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On the origin of the intermediate double-maxima in T/S profiles from the North Atlantic*

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With 10 figures and 1 table

Ein Beitrag zum Ursprung der intermediären Doppelmaxima in Temperatur- und Salzgehaltprofilen aus dem Nordatlantik

Zusammenfassung

Kontinuierliche Temperatur- und Salzgehaltsprofile aus dem NE-Atlantik zeigen häufig im Bereich des Mittelmeerwassers eine Doppelmaxima-Struktur. Als Erklärung dieser speziellen Schichtungsform findet man in der Literatur zwei Hypothesen: a) Der Ausstrom wird im Golf von Cádiz durch unterschiedlich beschaffene Kanäle in mittlere Tiefen des Atlantiks geführt. Aufgrund der resultierenden ungleichen Vermischung von Mittelmeerwasser mit Atlantikwasser in diesen Kanälen entstehen unterscheidbare Wasserarten, die entsprechend ihrer Dichte die Doppelmaxima beim Verlassen des Golfes von Cádiz bilden. b) Durch gezeitengesteuerte Vermischungsprozesse in der Straße von Gibraltar werden bereits unterschiedliche Ausstrom-Wasserarten erzeugt, welche nach Passieren des Golfs von Cádiz unterschiedliche Tiefenhorizonte aufsuchen.

In der vorliegenden Untersuchung wird gezeigt, daß der Ausstrom bereits die Merkmale von diskreten Wasserarten besitzt, noch bevor sich ein Einfluß von unterschiedlichen Mischungsarten in den Kanälen im Golf von Cádiz ausgewirkt haben kann. Folglich werden diese diskreten Wasserarten, welche die Doppelmaxima im Atlantik bilden, schon in der Straße von Gibraltar angelegt.

Der mediterrane Ausstrom ist starken Schwankungen vornehmlich aufgrund von Gezeitenströmen unterworfen. Die Variabilität der Doppelmaxima läßt sich besser daraus herleiten als auch den unveränderlichen topographischen Eigenschaften der einzelnen Ausstromkanäle.

Summary

Continuous temperature and salinity profiles from the NE-Atlantic frequently show a double-maxima structure within the depth range of the Mediterranean outflow. Two explanations for this special thermohaline stratification can be found in literature: a) The density of the outflow is varied by different outflow channels with unequal mixing properties. b) In the Strait of Gibraltar two different outflowing water types are produced by tidal currents. In both cases the different water masses spread in different density levels in the Atlantic.

Data presented here indicate that the bimodal structure must be caused primarily by tidal currents at the source. Two-layered outflowing Mediterranean water was observed even before a splitting of the under-current in the Gulf of Cádiz takes place. The variability of the double-maxima can be explained by varying outflow rates in the source region rather than by a steady influence of the bottom topography.

Introduction

Continuous temperature (T) and salinity (S) profiles from the North Atlantic often show a double-maxima structure in the Mediterranean Outflow (henceforth MO). This special form of vertical meso-scale structure can be observed over a wide geographical area in the Atlantic (e.g., COOPER 1962; HOWE & TAIT 1972; SIEDLER & ZENK 1973). Similar observations in the Red-Sea outflow range

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have been reported by KRAUSE (1968). The time dependence of the MO structure has been investigated during a ten-day anchor station 40 km west off Cape St. Vincente (Portugal) simultaneously by means of bathysonde records (ZENK 1971) and hydrocasts (GIESKES et al. 1970). Time averaged properties obtained from these measurements are summarized in table 1. The results show that there exist two predominant depths in the range of the MO where salinity and temperature tend to be higher than in adjacent depths. Characteristic density levels (σ_t) for these two depths were found to be 27.51 and 27.83.

At least two explanations for the double-maxima can be given: a) The different outflow channels of the MO in the Gulf of Cádiz influence the mixing of quasi-homogeneous Mediterranean water and North Atlantic Central Water (NACW) in different ways which causes slightly different types of MO (SWALLOW 1969; MADELAIN 1970). b) In the Strait of Gibraltar the Mediterranean water and NACW are mixed by tidal currents. Thus two different MO-types are present even before the water leaves the sill area (SIEDLER 1968).

In both cases the slightly different outflowing water types reach different density levels in the Atlantic where they can be observed as the double-maxima in T and S profiles shown in table 1.

Table 1 Characteristic depths of the intermediate double maxima in the outflow range of the Mediterranean water as derived from the anchor station 65 (37° 05′ N, 9° 53′ W) of "Meteor" cruise 8 in 1967 according to (a) 61 Bathysonde records (ZENK 1971) and (b) 14 hydrocasts (GIESKES et al. 1970).

Tabelle 1 Mittlere Tiefenlage der intermediären Doppelmaxima im Ausstrombereich des Mittelmeerwassers nach Messungen auf der Ankerstation 65 (37° 05′ N, 9° 53′ W) während der „Meteor"-Reise 8 im Jahre 1967 nach 61 Bathysondenmessungen (a) bzw. 14 hydrographischen Serien (b).

mean depth (m)		max. temperature (°C)		max. salinity (‰)		σ_t	
a	b	a	b	a	b	a	b
800	700	11.9	12.0	36.15	36.15	27.52	27.50
1170	1250	11.2	11.3	36.39	36.40	27.84	27.83

During "Meteor" cruise 23 (SIEDLER 1970) numerous CTD and current meter data were obtained from the Gulf of Cádiz. They allow detailed investigation of the origin of the double-maxima in the context of horizontal and vertical distribution of temperature and salinity in the Gulf area. The locations of the stations and the sections discussed here are summarized in fig. 1.

Influence of the Strait of Gibraltar

Theoretical considerations (DEFANT 1961) and observational results (LACOMBE 1972) have shown that the basic water exchange in the Strait of Gibraltar is modulated by surface tidal waves passing the sill. The pulsation of in/outflow in the Strait is coupled with an internal oscillation of the vertical thermohaline stratification which in conjunction with the varying current profile, controls the amount of salt leaving the Mediterranean Sea during a tidal period.

SIEDLER (1968) gave an estimate for the frequency distribution p of the outflow volume as a function of the outflow salinity S. His model assumes the outflow to be mixed totally within a time period shorter than the semidiurnal tides. A strong vertical mixing is essentially caused by high current shear with a Richardson number $Ri = 0(0.15)$. The resulting distribution p (S) for the conditions in the Strait of Gibraltar has two predominant peaks. This indicates that two mixed MO types with preferred salinities are produced by tidal currents and are already present in the outflow source.

Inhomogeneities in the undercurrent

In order to study the strongly focused MO entering the Gulf of Cádiz a hydrographic section A (fig. 2) and repeated CTD casts (station 98) were made. The results show that the undercurrent is not a homogeneous, highly saline layer in section A. A division of the water mass into three types was obtained. One would expect a homogeneous layer if the different water types were produced primarily in the outflow channels beyond the position of section A.

The main part of the MO with the highest speed is a relatively thin layer (1) on the continental margin. It is shown in T/S diagrams in fig. 5 where repeated observations of station 98 are plotted and in fig. 6 for the single station 92.

Both curves also show the less saline and colder layer (2) which was found above (1) in section A. The circles in fig. 6 reproduce the equivalent point cloud from fig. 5 where the dots were plotted after equidistant interpolation.

Less information about the variability of a near shelf outflowing water type (3) in section A is available. Since this water type (3) was found as the source for the two northerly outflow channels it is seen in fig. 7 at station 96 as well as stations 46 and 50. Its core layer can be described by $S_3^A = 36.90‰$ and $\sigma_3^A = 27.60$.

The properties of layers (1) and (2) were studied during 25 hours by means of repeated CTD casts. The obtained isotherms and isohalines are presented in fig. 3. Their mean profiles and standard deviations

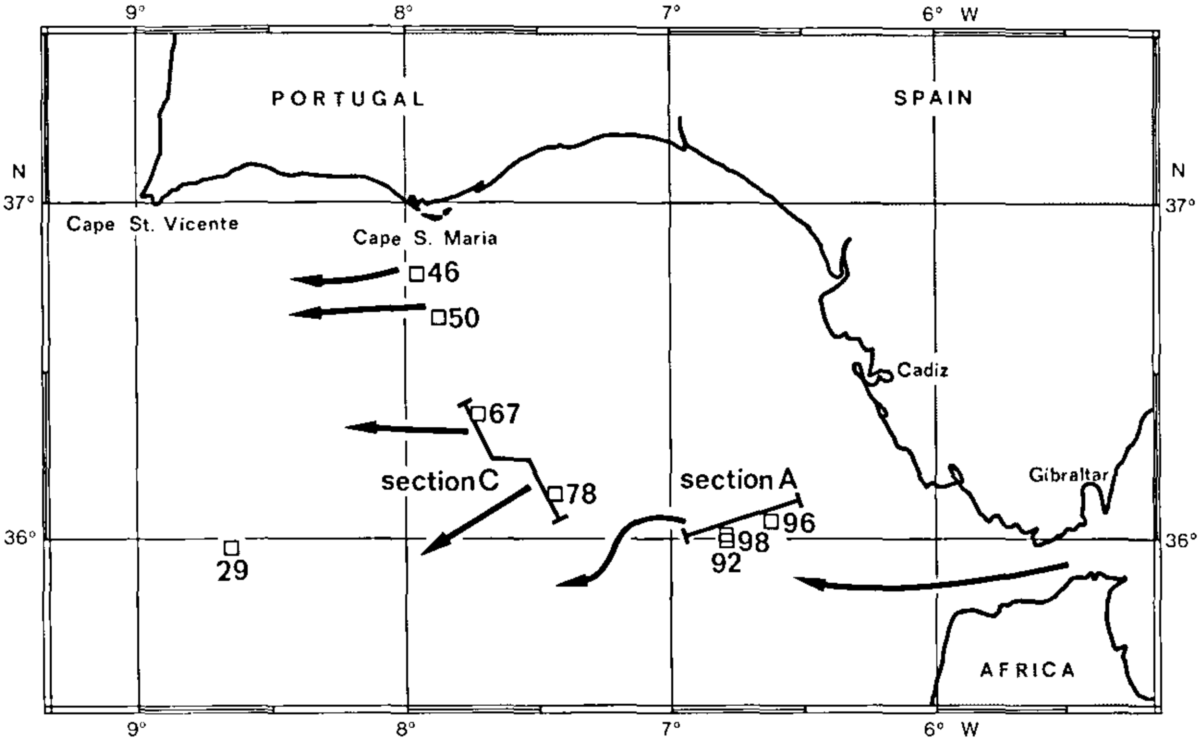

Fig. 1. Location of CTD stations and sections A and C in the Gulf of Cádiz. The arrows indicate mean outflow directions of the Mediterranean undercurrent.

Abb. 1. Lage der Hydrosondenstationen im Golf von Cádiz. Die Pfeile geben die mittlere Ausstromrichtung des Mittelmeerwassers an.

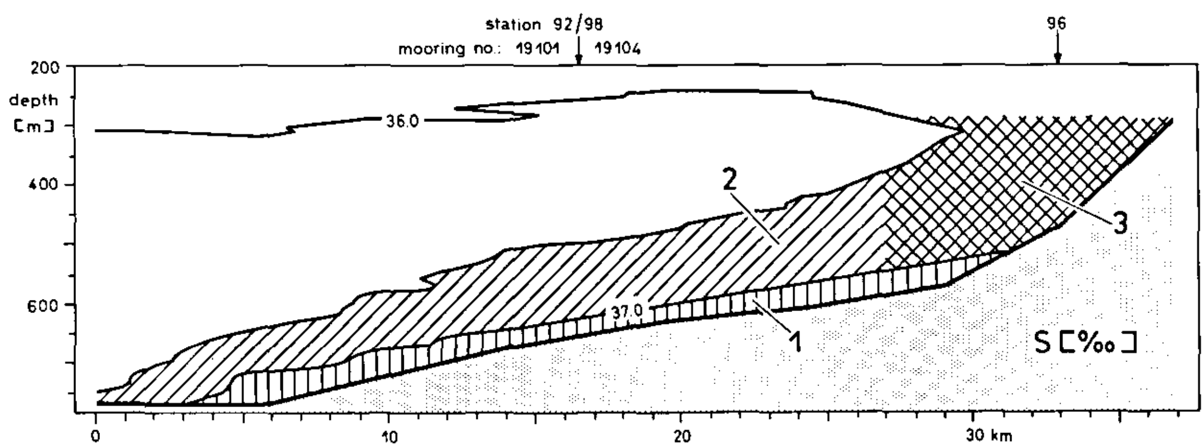

Fig. 2. Schematic section A through the undercurrent at the entrance to the Gulf of Cádiz. It shows the three different outflow water types.

Abb. 2. Schematischer Schnitt durch den Unterstrom beim Eintritt in den Golf von Cádiz. Drei verschiedene Ausstrom-Wassermassen sind eingezeichnet.

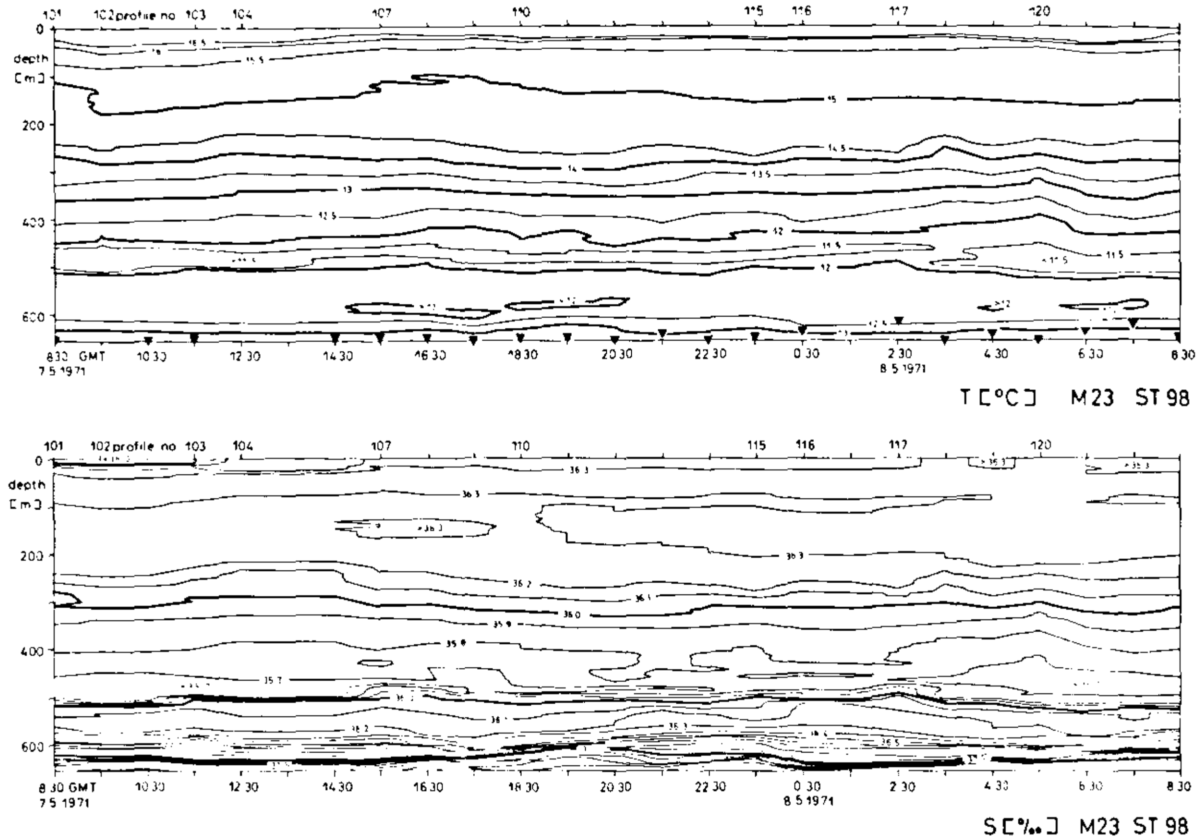

Fig. 3. Isopleth diagram of repeated CTD records at station 98 in the center of the undercurrent (section A). The triangles (▼) denote the maximum lowering depth of the single observations.

Abb. 3. Isoplethendiagramm von wiederholten Hydrosondenmessungen auf Station 98 innerhalb des Unterstromes (Schnitt A). Die Dreiecke (▼) geben die maximale Tiefe der Einzelmessungen an.

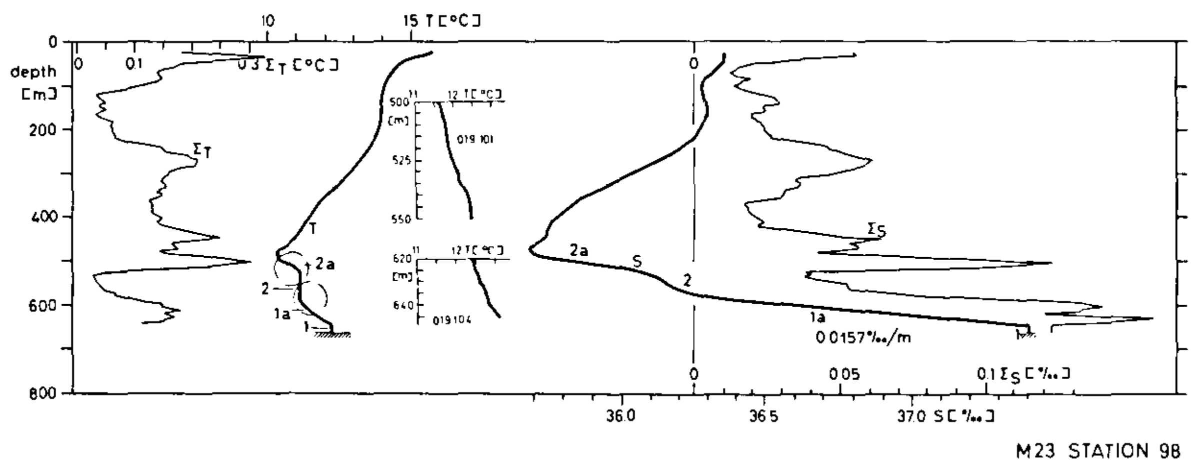

Fig. 4. Mean temperature (T) and salinity (S) profiles and their standard deviations (Σ) from repeated station 98. The inserts show two averaged temperature profiles in the depth intervals of thermistor chains 19101/4. These moored units have recorded during four weeks.

Abb. 4. Mittlere Temperatur- (T) und Salzgehaltsprofile (S) mit Standardabweichungen (Σ) von wiederholten Messungen auf Station 98. Außerdem sind die gemittelten Temperaturprofile der Thermistorketten 19101/4 eingezeichnet. Die verankerten Geräte haben vier Wochen lang registriert.

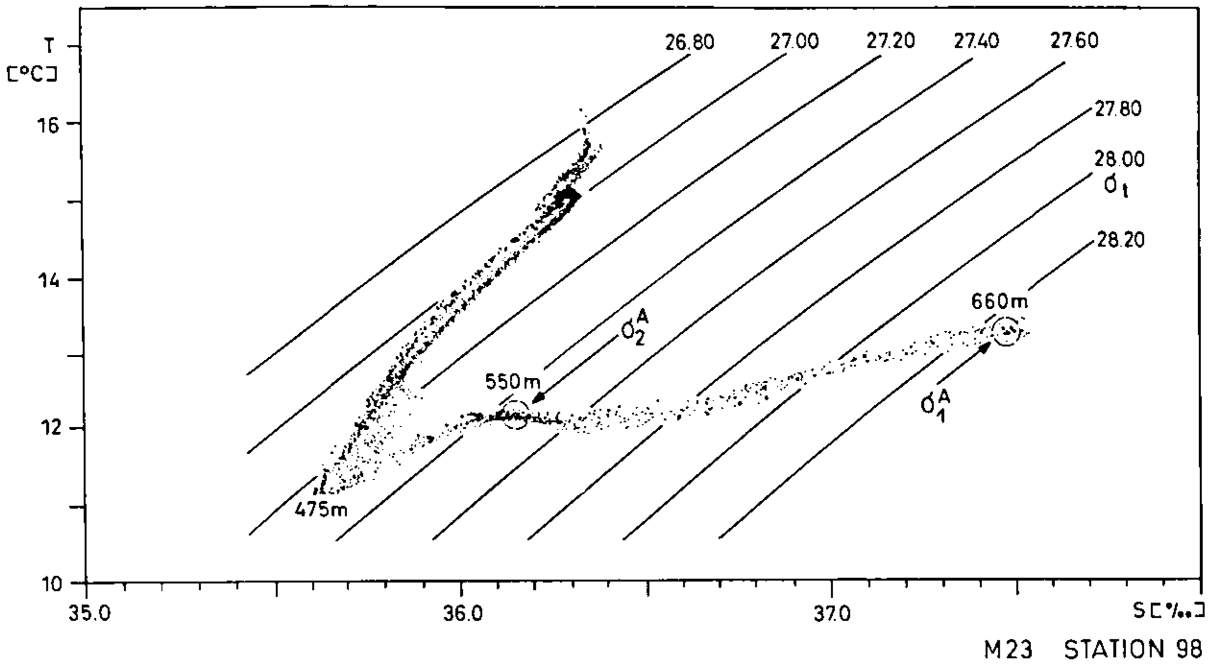

Fig. 5. T/S diagram of all records of station 98. This data from the center of the undercurrent were interpolated in 5 dbar-steps before plotting

Abb 5. T-S-Diagramm aller Messungen auf Station 98. Die Daten wurden vor der Eintragung in die Zeichnung auf 5-dbar-Intervalle interpoliert.

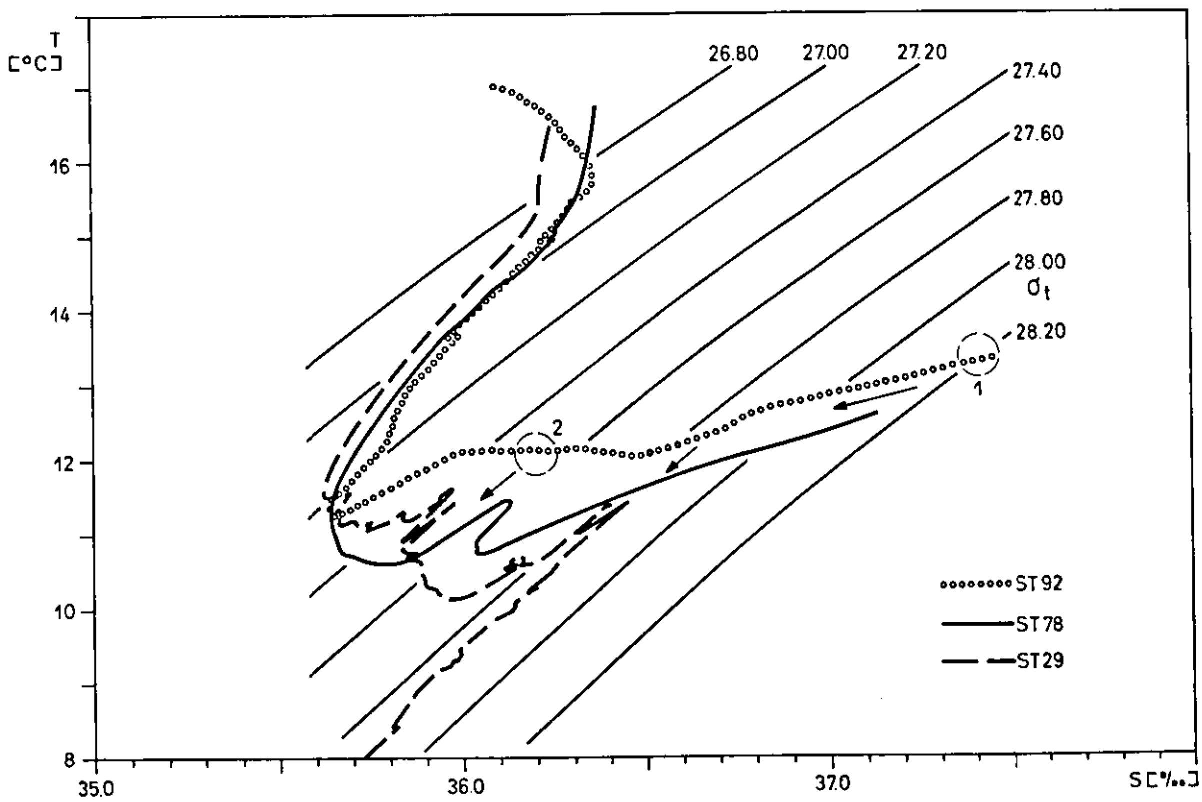

Fig. 6. T/S diagram of stations 29, 78 and 92. It shows the mixing of the main outflow branch between the gate way section A and the deep Atlantic.

Abb. 6. T-S-Diagramm der Stationen 29, 78 und 92. Die Kurven zeigen die Vermischung des Hauptausstroms zwischen Schnitt A und dem tiefen Atlantik.

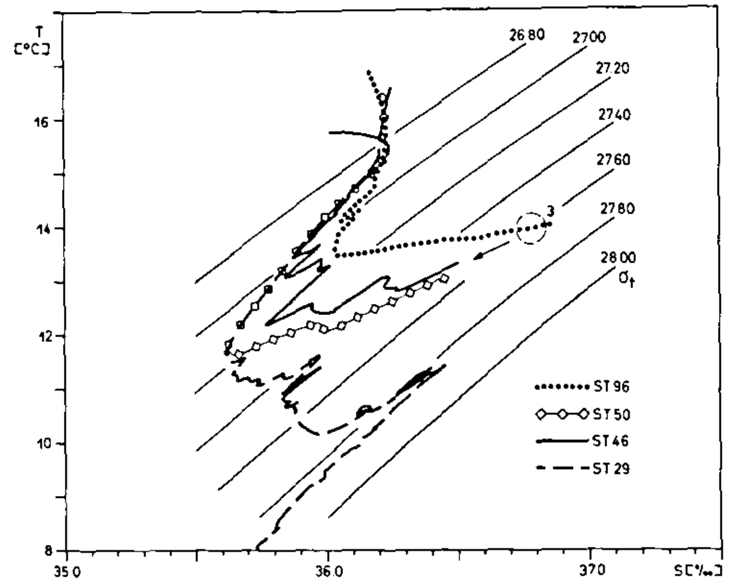

Fig. 7. T/S diagram of stations 29, 46, 50 and 96. The curves show the mixing within the near shelf outflow branches starting at gate way section A.

Abb. 7. T-S-Diagramm der Stationen 29, 46, 50 and 96. Die Kurven zeigen die Vermischung innerhalb des schelfnahen Ausstromarmes, die bei Schnitt A beginnt.

are given in fig. 4. The averaged profiles from two thermistor chains are inserted. These were obtained by mooring 19 which was situated 9 km northwestward from the section. The profiles are consistent with the 25 h CTD mean values. Figure 4 shows the stable double structured profile in the range of the MO with layers (1) and (2) separated by highly variable mixing zones (1a) and (2a). Typical value for stable layers are $S_1^A = 37.50‰$, $\sigma_1^A = 28.25$ and $S_2^A = 36.15‰$, $\sigma_2^A = 27.45$ (Fig. 5).

The presence of three instead of two predominant outflow water masses in the gate way section A hints that the mixing processes in the Strait of Gibraltar are more complicated than assumed in SIEDLER's model. Local effects at the continental shelf may also have an influence on the formation of type (3). BELDERSON & KENYON (1973) have found traces of a southeastward counter current in sonographs from that area.

Structure of the outflow entering the deep Atlantic

The MO splits into several branches on its way into the deep Atlantic. The existence of four separated outflow branches was shown earlier by the author (ZENK 1975).

Water from the highly dense layer (1) near the bottom of section A with the typical salinity >37.2‰ can be easily traced to its take off point at the SW edge of the Gulf of Cádiz. Some of this outflowing water was detected in station 78 on the SE side of the main outflow section C. Another filament of the same highly saline and rapidly flowing bottom layer in section A follows the contours of the south canyon which divides immediately to the west of section A. The interaction of this effective outflow vein with the sea floor was demonstrated impressively by KENYON & BALDERSON's (1973) sonographs.

The T/S diagram in fig. 6 shows clearly the relationship between station 92 (one example from section A) and station 78. The continuation of the main outflow branch down into the Upper Deep Atlantic Water is demonstrated by comparing these stations with the sample station 29 south of Cape St. Vincente. At station 29 the MO has found its density level of $\sigma_t = 27.85$. This is similar to the observations on the anchor stations west of Cape St. Vincente (see table 1).

In the same way the mixing of the lower saline layer (2) found in fig. 5 and reproduced in fig. 6, can be studied. It mixes downwards where it contributes to the formation of the upper maximum which was found in both stations 78 and 29.

In a similar way water type (3) of section A can be traced along the continental margin. The mixing between this water type and NACW leads directly to the T/S relations of stations from the shelf branch (station 46) and the intermediate branch (station 50) shown in fig. 7. Outflowing water from this origin has a density $\sigma_t = 27.55$ when it reaches the deep Atlantic near Cape St. Vincente which corresponds to the same level found for the upper

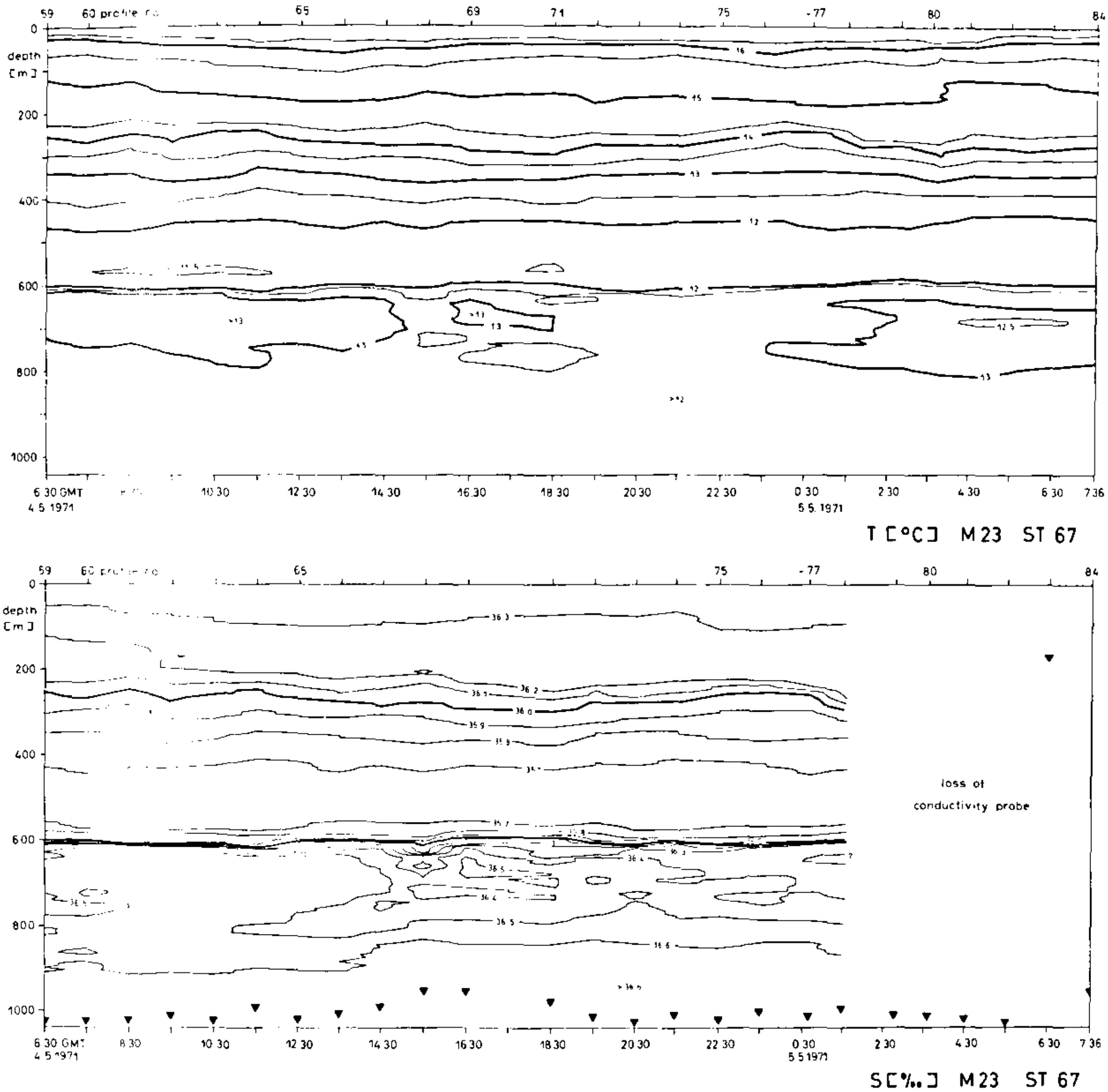

Fig. 8. Isopleth diagram of temperature and salinity from repeated CTD records at station 67.

Abb. 8. Isoplethendiagramm der Temperatur und des Salzgehaltes von wiederholten Hydrosondenmessungen auf Station 67.

maximum in the repeated profiles from the Meteor anchor station in 1967 (table 1). For comparison the T/S curve from station 29 with its typical behavior for the NE Atlantic is seen in fig. 7. Because of the geographical location, however, it is clear that this station is not influenced by the northern outflow branches.

Further evidence for the formation of the double structure comes from data on the NW side of section C. The remarkable difference between this side and the SE side lies in the unequal levels of the maximum speeds. The geostrophic current profile which fits the recorded current meter data indicates that the NW outflow feeds the depth level of the upper maximum. Repeated CTD observations were used to study the variability of this filament. Figure 8 and fig. 9 show isopleth diagrams for temperature and salinity and their mean values including standard deviations.

The high variability found in the depth interval 600–700 m indicates the rather atypical situation during the observation. From the insert in fig. 10 one recognizes that the data were taken during an extraordinary flow of warm Mediterranean Water. However, the bimodal structure persists even during this singular event of unusually high Mediterranean water flow as fig. 10 shows. The upper maximum associated with speeds >40 cm/sec was observed in

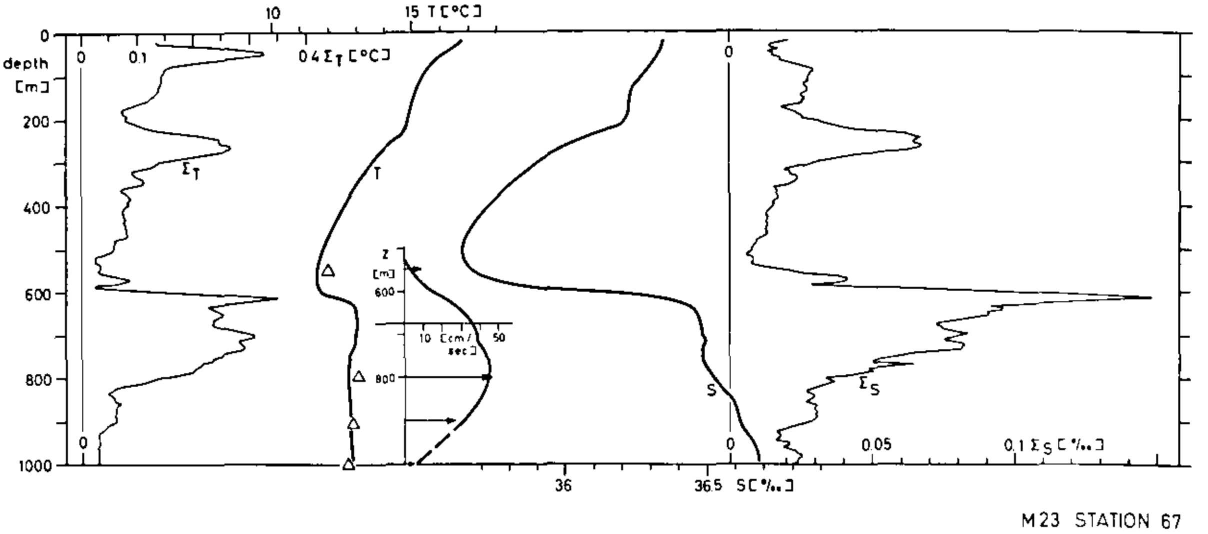

Fig. 9. Mean temperature (T) and salinity (S) profiles and their standard deviations (Σ) from repeated station 67. The insert shows the geostrophic current profile at station 67 together with mean speed arrows recorded by mooring 22.

Abb. 9. Mittlere Temperatur- (T) und Salzgehaltsprofile (S) mit Standardabweichungen (Σ) von wiederholten Messungen auf Station 67. Das eingezeichnete geostrophische Stromprofil von Station 67 stimmt mit den Geschwindigkeitsvektoren von Verankerung 22 überein.

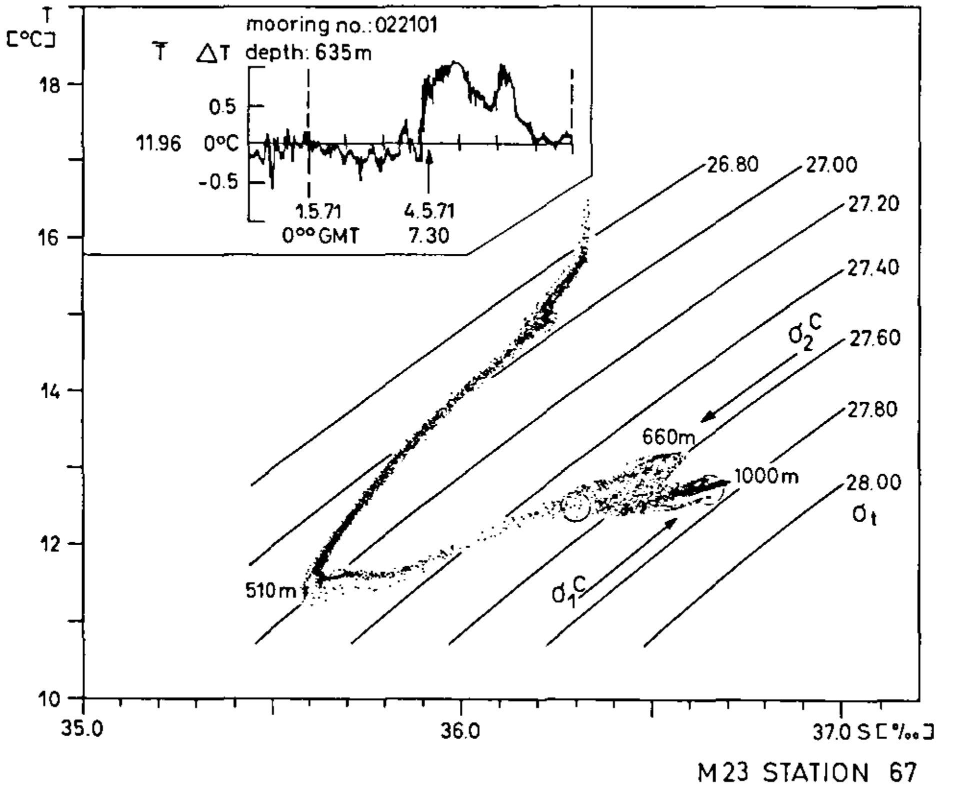

Fig. 10. T/S diagram of all records of station 67. The data were made equidistant ($\Delta p = 5$ dbar) before plotting. The insert shows the extraordinary high temperature during the observational time of station 67.

Abb. 10. T-S-Diagramm aller Messungen auf Station 67. Vor dem Zeichnen wurden die Daten äquidistant interpoliert ($\Delta p = 5$ dbar). Die Zusatzzeichnung zeigt die außergewöhnlich hohe Temperatur, die während der Beobachtungszeit auf Station 67 herrschte.

the density level $\sigma_2^C = 27.58$. The secondary maximum with its lower speed <30 cm/sec reaches a density $\sigma_1^C = 27.75$. Although these two predominant density levels do not coincide exactly with the preferred levels given in table 1, they are an example of the variability of the double maxima.

The origin of the water masses found in fig. 8–10 on the NW side of section C is difficult to explain uniquely. Probably it is a mixture of all three water types found at the gate way section A. This mixing takes place while traveling down to section C. By volumetric analysis (ZENK 1975) the near-shelf part alone can contribute only a minor part of this outflow type.

Conclusions

From the observations it is evident that the Mediterranean undercurrent is already structured when it enters the Gulf of Cádiz. Tidal currents in the Strait of Gibraltar have a strong effect in the formation of preferred outflowing water types. According to their different densities these water types are distributed into several outflow channels. When they leave the Gulf they are able to form sharp double maxima in the temperature and salinity profiles of the Atlantic.

Besides mixing on the way into the Atlantic these structures are influenced by seasonal effects and meteorological factors in the source area which leads to the variability in the sharpness of the double maxima. For instance air pressure differences between the Gulf of Cádiz and the Alboran Sea can have a major influence on the current in the Straits (CRÉPON 1965) and consequently on the MO. Therefore the origin of the double maxima is primarily related to modulations in the rate of mixing at the source region. The influence of the topography in the Gulf of Cádiz seems to be of secondary importance on the formation of the double maxima.

Acknowledgments

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