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Recent observations on the intermediate and deep water circulation in the Southern Tyrrhenian Sea

Tyrrhenian
Hydrography
Current meters
Deep circulation
Thermohaline budget

Mer Tyrrhénienne
Hydrographie
Courantomètres
Circulation profonde
Bilan thermohalin

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ABSTRACT

The circulation of the intermediate and deep waters of the Tyrrhenian are discussed in the light of recent observations in the Southern Tyrrhenian from current meters, submerged floats, and hydrographic data. The observed flow in the Sardinian Channel suggests that the deep circulation below the intermediate water level is such as to import Western Mediterranean deep water and export a mixed product (with the intermediate water) of sufficient magnitude (6 700 km^3/yr) to be of significance in the thermohaline circulation of the Western Mediterranean. The Levantine intermediate water layer is divergent : sustaining, in addition to this downwelling, an upward flux to the surface layer, and the horizontal fluxes north through the strait of Corsica and south through the Sardinian channel. To support this divergence approximately 40 000 km^3/yr, or most of the Levantine intermediate water passing through the strait of Sicily, must enter directly into the Tyrrhenian around the eastern tip of Sicily. Evaporation and the upwelling of intermediate water play approximately equivalent roles in salting the surface waters. Winter convective mixing appears to be the primary mechanism for the upward loss of intermediate-layer salt. The route of the intermediate water does not appear to completely follow the bathymetry through the Southern Tyrrhenian, most notably skirting the southeastern section. Current observations within the intermediate level showed a cyclonic tendency with southward exiting flow along Sardinia. The deep current observation in the southern center of the sea at 2 150 m showed a surprisingly steady flow of 1.4 cm/s to the north suggesting a barotropic component to the Tyrrhenian circulation.

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RÉSUMÉ

Observations récentes sur la circulation des eaux intermédiaire et profonde dans le sud de la Mer Tyrrhénienne.

La circulation des eaux intermédiaire et profonde de la Mer Tyrrhénienne est discutée à la lumière de récentes observations dans la partie sud de la Mer Tyrrhénienne, faites par courantométrie, immersion de flotteurs et mesures hydrologiques. Le flux observé au niveau du canal de Sardaigne semble indiquer qu'en profondeur, sous la couche d'eau intermédiaire, la circulation profonde est marquée par une pénétration en Mer Tyrrhénienne de l'eau profonde occidentale et par la sortie d'une eau résultant du mélange de cette dernière avec de l'eau intermédiaire. Le flux de sortie de cette eau de mélange est suffisamment fort (6 700 km^3/an) pour influencer de manière non négligeable la circulation thermohaline de la Méditerranée occidentale. L'eau intermédiaire a un comportement divergent : en dehors de cette contribution à un flux descendant, elle alimente un transport ascendant vers la surface ainsi que des advections horizontales de sortie à travers le détroit de Corse au Nord et le canal de Sardaigne au Sud. Pour alimenter cette divergence, environ 40 000 km^3/an (c'est-à-dire la plus grande partie de l'eau intermédiaire levantine passant le détroit de Sicile) doivent pénétrer directement en Mer Tyrrhénienne en contournant l'extrémité orientale de la Sicile. L'évaporation et la remontée de l'eau intermédiaire jouent des rôles à peu près équivalents dans l'augmentation de la salinité des eaux de surface. Le mélange vertical hivernal semble être le principal mécanisme par lequel est abaissée la salinité dans la couche d'eau intermédiaire. Le parcours de l'eau intermédiaire ne paraît pas suivre complètement la bathymétrie du sud de la Mer Tyrrhénienne, en particulier le long de sa section sud-est. Des mesures de courant à l'intérieur de l'eau intermédiaire montrent une tendance cyclonique avec un flux sortant vers le Sud le long de la Sardaigne. L'observation du courant profond dans la partie centrale méridionale à 2 150 m montre un flux étonnamment constant, de 1,4 cm/s vers le Nord, indiquant la présence d'une composante barotrope dans la circulation de la Mer Tyrrhénienne.

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INTRODUCTION

The Western Mediterranean (WMED) is composed of three major basins : the Liguro-Provencal, the Algerian, and the Tyrrhenian basins. Of these the Tyrrhenian is slightly less in volume (~ 328 000 km^3) but deeper. The division between the other two is without a sill restriction at typical bottom depths of ~ 2 700 m, whereas the communication with the Tyrrhenian is through the Sardinian Channel with a sill < 2 000 m and a cross section of 50 km^2 below the 500-m depth. The areal portion of the Tyrrhenian with depths greater than 2 800 m, *i.e.* greater than the WMED, is about 4 000 km^2 or slightly less than a fifth of the Tyrrhenian surface area.

The Tyrrhenian deep circulation is generally considered to be incidental to the main thermohaline circulation of the WMED, primarily because no deep water is considered to be locally produced. As a consequence the Tyrrhenian Deep Water (TDW) has not received much discourse, it being considered an isolated derivative of the WMED Deep Water (WMDW) of slightly greater age. For example, the data of Miller *et al.* (1970) show the TDW to have temperature and salinity values of ~ 0.2 °C and ~ 0.03 ppt greater than and oxygen values ~ 0.15 ml/l less than the WMDW values. There has been speculation that the warmer TDW is a result of a bottom heat flux (Miller, 1972). As yet no evidence is available to support this, including several bottom heat probe stations conducted during the observations reported herein. The TDW is located on the *T-S* regression line between WMDW and Levantine Intermediate Water (LIW) and thus some interaction mixing these two water masses seems the most probable explanation of the TDW origin.

These circumstances make the Tyrrhenian thermohaline circulation anomalous with respect other Mediterranean basins. The fact that the water columns in the Tyrrhenian above the sill depth tend to be slightly less dense than those in the WMED suggests a higher steric sea level inside the basin with the tendency for the exchange to be out of the basin at the surface and in the basin over the sill. The simpliest deep interior circulation would be for a weak inflow of WMDW underneath an outflow upper layer waters, in which case the only loss of TDW would be through entrainment in the upper layer and the vertical exchange would be balanced between downward diffusion of heat and salt and an upward advective flux.

There does exist some evidence in support of a rather inactive interior. Cortecci *et al.* (1974) found the null Tritium value level at ~ 1 400 m in the central Tyrrhenian implying no downward diffusion of Tritium from the LIW during ~ 10 yr time scale. The water columns mostly over the Tyrrhenian abyssal plain have been observed to have a stable (over a 3-yr period) staircase structure in temperature and salinity between 600 and 1 500 m with lateral coherence of up to 100 km (Molcard, Tait, 1978). A possible explanation (also Tait, 1984) is that they are the result of double-diffusive processes and that they are maintained against diffusive erosion by some stirring mechanism. In any case, a fairly low-energy environment seems to be implied. Finally, the depressed oxygen values of the TDW, relative to the rest of the WMDW, suggest that the TDW is older than the WMDW. Despite these facts, our data suggest a more active and complicated circulation for the deep waters of the Tyrrhenian.

The intermediate and surface layers have received more attention than the deep water, perhaps again because they are considered to be more coupled to the WMED general circulation. Of particular interest has been the role that the Tyrrhenian plays in modifying the Levantine Intermediate Water (LIW). There has been some disagreement on the relative proportion of the LIW taking any one of three possible routes from the strait of Sicily : directly west without entering the

Tyrrhenian (Katz, 1972), recirculating within the southern Tyrrhenian (Ovchinnikov, 1966), and transversing the Tyrrhenian through to the Ligurian Sea (Béthoux, 1980 from Stocchino, Testoni, 1968). Both the latter two routes involve eventual entry into the Ligurian Sea, either *via* the west coast of Sardinia (Lacombe, Tchernia, 1960) or directly through the strait of Corsica, and thus convey the effect of mixing in the Tyrrhenian on the LIW prior to its eventual involvement in WMDW production (*e.g.* Hopkins, 1978). The loss of salt by the LIW in transitting the Tyrrhenian in either case has been assumed to be to the surface layer. Our data suggest an additional downward flux of salt to the deep layer.

The circulation for the LIW and surface water of the Tyrrhenian have been estimated from geostrophic computations of composite data (*e.g.* Krivosheya, Ovchinnikov, 1973 ; Krivosheya, 1983) ; from the contours of the salinity maximum (core method) (Wüst, 1961 ; Lacombe, Tchernia, 1960) ; and from a seasonal wind-driven numerical model (Moskalenko, 1983). These agree in demonstrating that the basic flow pattern is cyclonic. The circulation tends to fractionate into northern and southern cyclonic structures separated at approximately the 40° N latitude. This tendency and the scale of horizontal structure decreases from winter to summer. The recirculating portion would thus be confined to the southern portion with a longer route in the winter than in the summer. The general agreement between the wind-driven and geostrophic circulations verifies the importance of wind forcing for the upper layers.

It is the purpose of this paper to discuss some of these aspects of the Tyrrhenian circulation in the light of recent observations taken during the autumn of 1984 mostly in the southeastern portion of the Tyrrhenian Sea.

OBSERVATIONS

Hydrographic data were collected from a sequence of three cruises in the Southern Tyrrhenian spanning an interval of about 74 days during which moored instrumentation was in place (Fig. 1). The CDT casts were made with a Neil Brown Instrument Systems (NBIS Mk III) from the R/V *Maria Paolina* during the periods 19 to 31 August and 22 October to 4 November 1984 and from the R/V *Magnaghi* from 2 to 13 October 1984. Observational focus for the CTD sampling was in the southwestern portion near the moored instrumentation and along the perimeter of the southern portion of the basin.

The subsurface floats used were a modified version of the Sofar floats (Tillier, 1980 ; Pistek *et al.*, 1984). They were about 50 cm in diameter, were designed to remain at a constant pressure, and were recoverable by means of an acoustic releasing of balast. They sent an ~ 1 570 Hz acoustic signal every 2 h to listening stations attached to each of the 4 moorings. Delay times were computed by correlating the transmitted signal with a synchronized reference signal. The current meters attached to the moorings were of the NBIS manufacture except for a VMCM/Davis-Weller at 335 m on mooring 1. Another two current meters were deployed but returned faulty or incomplete data. The depths and start/end time of the current meter records and float records which returned good data are illustrated in the progressive vector diagrams of Figure 8 *b*. Further details of the moorings and hydrography are given in Hopkins and Zanasca (1987).

Deep water inflow

The two current meters positioned in the Sardinian Channel were located at 348 m in the intermediate

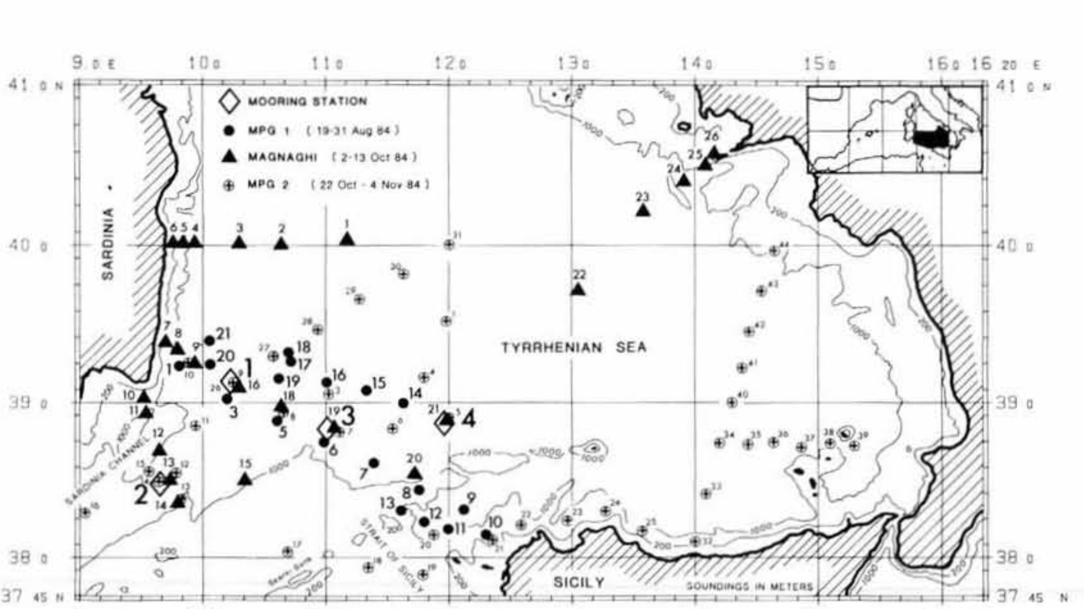

Figure 1

The location of the CTD stations and of the moorings in the Southern Tyrrhenian from August to November 1984. The sequence of CTD stations from each of these three cruises are distinguished in the legend. The insert in the upper right-hand corner shows the area of observation relative to the Western Mediterranean.

water and at 1 763 m in the deep water. The 40-h filtered time series of Figure 2 shows the along-channel (053° T) and cross-channel (143° T) velocity components. The deep flow was slightly more variable with sub-inertial oscillations with approximately 4-10- and 45-day periodicities. The gross similarity of the along-channel components (Fig. 2 *a*) suggests a predominate low frequency barotropic variability. However the greater variance at higher frequencies in the deep component suggests a baroclinic variability, caused by changes in the cross-channel slope of the isopycnals. The series means for these two components were 2.0 cm/s directed out at the 348-m depth and 0.9 cm/s directed in at the 1 763-m depth (*see* Fig. 7 *b*).

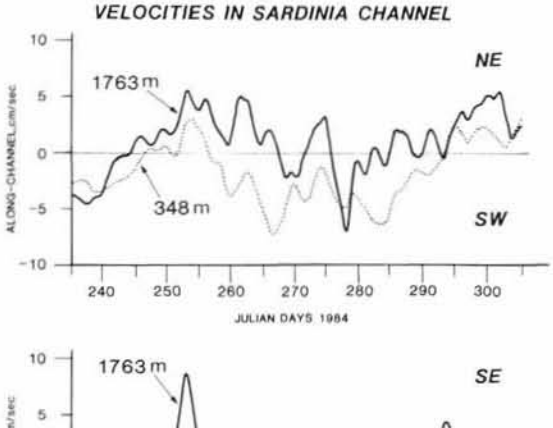

Figure 2

The 40 hr filtered time series of the two current meters located in the Sardinia Channel. The along-channel components (053° T is positive) are given in the upper panel and the cross-channel components (143° T is positive) in the lower panel.

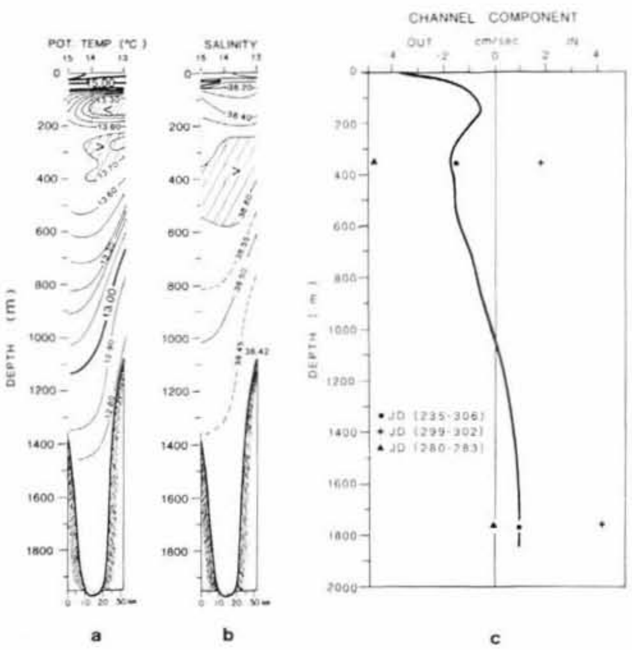

Figure 3

a) *The potential temperature across the channel at the location of the current meters.* b) *Likewise the salinity.* c) *The baroclinic geostrophic shear adjusted to the series mean of the deep, parabathic component. The series means are plotted with a (.) and the 3-day means prior to the two CTD samplings are given with the symbols (+, ▲).*

CTD cross sections of the Sardinian Channel were taken twice during the experiment, on days JD 283 and JD 302. The latter of these more closely coincided physically with the mooring (Fig. 1) and better corresponded to the mean flow condition (Fig. 2). The salinity, potential temperature, and vertical shear for this section are shown in Figure 3. The vertical profile of the along-channel velocity component (Fig. 3 *c*) was adjusted relative to the mean of the entire series at the 1 763-m depth. This resulted in an upper layer outflow and a lower layer inflow. An adjustment relative to the series mean at the 348-m depth would have given virtually the same results. However, adjustment relative to the shorter three-day averages corresponding to the hydrographic samplings would have rendered very different results : for the earlier case (JD 280-283) the flow would have been out at all depths and for the latter case (JD 299-302) the flow would have been in at all depths. Note that the fact that the shear between the two depths is the same for the (JD 299-302) period and the (JD 235-306) period tends to justify our adjustment of the vertical profile using the baroclinic shear observed JD 302 with the time-averaged flow of the entire period. In fact, the consistency in the vertical shear [also during (JD 280-283)] suggests that most of the low-frequency variability (greater than several days) is barotropic.

On the assumption that Figure 3 *c* represents the flow through the channel, we can make a series of useful estimations. Figure 3 *c* shows the depth of zero flow to be at 1 050 m. Integrating from the bottom upward and, assuming that our velocity profile is still representative across the channel, we have computed the depth of zero transport to be at about 700 m and the deep water influx to be 4,100 km^3/yr. This assumption is reasonable below the depth of 500 m where the channel width at that depth is only four times that at the 1 500 m depth.

Since there is no other exit, the basin below 700 m might be considered as closed, with the deep water entering, upwelling, and leaving. However, more salt is exported in the 700-1 000-m layer than enters, and not surprisingly, the *T-S* properties of this modified deep water (mTDW) show admixture of LIW. Therefore we suggest a downward flux of LIW. A salt balance for the deep water gives

$$V_i^D S_i^D + W_d^L S_d^L = V_o^D S_o^D \qquad (1)$$

where $S_i^D = 38.43$ is the cross-sectional average inflow, $S_o^D = 38.52$ is the cross-sectional average outflow, $S_d^L = 38.68$ is the LIW core average, and V_i^D, V_o^D, and W_d^L are the volume flows (km^3/s) in, out, and down, respectively. This results in $V_o^D = 6{,}400$ and $W_d^L = 2{,}300$ km^3/s. Using the volume below the 700-m level gives the relatively short residence time of ~ 30 yr. The lower oxygen values of the TDW (~ 4.3 ml/l) relative to those of the WMDW (~ 4.4-4.7 ml/l) may reflect more the effect of downwelling the relatively oxygen-poor LIW (~ 4.1 ml/l) than the effect of *in situ* oxygen consumption which, by itself, would give a much longer residence time of ~ 200 yr using an oxygen consumption rate of 1 µl O$_2$/l/yr.

At the rate of 6,400 km^3/yr, the exported mTDW would constitute a significant deep water mass component of the WMED, but its distribution might be difficult to ascertain since its water type of ~ 13.2 °C, ~ 38.52 coincides with other mixed products of WMDW and LIW. These transports of TDW in and mTDW out, if approximately correct in magnitude, would alter our understanding of the role of the Tyrrhenian Sea with respect to the sub-LIW layer WMED circulation : from that of an inactive deep water cul-de-sac to an active zone for recirculating mixing deep water upwards.

Water and salt balances for the surface and intermediate layers

We first construct a balance for the surface layer by making the following assumption : that the depth of the surface layer is defined by the depth of the temperature minimum, or equivalently, by the vertical extent of the previous winter's convective overturn. This depth may vary interannually ; our observations from 1984 place it at about 150 m ± 30 m. Using this mean plus one standard deviation, or 180 m, and an area of 200,000 km^2 at the 90 m depth yields an annual production of 36,000 km^3. Thus, the annual average transports in and out of the surface layer must independently equal this volume :

$$V_i^s + W_u^L = 36{,}000 \tag{2 a}$$

$$V_o^s + W_d^s + 170 = 36{,}000 \tag{2 b}$$

where the V_i^s is the inflow of North Atlantic Water (NAW), the V_o^s is the combined outflow through the Corsica and Sardinian Channels, the W_d^s is the amount of surface water mixed downward, the W_u^L is the amount of LIW mixed upward, and the value 170 is the net loss of water vapor to the atmosphere, from Béthoux (1980). All units are in km^3/yr. The corresponding salt balance is,

$$37.30\, V_i^s + 38.68\, W_u^L = 38.00 \times 35{,}830 \tag{3}$$

where the values 37.30, 38.68, and 38.00 are the respective practical salinities for the NAW, the LIW-layer average, and the surface-layer average. The latter two were taken from Brown *et al.* (1979). The former was taken as 0.1 higher than that estimated for the NAW exiting the WMED *via* the strait of Sicily (Hopkins, 1985 ; Garzoli, Maillard, 1979) to account for mixing on entry over the Skerki Bank region.

Béthoux (1980) has estimated the loss of LIW northward through the Corsican Channel to be 10,400 km^3/yr at a salinity of 38.55. In order to estimate the amount lost southward through the Sardinian Channel, we make the assumption that the loss in LIW core salinity is proportional to the loss in LIW volume. This yields the following relationship :

$$\frac{V_i^L - V_o^L}{38.74 - 38.62} = \frac{V_i^L - 10{,}400}{38.74 - 38.55} \tag{4}$$

where V_i^L is the transport and 38.74 the salinity of the entering LIW, and V_o^L is the transport and 38.62 the salinity of the LIW exiting the Sardinian Channel. The two salinity values were taken from the October and November 1984 data.

The LIW volume and salt balances now become,

$$V_i^L + W_d^s = W_u^L + V_o^L + 2{,}300 + 10{,}400 \tag{5}$$

$$38.74\, V_i^L + 38.00\, W_d^s = 38.68\, W_u^L + 38.62\, V_o^L$$
$$+ 38.55 \times 10{,}400 + 38.68 \times 2{,}300 \tag{6}$$

where the volume flux of 2,300 is that to the TDW as calculated from equation (1). The values of the various volume fluxes calculated from equation (2) to (6) are given in Figure 4.

No distinction is made for the surface outflow of 28,390 km^3/yr as to which exists *via* the Corsican or Sardinian Channels. The amount exiting to the Ligu-

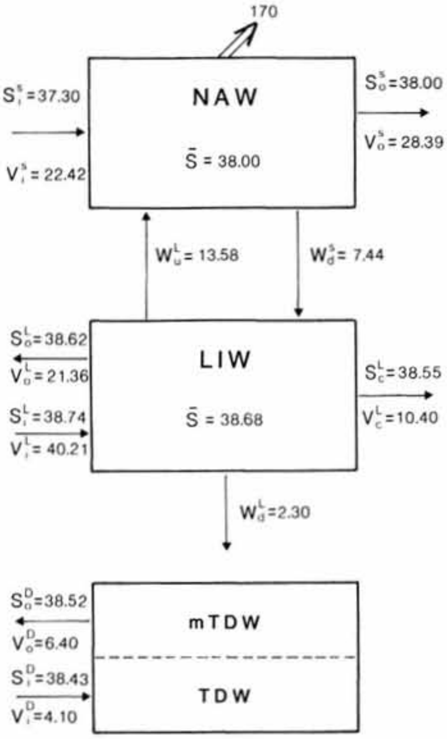

Figure 4

Schematic of the Tyrrhenian conservation of salt and volume calculations. A letter V represents horizontal transport and W vertical. The salinities are practical salinities and the transports are in 1 000 km^3/yr. *The superscripts indicate the donor water mass and the subscript indicates the direction of transport,* i.e. *s = surface, L = intermediate, D = deep, o = outflow, i = inflow, and u = up. The overbars indicate spatial means.*

rian has been estimated to be at least 20,000 km^3/yr (Manzella, personal communication), which leaves $\leq$ 8,400 km^3/yr to exit to the south of Sardinia. One will note that the outflow exceeds the inflow because of the net flux upward of LIW water at a rate of 6,140 km^3/yr, or roughly 2 1/2 times the amount lost downward to the TDW. The amount of LIW leaving to the south is equivalent to a 500-m layer extending from the Channel center west to Sardinia (~ 65 km) and exiting at 2 cm/s. Whereas the amount entering is equivalent to the water below 100 m in the eastern third (about 100 km) of the Sardinia-Sicily opening flowing in at 3 cm/s. The implication for the interior is that about 1/2 of the entering LIW recirculates out to the south, about 1/4 exits to the north, and about 1/4 is lost to mixing. It also implies that almost all of the LIW from the Sicilian strait (*i.e.* 38,000 km^3/yr Béthoux, 1980 ; or 44,000 km^3/yr Hopkins, 1985) enters the Tyrrhenian, a possibility proposed earlier by Krivosheya and Ovchinnikov (1973).

Variability

Without access to long time series of data, little quantitative can be said about the seasonal or interannual variability. Given the consistency of the WMDW and a TDW residence time of 30 yr, it is unlikely that seasonal variations of these waters would be detectable. However, the input-to-volume ratio for the LIW is much smaller, on the order of 2 to 3 yr, making observable seasonal signals of that water mass quite probable. On the basis of a volumetric *T-S* analysis, Brown *et al.* (1979) concluded that the volume of LIW does vary seasonally and that it is greater in the winter than summer. This appears to be supported by the observed distinct winter maximum in the westward transport of LIW through the strait of Sicily (Manzella, pers. comm.). However, the analysis of Brown *et al.* (1979) included only the region north of 39° N, thereby excluding the very southern portions of the Tyrrhenian where larger seasonal fluctuations might be expected to occur given the evidence that the LIW takes a shorter recirculation route in the summer. Also the lag between a maximum in supply and a maximum in the interior may be on the order of 1 to 3 months. In fact, contra-indicative of a LIW-volume maximum during winter in the Gulf of Naples is the observed deepening of the upper LIW boundary (38.6) to ~ 300 m in winter compared to ~ 200 m in the summer (Hopkins, Goneg, 1977).

The vertical structure was qualitatively similar throughout the observational period, as shown by the three stations in Figure 5, two stations of which (17, 27) were taken at nearly the same location in the west but separated by about 2 months and the other station (36) was taken in the east at nearly the same time as station 27. The persistence of the temperature-minimum feature (Fig. 4), created as result of the previous winter's convection, indicates a lack of vertical heat flux between the LIW temperature-maximum layer and the surface waters. Figures 6 *b*, *c* also show this feature as having been present nearly everywhere throughout the sampled region, albiet varying in strength.

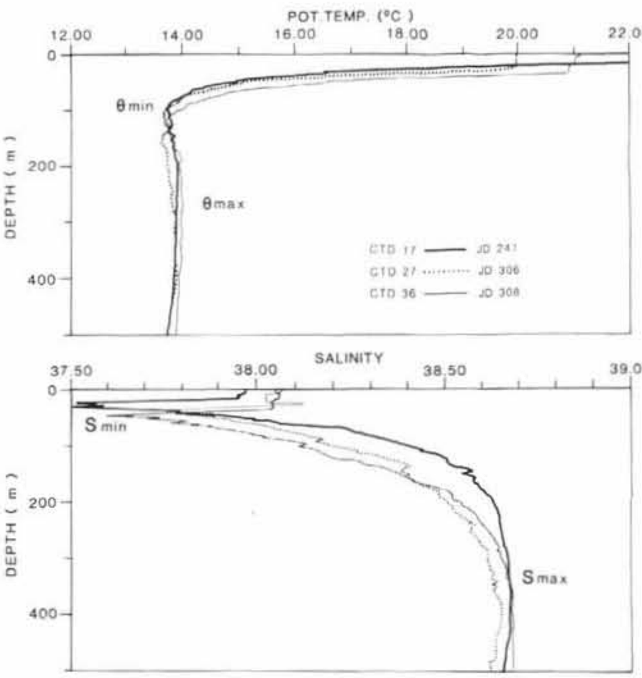

Figure 5

The characteristic vertical θ-S structure during the late summer early fall in the southern Tyrrhenian. Stations 17 and 27 were taken at nearly the same location but 65 days apart, and stations 27 and 36 were taken to the southwest and southeast, respectively as in Figure 1, but only 2 days apart. The temperature minimum and maximum and the salinity minimum and maximum features are labeled.

The salting of the surface mixed layer, relative to the salinity minimum, is also demonstrated in Figure 5. The salinity of the surface layers varies in time and space somewhat, probably due to advective changes but apparently not due to salting from local upwelling of LIW, which is precluded by the persistence of the underlying salinity minimum. The magnitude of the surface salinity increase is accountable through evaporation. For example, a salinity increase of 0.35 in the upper 30 m would require ~ 28 cm of evaporation, or the equivalent of ~ 90 Ly/d over 6 months. It appears then that the vertical mixing associated with winter convection must be considered as the primary mechanism for an upward LIW flux. However, our data did not extend to the northern sector of the Tyrrhenian where Moen (1984) has reported regions of upwelling and downwelling induced by spatial variability in the wind field. For example, in the cyclonic gyre east of the Bonifacio Strait he observed in October a patch of water at 100 m of about 3,000 km^3 with salinities greater than 38.5 and to the south a similarly sized patch in an anticyclonic gyre with salinities less than 38. Even the depth of the Corsica outflow and its reduced salinity is indicative of LIW upwelling and mixing with the surface waters. Thus, wind induced vertical circulations must be considered as an important additional mechanism for surface-to-intermediate layer exchange in the northern and coastal regions.

Horizontal distributions

The spatial distribution of the four vertical features identified in Figure 5 are shown in Figure 6. The value

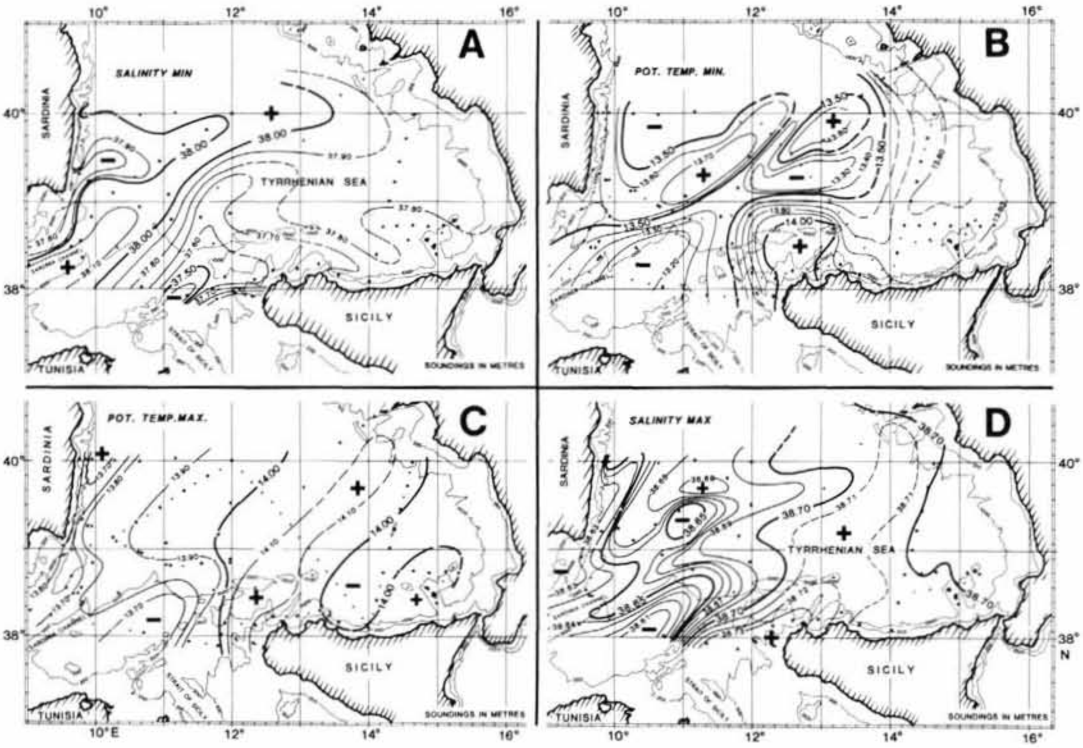

Figure 6

The contours of the vertical features of the salinity minimum (A), *potential temperature minimum* (B), *potential temperature maximum* (C), *and salinity maximum* (D) *for the two later cruises.*

of the salinity minimum (Fig. 6 A) can be interpreted as indicating the amount of NAW present, ≤ 37.5 being an unmixed input and ≥ 38.0 being a completely mixed or old surface water. Assuming a cyclonic pattern, the isohalines suggest flow in through the eastern portion of the Sardinia-Sicily opening, around to the east, and up the west coast of Italy. The low values off of southeastern Sardinia presumably would represent return, or exiting, surface flow. However, their values are too low to suggest an origin *via* a cyclonic closure of the isohalines from the north, thus suggesting that this patch of NAW was either seasonal variation in input or of local entry south of Sardinia. Variations in the input are expected not only at seasonal but also at higher frequencies, because the surface influx is responsive to wind forcing and to the availability of the NAW south of the Sardinia-Sicily opening. The latter is function of both the circulations of the Western and Eastern Mediterranean (*cf.* Hopkins, 1985) and thus is expected to have a fairly broad spectral response.

In contrast to the salinity-minimum layer, the deeper temperature-minimum layer is formed by a completely differently mechanism : as a result of winter convection instead of lateral input. Thus, the salinity-minimum layer is an advective feature distributed in proportion to the horizontal flux of the source NAW, but with some modification by vertical mixing ; whereas, the temperature-minimum layer is the result of vertical mixing processes (formed by winter convection and destroyed by vertical mixing) with some modification by advection. The temperature of this layer is limited to approximately 12.7 °C, the temperature at which it would become more dense than the underlying temperature maximum layer. Such temperatures are not observed in the open Tyrrhenian ; the results of Brown *et al.* (1979) showed a lower limit closer to 13.2 °C. If one assumes that the distribution at the end of its winter formation was laterally homogeneous, then the deviations shown in Figure 6 B reflect the effects of vertical mixing. Most notable is the 14 °C region north of the eastern tip of Sicily where apparently vertical mixing has all but destroyed the feature ; and the center and southern regions of < 13.5 °C where mixing appears to have been less.

The temperature maximum layer (Fig. 6 C) was found above the salinity maximum layer (Fig. 6 D). The average vertical separation was ~ 140 m and its horizontal distribution had no discernible spatial trend. Both of these fields indicate the distribution of the LIW with the salinity maximum being considered a more reliable indicator. For the distribution of the temperature maximum, additional XBT data from cruises were used in drawing Figure 6 C. The two distributions are similar. In particular, they both show the maxima leading from the entry point west of Sicily to the northeast towards the Gulf of Naples. Also significant is that the input of LIW appears to extend further eastward than that of the Atlantic water (*cf.* Fig. 6 A, D).

The vertical relationship between these features can be seen from their locations in the *T-S* composite shown in Figure 7 for the third cruise period. The TDW location at the 2 000-m depth implies about a 9 : 1 mixture of WMDW and LIW ; and the mTDW

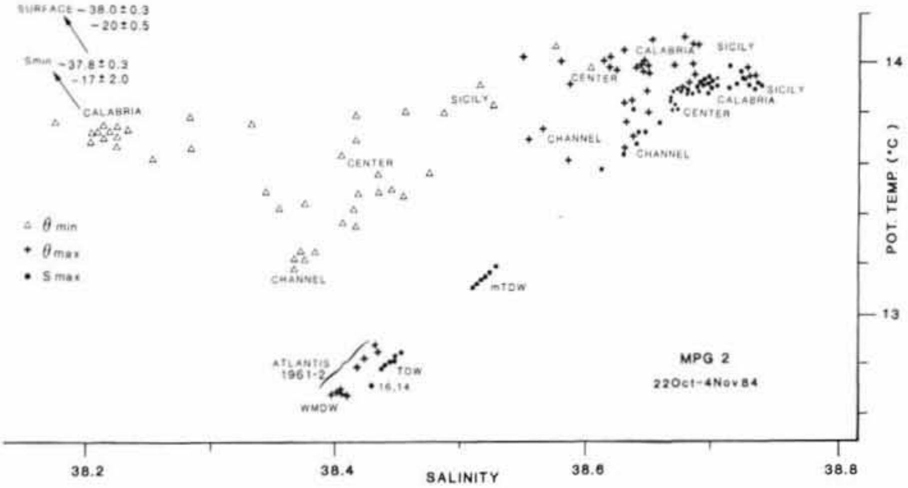

Figure 7

θ-S diagram from the third cruise period showing the O_{min}, O_{max} features and the location of the mTDW (station 16) and the 2 000-m TDW. Also shown are the 2 000-m WMDW from the area between Tunisia and Sardinia taken from 1961 *Atlantis* 263 *Cruise and the* 2 000*-m TDW taken from the* 1962 *Atlantis* 273 *cruise (Miller* et al., 1970).

location implies a 5 : 2 mixture of TDW and LIW. The 2 000-m *Atlantis* data (Miller *et al.*, 1970) for the WMDW in between Sardinia and Tunisia and the TDW for the center Tyrrhenian are plotted. Their salinities from 1961 and 1962 are ~ 0.2 fresher than ours from 1984. It is not clear whether this is an observational offset or one caused by natural variability. The 2 000-m values from stations 14 and 16 outside the sill and over the sill are also shown indicating an entering WMDW water type of 12.73 °C and 38.43.

It has been suggested in the case of other ocean environments where there occurs a separation between the maxima in temperature and salinity in intermediate waters that it results from the effect of double diffusive processes (*e.g.* Carmack, Aagaard, 1972). In the Tyrrhenian case, it can be explained more simply without necessarily evoking a double diffusive mechanism : *i.e.* the gradient in temperature immediately above the LIW is much smaller than that of salinity (Fig. 5) such that any mixing will result in a larger gradient in salinity than temperature and a relative temperature maximum will result.

A final point demonstrated by Figure 7 is the geographical grouping evident particularly in the temperature-minimum feature. The Calabrian stations in a tight cluster with low salinities suggests that this water was made locally through winter cooling of Atlantic water and remained there with little loss or admixture. The stations along the north coast of Sicily showed considerable spread in the T_{min} and T_{max}, but little difference, indicating more active mixing. And the stations to the southeast and towards Sardinia (labelled Channel and Center in the Figure) showed colder less saline water types.

The steric heights of the upper 500 m, calculated relative to the specific volume of the bottom water, showed a sea-level trough extending from the channel inward towards the Gulf of Naples and then southward towards Sicily. The high off the northeast coast of Sicily was a result of the warmer waters there (Fig. 8 *a*). The high at ~ 40° N off of Sardinia appears

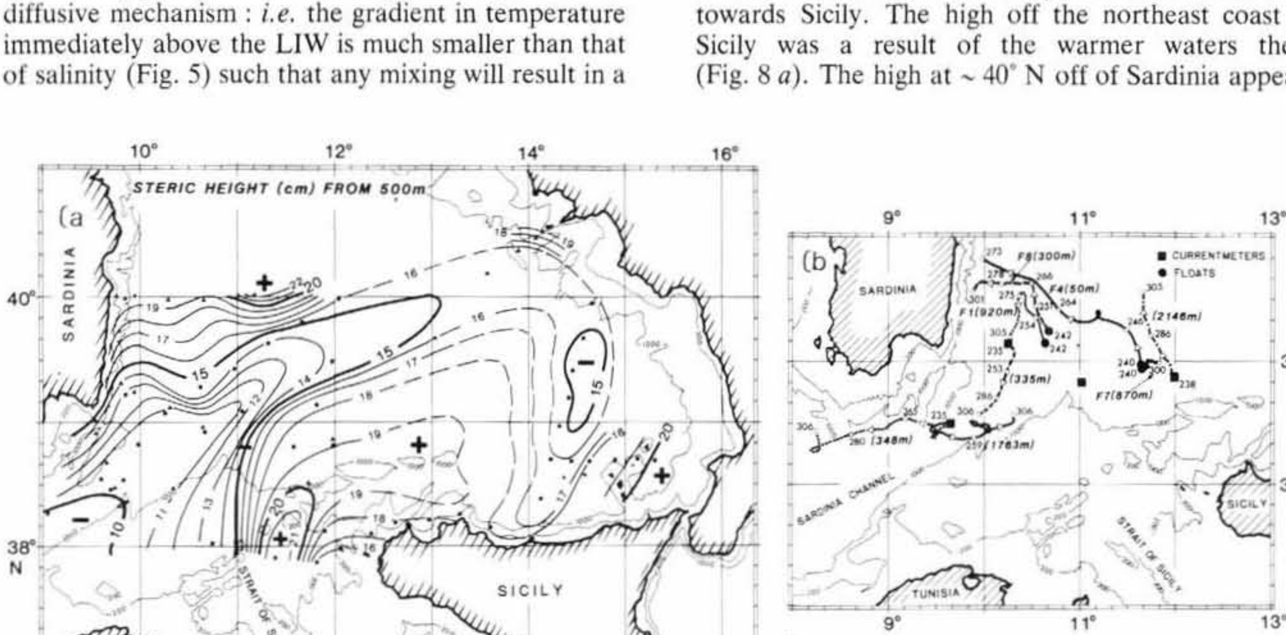

Figure 8

a) *The steric height field of the upper 500-m, computed relative to a reference density of* 1.02912, *using a data composite of the Magnaghi and MPG* 2 *cruises (Fig.* 1*)* ; b) *The progressive vector diagrams of the current meters and the trajectories of the floats. The instrument depths are in parentheses and Julian day times are given along the tracks. Mooring number* 3 *cited in the text is located by a solid square.*

to have been part of the ridge that causes the separation of the cyclonic circulation in the southern Tyrrhenian and the cyclonic circulation in the northern part of the Tyrrhenian (*cf.* Krivosheya, 1983 ; Moen, 1984). Of interest is the indication of a high off the Calabrian coast in the area east of 15° E, which appears to have received the Atlantic surface water (Fig. 6 A) but not the LIW. The LIW on the other hand appears (Fig. 6 C) to have skirted this eastern portion having taken a more northeasterly route from its entry east of Sicily. In the case of an inactive circulation of LIW from the strait of Sicily to the Calabrian area, there exists the possibility of an accumulation of LIW water entering from the Messina strait. This is a small influx at ~ 400 km^3/yr but is a water type slightly warmer than the normal LIW T-S regression, *i.e.* ~ 14.2 °C, ~ 38.6 (Hopkins *et al.*, 1984). Figures 6 C, D show this area to have a greater $\theta_{\max}$ relative to the $S_{\max}$.

In the southwest portion of the Tyrrhenian, the observed flow at the depth of the LIW was in general agreement with the steric-height field of Figure 8 *a*. To the west, the float F8 at 300 m (Fig. 8 *b*) moved to the northwest and then curved to the south. The flow recorded at the 335-m depth on mooring 1 moved southward towards the Sardinian channel at ~ 1.1 cm/s (Fig. 8 *b*) ; and the end of its progressive vector trajectory nearly reached the beginning of that belonging to the current meter at the 348-m depth in the channel suggesting continuous outflow of LIW in that region. The progressive vector diagram of the current meter at 358 m on mooring 3 (not shown in Figure 8 *b* because the speed was often below threshold) indicated northeasterly flow of ~ 2 cm/s, during the last week of October, in agreement with the steric height field.

Below the LIW there were two floats at ~ 900 m. The western one (F1) made a similar cyclonic curvature as did F8 above it (Fig. 8 *b*). The deep float in the interior (F7) moved only very little eastward (0.3 cm/s). This contrasted with the current meter record at 2 146 m nearby, which showed consistent northward movement (at 1.4 cm/s). This deep record did not show the same directional variability as the deep record near the sill but it did show a modulation in amplitude of about 3 cm/s and at approximately the same periodicity of about 45 days. This is not conclusive evidence but does suggest that the barotropic variations evident in the channel are also manifest in the interior of the basin. It also suggests that considerable energy is available at the continental shelf to force the coastal circulations about the Tyrrhenian.

The direction of deep flow (2 146 m) is consistent with the thermohaline circulation of the deep water flowing into the basin interior and the very slow movement at 870 m (Float 7) is consistent with the previously observed interior region of little mixing (Molcard, 1976), but the two are not compatible without sufficient baroclinicity between them. The hydrographic data at this location extended only to 1 000-m so that the existence of a shear between the ~ 800- and 2 200-m depths could not be computed. Other interior deep stations showed very little baroclinic structure between these depths. We have no explanation for the apparently anomalous track of Float 7 at 870 m relative to Float 4 at 50-m and the current meter at 2 126-m (Fig. 8 *b*). However, if we accept the validity of the deep flow, then we must consider the Tyrrhenian to have a significant barotropic pressure field that must be added to steric sea level depictions such as Figure 8 *a*.

CONCLUSIONS

The analysis of these data has shown that the deeper portions of the Tyrrhenian have both a relatively energetic circulation and are actively coupled to the WMED. The calculated input of WMDW to the Tyrrhenian at ~ 4 000 km^3/yr, or even at half this, is a large portion of the annual WMDW production at ~ 5 000 km^3/yr (Sankey, 1973) and thus makes the Tyrrhenian a major sink for WMDW with the possibility that a corresponding proportion of the WMDW flowing southward from its production area takes a route into the Tyrrhenian instead of a southwestern route towards Gibraltar. The exported mTDW, in the amount calculated, suggests an important coupling, between the deep circulation of the Tyrrhenian and the rest of the WMED, that accelerates the LIW-WMDW mixing cycle.

The thermohaline circulation appears to be driven by a steric height anomaly (higher) caused by the less dense water columns inside the Tyrrhenian than those of the adjacent WMED. The higher sea level forces the upper-layer water out of the Tyrrhenian through both openings. At depth a compensating internal pressure forces water into the basin, but only the Sardinia-Sicily opening is sufficiently deep to be affected. The thermohaline flow through the much shallower Corsican opening is unidirectional, or northward into the Ligurian. This would not be the case, of course, if the Corsican opening were the only opening of the Tyrrhenian. As it is, the divergence created by the Corsican outflow must be satisfied elsewhere, namely, in the Sardinia-Sicily opening which is wide enough above the 500-m depth to accommodate a bidirectional, but net outward, upper-layer flow. An important consequence of this configuration is that the Corsican outflow is strongly coupled to the upper layer inflow through the Sardinia-Sicily opening and likewise coherent within the basin interior.

The analysis indicated that most of the LIW inflow follows the bathymetry directly from the strait of Sicily into the Tyrrhenian. The circulation of the LIW within the Tyrrhenian, deduced from these observations, is that of a cyclonic internal route with ~ 1/4 continuing northward for exit to the Ligurian and ~ 1/2 recirculating south of 40° N and exiting through the western portion of the Sardinia-Sicily opening. The data suggested, however, that the LIW may not circuit completely to the east along the appropriate depth contours off the Calabrian coast but instead transits directly across the abyssal depths from northwestern Sicily to the coast Campania. Such a deviation appears to be controlled by a local sea level (steric) high off the Calabrian coast, a feature which tends to isolate the surface waters of that locale. Also of importance is the question of where, within the Tyrrhenian, the LIW downwelling might occur given the existence of the stable vertical structure observed below the LIW layer of the central abyssal plain (*i.e.* Molcard, 1976). We expect that this downward flux of LIW occurs about the basin perimeter, particularly in the north, where this sub-LIW layer intersects a quite irregular bathymetry causing a large-scale convergence and smaller-scaled mixing with the deeper waters.

The vertical coupling between the LIW and the layer above appears to be mostly seasonal. The fact that the surface layer receives more salt than can be accounted for by evaporation implies an upward flux of salt from the LIW. South of 40° N this flux throughout the stratified season appears to be negligible due to the persistence of the winter water type just above the LIW. The obvious mechanism for this upward flux is that of the winter convective mixing. North of 40° N, there is an additional effect occurring during the stratified season of the upwelling of LIW induced by the mesoscaled cyclonic circulation feature found in the northwestern Tyrrhenian at the latitude of southern Corsica (Moen, 1984). To this internal seasonality must be added that associated with the availability of each of the Atlantic and Levantine Intermediate Water inputs, to that occurring in the wind forcing, and to that forcing the entire basin's thermohaline circulation, in order that, the seasonal characteristics of the surface and LIW circulations be well described.

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REFERENCES

Béthoux J.-P., 1980. Mean water fluxes across sections in the Mediterranean Sea, evaluated on the basis of water and salt budgets and of observed salinities, *Oceanol. Acta,* **3,** 1, 79-88.

Brown S., Moretti M., Trotti L., Vultaggio M., 1979. The Tyrrhenian water masses, a seasonal volumetric statistical analysis. *Annal. Ist. Univ. Nav. Napoli,* **47-48,** 185-200.

Carmack E., Aagaard K., 1972. The formation of bottom water in the Greenland Sea, in : Processus de formation des eaux océaniques profondes, *Colloq. Inter. CNRS,* **215,** 65-82.

Cortecci G., Noto P., Molcard R., 1974. Tritium and sulfate-oxygen isotopes in the Mediterranean Sea. Some profiles in the low Tyrrhenian Basin, *Boll. Geofis. Teor. Appl.,* **16,** 64, 292-298.

Garzoli S., Maillard C., 1979. Winter circulation in the Sicily and Sardinia straits region, *Deep-Sea Res.,* **26,** 933-954.

Hopkins T. S., 1978. Physical processes in the Mediterranean basins, in : *Estuarine transport processes,* edited by B. Kjerfve, Univ. South Carolina Press, Columbia.

Hopkins T. S., 1985. Physics of the sea, in : *Western Mediterranean,* edited by R. Margalef, Pergamon Press, Oxford, 100-125.

Hopkins T. S., Goneg, 1977. The existence of the levantine intermediate water in the Gulf of Naples, *Rapp. Comm. Inter. Mer Médit.,* **24,** 2, 39-41.

Hopkins T. S., Zanasca P., 1988. Oceanographic data from the Southern Tyrrhenian Sea : August to October 1985. Data Report, Part I : Floats and moored instrumentations ; Part II : Hydrography.

Hopkins T. S., Salusti E., Settimi D., 1984. Tidal forcing of the water mass interface in the Strait of Messina, *J. Geophys. Res.,* **89,** C2, 2013-2024.

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

Krivosheya V. G., 1983. Water circulation and structure in the Tyrrhenian Sea, *Oceanology,* **23,** 2, 166-171.

Krivosheya V. G., Ovchinnikov I. M., 1973. Pecularities of the geostrophic circulation of the waters of the Tyrrhenian Sea, *Oceanology,* **13,** 822-827.

Lacombe H., Tchernia P., 1960. Quelques traits généraux de l'hydrologie méditerranéenne, *Cah. Océnogr.,* **12,** 527-547.

Miller A. R., 1972. Speculation concerning bottom circulation in the Mediterranean Sea, in : *The Mediterranean Sea : a natural sedimentation laboratory,* edited by D. J. Stanley, Dowden, Hutchinson and Ross, Stroudsburg, Penn., 37-42.

Miller A. R., Tchernia P., Charnock H., McGill W. D., 1970. Mediterranean Sea Atlas of temperature, salinity, oxygen profiles and data from cruises of R/V Atlantis and R/V Chain with distribution of nutrient chemical properties, The Woods Hole Oceanographic Institution Atlas Series, **3,** Woods Hole, Massachussetts, 190 p.

Moen J., 1984. Variability and mixing of the surface layer in Tyrrhenian Sea : MILEX'80 (Final Report), Saclantcen SR-75, La Spezia, Italy, Saclant ASW Res. Cent.

Molcard R., 1976. A review of the stepped structure in the Tyrrhenian Sea, *Rapp. Comm. Inter. Mer Médit.,* **23,** 5, 21-31.

Molcard R., Tait R. I., 1978. The steady state of the step structure in the Tyrrhenian Sea, Saclantcen SR-24, La Spezia, Italy, Saclant ASW Res. Cent.

Moskalenko L. V., 1983. Seasonal variability of integrated wind-driven circulation in the Tyrrhenian Sea, *Oceanology,* **23,** 4, 405-409.

Ovchinnikov I. M., 1966. Circulation in the surface and intermediate layers of the Mediterranean, *Oceanology,* **6,** 48-59.

Pistek P., Strobel F. de, Montanari C., 1984. Low frequency recoverable acoustic Swallow floats for measuring mid and deep water circulation, *Atti 6 Congr. Assoc. Ital. Oceanol. Limnol., 12-14 Aprile 1984, Livorno,* 173-184.

Sankey T., 1973. The formation of deep water in the North-western Mediterranean, *Progr. Oceanogr.,* **6,** 159-179.

Stocchino C., Testoni A., 1968. Le correnti nel Canale di Corsica e nell'Arcipelago Toscano, Ist. Idrogr. Mar., F.C. 1036, Genova, Italy.

Tait R. I., 1984. The physical oceanography of the Tyrrhenian and Ligurian Seas, *Atti 6 Congr. Assoc. Ital. Oceanol. Limnol., 12-14 Aprile 1984, Livorno,* 48-84.

Tillier P., 1980. Expendable mid-range Sofar floats and shipborne receiver, *Polymode News,* **73,** 7-8.

Wüst G., 1961. On the vertical circulation of the Mediterranean Sea, *J. Geophys. Res.,* **66,** 10, 3261-3271.