Origin of the Mediterranean outflow

by Harry L. Bryden[1] and Henry M. Stommel[2]

ABSTRACT

The origin of the Mediterranean outflow is one of oceanography's oldest problems. In this work, the flow of western Mediterranean deep water up and over the sill at Gibraltar is investigated from hydrographic observations and current measurements. The deep water is found to flow westward along the Moroccan continental slope in the western Mediterranean or Alboran Sea and to rise as it approaches the Strait of Gibraltar. As it enters the Strait, the deep water has potential temperature and salinity characteristics identical to those of newly formed deep water off the southern coast of France, and it is at a depth of 400 m, only 100 m below sill depth. Year-long current meter measurements show the outflow of deep water to be quite steady. The transport of this outflow of western Mediterranean deep water is estimated to be 0.26×10^6 m^3s^{-1}, which is comparable with estimates of its formation rate. This outflow then provides a direct exodus of the deep water from the western Mediterranean basin.

The deep westward flow along the Moroccan continental slope indicates that the anticyclonic gyre in the Alboran Sea extends throughout the water column. This gyre provides the high velocities necessary to raise the deep water up toward the Strait of Gibraltar. The upward flow of deep water, in turn, provides the source of anticyclonic vorticity necessary to maintain the gyre against frictional dissipation.

1. Introduction

The source of the Mediterranean outflow is one of the oldest oceanographic problems (Deacon, 1971). While it was recognized that evaporation over the Mediterranean greatly exceeds precipitation and river runoff, the inflow of surface water from the Atlantic into the Mediterranean through the Strait of Gibraltar is clearly larger than the excess evaporation, and schemes for returning water to the Atlantic by underground channels were imagined. By means of an ingenious laboratory experiment in which he separated two water types of different density in a tank, removed the partition, and observed the denser water to flow under the less dense water, Marsigli (1681) demonstrated that water could be returned to the Atlantic by a deep outflow of denser Mediterranean water through the Strait of Gibraltar beneath the inflowing Atlantic water. Two centuries later, this deep

1. School of Oceanography, WB-10, University of Washington, Seattle, Washington, 98195, U.S.A.

2. Department of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, 02543, U.S.A.

outflow was finally confirmed when Carpenter lowered a drogue from a small boat to 250 fathoms and observed the boat to drift westward opposite the eastward surface current (Carpenter and Jeffreys, 1870).

The outflowing Mediterranean water at Gibraltar is generally considered to be made up of two types of water: Levantine intermediate water formed near Rhodes and characterized throughout the Mediterranean by a mid-depth or intermediate maximum in both temperature and salinity (Wüst, 1961) and western Mediterranean deep water formed south of France and characterized by a potential density of 29.10 kg m^{-3} or greater and a potential temperature less than 12.90°C (Stommel, 1972). Wüst emphasized the contribution of Levantine intermediate water to the outflow at Gibraltar. Lacombe and Tchernia (1972), however, pointed out that its intermediate maximum is much diminished even in the Alboran Sea between Spain and Morocco because of mixing with western Mediterranean deep water, and hence the outflowing water should be considered to be made up essentially of western Mediterranean deep water.

Because of the recent studies of the formation process of western Mediterranean deep water (Medoc Group, 1970), it is of interest to investigate whether this water might flow directly up and over the sill at Gibraltar, thereby providing a direct exodus from the deep western basin. Such a direct flow would be in contrast with the common view that the deep water percolates slowly upward throughout the western Mediterranean to mix with the intermediate water. Such a direct flow seemed possible on the basis of a Bernoulli equation argument, but observational evidence in historical data was scanty (Stommel *et al.*, 1973). Therefore, a set of Conductivity-Temperature-Depth (CTD) measurements and moored current meter measurements was carried out in the Alboran Sea to search for a direct flow of western Mediterranean deep water up and over the Gibraltar sill. This report presents the resulting observational evidence for such a direct flow.

2. Measurements

A hydrographic survey in the Alboran Sea (Fig. 1) was carried out during February 1975 aboard R/V *Chain* using the CTD system developed by Brown (1974). This survey was designed to obtain three types of information. Initially, transects (labeled I and II in Fig. 1b) were made across the Alboran Sea from Morocco to Spain to identify the region of strongest flow of western Mediterranean deep water. After this signal was detected on the southern side, short transects across the Moroccan continental slope were made east and west of the initial sections to trace the course of flow of western Mediterranean deep water. Finally, a long east-west transect was made along the deepest part of the Alboran Sea and was extended from the Gibraltar sill at CTD station 25 to the eastern basin south of Greece at CTD station 84. Because we were unable to obtain clearance from the Spanish government of that time to make stations within her 6-mile territorial sea,

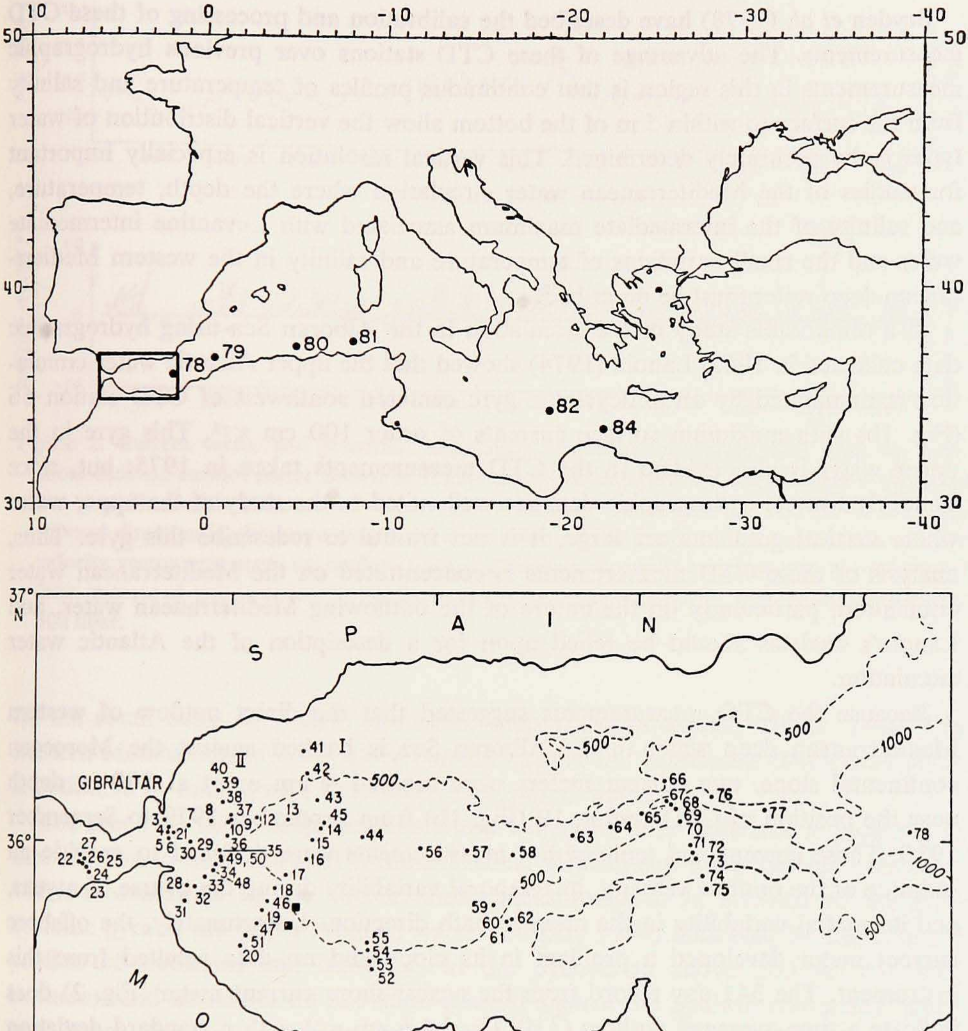

Figure 1. Location of measurements: (a) positions of CTD stations 78 through 84 taken across the Mediterranean and location of the Alboran Sea (enclosed by heavy lines) where most CTD stations were taken; (b) positions of CTD stations 3 through 78 and of current meter mooring positions, denoted by darkened squares, in the Alboran Sea.

no transects could be made across the Strait of Gibraltar or close to Ceuta, which is the Spanish territory directly south of Gibraltar, and sections I and II were ended prematurely 7 miles from the Spanish coast at CTD stations 41 and 40, respectively.

Bryden *et al.* (1978) have described the calibration and processing of these CTD measurements. The advantage of these CTD stations over previous hydrographic measurements in this region is that continuous profiles of temperature and salinity from the surface to within 5 m of the bottom allow the vertical distribution of water types to be accurately determined. This vertical resolution is especially important for studies of the Mediterranean water circulation where the depth, temperature, and salinity of the intermediate maximum associated with Levantine intermediate water and the small variations of temperature and salinity in the western Mediterranean deep water must be described.

In a remarkable study of the circulation in the Alboran Sea using hydrographic data collected in 1962, Lanoix (1974) showed that the upper Altantic water circulation is dominated by an anticyclonic gyre centered southwest of CTD station 56 (Fig. 1b) with maximum surface currents of order 100 cm s^{-1}. This gyre in the upper water is also evident in the CTD measurements taken in 1975; but, since Lanoix's discrete hydrographic data are well suited to the study of the upper water where vertical gradients are large, it is not fruitful to redescribe this gyre. Thus, analysis of these CTD measurements is concentrated on the Mediterranean water circulation, particularly on the nature of the outflowing Mediterranean water, and Lanoix's analysis should be relied upon for a description of the Atlantic water circulation.

Because the CTD measurements suggested that the direct outflow of western Mediterranean deep water in the Alboran Sea is banked against the Moroccan continental slope, two current meters were moored 8 km apart at 500 m depth near the position of CTD station 19 (Fig. 1b) from September 1979 to September 1980. These current and temperature measurements were designed to provide an estimate of the outflow velocity, its temporal variability during the course of a year, and its spatial variability in the cross-isobath direction. Unfortunately, the offshore current meter developed a problem in its clock and no data resulted from this instrument. The 341-day record from the nearer-shore current meter (Fig. 2) does indicate a time-averaged outflow (310°T) of 4.6 cm s^{-1} with a standard deviation due to temporal variations of only 4.3 cm s^{-1}.

3. Deep water circulation

The most notable feature in the distribution of potential temperature and salinity in sections I and II across the Alboran Sea from Spain to Morocco (Figs. 3 and 4) is the sharp slope of isotherms colder than 12.90°C and isohalines below the salinity maximum against the southern or Moroccan continental slope. This water is essentially pure western Mediterranean deep water. For example, the water at 450 m depth at CTD station 34 has a potential temperature (θ) of 12.79°C, salinity *(S)* of 38.432‰ and potential density (σ_θ) of 29.113 kg m^{-3}. Such properties place it in the transition region between deep water observed to form in late winter of 1969

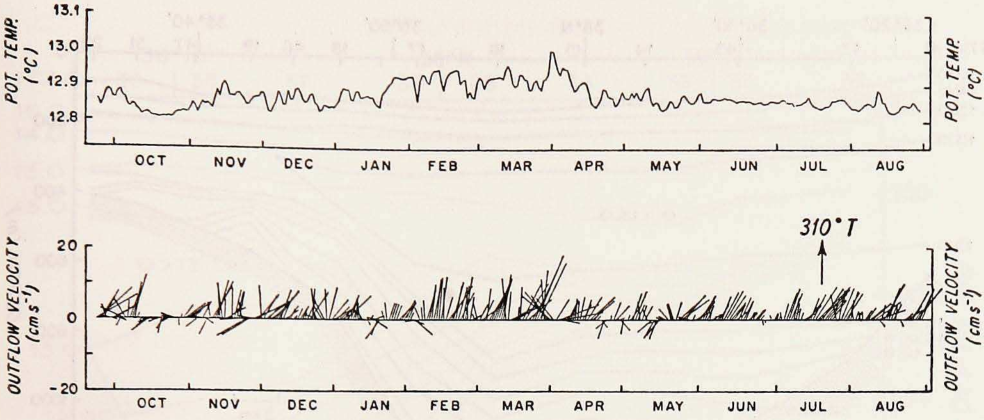

Figure 2. Current vector and potential temperature measurements versus time from the near-shore moored current meter shown in Figure 1b. Measurements are put through a Gaussian low-pass filter with 24-hour half-width and subsampled daily. For the current vectors, the upward direction is chosen to match the orientation of the local isobaths so that an upward velocity vector represents an outflow toward Gibraltar. Potential temperatures are calculated from measured temperatures by assuming constant salinity, 38.4‰, and constant pressure, 500 dbar.

off the south coast of France and older deep water (Stommel, 1972). Thus, this western Mediterranean deep water banked against the Moroccan continental slope is undiluted by mixing with Levantine intermediate water.

The slope of these deep isotherms and isohalines also indicates a geostrophic flow relative to the bottom of western Mediterranean deep water toward Gibraltar, which is confirmed by the current meter measurements. In contrast to the anti-cyclonic gyre in the upper Atlantic water (Lanoix, 1974) indicated by the concave profiles of isotherms and isohalines in the pycnocline above 200 m, the deep isotherms and isohalines do not slope upward against the Spanish continental slope and, hence, there is no return flow at the same depth of western Mediterranean deep water back into the Mediterranean along the Spanish side. If a return flow of deep water did occur, it would have to plunge from 400 m depth at station 34 to 800 m depth at station 38 in a distance of order 30 km. Such a great change in depth seems unlikely. Thus, western Mediterranean deep water not only flows toward Gibraltar along the Moroccan continental slope, but it does not recirculate back into the Mediterranean; hence, the conclusion must be that this water flows over the sill at Gibraltar into the Atlantic.

The circulation of the Alboran Sea can be quantified by making geostrophic calculations of currents from the CTD measurements. The traditional reference level for geostrophic calculations in this region is the depth of transition between Atlantic and Mediterranean waters which closely follows the 14°-isotherm in these measure-

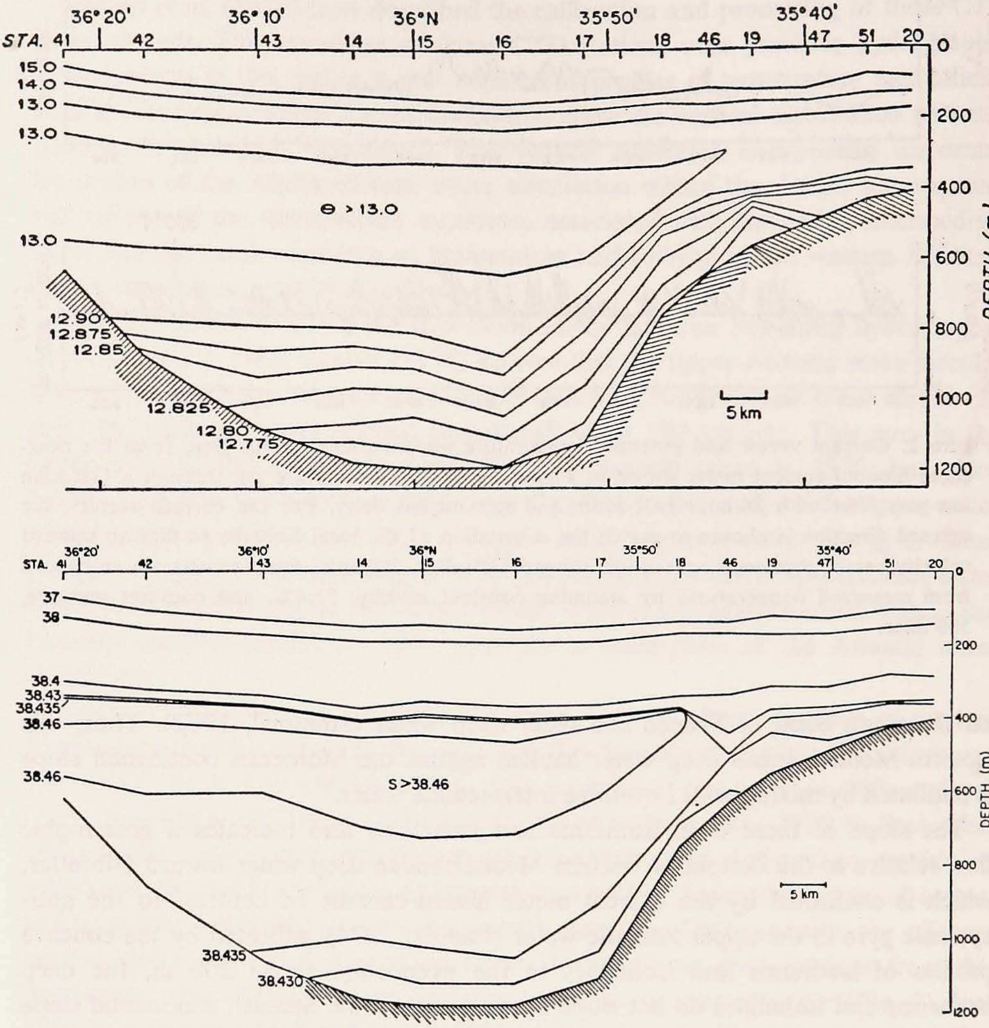

Figure 3. Distribution of (a) potential temperature and (b) salinity on section I, between CTD station 41 in the northern Alboran Sea and station 20 in the southern Alboran Sea. Contours are chosen to emphasize the banking of western Mediterranean deep water, $\theta \leqslant 12.90°C$, $S \leqslant 38.435‰$, against the Moroccan continental slope.

ments. The argument for such a reference level is that Atlantic water must be flowing one way, presumably into the Mediterranean, and Mediterranean water in the opposite direction. It is obvious from the concave shape of the 14°-isotherm (Fig. 3a) that such a reference level would yield an anticyclonic gyre in the Atlantic water but a cyclonic gyre in the Mediterranean water. Because such a deep cyclonic gyre would have the western Mediterranean water banked against the Moroccan slope flowing into the Mediterranean from an apparent source in the Strait of Gibraltar,

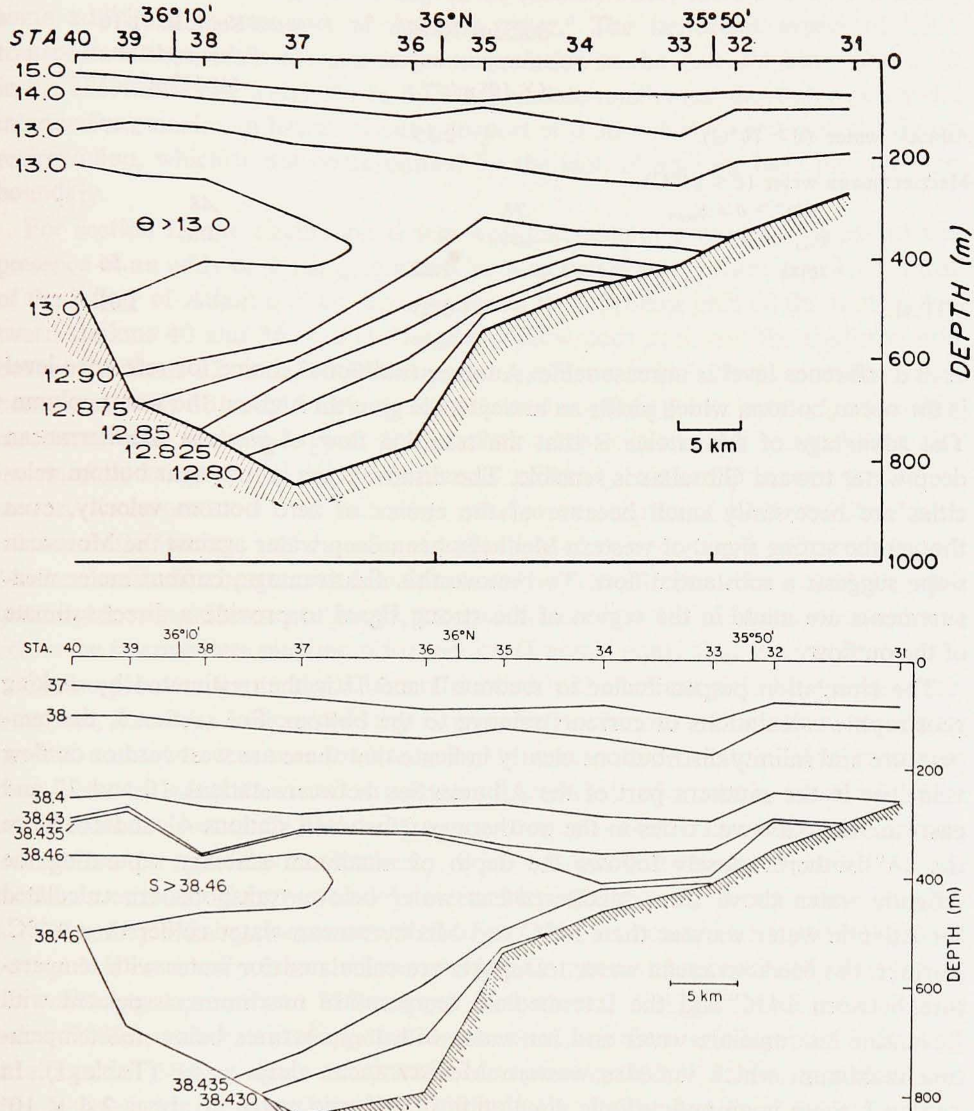

Figure 4. Distribution of (a) potential temperature and (b) salinity on section II, between CTD station 40 in the northern Alboran Sea and Station 31 in the southern Alboran Sea. As in Figure 3, contours are chosen to emphasize banking of western Mediterranean deep water against the Moroccan continental slope.

Table 1. Geostrophic transports relative to the bottom for section I.

		Stations 20-16 transport out ($\times 10^6$ m^{3}s^{-1})		Stations 41-16 transport in ($\times 10^6$ m^{3}s^{-1})
Atlantic water ($\theta > 14$°C)		2.33		2.47
Mediterranean water ($\theta < 14$°C)				
$14°C > \theta > \theta_{max}$	.78		.48	
$\theta_{max} > \theta$	.44		.08	
total		1.22		.56
TOTAL		3.55		3.03

such a reference level is unreasonable. Another traditional choice for reference level is the ocean bottom, which yields an anticyclonic gyre throughout the water column. The advantage of this choice is that the resulting flow of western Mediterranean deep water toward Gibraltar is sensible. The disadvantage is that near bottom velocities are necessarily small because of the choice of zero bottom velocity, even though the strong signal of western Mediterranean deep water against the Moroccan slope suggests a substantial flow. To remove this disadvantage, current meter measurements are made in the region of the strong signal to provide a direct estimate of the outflow.

The circulation perpendicular to sections I and II is then estimated by making geostrophic calculations of currents relative to the bottom. For section I, the temperature and salinity distributions clearly indicate that there are westward or outflow velocities in the southern part of the Alboran Sea between stations 16 and 20 and eastward or inflow velocities in the northern part between stations 41 and 16. Since the 14°-isotherm closely follows the depth of maximum stability separating the Atlantic water above from Mediterranean water below, transports are calculated for Atlantic water warmer than 14°C and Mediterranean water colder than 14°C. Further, the Mediterranean water transports are calculated for water with temperature between 14°C and the intermediate temperature maximum associated with Levantine intermediate water and for water with temperatures below the temperature maximum which includes western Mediterranean deep water (Table 1). In section I, there is an anticyclonic circulation of Atlantic water of about 2.4×10^6 m^3 s^{-1} and of Mediterranean water of about 0.6×10^6 m^3 s^{-1}. There is a net inflow of Atlantic water and a net outflow of Mediterranean water in these calculations which suggest that in an average sense there is a reference level at a depth between Atlantic and Mediterranean water even though the bottom is a more appropriate reference level for individual stations. In terms of overall mass balance it is expected that transport into the Mediterranean should exceed transport out of the Mediterranean by about 0.05×10^6 m^3 s^{-1} (Lacombe, 1971). For section I, out-transport exceeds in-transport by 0.5×10^6 m^3 s^{-1}, probably because of the lack of stations near the northern boundary of the section, where there is almost certainly some additional in-transport of Atlantic water.[3] The important aspect of these transports is that, while there is large recirculation in the Atlantic water and even in the Mediterranean water above the intermediate maximum, the water below the intermediate maximum has a net out-transport of 0.36×10^6 m^3 s^{-1} with nearly no recirculation, which is not compromised by the lack of stations near the northern boundary.

For section II, the circulation is less well determined, probably because of the presence of an eddy or small gyre near Ceuta as described by Lanoix (1974). Most of the inflow of Atlantic water does occur on the northern part of the section between stations 40 and 36, and the largest outflow does occur on the southern side between stations 32 and 33. But there is significant inflow on the southern side between stations 33 and 35 in both Atlantic and Mediterranean waters, presumably associated with the small gyre. The outflow of Mediterranean water below the intermediate temperature maximum occurs relatively uniformly across the entire section. As in section I, this water has a net out-transport of 0.09×10^6 m^3 s^{-1} relative to the bottom, and there is no indication of recirculating flow back into the Mediterranean. If a bottom outflow velocity of less than 2 cm s^{-1} were added to the geostrophic velocities on section II, the net out-transport of Mediterranean water below the intermediate maximum for section II would equal that for section I.

Geostrophic transport calculations referenced to the bottom yield little deep water transport, since the bottom velocity is assumed to be zero. One objective of the moored current meters was to determine the transport of western Mediterranean deep water by using measured currents as reference level velocities in geostrophic calculations for section I. With only one record, however, it is ambiguous how to extrapolate the reference level velocity. With a single current record, it is felt that the fairest estimate of the outflow of western Mediterranean deep water can be made at section I by defining deep water to have potential temperatures less than 12.90°C so that it is essentially undiluted western Mediterranean deep water; by restricting the outflow to depths above 750 m depth since there is a suggestion of recirculation below 750 m; and by assuming that the measured outflow velocity of 4.6 cm s^{-1} at a depth of 500 m where the potential temperature is 12.87°C is typical of the area between the 12.90 isotherm and 750 m depth of 5.75×10^6 m^2. The transport of western Mediterranean deep water toward Gibraltar across section I then is estimated to be 0.26×10^6 m^{3}s^{-1}. Such a transport would make up 22% of the Mediterranean outflow transport of 1.16×10^6 m^{3}s^{-1} measured at the Gibraltar sill by Lacombe (1971). Such a transport of western Mediterranean deep water is slightly larger than Sankey's (1973) estimates of its formation during the winters of 1969 and 1970 of 0.16 and 0.10×10^6 m^{3}s^{-1}.

3. If the dynamic height differences between stations 41 and 42 are assumed to continue 3 miles north of station 41, then in-transport would exactly balance out-transport for section I.

Table 2. Characteristics of western Mediterranean deep water along the Moroccan continental slope in the Alboran Sea.

Potential temperature (°C)	Station 34 depth (m)	Station 34 salinity (‰)	Station 19 depth (m)	Station 19 salinity (‰)	Station 52 depth (m)	Station 52 salinity (‰)	Station 75 depth (m)	Station 75 salinity (‰)
12.875	365	38.430	412	38.437	446	38.437	550	38.446
12.850	389	38.432	420	38.435	459	38.435	576	38.442
12.825	416	38.435	431	38.435	487	38.434	620	38.438
12.800	438	38.433	448	38.434				

The outflow measured by the current meter (Fig. 2) exhibits surprisingly little variability: the standard deviation of the temporal fluctuations in measured currents of 4.3 cm s^{-1} is smaller than the time-averaged current of 4.6 cm s^{-1}; the standard deviation of temperature fluctuations is only 0.036°C, and the range in measured potential temperature is only 12.81°C to 13.01°C; there is a suggestion of annual variability in temperature with an amplitude of 0.025°C and a maximum in April, but the annual signal in currents is less than 1 cm s^{-1}. By dividing the standard deviation of the measured currents by the number of integral time scales contained in the 341-day record length, the standard error in the mean outflow velocity is estimated to be only 0.6 cm s^{-1}. Thus, the mean outflow velocity is significantly different from zero. One unexpected feature of this record is that fluctuations in outflow velocity are correlated with warmer temperature fluctuations, rather than with colder temperature fluctuations. A possible explanation for this correlation is that a stronger outflow is associated with movement of the deep temperature front up the Moroccan continental slope resulting in slightly warmer water at the moored current meter. Overall, the outflow of western Mediterranean deep water as measured by the current meter appears to be a nearly permanent feature on the southern side of the Alboran Sea.

As this western Mediterranean deep water flows along the Moroccan continental slope toward Gibraltar, it rises. The water observed at 450 m depth on station 34 has the same potential temperature and salinity observed at about 1200 m in the deep basin of the western Mediterranean (stations 79, 80, 81). From isotherm depths observed at stations along the Moroccan continental slope (Table 2), the deep water can be seen to rise by about 200 m over the 200 km distance between stations 75 near the Isle of Alboran and 34 at the entrance to the Strait of Gibraltar. Water at station 34 with a potential temperature of 12.85°C, which is identical to western Mediterranean deep water observed to form off the southern coast of France in 1969, is only 100 m below the Gibraltar sill depth of 284 m (Frassetto, 1960). Thus, there is a direct flow of pure western Mediterranean deep water along the Moroccan continental slope which arrives at the Strait of Gibraltar only 100 m below sill depth.

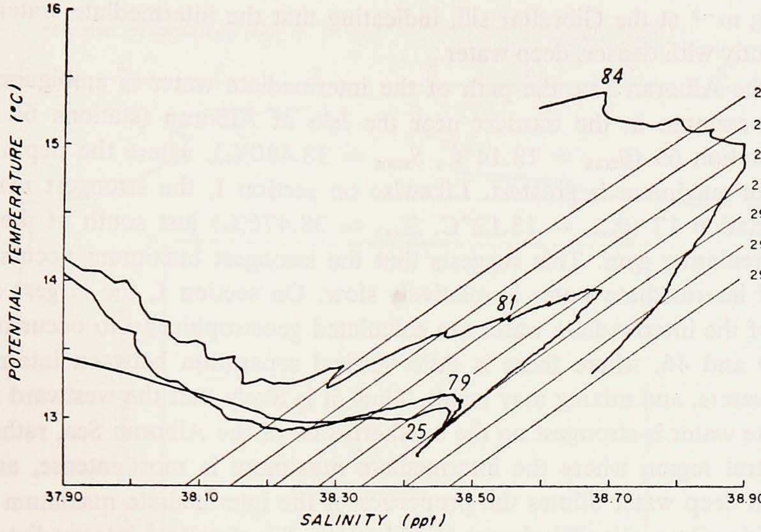

Figure 5. Potential temperature - salinity diagrams for CTD stations 25, 79, 81, and 84 across the Mediterranean to exhibit large-scale changes in properties of the intermediate potential temperature - salinity maximum associated with Levantine intermediate water. Lines of constant potential density are shown to indicate that the intermediate maximum occurs at higher density as Levantine water moves westward away from its formation region.

4. Intermediate water circulation

The circulation of Levantine intermediate water in the Alboran Sea is more difficult to trace than that of the deep water. On the large scale, the intensity of the intermediate maximum associated with Levantine water decreases as the intermediate water progresses westward from its formation region in the eastern basin. In these CTD measurements, the intermediate maximum is strongest at station 84 south of Greece, where $\theta_{max} = 15.0°C$, $S_{max} = 38.90‰$, and decreases to $\theta_{max} = 13.076°C$, $S_{max} = 38.466‰$ at station 25 at the Gibraltar sill (Fig. 5). Most of the change in properties of the intermediate maximum appears across the Strait of Sicily separating eastern and western basins of the Mediterranean between stations 81 and 84, and in the western Mediterranean between stations 81 and 79, where Katz (1972) suggested the intermediate water deflects to the right to undergo a cyclonic circulation around the western basin. In the Alboran Sea, where this CTD survey was concentrated, there is relatively little change in properties of the intermediate maximum, which decrease only from $\theta_{max} = 13.177°C$, $S_{max} = 38.485‰$ at station 79 at the eastern entrance to the Alboran Sea to $\theta_{max} = 13.076°C$, $S_{max} = 38.466‰$ at the Gibraltar sill. On the large scale, the potential density of the intermediate maximum increases monotonically from 28.98 kg m^{-3} in the eastern basin to 29.08 kg m^{-3} at the Gibraltar sill, indicating that the intermediate water mixes predominantly with denser, deep water.

Within the Alboran Sea, the path of the intermediate water is ambiguous. The strongest maximum in the transect near the Isle of Alboran (stations 66 to 75) occurs at station 69 (θ_{max} = 13.14°C, S_{max} = 38.480‰), where the depth of the intermediate maximum is greatest. Likewise on section I, the strongest maximum occurs at station 17 (θ_{max} = 13.12°C, S_{max} = 38.476‰) just south of the center of the recirculating gyre. This suggests that the strongest maximum occurs where the flow of intermediate water is relatively slow. On section I, the largest outflow velocities of the intermediate water are calculated geostrophically to occur between stations 19 and 46, where there is little vertical separation between intermediate and deep waters, and mixing may result. Thus, it is likely that the westward flow of intermediate water is strongest on the southern side of the Alboran Sea, rather than in the central region where the intermediate maximum is most intense, and that mixing with deep water dilutes the properties of the intermediate maximum on the southern side. On section II closest to Gibraltar, the strongest intermediate maximum occurs at station 37 (θ_{max} = 13.05°C, S_{max} = 38.464‰), again near the center of the section. On the southern side south of station 35, where mixing is likely, the intermediate maximum is barely distinguishable.

Thus, the strongest intermediate maximum occurs near the center of the Alboran Sea from the Isle of Alboran to the entrance to the Strait of Gibraltar. Geostrophic calculations, however, indicate that the largest outflow of intermediate water occurs along the Moroccan continental slope, where it mixes with western Mediterranean deep water, thereby diluting the strength of its maximum. In combination with the circulation of Atlantic water described by Lanoix (1974), it appears then that the entire water column including Atlantic water, Levantine intermediate water, and western Mediterranean deep water circulates anticyclonically in the Alboran Sea with westward or outflow velocities occurring along the Moroccan continental slope.

5. Outflow at the Gibraltar sill

The currents and hydrographic conditions at the sill of the Strait of Gibraltar are known for their large variation during a tidal cycle. For example, Lacombe (1971) observed the current to change by 3 knots during a half hour and the 38‰-isohaline and 13°C-isotherm to undergo depth excursions of 200 m during a four-hour period. These variations seem to remain in constant phase relative to the tide at Tarifa and maximum outflow of cold, salty water occurs approximately two hours before high tide at Tarifa. During the CTD survey in 1975, station 25 was taken less than a quarter-mile from the location of the sill reported by Frassetto (1960) about three hours after high tide at Tarifa. While this station is not at an optimal time to observe western Mediterranean deep water flowing over the sill, it is of

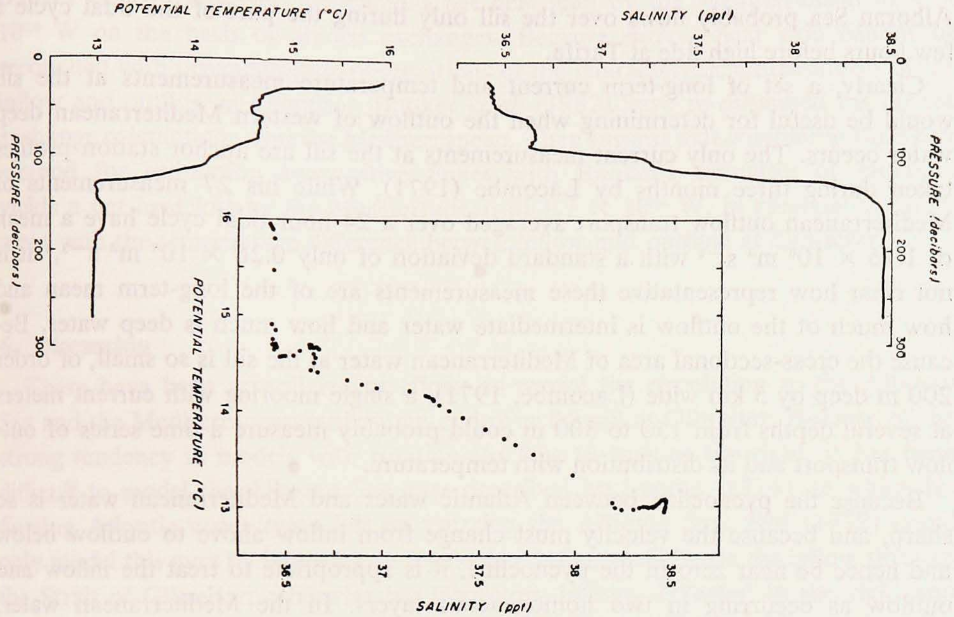

Figure 6. Vertical distribution of potential temperature and salinity and a potential temperature - salinity diagram for CTD station 25 at the Gibraltar sill. Note the relatively homogeneous layers of Atlantic water and Mediterranean water separated by a thin thermocline and halocline and the presence of a well-defined intermediate maximum in the potential temperature - salinity diagram.

interest to examine the detailed vertical distribution of salinity and temperature at this sill station.

At station 25, the Atlantic water is separated from the Mediterranean water by a sharp pycnocline between 90 and 140 m depth (Fig. 6). In the upper part of the Mediterranean water between 160 and 180 m depth, the intermediate maximum ($\theta_{max} = 13.08$°C, $S_{max} = 38.466$‰) associated with the Levantine water is still evident. Below this intermediate maximum a mixture of intermediate and deep water is present, with the densest water having $\sigma_\theta = 29.09$ kg m^{-3}, $\theta = 12.95$°C, $S = 38.457$‰. Thus, there is no undiluted western Mediterranean deep water present at this sill station. One explanation is that it mixes with intermediate water as it flows through the Strait of Gibraltar. A more likely explanation is that the outflow of western Mediterranean deep water occurs during a different part of the tidal cycle. Allain (1964) showed evidence of water colder than 12.90°C at the sill three hours before high tide at Tarifa, and of water with potential temperature below 12.85°C at 200 m depth at high tide. Thus, the direct flow of western Mediterranean deep water observed in this CTD survey along the Moroccan continental slope in the

Alboran Sea probably flows over the sill only during the part of the tidal cycle a few hours before high tide at Tarifa.

Clearly, a set of long-term current and temperature measurements at the sill would be useful for determining when the outflow of western Mediterranean deep water occurs. The only current measurements at the sill are anchor station profiles taken during three months by Lacombe (1971). While his 27 measurements of Mediterranean outflow transport averaged over a 24-hour tidal cycle have a mean of 1.16×10^6 m^3 s^{-1} with a standard deviation of only 0.26×10^6 m^3 s^{-1},[4] it is not clear how representative these measurements are of the long-term mean and how much of the outflow is intermediate water and how much is deep water. Because the cross-sectional area of Mediterranean water at the sill is so small, of order 200 m deep by 5 km wide (Lacombe, 1971), a single mooring with current meters at several depths from 150 to 300 m could probably measure a time series of outflow transport and its distribution with temperature.

Because the pycnocline between Atlantic water and Mediterranean water is so sharp, and because the velocity must change from inflow above to outflow below and hence be near zero in the pycnocline, it is appropriate to treat the inflow and outflow as occurring in two homogeneous layers. In the Mediterranean water, salinity varies only from 38.440 to 38.466‰ and potential temperature from 13.076 to 12.952°C, so the Mediterranean outflow can be characterized by $S = 38.45$‰, $\theta = 13.0$°C. There seems to be no justification for characterizing the outflow by a salinity less than 38‰ as Sverdrup *et al.* (1942) and Lacombe (1971) have done. While the Atlantic water is not as uniform as the Mediterranean water, the average salinity and potential temperature in the upper 90 m are 36.5‰ and 15.2°C.

From Lacombe's (1971) measured outflow and the characteristic salinities of the Atlantic and Mediterranean waters, a simple salt conservation calculation shows that the difference between inflow and outflow transports, which should equal the excess evaporation over precipitation and run-off over the Mediterranean basin, is 6.2×10^4 m^{3}s^{-1}, or 0.66 m yr^{-1} averaged over the surface area of the Mediterranean. This value is slightly larger than Lacombe's (1971) value because of the higher salinity, but is less than the values of about 1 m yr^{-1} estimated by Sverdrup *et al.* (1942) and Bethoux (1979), who used higher inflow and outflow transports at Gibraltar of order 1.7×10^6 m^{3}s^{-1}. In a similar type of calculation, the product of outflow transport times the temperature difference of 2.2°C between Atlantic and Mediterranean waters suggests that the Mediterranean must lose a net amount of heat to the atmosphere of at least 1×10^{13} W, since this February temperature difference is nearly the minimum during the year. Bethoux (1979) estimated a slightly larger heat loss of 1.6×10^{13} W because of his larger outflow transport.

4. Lacombe's outflow measurements probably have smaller error than his inflow because the outflow occurs over a smaller width and hence there is less extrapolation of currents measured at a single station. Also, his outflow transports averaged over a 24-hour tidal cycle exhibit only one-third the variance of outflow transports averaged over a 12-hour tidal cycle.

Bunker (1976), however, estimated a net heat gain by the Mediterranean of 4×10^{13} W on the basis of air-sea exchanges. Because such a heat gain cannot be reconciled with oceanographic observations of the characteristic temperatures of the inflow and outflow at Gibraltar, Bunker *et al.* (1982) have re-examined the air-sea exchange calculations over the Mediterranean. They suggest that combining Budyko's method for estimating evaporative fluxes with Bunker's estimates of radiation yields a net heat loss by the Mediterranean of 1.7×10^{13} W, in reasonable agreement with the temperature difference betwen inflow and outflow at Gibraltar.

6. Discussion

There have been several recent efforts to model the circulation in the Alboran Sea and the Mediterranean outflow up and over the sill at Gibraltar. Because of the strong tendency in models with rotation for flow to turn to the right, it has been difficult to model the Alboran Sea gyre described by Lanoix (1974), in which inflowing Atlantic water turns left on entering the Alboran Sea. Nof (1978) could only model this gyre by imposing anticyclonic relative vorticity on the inflow through the Strait of Gibraltar; otherwise his laboratory inflows deflected to the right and followed the southern boundary. Whitehead and Miller (1979) could reproduce the Alboran Sea anticyclonic gyre only at a slow rotation rate when the inflow separated from a sharply curved southern boundary. When the inflow encountered a stagnation point near Cape Tres Forcas on the African coast at 3W, the resulting recirculation formed the anticyclonic gyre. Likewise, Sambuco and Whitehead's (1976) model of the outflow from a deep basin over a sill showed that the uniform upstream flow quickly turned to the right and the outflow became banked against the northern boundary. Gill (1976) argued that upstream of a sill the outflow could lie against the southern boundary if the problem were posed as an initial disturbance at the sill which propagated upstream as a Kelvin wave along the southern wall of an east-west channel.

To maintain a time-averaged anticyclonic gyre in the Alboran Sea in the presence of friction requires a source of anticyclonic vorticity. Only Nof's (1978) model explicitly accounts for such a source of vorticity, which derives from the inflow through the Strait of Gibraltar. The flow of western Mediterranean deep water toward the Strait of Gibraltar can provide such a source of anticyclonic vorticity. Its near-bottom upward velocity must shrink vortex lines and hence generate anticyclonic vorticity in the water column above. Along the Moroccan continental slope, this upward velocity, w, can be estimated, by multiplying the isotherm slopes in the deep water between stations 75 and 34 of 1×10^{-3} (Table 2) by the measured outflow velocity of 4.6 cm s^{-1}, to be 4.6×10^{-3} cm s^{-1}. The source of anticyclonic vorticity for the gyre, fw where f is the Coriolis parameter, is estimated to occur over only 10% of the area of the gyre, and hence to be 4×10^{-8} cm s^{-2}. If the anticyclonic vorticity of the surface gyre, which is of order 2×10^{-5} s^{-1} (Lanoix, 1974), is assumed to decrease to zero at 500 m depth, this source of vorticity is sufficient to generate the gyre from rest in about 150 days. Alternatively, this vorticity source is sufficient to balance frictional dissipation with a temporal decay scale of 150 days.

In return, the anticyclonic gyre helps to bring deep water up toward the sill. Stommel *et al.* (1973) showed by a Bernoulli equation argument how high velocities in the Strait could provide an energy source to raise water from great depth in the Mediterranean up and over the sill. They were concerned, however, how the observed rise of the deep water could occur in open basins like the Alboran Sea where velocities were presumably lower than in the Strait. From these measurements and Lanoix's (1974) description, it is clear that the anticyclonic gyre in the Alboran Sea can provide the high velocities, estimated by Stommel *et al.* (1973) to be of order 50 cm s^{-1}, necessary to bring the deep water upward toward Gibraltar along the southern boundary of the Alboran Sea.

Thus, this discussion suggests that the upward flow of western Mediterranean deep water provides the necessary source of anticyclonic vorticity to maintain the Alboran Sea gyre against friction and that the gyre, in turn, provides the necessary energy for raising the deep water in the Alboran Sea so it can eventually flow over the sill. Models of the Alboran Sea gyre which include frictional dissipation should include a flow of Mediterranean water up and over the Gibraltar sill to provide a source of anticyclonic vorticity and models of the outflow of Mediterranean water over the sill should include an anticyclonic gyre to provide a source of energy to bring up the deep water.

Acknowledgments. The CTD measurements were collected and processed with the support of the National Science Foundation under grants OCE 74-19782 and OCE 76-10940. The moored current meter measurements and analysis of both CTD and current meter measurements were carried out with the support of the Office of Naval Research under contract N00014-76-C0197, NR 083-400. Final preparation of this work was accomplished while one author was supported at the Joint Institute for the Study of the Atmosphere and Ocean under a grant from the National Oceanic and Atmospheric Administration. The perseverance of David Porter in calibrating the CTD measurements, the skill of Robert Millard and Susan Tarbell in processing CTD and current meter measurements, and the independence of Erika Francis in making the calculations reported here are greatly appreciated. Comments by Thomas Kinder, Gregorio Parrilla, and John Whitehead helped to clarify the text. Contribution number 5012 from the Woods Hole Oceanographic Institution.

REFERENCES

Allain, C. 1964. L'Hydrologie et les courants du Détroit de Gibraltar pendant l'été de 1959. Rev. Trav. Inst. Pêches Marit., *28*, 1–99.

Bethoux, J. P. 1979. Budgets of the Mediterranean Sea. Their dependance on the local climate and on the characteristics of the Atlantic waters. Oceanologica Acta, *2*, 157–163.

Brown, N. L. 1974. A precision CTD microprofiler. Proceedings of I.E.E.E. Ocean 74 Conference, Halifax, *2*, 270–278.

Bryden, H. L., R. C. Millard and D. L. Porter. 1978. CTD observations in the western Mediterranean Sea during cruise 118, leg 2 of R/V *Chain*, February, 1975. Woods Hole Oceanographic Institution Technical Report 78-26, 38 pp.

Bunker, A. F. 1976. Computations of surface energy flux and annual air-sea interaction cycles of the North Atlantic Ocean. Mon. Wea. Rev., *104*, 1122–1140.

Bunker, A. F., H. Charnock and R. A. Goldsmith. 1982. A note on the heat balance of the Mediterranean and Red Seas. J. Mar. Res., *40* (Supp.), 73–84.

Carpenter, W. B., and J. G. Jeffreys. 1870. Report on deep-sea researches carried on during the months of July, August, and September, 1870 in H. M. Surveying-ship 'Porcupine.' Proc. Roy. Soc. London, *19*, 146–221.

Deacon, M. 1971. Scientists and the Sea, 1650-1900: A Study of Marine Science. Academic Press, New York, 445 pp.

Frassetto, R. 1960. A preliminary survey of thermal microstructure in the Strait of Gibraltar. Deep-Sea Res., *7*, 152–162.

Gill, A. E. 1976. Adjustment under gravity in a rotating channel. J. Fluid Mech., *77*, 603–621.

Katz, E. J. 1972. The Levantine intermediate water between the Strait of Sicily and the Strait of Gibraltar. Deep-Sea Res., *19*, 507–520.

Lacombe, H. 1971. Le Détroit de Gibraltar, oceanographie physique. Notes et Mémoires du Service Géologique du Maroc, *222*, 111–146.

Lacombe, H. et P. Tchernia. 1972. Caractères hydrologiques et circulation des eaux en Mediterranée, *in* The Mediterranean Sea: A Natural Sedimentation Laboratory, D. J. Stanley, ed. Dowden, Hutchinson and Ross, Stroudsburg, Pennsylvania, 765 pp.

Lanoix, F. 1974. Projet Alboran: Etude hydrologique et dynamique de la Mer d'Alboran. North Atlantic Treaty Organization Technical Report 66, 74 pp.

Marsigli, L. F., 1681. Internal observations on the Thracian Bosphorus, or true channel of Constantinople, represented in letters to her majesty, Queen Christina of Sweden. Translated by E. Hudson, *in* Oceanography: Concepts and History, M. B. Deacon, ed. Dowden, Hutchinson and Ross, Stroudsburg, Pennsylvania, 394 pp.

Medoc Group. 1970. Observation of formation of deep water in the Mediterranean Sea. 1969. Nature, *227*, 1037–1040.

Nof, D. 1978. On geostrophic adjustment in sea straits and wide estuaries: Theory and laboratory experiments. Part II — Two-layer system. J. Phys. Oceanogr., *8*, 861–872.

Sambuco, E. and J. A. Whitehead. 1976. Hydraulic control by a wide weir in a rotating fluid. J. Fluid Mech., *73*, 521–528.

Sankey, T. 1973. The formation of deep water in the northwestern Mediterranean. Prog. in Oceanogr., *6*, 159–179.

Stommel, H. 1972. Deep winter-time convection in the western Mediterranean Sea, *in* Studies in Physical Oceanography, Vol. 2, A. L. Gordon, ed. Gordon and Breach, New York, 232 pp.

Stommel, H., H. Bryden and P. Mangelsdorf. 1973. Does some of the Mediterranean outflow come from great depth? Pageoph, *105*, 879–889.

Sverdrup, H. U., M. W. Johnson and R. H. Fleming. 1942. The Oceans. Prentice-Hall, New York, 1087 pp.

Whitehead, J. A., Jr. and A. R. Miller. 1979. Laboratory simulation of the gyre in the Alboran Sea. J. Geophys. Res., *84*, 3733–3742.

Wüst, G. 1961. On the vertical circulation of the Mediterranean Sea. J. Geophys. Res., *66*, 3261–3271.

Received: *14 September, 1981;* revised: *25 January, 1982.*