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On the role of the Froude number in geostrophic coastal currents around Italy

Coastal currents
Froude number
Hydraulic control
Satellite imagery
Geostrophic balance

Courant côtier
Nombre de Froude
Contrainte hydraulique
Imagerie satellitaire
Équilibre géostrophique

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ABSTRACT

In recent studies on the Norwegian coastal current, McClimans, Vinger and Mork have shown that the densimetric Froude number F has the role of a controlling parameter for the development of the flow of baroclinic coastal currents. In general, its value proves useful in evidencing non-linear effects in comparison with the Coriolis force, but it also governs the growth of disturbances within the flow and at its boundary. Stimulated by such considerations, the purpose of the present note was to check the efficacy of these ideas when applied to known coastal currents in three areas of the Italian seas (the eastern Sicilian shelf, the central Adriatic Sea and Cape Santa Maria di Leuca). Here we show that these ideas prove useful in the synthesis of current properties: the results obtained are confirmed by comparison with the flow patterns in satellite imagery.

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RÉSUMÉ

Le nombre de Froude et les courants géostrophiques voisins des côtes italiennes

McClimans, Vinger et Mork ont montré récemment que le développement des courants baroclines côtiers est lié au nombre de Froude. En général, ce nombre permet de mettre en évidence des effets non linéaires comparés à la force de Coriolis, mais il traduit aussi la croissance des instabilités dans le flux et à sa limite. Le présent travail applique ses considérations à des courants côtiers connus dans trois régions voisines des côtes italiennes (plateau continental à l'est de la Sicile, centre de la Mer Adriatique et cap Santa Maria di Leuca). La synthèse des caractéristiques du courant montre l'utilité de cette démarche : les résultats obtenus sont confirmés par les modèles de circulation établis à partir de l'imagerie satellitaire.

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INTRODUCTION

In recent works the role of the densimetric Froude number F of a coastal baroclinic current, $F=u/c$ (u is the alongshore velocity of the upper layer and c is the celerity of internal waves), was emphasized in particular for laboratory experiments (Vinger and McClimans, 1980; McClimans and Green, 1982) and for coastal currents along the west coast of Norway (Lonseth *et al.*, 1983; McClimans and Nilsen, 1982; McClimans *et al.*, 1985). In general the Froude number F is considered useful in underlining the non-linear effects in geostrophic currents; but in our case it is of particular interest that when $F < 1$ (as in the Norwegian coastal current), instabilities and meanders develop into large eddy pairs while for $F > 1$ the flow follows the coast only allowing the growth of cyclonic eddies along the seaward front (Fig. 1).

Our paper studies these ideas as applied to known coastal currents in areas of the Italian sea (eastern Sicilian shelf, central Adriatic Sea and Cape Santa Maria di Leuca). We have evaluated the velocity u of the upper layer from which we have drawn the Froude number F and other parameters. These results are compared both with the values of the parameters found in the literature and with the flow patterns suggested by thermal imagery, with stimulating results.

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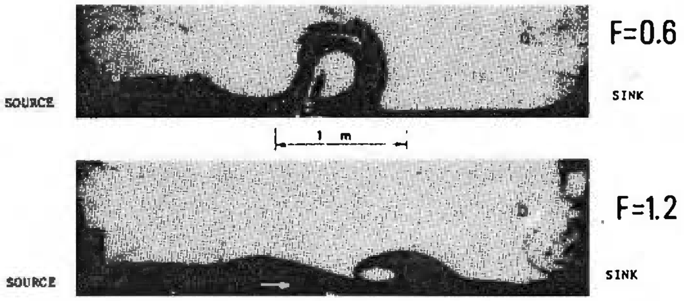


Figure 1
Plan view of coastal current instabilities: a) F=0.6; b) F=1.2 (from Vinger and McClimans, 1980).

WIDTH OF COASTAL CURRENTS

Assuming a geostrophic balance for a two-layer fluid flowing steadily along a straight coast ($y=0$), with a seaward front at $y=\mathrm{B}$ (Fig. 2), one has

$$gh_1(\rho_2-\rho_1)=g'h=\mathrm{B}fu \tag{1}$$

where u, h_1 and ρ_1 are respectively the alongshore velocity of the current of the upper layer, its thickness at the coast and its density; h_2 and ρ_2 are the analogous quantities of the lower layer, g is the gravity and $f \sim 10^{-4}$ s is the Coriolis parameter. We assume that the lower layer is at rest. The densimetric Froude number F can usefully be introduced at this stage:

$$\mathrm{F}=u/c \tag{2}$$

where

$$c=\sqrt{\frac{(\rho_2-\rho_1)g}{\rho_2}\cdot\frac{h_1h_2}{h_1+h_2}} \tag{3}$$

is the velocity of the internal waves.

By examining the relation between the width of a baroclinic coastal current, B, and the Rossby deformation radius $r_d \equiv c/f$, from equations (1), (2) and (3) one has

$$\mathrm{B}/r_d=\frac{h_1+h_2}{h_2}\,\frac{1}{\mathrm{F}}. \tag{4}$$

It is interesting to note that Griffiths and Linden's (1981) tank experiemnt gives $\mathrm{B} \sim 3r_d$; James and McClimans (1983) assume this relation to give good numerical simulation for $\mathrm{F} \sim 0.6$ for the Norwegian coastal current. Equation (4) gives

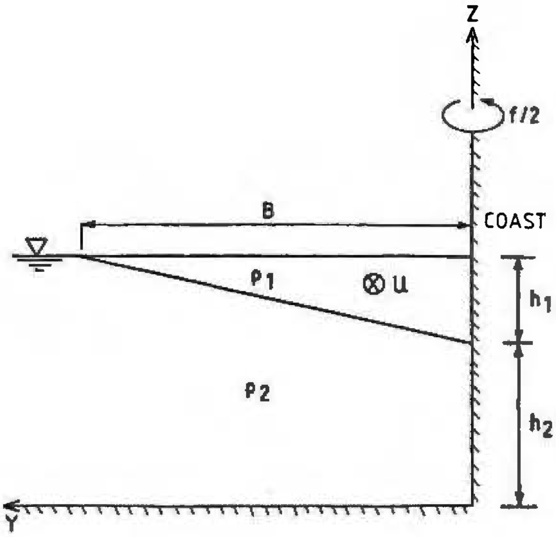


Figure 2
Cross-section of the coastal current (from McClimans et al., *1985).*

$$\frac{h_2}{h_1+h_2}\mathrm{F}=\frac{r_d}{\mathrm{B}}\xrightarrow[h_1/h_2\to 0]{}\mathrm{F}. \tag{5}$$

If $h_1 \ll h_2$ (as it is in some of the situations discussed below) this gives $\mathrm{F} \sim 0{,}3$. In the general case, equation (5) is a rather puzzling relation since it links a dynamic parameter F and a local quantity, h_1/h_2, to a supposed constant quantity $\mathrm{B}/r_d \sim 3$: F would be practically dependent on h_1 and h_2 only. To analyze this interesting question further, we applied the preceeding considerations to known currents around Italy, in order to check empirically whether F can be reasonably considered as a control quantity for baroclinic coastal currents around Italy as well.

WORKING METHOD

We have estimated the values of surface velocities, u, for several currents using the geostrophic balance for a two-layer flow. From the knowledge of u we computed Φ ($\Phi=\mathrm{B}uh_1/2$), F and other parameters: F and B/r_d are the most physically interesting parameters while the others were estimated as a general check.

a) For currents on the eastern Sicilian shelf (Table 1), we have used the experimental data collected during the cruise PRIME '82 (Bohm and Salusti, 1984). The values of ρ_2 listed in Table 1 are bottom densities, while those of ρ_1 are the mean densities over the

Table 1
Data for the Sicilian currents. The symbol $\Delta\sigma$ means the variance of the physical quantity σ.

Section	σ_1	$\Delta\sigma$	σ_2	h_1 (m)	Δh (m)	B (km)	ΔB (km)	u (m/s)	F	Φ (Sv)	r_d (km)	B/r_d	FB/r_d
S_1	28.8	0.2	29.16	190	10	8.9	0.2	0.7	0.9	0.6	8.1	1.1	1.0
S_2	28.8	0.3	29.16	210	10	21.3	0.2	0.3	0.4	0.7	8.5	2.5	1.0
S_3	28.8	0.3	29.16	190	10	15.6	0.2	0.4	0.5	0.6	8.1	1.9	0.95
S_4	28.8	0.3	29.16	210	10	17.3	0.2	0.4	0.5	0.7	8.5	2.0	1.0
S_5	28.8	0.3	29.16	140	10	18.7	0.2	0.3	0.4	0.4	6.9	2.7	1.1

thermocline. Finally, B and h_1 were estimated from the isopycnals.

Hydrological data were collected at 15 stations, divided into five groups (Fig. 3, 4). The values of the velocities can be compared with the values estimated by Bohm and Salusti (1984): $u \sim 0.5$ m/s at the northernmost location and $u \sim 0.2$ m/s at the southernmost location, which agrees with our values. Moreover, these authors estimated a flux $\Phi \simeq 0.1$ Sv, while our mean flux is larger: (0.5 ± 0.2) Sv. The mean value of the Rossby deformation radius is $\langle r_d \rangle = (8.0 \pm 0.7)$ km and the mean value of the Froude number is $\langle F \rangle (0.5 \pm 0.2)$. Moreover, disregarding the northernmost section, we see that $\langle F \rangle = (0.5 \pm 0.1)$, *i. e.* is fairly constant. Since $h_2 \gg h_1$, theoretically we have $FB/r_d \sim 1$ in good agreement with the data.

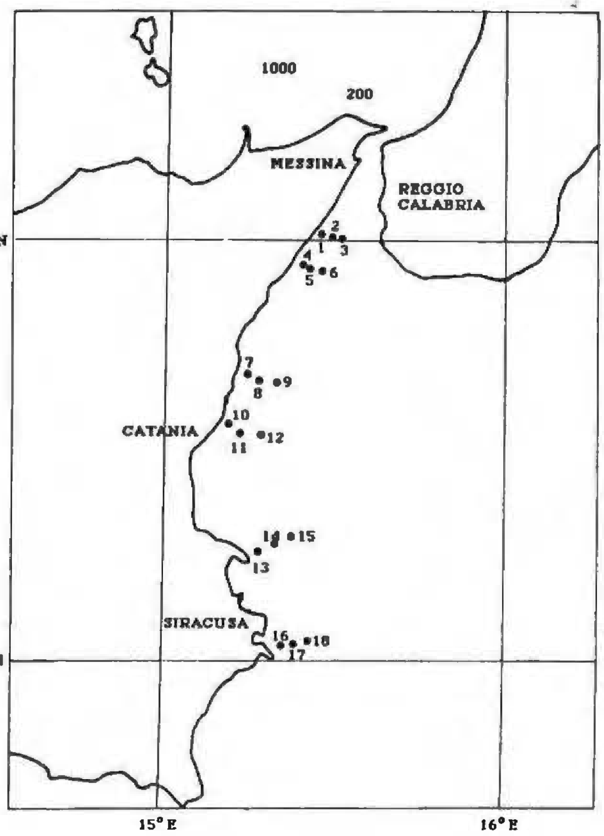


Figure 3
Location of the CTD transects performed off the Eastern Sicilian coast (from Böhm et al., 1984).

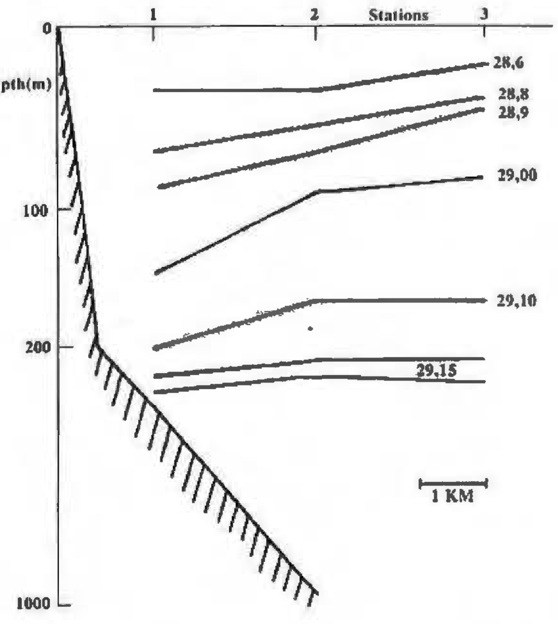


Figure 4
Isopycnals relative to the northernmost transect shown in Figure 3 *(from Böhm* et al., 1984).

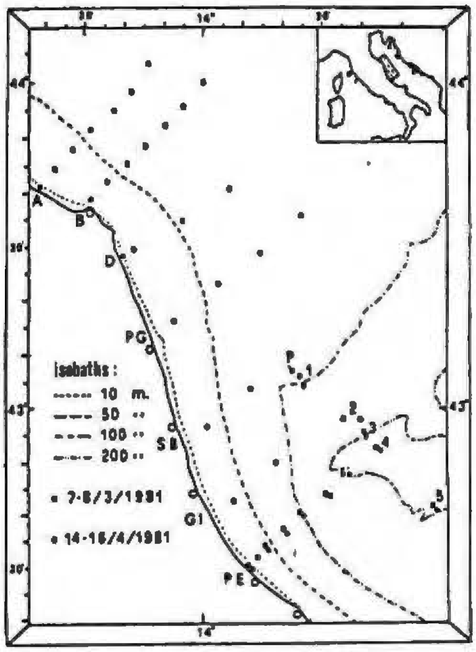


Figure 5
Location of the CTD transects performed off the Mid-Adriatic Italian coast (from Artegiani et al., 1988).

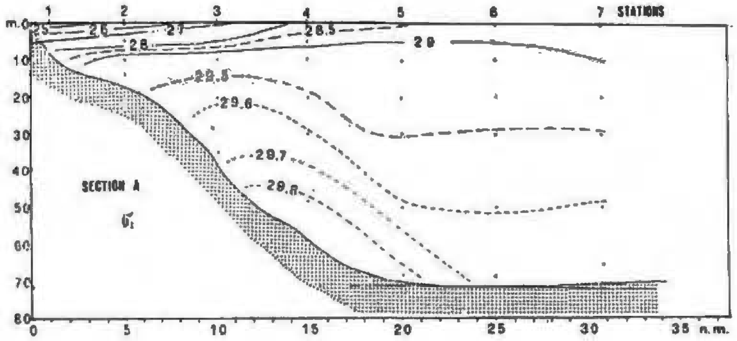


Figure 6
Isopycnals relative to the northernmost transect shown in Figure 5 *(from Artegiani* et al., 1988).

b) Hydrological data referring to the currents along the Italian coast in the central Adriatic Sea were extracted from the isopycnals shown in Artegiani and Salusti (1988; *see* Fig. 5 and 6). Here the hypothesis $h_2 \gg h_1$ is no longer valid and so $BF/r_d \neq 1$. The main results are listed in Table 2; from there we calculated $\langle B \rangle = (3.9 \pm 0.6)$ km, $\langle F \rangle = (0.4 \pm 0.2)$. Only for three sections, namely (B, D, PE), is $B/r_d \sim 3$ obtained. In general, the flow looks less regular than in the previous case.

c) The values of the hydrological parameters for the currents around Cape Santa Maria di Leuca were estimated from the isopycnals shown in Bohm

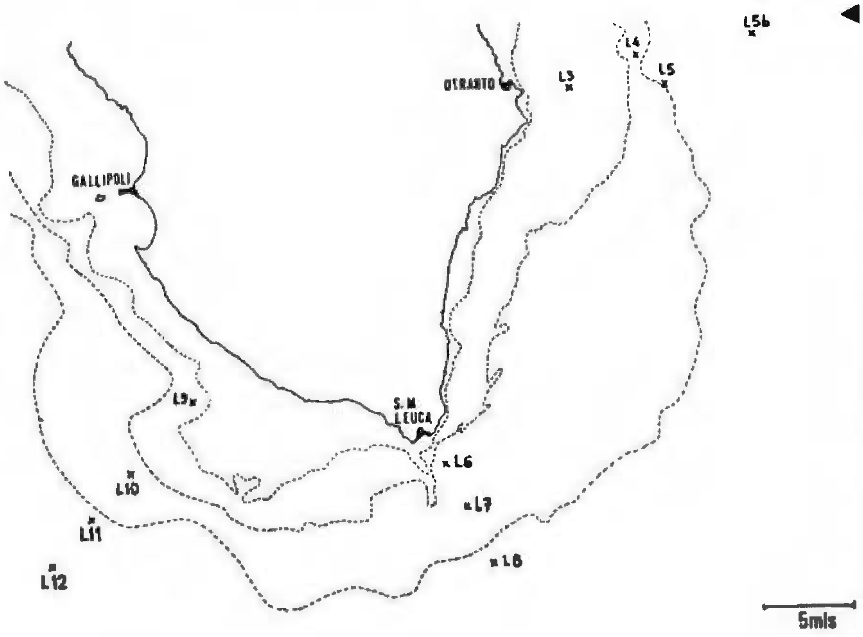


Figure 7

Location of the CTD transects performed around Cape Santa Maria di Leuca (from Böhm et al., 1986).

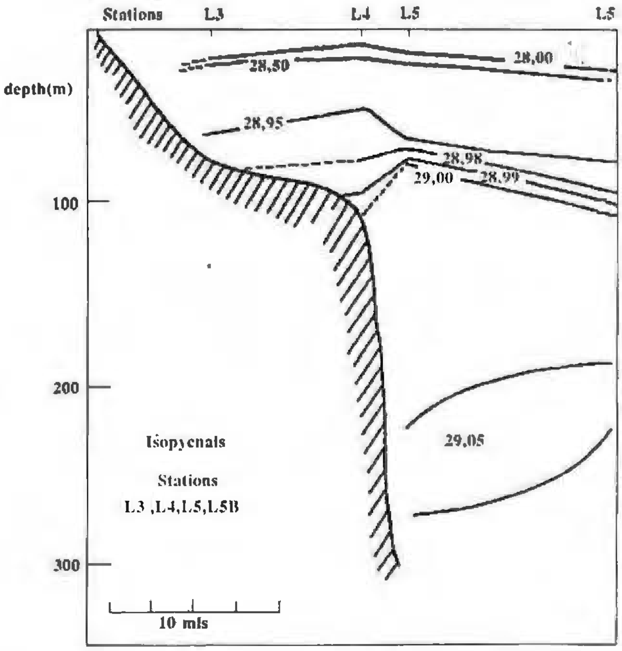
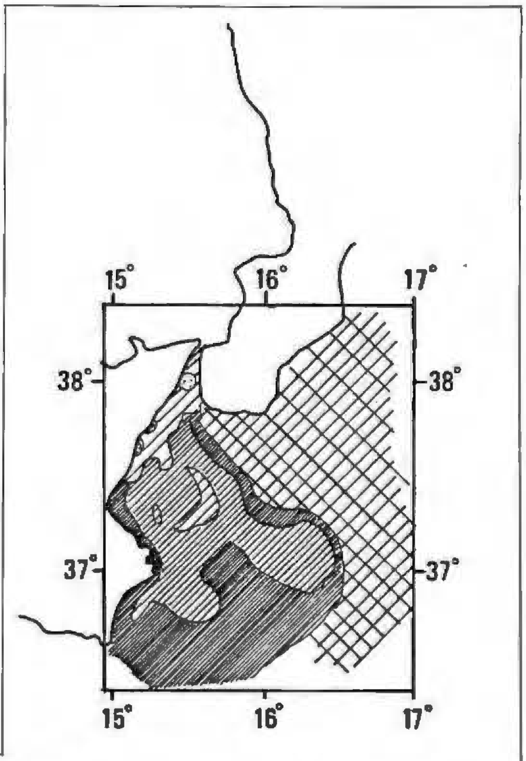


Figure 8

Isopycnals relative to the northernmost transect shown in Figure 7 (from Böhm et al., 1986).



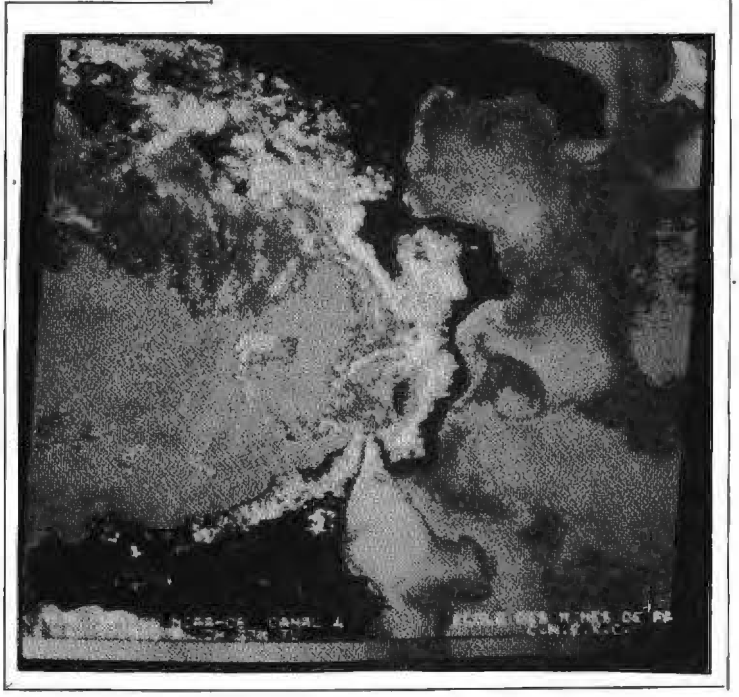


Figure 9

Flow pattern off the Eastern Sicilian coast as observed by TIROS-7, 14 July 1980.

Table 2

Main results for the Adriatic currents.

Section	σ_1	$\Delta\sigma$	σ_2	h_1 (m)	h_2 (m)	Δh (m)	B (km)	ΔB (km)	u (m/s)	F	Φ (Sv)	r_d (km)	B/r_d	FB/r_d
A	26	0.5	29.7	5	42	4	20	1	0.1	0.2	$5\ 10^{-3}$	4.3	4.6	1.0
B	27	0.5	29.7	8	25	4	11	1	0.2	0.4	$9\ 10^{-3}$	4.6	2.4	1.0
D	26	0.5	29.6	12	18	4	16	1	0.3	0.5	$29\ 10^{-3}$	6.6	2.4	1.1
PG	28	0.5	29.7	9	55	4	29	1	0.1	0.4	$13\ 10^{-3}$	3.9	7.4	2.9
SB	28	0.5	29.8	7	55	4	19	1	0.1	0.3	$7\ 10^{-3}$	3.5	5.4	1.6
GI	28	0.5	29.7	14	51	5	21	2	0.1	0.2	$15\ 10^{-3}$	4.9	4.3	0.9
PE	28	0.5	29.5	10	29	8	9	2	0.2	0.5	$9\ 10^{-3}$	3.9	2.3	1.2

Figure 10
Flow pattern along the Adriatic coast, showing the classical instabilities of $F < 1$ (NOAA 6 satellite thermal image of 12 June 1979).

Table 3
Main results obtained for currents around Cape Santa Maria di Leuca.

Section	σ_1	$\Delta\sigma$	σ_2	h_1 (m)	Δh (m)	B (km)	ΔB (km)	u (m/s)	F	Φ (Sv)	r_d (km)	B/r_d	FB/r_d
S_2	28.8	0.1	29.05	91	7	28	2	0.08	0.2	0.1	4.7	6.0	1.2
S_3	28.8	0.1	29.05	143	7	87	2	0.04	0.07	0.2	5.8	14.9	1.0

et al. (1986). The stations were located in three sections: in front of Otranto, off Cape Santa Maria di Leuca and near Gallipoli (Fig. 7). The isopycnals of the Otranto section show the existence of a three-layer flow (*see* Fig. 8); therefore in Table 3 we list the main results only for the second and the third sections. Velocities were estimated by Bohm *et al.* (1986) as 0.11 m/s at the second section and 0.05 m/s at the third section, where the flow was moreover somewhat scattered, B being very large. The flux was estimated as 0.4 Sv, while our mean flux is (0.2 ± 0.1) Sv. In this case also $h_2 \gg h_1$, so that $FB/r_d \sim 1$.

DISCUSSION

Stimulated by a work by McClimans *et al.* (1985) on the effect of the Froude number on the flow pattern of the Norwegian Coastal Current, we checked their idea by applying it to known coastal currents flowing along the Italian coasts.

In the three cases studied here $F < 1$, *i. e.* the baroclinic coastal currents are subcritical. In particular, F is ~ 0.5 and is fairly regular along the eastern Sicilian coast. This is probably due to the constriction at Messina and to the regularity of the tidal source of this water (Hopkins *et al.*, 1984). For the central Adriatic Coastal Current, we have $F \sim 0.3$ and a more irregular flow, probably due to the origin of this flow: meteorological features and river inflows. These results are rather satisfactory, but around Cape Santa Maria di Leuca the model is not applicable since in a three-layer system our assumption that the lower layer is at rest does not hold.

As far as the role of F is concerned, we show that if the upper layer is thin, namely $h_1 \ll h_2$, then $F \sim r_d/B$ is a fairly well established relation, even if the flow is irregular. If $h_2 \simeq h_1$, the situation is more complex.

It is also interesting to check the stability of these currents by examining available satellite imagery. McClimans *et al.* (1985) point out that instabilities become faster as F decreases: their growth velocity reaches its maximum value as $F \rightarrow 0$. Therefore one can expect that if coastal currents have different F values, those with the smallest values F lose their characteristics after running a shorter path than the others.

Along the Sicilian coast (Fig. 9) one has typical patterns reminiscent of Figure 1 *a*. Since $F \sim 0.5$, one would expect a rather regular motion, as is indeed the case: this small current can be observed for ~ 200 km. The central Adriatic Coastal Current (Fig. 10) is more irregular, in agreement with the $F = 0.3$ value. But the most remarkable effect is that the current flowing around Cape Santa Maria di Leuca ($F \sim 0.05$-0.1; Fig. 11) disappears downstream from the Cape, where we have seen that the model is not applicable.

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