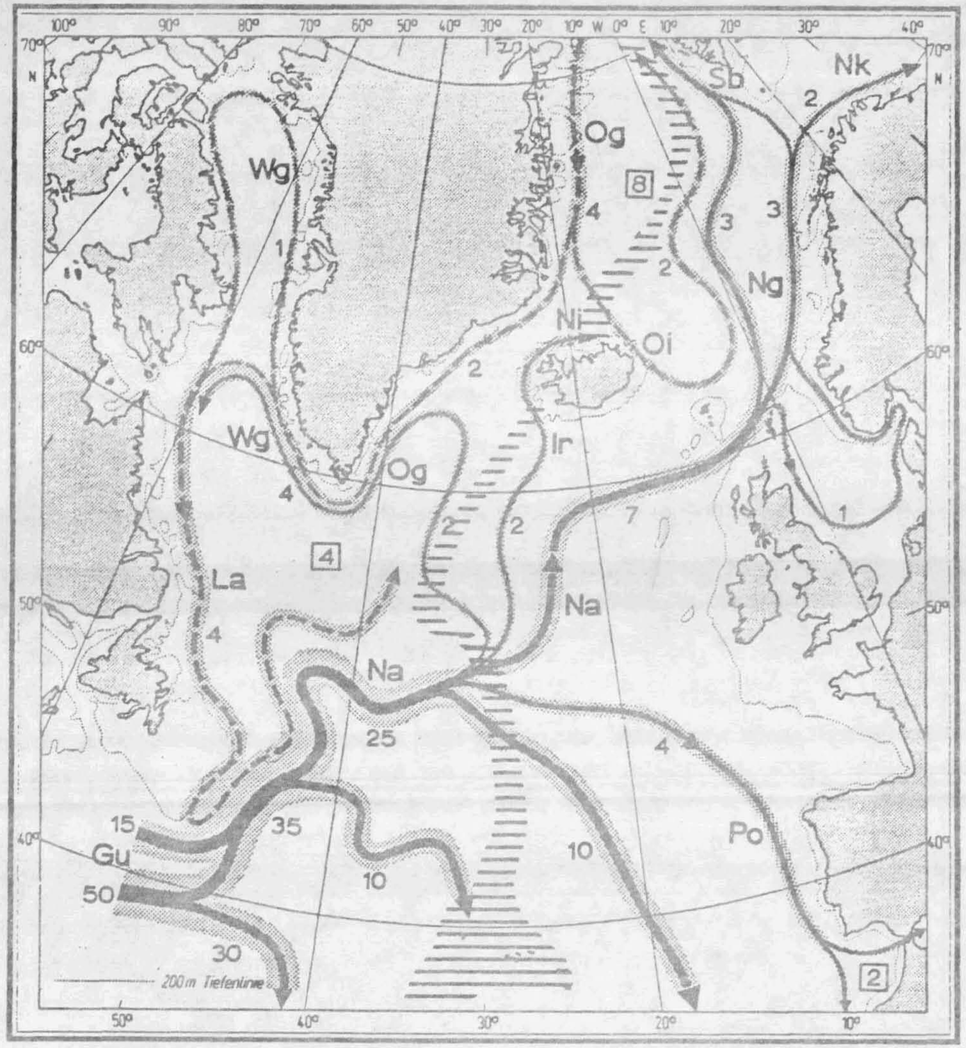


Fig.11: The North Atlantic Current after DIETRICH, KALLE, KRAUSS and SIEDLER (1975).

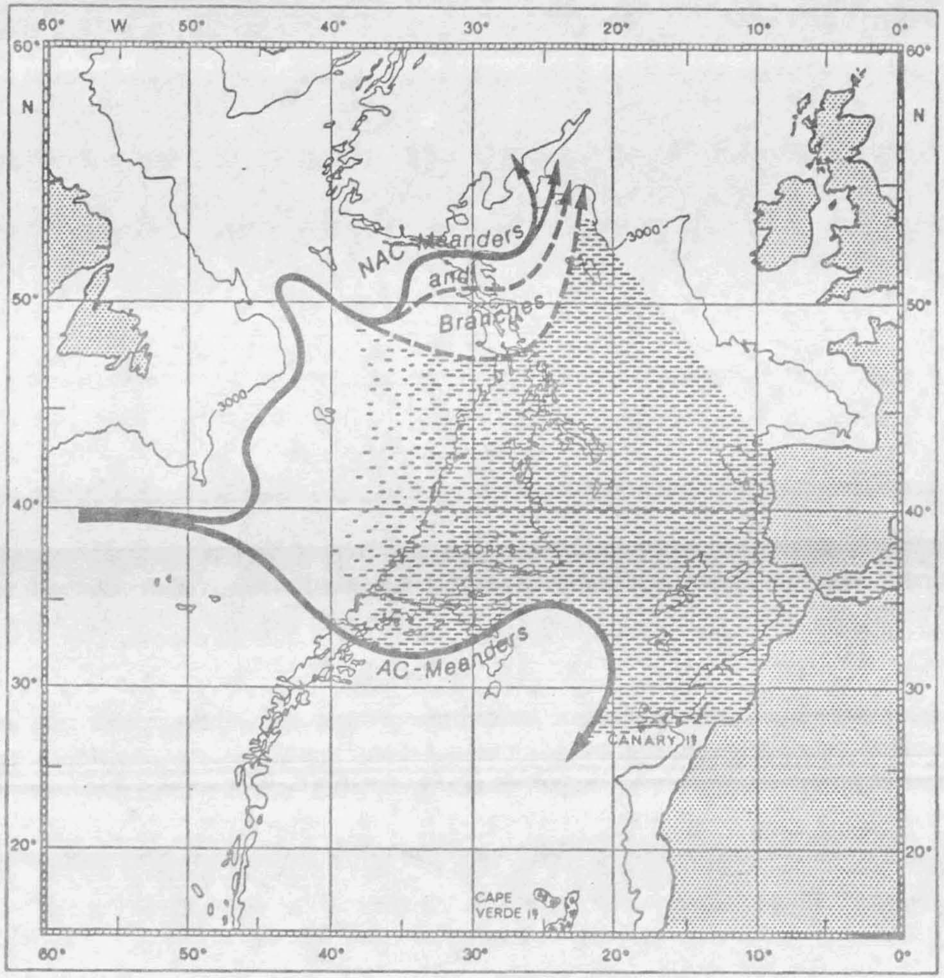


Fig.12: Diagrammatic map of the Gulf Stream extension currents NAC and AC and the MW tongue as an attempt to produce a coherent scheme deduced from this analysis and selected literature.