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Satellite and field observations of shelf currents off Cape Santa Maria di Leuca, Southern Italy

Thermal satellite imagery
Coastal current
Adriatic Sea
Velocity estimation
Thermographie
Courant côtier
Mer Adriatique
Estimation de la vitesse

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ABSTRACT

Satellite imagery and current measurements over the Italian shelf of the southern Adriatic Sea show that, in the period October - April, the coastal current follows depth contours to form a steady (anticyclonic) circulation over the shelf, in agreement with the potential vorticity conservation. The streamlines can easily be measured on satellite infrared images since the coastal current is separated from the offshore marine waters by a temperature front, clearly detectable in the satellite data. In this paper we discuss this motion and present a simple method to estimate its velocity when the current passes around a sharp promontory. Deviations of the streamlines from the isobaths, due to centrifugal forces, permit the estimation of current velocities from thermal satellite images via a very simple algebraic model. The application of this method to Cape Santa Maria di Leuca gives theoretical values of velocity in the 10-40 cm/s range, in good agreement with *in situ* determinations.

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RÉSUMÉ

Observations satellitaires et mesures des courants côtiers au large du cap San Maria di Leuca, Adriatique

Les images du satellite et les mesures du courant sur la plate-forme italienne du Sud de la Mer Adriatique montrent que pendant la période octobre-avril, le courant côtier suit les isobathes, pour former une circulation stationnaire (anticyclonique) sur la plate-forme en accord avec la conservation de la vorticité potentielle. Les lignes de courant peuvent être facilement mesurées grâce aux images infrarouges des satellites puisque le courant côtier est séparé des eaux profondes par un front de température qui apparaît dans les données du satellite. Dans le document, nous discutons ce mouvement et présentons une méthode simple pour estimer la vitesse quand le courant contourne un promontoire prononcé. En effet les écarts entre lignes de courants et isobathes, dus aux forces centrifuges, nous permettent d'estimer les vitesses du courant à partir des thermographies satellitaires grâce à un modèle algébrique très simple.
L'application de cette méthode au Cap de Santa Maria di Leuca nous donne des valeurs théoriques de la vitesse dans un intervalle de 10-40 cm/s en bon accord avec les déterminations *in situ*.

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INTRODUCTION

This study was stimulated by the observation of a sharp thermal front, during the period October-April, near the Italian border of the southern Adriatic Sea and around Cape Santa Maria di Leuca. It is interesting to note that this front is perturbed by many meanders of rather large, but bounded, spatial dimensions.

This is a rather general fact. Using satellite imagery, currents flowing along narrow shelves can be observed in various geographical regions, *e.g.* cold or warm water masses whose flow follows the bathymetry, while external waters have little influence on their motion. Lateral instabilities, eddies and meanders are, moreover, very often observed at the boundary of the two water masses.

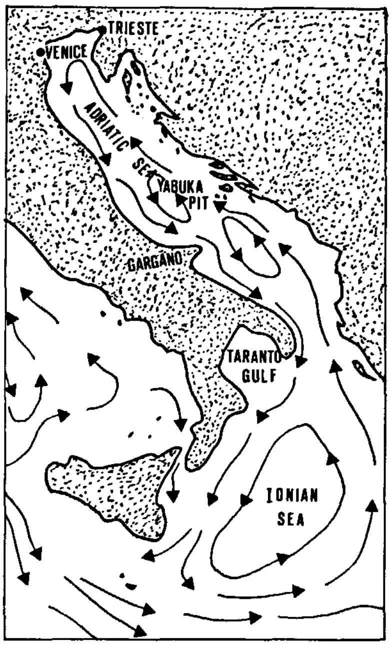


Figure 1
Map of geostrophic surface currents in the Adriatic Sea (Hopkins, 1978).

The importance of the inertial effect on deep shelves with large vertical-scale bathymetric features of short horizontal-scales stresses the efficacy of conservation of potential vorticity. In the Mediterranean, a clear example is the surface Adriatic water following the Italian shelf of the southern Adriatic Sea up to Cape Santa Maria di Leuca (Fig. 1). When this shelf current reaches the cape, it flows following the bathymetry. Downstream from the cape, satellite images show that the streamlines (assuming that in these cases the temperature can be considered a tracer) are shifted offshore from the 100 m toward the 200-500 m isobath lines (Fig. 2). Therefore, an estimate of the velocity of these shelf currents is possible by means of satellite imagery alone.

We apply our idea to the shelf currents flowing from the Adriatic to the Ionan Sea; our results are in fairly good agreement with *in situ* measurements.

GENERAL PROPERTIES OF MARINE CURRENTS IN THE SOUTHERN ADRIATIC SEA

In the Adriatic Sea (Fig. 1), surface waters first flow northwards along the Yugoslavian coast and then split into three cyclonic branches (off Gargano; the mid-Adriatic trench; gulfs of Trieste and Venice). Then the surface current turns south and, after following the Italian coastline, ultimately reaches the Ionian Sea and Taranto Gulf (Buljan *et al.*, 1976; Hopkins, 1978).

These currents can be compared with the one-year long satellite data analysis (Philippe, 1980; Fig. 3) of the Mediterranean Sea, *i.e.* a map of surface thermal fronts and associated phenomena. For the Adriatic Sea, during the period October-April, a thermal front located a few kilometers off the Italian Adriatic coastline separates cold coastal water masses from warmer external ones, all flowing south. During that period, according to Philippe (1980), the production of cold water is mainly due to river runoff and deep-water formation induced by strong NE winds (Bora). The southern part of this thermal front envelops the Italian shelf up to the Gulf of Taranto (Ionian Sea).

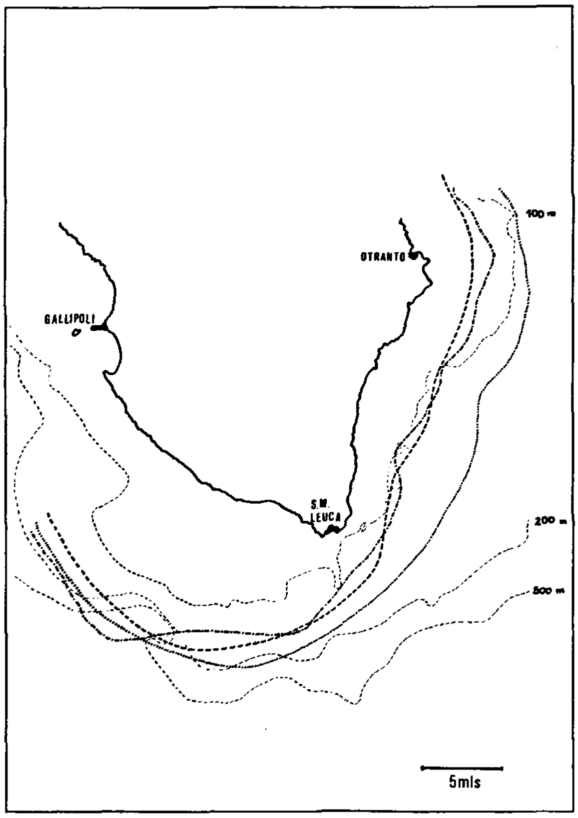


Figure 2
Comparison between the 100, 200, 500 m isobath lines (thin dashed curves) and 3 representative thermal fronts obtained from IR March images: 10 February 1982 (thick dashed - dotted line), 9 March 1983 (thick dashed line), 17 April 1983 (dotted line).

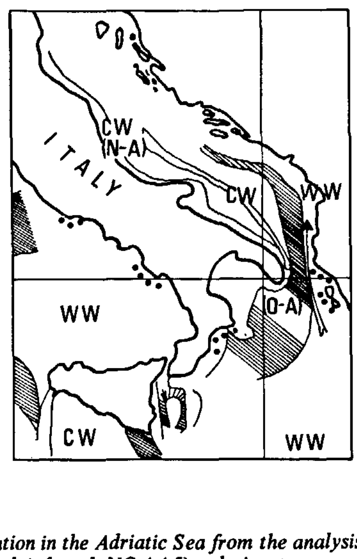


Figure 3
Surface circulation in the Adriatic Sea from the analysis of 402 satellite images (thermal infrared NOAA 5) relative to a period of 1.5 year (from Philippe, 1980).

Recently Moretti *et al.* (1981) carried out hydrological and current meter measurements in this zone (March 1980; Fig. 4*a*): they observed currents ranging from 5 to 25 cm/s (Fig. 5).

During the VERA 83 cruise onboard the R/V Bannock of Italian CNR, Böhm *et al.* (1983) observed, in May, a strip of well marked (Fig. 5) marine water flowing on the shelf near Santa Maria di Leuca (Fig. 4*a*, *b*, *c*). The water was less stratified than the offshore water masses (Zoccolotti *et al.* 1984); the velocities near the cape were ~ 30 cm/s. Unfortunately thermal images of the zone during this period are not available.

THE METHOD

Field data underline the effect of potential vorticity conservation in the south-eastern part of the Italian peninsula. The latter entails a steady flow of a rotating, inviscid, constant-density fluid following isobaths. This effect can be modified by external forces, stratification and viscosity. Several scaling parameters are of importance, *i.e.* the Rossby number ε and the Ekman numbers: all have to be small in order to allow steady geostrophic flows, as in the present case (Tab. 1). Therefore a steady, barotropic, inviscid, quasi-geostrophic potential vorticity equation in an f_o-plane can be derived by expansion of the momentum and continuity equations in power of ε. It yields:

$$0 = (u\,\partial_x + v\,\partial_y)\left(\frac{f_o+\xi}{h}\right)$$

$$\neq (u\partial_x + v\partial_y)\left(\frac{f_o+\partial_x v-\partial_y u}{h}\right) \quad (1)$$

where f_o is the Coriolis parameter, h is the bottom depth, x,y the alongshore, across-shore coordinates, u,v the corresponding velocity components. For small Rossby numbers the flow tends to form an anticyclonic circulation around the shelf. With decreasing ε the flow tends to become more of a jet-like current confined to the region of greatest topographic relief. This result is due to the small Rossby number limit: streamlines closely follow isobaths. When the latter converge, so will the streamlines, causing stronger flow over steeper topography (Lagerloef, 1983).

Table 1

Scales and scaling parameters appropriate to Santa Maria di Leuca

$v \sim 10\text{-}40\,cm/s^{-1}$	velocity scale
$L \sim 40$ km	length scale
$f_o \sim 10^{-4}s^{-1}$	Coriolis parameter
$A_v \sim 10^2\,cm^2\,s^{-1}$	vertical eddy viscosity
$A_H \sim 10^2\,cm^2\,s^{-1}$	horizontal eddy viscosity
$h \sim 200$ m	depth scale
$\varepsilon = v/f_oL \sim 0.03 \div 0.1$	Rossby number
$1/2\,E_v = A_v/f_oh^2 \sim 2.10^{-3}$	vertical Ekman number
$1/2\,E_H = A_H/f_oL^2 \sim 2.10^{-4}$	horizontal Ekman number

When the potential vorticity, as in our case, can be considered constant, equation (1) can be further simplified:

$$\frac{f_o+\partial_x v-\partial_y u}{h} \sim \left(-\frac{|v|}{hR}+\frac{f_o}{h}\right) = \text{const} \quad (2)$$

along a streamline, R(x,y) being the local radius of curvature of the current. Moreover, the mass conservation gives:

$$\Phi \equiv \int_0^L vhdx \sim \frac{1}{2}vhL = \text{const}' \quad (3)$$

where L is the distance between the thermal front and the coastline. By applying these two equations to different points on the streamline that represents the boundary of the shelf current (Fig. 4*a*), we get:

$$v = f_o\frac{h\text{-}h'}{\dfrac{h^2L}{h'L'R'}-\dfrac{h'}{R}}$$

$$v' = v\frac{hL}{h'L'} \quad (4)$$

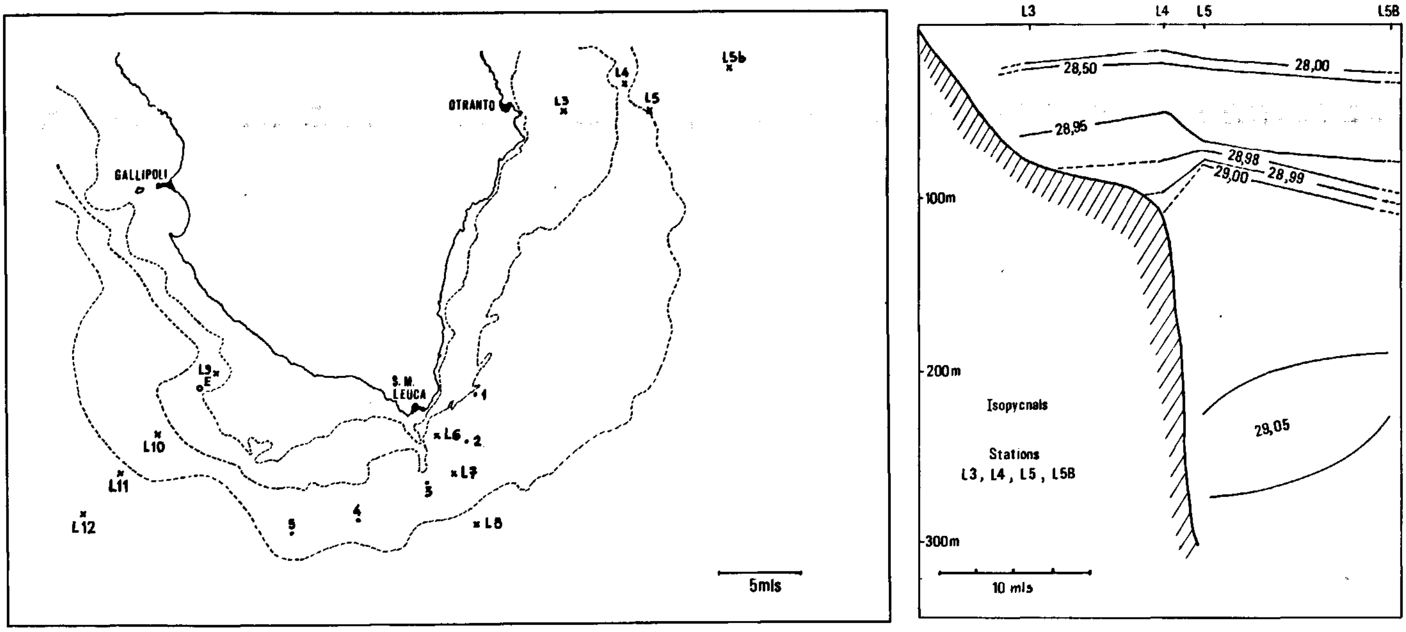
where the quantities L, L', h, h', R, R' are obtained from the thermal imagery (Tab. 2) and $f_o = 10^{-4}s^{-1}$.

In particular we discuss 12 of the various thermal images to which our idea can be applied, in which meteorological data indicate that wind curl had no effect for the marine motion under analysis. The theoretical velocities and corresponding fluxes computed through this model are presented in Table 3 and Figure 2.

Table 2

Depth (h), radius of curvature (R) and distance from the coast (L) of the sample points used for current computations.

	Points														
	1			2			3			4			5		
Date	h(m)	L(km)	R(km)	h(m)	L(km)	R(km)	h(m)	L(km)	R(km)	h(m)	L(km)	R(km)	h(m)	L(km)	R(km)
28 February 1980	125	10	12	150	12	20	156	13	42	160	19	48	–	–	–
7 February 1982	120	9	18	135	11	20	150	13	25	160	14	33	170	20	51
10 February 1982	115	5	25	120	5	29	125	8	31	130	13	37	135	20	53
14 March 1982	120	6	20	130	8	22	135	11	24	140	16	31	145	21	46
8 March 1983	135	11	26	140	11	31	150	17	38	155	22	46	–	–	–
9 March 1983	125	8	28	135	11	30	145	18	39	150	27	52	–	–	–
10 March 1983	115	5	17	130	7	18	140	9	23	145	12	28	150	17	39
14 March 1983	100	4	14	110	5	15	120	8	20	125	11	28	130	16	40
7 April 1983	115	5	15	120	5	17	130	7	24	135	10	32	–	–	–
17 April 1983	125	10	14	165	12	20	180	14	30	185	20	39	187	22	54
31 May 1983	120	8	17	135	10	20	145	12	24	150	17	36	–	–	–
14 July 1980	100	7.5	11	122	10	25	125	16.5	25	120	19	30	–	–	–



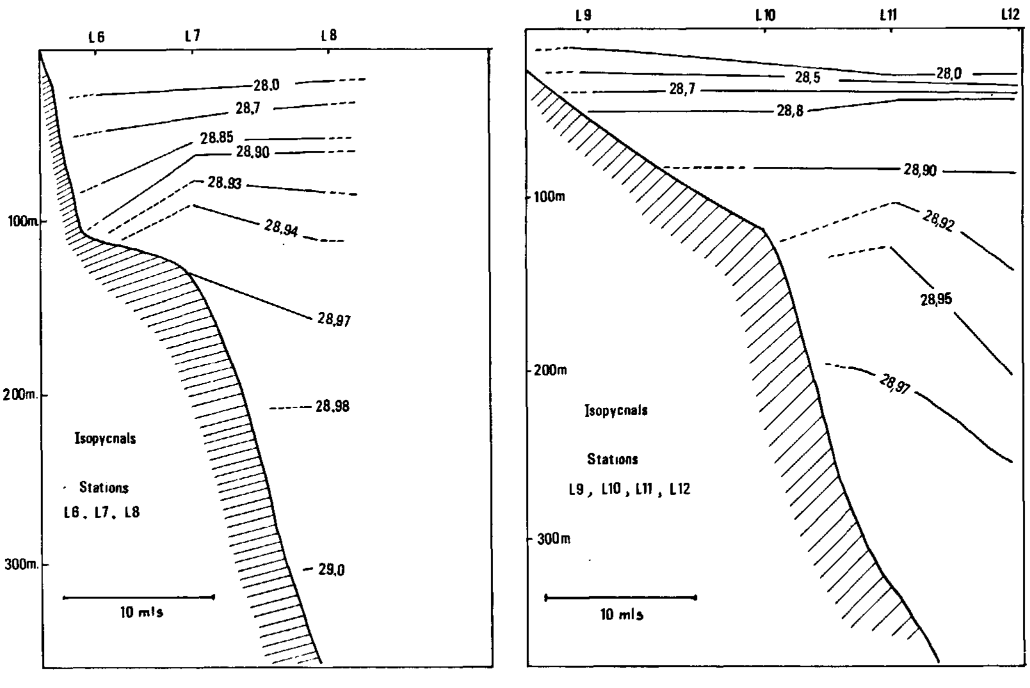


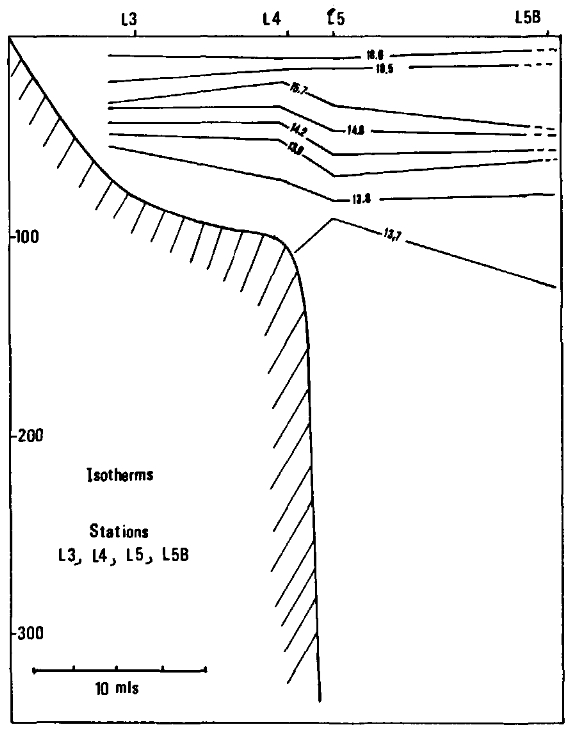
Figure 4

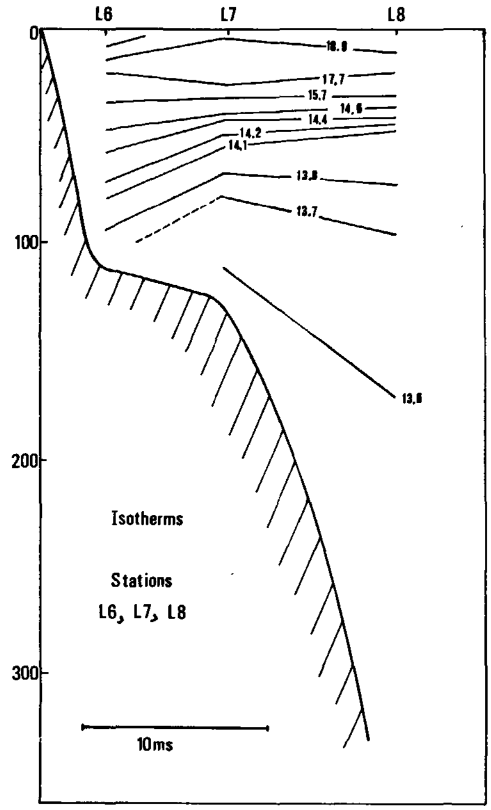
a) Bathymetric map of area with 50, 100, 200 m isobaths; hydrological stations (x) of VERA 83 cruise; position (o) of point E; positions (.) of 1-5 points (see also Table 3) from IR satellite image of March 9th, 1983, of Puglie peninsula;
b) Hydrological sections of the VERA 83 cruise: isopycnals;
c) Hydrological sections of the VERA 83 cruise: isothermals.

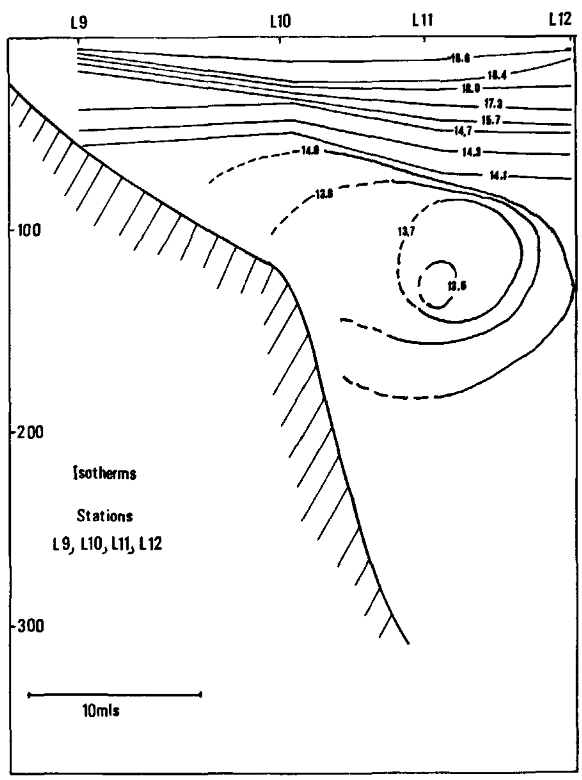
Table 3

Meteorological conditions (courtesy of Uff. Meteorologico dell'Aereonautica Militare, *Rome, Italy), velocities v off Santa Maria di Leuca and near point E, inside the Gulf of Taranto, and estimates of the corresponding fluxes Φ.*

Date	Air temperature (°C)	Wind Direction (°)	Wind Velocity (kn)	Water Velocity off Santa Maria di Leuca $v \pm \Delta v$ (cm/s)	Water Velocity near Point E ($v \pm \Delta v$ (cm/s)	Estimate of water flux Φ $\times 10^5$ m³/s
28 February 1980	5	340	8	31 ± 4	24 ± 17	4.3
7 February 1982	6	148	5	48 ± 4	32 ± 4	6.7
10 February 1982	7	212	6	50 ± 8	23 ± 12	2.4
14 March 1982	6	105	9	37 ± 7	20 ± 1	3.2
8 March 1983	5	254	6	42 ± 7	30 ± 7	6.7
9 March 1983	8	255	1	49 ± 9	24 ± 6	5.5
10 March 1983	·8	224	1	42 ± 3	18 ± 9	2.6
14 March 1983	6	293	3	33 ± 3	19 ± 10	1.7
7 April 1983	7	142	3	33 ± 7	17 ± 15	1.6
17 April 1983	10	191	2	51 ± 8	12 ± 3	5.3
31 May 1983	17	162	1	41 ± 2	14 ± 7	3.7
14 July 1980	24	285	5	25 ± 2	13 ± 4	3.1







The main source of error is indetermination in h due to satellite spatial resolution, image distortion and sea bottom slope:

$$\Delta h = \Delta x . \tan \gamma$$

where $\Delta x \sim 10^3$m is the horizontal uncertainty due to the spatial resolution of the satellite, γ is the maximum slope of the sea-bottom.

DISCUSSION

Some regularities are apparent in Table 3 and Figure 2. The images taken between January to April are rather clear and regular (in agreement with the clear images stored at the Lannion Center bank) with velocities ranging between 31 ± 4 to 51 ± 8 cm/s. The images show few variations of the front for this period. The time-averaged velocity at Cape Santa Maria di Leuca is thus found to be 41 ± 8 cm/s and the corresponding flux is $\sim 4.10^5$ m^3/s. Moreover, the comparison between the thermal front positions obtained from satellite images and the 100 m isobath shows that, downstream from the cape, the thermal front displays a radius of curvature larger than that of the underlying isobath, due to the effect of centrifugal force.

For later periods of the year, the images are less clear and eventually show large fluctuations of the thermal front; probably similar currents flow over the shelf but the thermal resolution on the images is much less relia-

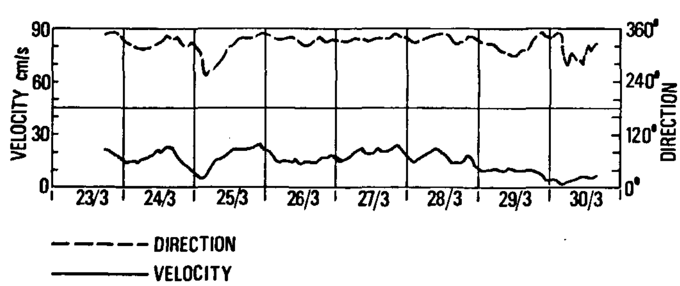


Figure 5

Amplitude and direction of velocity at point E (see Fig. 4a) in the period between March 23th and 30th, 1980 (Moretti et al., 1981).

ble. Moreover the velocity values obtained for the two samples observed during May and July are smaller than those of the preceding months. Some intrusions of water of different temperature over the shelf can be also observed. The hydrodynamic instability of these processes is not surprising: we know theoretically that these currents are not stable. On the other hand we now know that a stable version of these currents is made up of a serie of bloobs, interrupted by intrusions of water masses over the shelf (Killworth, priv. comm.).

To compare our results with field observations, we consider the Moretti *et al.* (1981) current meter data. For the period 23-30 March 1980, the mean velocity at point E (Fig. 5) is thus found to be 17 cm/s with some large fluctuations, mostly with a periodicity of 7-8 hours. The value we obtained by averaging the velocities computed in points close to the site E, but mostly localted a few kilometers upstream, amounts to $\sim 22 \pm 6$ cm/s.

With regard to VERA 83 hydrologic determinations during June 1983, it can be said that Stations L3,L4,L5,L5b refer to a cold vein flowing over the shelf, with velocities of about 22 cm/s (although the offshore velocity is not known). The other stations refer to a different, rather warm water flowing over the shelf. The velocities are much smaller (about 11 cm/s at Santa Maria di Leuca and 5 cm/s near point E). Therefore we have concording indications that another warm water mass intruded into the shelf.

It is moreover of interest that the hydrologic section of Stations L3,L4,L5,L5b show that the current over the shelf is essentially barotropic and no evidence of lateral shear can be found, thus partially supporting the hypotheses on which our model is based.

SUMMARY AND CONCLUSIONS

The southeastern tip of Italy (Cape Santa Maria di Leuca) is characterized by a narrow shelf surrounded by a steep continental slope. The descending branch of Adriatic current follows the bathymetry, leaving the coastline on its right-hand side. Over the shelf the flow is steered by the topography and forms a steady alongshore (anticyclonic) circulation. This motion is governed by the conservation of potential vorticity, which predicts that if the Rossby number is suitably small, the strongest flow will occur in association with the steepest topography. This is because streamlines are constrained to follow isobaths and are therefore concentrated over steeper topography. A deviation from the bathymetric constraint signifies centrifugal effects which allow an estimate of the current velocity via a simple algebraic method based on the conservation of potential vorticity and of flux. These deviations can be determined from the inspection of thermal fronts in satellite thermal images. In particular, in the case of currents flowing around Cape Santa Maria di Leuca the current velocity is found to be ~ 40 cm/s, with rather small fluctuations, $\sim 20\%$. Field observations relative to this area are rather sparse but current meter measurements in March 1980 (Moretti *et al.* 1981) and hydrological measurement are in comforting agreement with the results of our simple method.

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