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Coastal currents on the Sicilian shelf south of Messina

Coastal current
Tidal mixing
Water mass
Strait of Messina

Courant côtier
Brassage de courant
Masse d'eau
Détroit de Messine

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ABSTRACT

The dynamics of a coastal current flowing on the eastern shelf of Sicily are investigated by means of hydrological data and satellite-derived imagery. Strong tidal mixing occurring near the sill of the Strait of Messina generates a water mass whose hydrological characteristics are intermediate between Levantine and Atlantic waters. This water mass flows southward along the Sicilian coast as far as 100 km from the sill and as far offshore as 10 km. It therefore affects a major part of the eastern coast of Sicily. Furthermore, this current can become unstable and display meanders and studies.

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RÉSUMÉ

Courants côtiers sur le plateau continental sicilien au sud de Messine

La dynamique d'un courant côtier s'écoulant sur le plateau continental à l'est de la Sicile a été étudiée à partir des données hydrologiques et de l'imagerie satellitaire. Le brassage interne par la marée à proximité du seuil du détroit de Messine engendre une masse d'eau dont les caractéristiques hydrologiques sont intermédiaires entre celles des eaux levantine et atlantique. Cette masse d'eau s'écoule vers le Sud en longeant la côte sicilienne jusqu'à 100 km du seuil, et jusqu'à 10 km au large. Elle affecte ainsi la plus grande partie de la côte orientale de Sicile. De plus, ce courant peut devenir instable et présenter des méandres et des tourbillons.

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INTRODUCTION

This paper describes the dynamics of the water mass generated in the Strait of Messina by tidal mixing of surface Atlantic water and Levantine Intermediate Water (LIW), which subsequently flows southward along the eastern Sicilian shelf.

The Strait of Messina separates the Italian peninsula from Sicily (Fig. 1) and is a natural connection between the Tyrrhenian Sea and the Ionian Sea. The width of the strait at its narrowest point is approximately 3 km and the average depth is 75 m. The sea bottom slopes down approximately 1 300 m towards the Ionian, and 300-600 m towards the Tyrrhenian side. Thus the strait constitutes a submarine barrier or sill to the water flowing through it.

From Vercelli's 1922 and 1923 measurements, the following picture, concerning the current distribution in the Strait of Messina, has emerged (Vercelli, 1925; Hopkins *et al.*, 1984). At the narrowest point there are two layers of marine water: surface Tyrrhenian water of Atlantic origin ($T=16.6°C$, $S=38.0$, $\sigma_t=27.93$) and deeper LIW ($T=14.2°C$, $S=38.6$, $\sigma_t=28.94$). A steady surface current flows southward ($v\sim 10$ cm/s) while a steady bottom current flows northward ($v\sim 13$ cm/s).

A semidiurnal tidal current originating in the co-oscillation of the water masses of the strait with the tides of adjacent seas is superimposed on these steady currents. These tides are almost in phase opposition. Although the tidal amplitudes are relatively small (~ 10 cm, Fig. 2), the sea surface slope can attain values of 1-

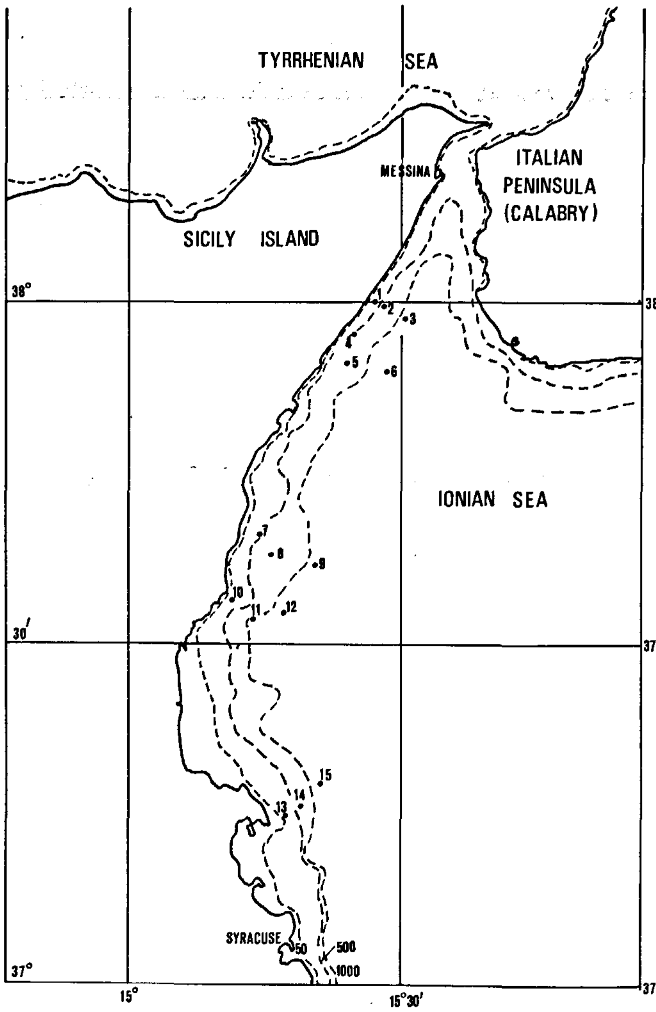


Figure 1
General map with the stations. Morphobathymetric map of Messina Strait area.

2 cm/km, which lead to strong currents, as high as 2-3 m/s at spring tide.

The interface time-averaged depth is 150 m in the Ionian and Tyrrhenian Seas, but it rises to a mean depth of 30 m at the sill. Large-amplitude internal waves, due to strong tidal action, give rise to extensive mixing of surface and Levantine waters. Turbulence on the sill is caused by large tidal currents (typical values of velocity v, width of the strait L and depth h, are 2 m/s, 3 km and 100 m respectively). Thus, the Reynolds number is 10^6-10^8 (Abbate *et al.*, 1982), and $h/u^3 \sim 12$ s^3/m^2. The latter parameter indicates areas of strong tidal mixing; h is the bottom depth and u the

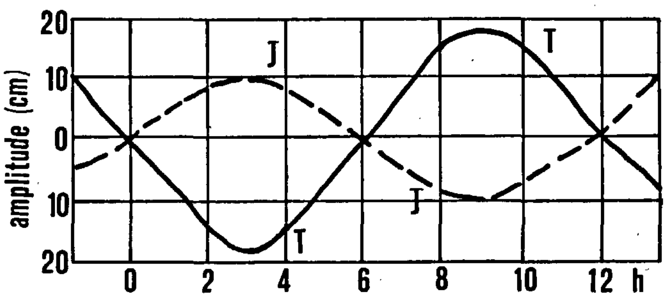


Figure 2
Ionian and Tyrrhenian tidal amplitudes in the semidiurnal period.

velocity of the tidal current. When $h/u^3 < 50$-100 s^3/m^2, tidal mixing can be observed (Simpson *et al.*, 1978).

During the so called "rema montante" (tidal current flowing from the Ionian to the Tyrrhenian Sea) LIW reaches the surface and mixes with surface water. After current reversal, the Tyrrhenian water flows southward ("rema scendente") and is entrained in the surface cyclonic circulation of the Ionian Sea (Vercelli, 1925; Vercelli, Picotti, 1926; Krivocheia, Ovchinnikov, 1973). This southward flow is also fed by the deep northward current rising to the surface in the strait as well as by the steady surface current flowing in the innermost part of the strait. Vercelli and Picotti (1926) estimated a time-averaged transport of ~ 1.3 $10^4 m^3/s$ in each direction.

The above mentioned tidal mixing generates a water mass whose hydrological characteristics are intermediate between LIW and water of Atlantic origin. The purpose of this paper is to analyse the southward flow of this water mass, called C water in the following.

Grancini and Magazzù (1973) recently described the hydrological properties of the marine region south of the Strait of Messina by means of thermohaline data. They found that, in the coastal region, there are mixed waters of Atlantic (warmer and less salty) and Levantine origin (colder and saltier). In the offshore region a typically Ionian water can be observed. The importance of this coastal current to the coastal environment is clear if one takes into account that it can even reach Syracuse, ~ 100 km from its place of origin. This coastal current was not detected beyond Syracuse in the satellite imagery. Entrainment of local Ionian water may well be a removal mechanism of the surface signature of this current.

SATELLITE IMAGERY

The southward flow of C water can easily be detected in the satellite imagery: 16 AVHRR cloud-free images obtained from Tiros N and NOAA 6 were used. Two different phenomena were observed in the spring, summer and autumn imagery. The first was a cold water spot bounded by a thermal front ($\Delta T \sim 2°C$) a few kilometres north and 15-25 km south of the sill (Fig. 3). The second phenomenon was a cold coastal water strip which extended southward from the sill (up to 100 km long and 4 to 10 km wide) following the shelf of Sicily (Fig. 4). These two phenomena can even be observed at the same time.

This cold water spot is linked to the tidal current which mixes intermediate with surface water masses. The distance between the sill and the southern edge of the cold spot was compared with the distance of the outcropping interface between the two layers (Tab.), computed by Hopkins *et al.* (1984), by means of a two-layer model of the tidal evolution of the interface. This model is very simple but compares well with experimental data.

This cold coastal water strip which, in the satellite imagery, sometimes seems to reach Syracuse is the C

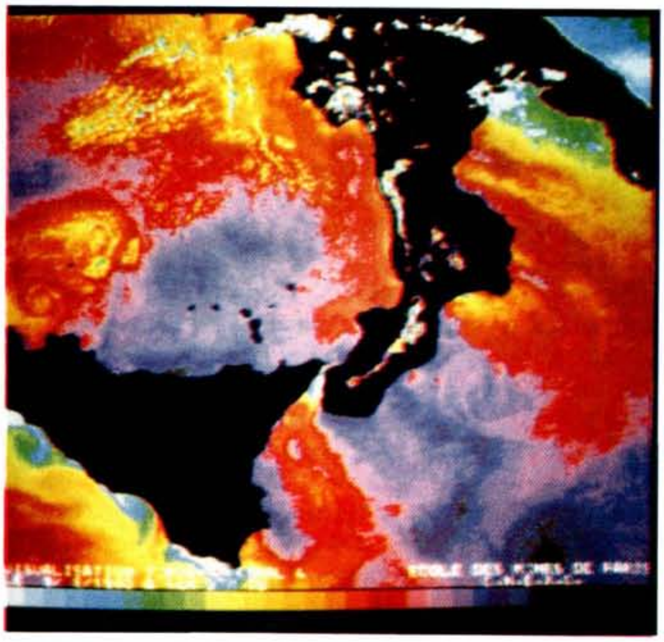


Figure 3
Satellite thermography (Ch. 4 AVHRR of Tiros N, August 9 1980 14.27 GMT) with the tidally generated cold spot.

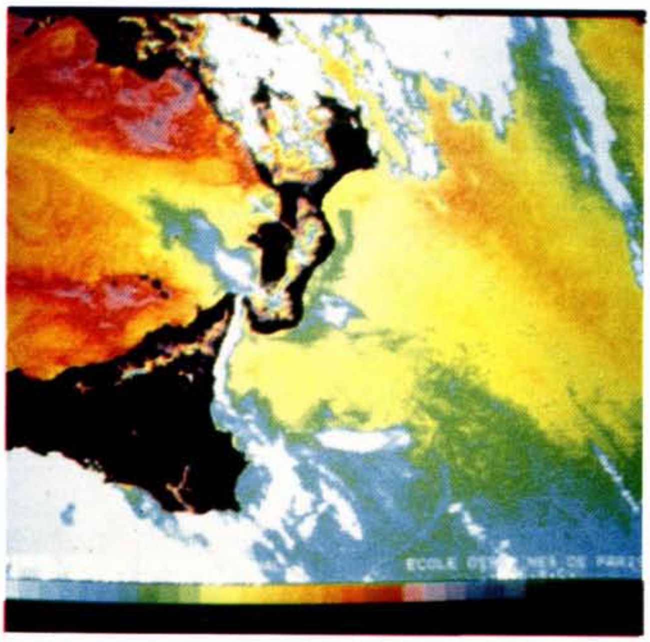


Figure 4
Satellite image (Ch. 4 AVHRR of NOAA 6, June 2 1981 7.32 GMT) with the cold strip along the Sicily shelf.

Table
Comparison between observed (by satellite) and theoretical (Hopkins et al., 1984) *distance of the outcropping interface, south of the sill. For the satellite data to obtain the distance, its average value for southflowing current has been subtracted (15 km) to each to the data representative of northflowing situations.*

Phase	HSS	Satellite
3	(0 ± 0.5) km	missing
8	(9.4 ± 0.5) km	(8 ± 2) km
6	(10.1 ± 0.5) km	(10 ± 2) km
5	(9.2 ± 0.5) km	(7 ± 2) km
6	(10.1 ± 0.5) km	(8 ± 2) km
7	(9.4 ± 0.5) km	(5 ± 2) km

HSS = Hopkins, Salusti, Settimi (1982) model computation.

water coastal current, which is colder than the surrounding Ionian water masses.

Meanders and eddies which affect the linear shape of the cold water strip can also be observed (Fig. 5). While the eddy size is of the order of 30 km, their time scale cannot be determined owing to lack of continuous satellite coverage. But, from the displacement of the southernmost location of the strip front in a pair of subsequent images (April 7, 1980, 0659 and 1808 GMT), the velocity normal to the front of the strip was estimated at 20 cm/s. This cold water strip is not always visible in the satellite imagery, suggesting that C water may sometimes flow below the sea surface.

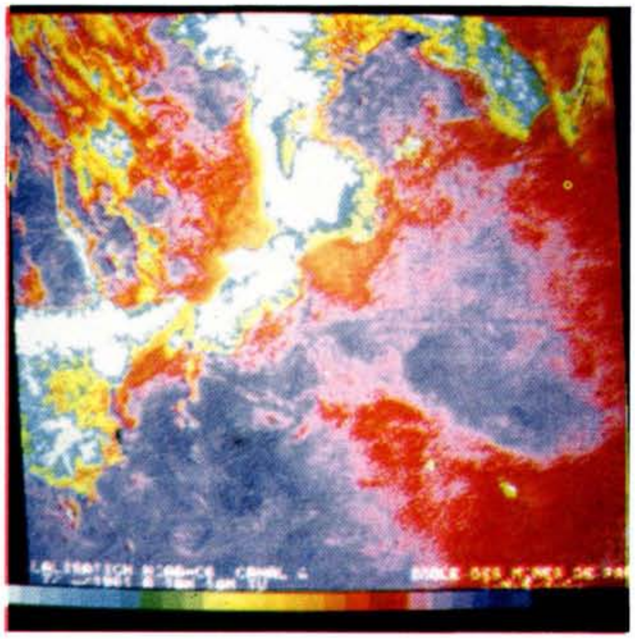


Figure 5
Thermography (Ch. 4 AVHRR of NOAA 6, July 14 1981 7.37 GMT) with a large eddy of C water.

HYDROLOGICAL DATA

Hydrological data were collected at 15 stations (Fig. 1) on May 30 and 31, 1982, during the oceanographic cruise Prime on the Italian R/V Bannock. At each station, salinity, temperature, conductivity and depth were recorded by a Neil Brown bathysonde. Ten-metre deep temperature data were used to trace isotherms which ran parallel to the thermal front observed in satellite imagery (Fig. 6). A north-south thermal gradient, in agreement with the result obtained by Grancini and Magazzù (1973), was also observed.

Vertical T-S diagrams of each of the 15 stations show the presence of two different waters, C water (closer to the Sicilian coast) and Ionian water (offshore). These T-S diagrams have been divided into three types (Fig. 7):

a) C water only (station 1, 4 and 5);

b) C water ovelaid by mixed C and Ionian waters (station 2, 6, 7, 8, 10, 11, 13 and 14);

c) Ionian water only (offshore stations 3, 9, 12 and 15).

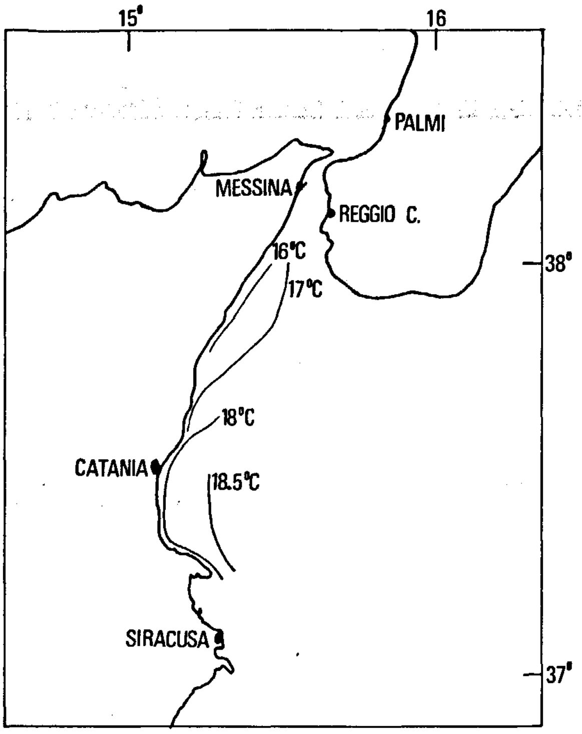


Figure 6
Plot of the ten-metre isotherm from the Prime cruise hydrological stations.

The main difference between C and Ionian water is that the former is stratified in both temperature and salinity while the latter is only stratified in temperature. The border between Ionian and C water was found at 5-10 km offshore. Hydrologically, C water ranges from t=16.0°C and S=38.2 (at the surface) to t=14.0°C and S=38.7 (at roughly 100 m).

Inspection of T-S diagrams reveals two interesting features. The first is a remarkable variability due to the complex history of C water, which results from mixing of surface Tyrrhenian water, LIW and surface Ionian water in time-dependent ratios due to tidal variations, atmospheric forcing and intrusions of Ionian water masses. Temperatures and density cross-sections (5 transects normal to the Sicilian coast, Fig. 1) indicate a relatively cold and less dense water which flows southward on the Sicilian shelf (Fig. 8 *a* and *b*). Moreover, an interesting similarity between C water T-S diagrams and the Tyrrhenian water T-S diagram can be observed in the 30-100 m depth range (upper panels Fig. 7). This similarity indicates that Tyrrhenian water is the main component of C water. Tyrrhenian water below the thermocline rises ~30 m during the initial phase of "rema scendente" is then strongly mixed with local water and finally crosses the sill retaining its own T-S properties (Vercelli, Picotti, 1926).

Ship's drift data taken in windfree conditions indicated a persistent southward orientation of currents which was weakly dependent on the offshore distance. The absolute current velocity ranged from 0.2 to 0.5 m/s, where the maximum value was measured at the northernmost transect. A gross estimate of the C water transport, $\Phi = 1.5\ 10^5\ m^3/s$, in the northernmost sections was obtained. The area of this section was computed from the 28.9 density surface. The above transport value is closer to the C water production due to tidal mixing (maximal value $\Phi' = 3\ 10^5\ m^3/s$; Vercelli, 1925) than to the hydrological transport ($\Phi'' = 1.3\ 10^4\ m^3/s$; Vercelli, 1925).

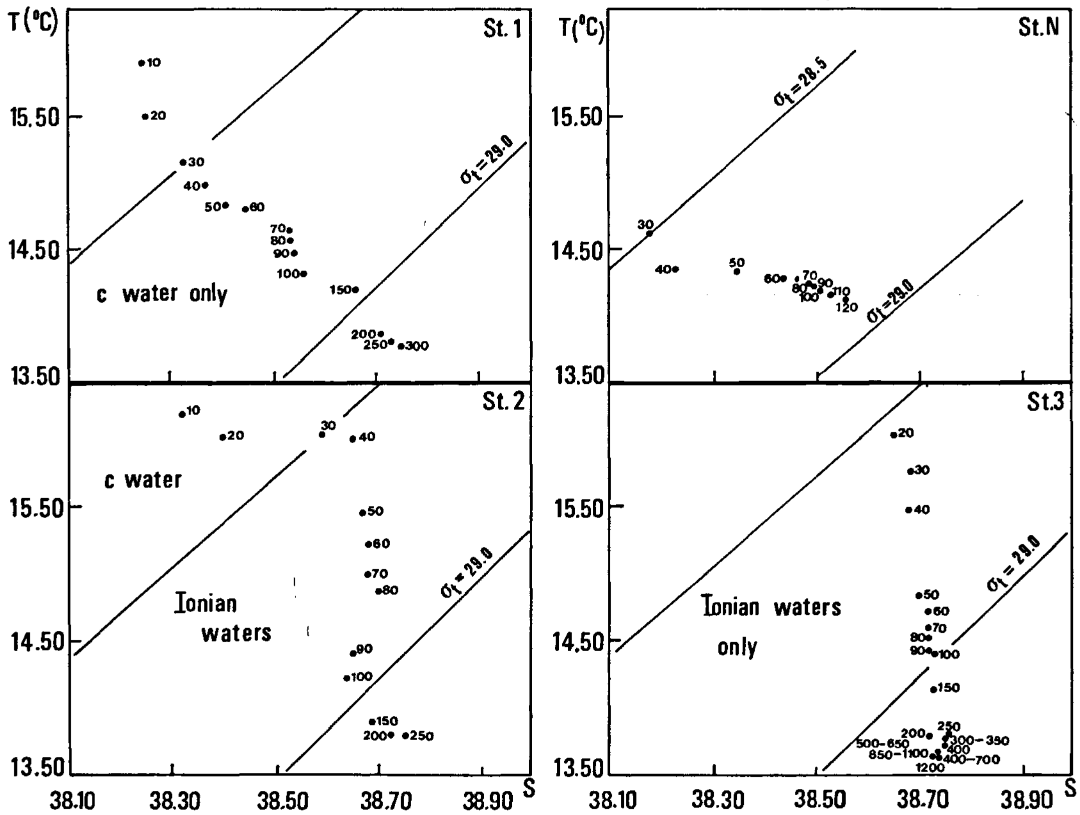


Figure 7
T-S diagrams of station N (Tyrrhenian Sea), station 1 (type a in text), station 2 (type b in the text) and station 3 (type c in text). Numbers represent depths in metres.

b

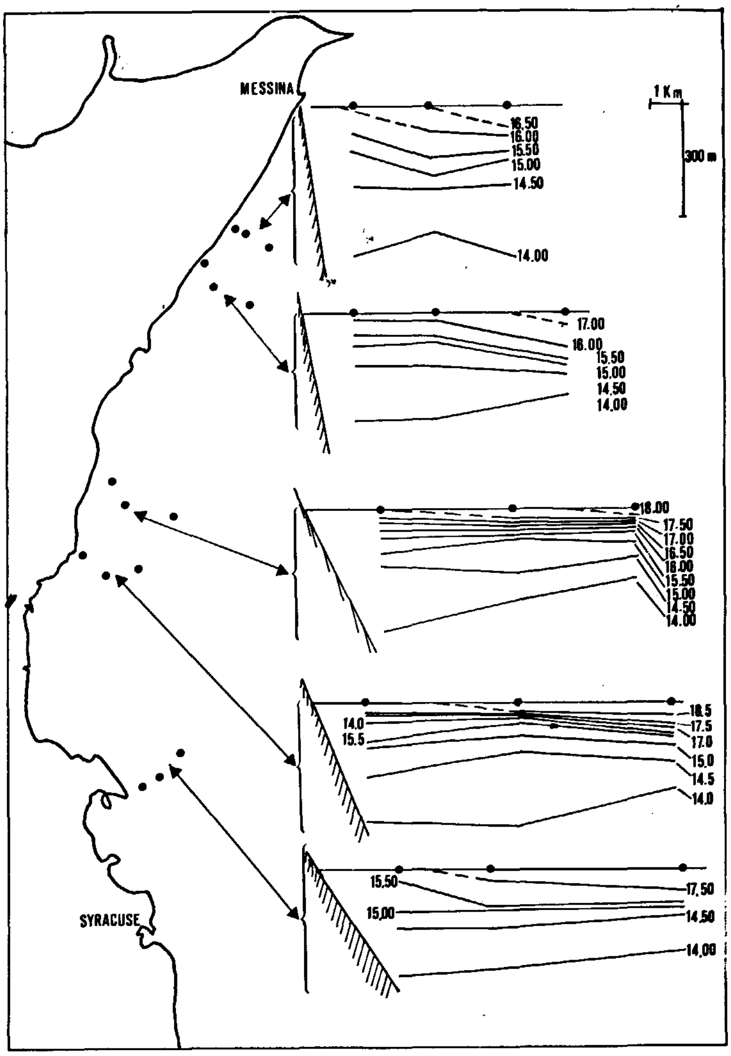
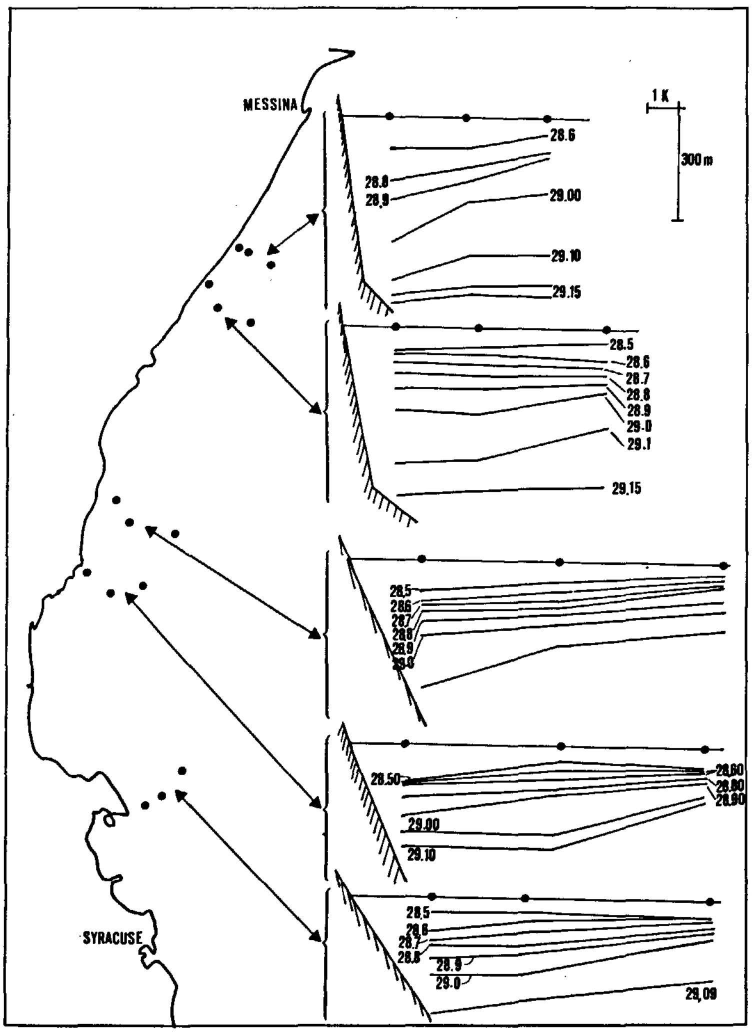


Figure 8
a) Density cross sections obtained from cross shore CTD casts (see *text and Fig.* 1).
b) Temperature cross sections obtained from cross shore CTD casts (see *text and Fig.* 1).

a



DISCUSSION AND CONCLUSIONS

A coastal water, called C water, which flows on the Sicilian shelf south of Messina was detected in satellite imagery and by CTD casts carried out during the oceanographic cruise Prime. Grancini and Magazzù (1973), found a mixed water mass on the Sicilian shelf (like that which we found) and, further offshore, a southward flowing, typically Ionian water mass. Salinity ranged between 38.0 and 38.5 in the upper 100 m of the coastal region, and between 38.7 and 38.9, in the upper 100 m of the offshore region. Both salinity and temperature increased southward. From a dynamical viewpoint they observed southward flowing Ionian water (max velocity 0.5 m/s at about 10 nautical miles offshore), which constituted a dynamical barrier to the coastal waters.

C water is generated by mixing of waters of Atlantic origin ($t=16.6°C$, $S=38.0$, $\sigma_t=27.93$) and LIW ($t=14.2°C$, $S=38.6$, $\sigma_t=28.94$) at the sill of the Strait of Messina. It occupies a region bounded by a northern border (within 10 km north of the sill) and by the Calabrian and Sicilian coastlines. South of the sill, C water flows along the shelf of Sicily as a narrow coastal current (4 to 10 km wide) up to 100 km long. A gross estimate of the C water transport computed from windfree ship's drift data is $1.5\ 10^5 m^3/s$.

T-S properties indicate that C water is only slightly mixed with offshore water masses. Therefore, to first order, we can assume that both shelf (C water) and off shelf (Ionian water) transport are individually conserved. Conservation of potential vorticity of a C water parcel (Ionian water parcel) takes the following form:

$$(\omega+f)/h=(\delta_x v-\delta_y u+f)/h=\text{constant} \quad (1)$$

where $u(v)$ is the horizontal component of the velocity field in the x, along shore (y, across shore) direction, f is the Coriolis parameter and h the local depth of the sea.

During the hydrological measurements the drift of the ship was weakly dependent on the across shore coordinate. Therefore the current shear was probably limited to a narrow coastal boundary layer. Hence, offshore of the latter, the flow of C water can be expressed by:

$$|\omega| \ll f \quad (2)$$

from (1) and (2) one has:

$$|\delta h|/h=|\omega|/f=\varepsilon \ll 1 \quad (3)$$

where ε is the Rossby number and $|\delta h|$ is the absolute thickness change of the water parcel. The departure of the flow from the isobaths will be of order $h\varepsilon$. Therefore, if no additional vorticity is added by wind stress or friction, C water should remain on the narrow shelf. Conversely the Ionian water mass, which flows at depths of 1000-2000 m cannot intrude on the shelf (100-200 m deep) under most meteorological conditions. It is noteworthy that Shaw and Csanady (1983) obtained the same result for deep-sea currents. Moreover, since the narrow shelf has a rather constant depth and width, conservation of mass implies that the velocity is almost constant along the Sicilian shelf. The along-shore velocity takes the following form:

$$u \leqslant \Phi/\int_{\Phi}^{L} h\,dy \approx 2\,\Phi/[h(x)\,L(x)] \quad (4)$$

The latter is an upper velocity limit since friction, mixing and entrainment in the Ionian current obviously affect the motion. However, satellite imagery and hydrological measurements demonstrate that C water propagates to a distance of as much as 100 km from the sill with a smaller velocity (0.2 m/s) than the initial one (0.5 m/s). This type of surface shelf current, of tidal origin, is rather unique in the Mediterranean Sea.

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