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A numerical investigation of the wind-driven circulation in the Archipelago of La Maddalena

Maddalena
Bonifacio
Currents
Wind
Numerical model

Maddalena
Bonifacio
Courants
Vent
Modèle numerique

A. Bruschi[a], G. Buffoni[a], A. J. Elliott[b], G. Manzella[c].
[a] Laboratorio per lo Studio dell'Ambiente Marino, CNEN, Euratom, Fiascherino, La Spezia, Italy.
[b] Institute of Oceanographic Sciences, Wormley, Godalming, Surrey GU8 5UB, GB.
[c] Istituto per lo Studio della Dinamica delle Grandi Masse, Stazione Oceanografica, CNR, San Terenzo, La Spezia, Italy.

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ABSTRACT

In the region of the Straits of Bonifacio, the straits which separate Corsica and Sardinia, the winds are orographically controlled. The prevailing winds are consequently found to be from the west and to be steady at times for periods of up to 10 days. Currents measured in the channels which separate the islands in the Archipelago of La Maddalena were found to be predominantly along the axes of the channels and to be driven by the E-W winds. There was high coherence between the wind and the currents at low frequency. The low-passed currents showed significant energy at time scales of 4-5 days with the maximum current reaching about 25 cm/sec., the residual currents being of the order of 3 cm/sec. In view of the relatively steady prevailing winds a two-dimensional depth-averaged hydrodynamical model was applied to the region. An outer model, with a grid spacing of 2 km, was used to estimate the steady-wind driven flow through the Straits of Bonifacio and the surrounding area. This was then used to drive an inner model, with a 0.5 km grid size, in the region of the islands of La Maddalena. The computed steady currents in the channels were found to be in good agreement with the observations. However, unrealistic gyres were generated in the open areas of the grid and these were probably caused by problems in matching the elevations near the boundary of the inner model with the results from the outer model.

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RÉSUMÉ

Une investigation numérique de la circulation provoquée par le vent dans l'Archipel de La Maddalena

Dans la région des détroits de Bonifacio, qui séparent la Corse de la Sardaigne, les vents sont contrôlés orographiquement. En conséquence, les vents dominants sont les vents d'Ouest, qui peuvent être stables pendant des périodes allant jusqu'à 10 jours. L'étude a montré que les courants mesurés dans les détroits qui séparent les îles de l'archipel de La Maddalena sont prédominants le long des axes des détroits, et sont engendrés par les vents EW. Il existe une forte corrélation entre les vents et les courants à basse fréquence. Ces derniers ont une énergie mesurable à une échelle de 4-5 jours avec une vitesse maximale de 25 cm/s, les courants résiduels étant de l'ordre de 3 cm/s. Étant donné les vents relativement dominants, un modèle hydrodynamique à deux dimensions a été appliqué dans la région. Un modèle externe, avec une grille espacée de 2 km, a été utilisé pour estimer le flux engendré par le vent à travers les détroits de Bonifacio et les régions voisines.
Les résultats ont été utilisés pour mettre au point un modèle interne avec une grille de 0,5 km dans la région des îles de La Maddalena.

Les courants stables calculés dans les détroits correspondent bien aux courants observés. Cependant des mouvements circulaires (ou tourbillons) qui ne correspondent sans doute pas à une réalité, sont engendrés dans les espaces ouverts de la grille. Ils résultent probablement de la difficulté à faire coïncider l'élévation près des limites du modèle interne et les résultats fournis par le modèle externe.

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INTRODUCTION

Current measurements from moored current meters, CTD measurements, and diffusion experiments using rhodamine B as a tracer, were made as part of an environmental survey of the Archipelago of La Maddalena (Fig. 1). This was part of a detailed physical, chemical and biological study that covered an area 10 km in radius, centered on the island of San Stefano. Cruises and measurements were carried out by the Stazione Oceanografica of CNR in San Terenzo (La Spezia) and by the Laboratorio per lo Studio dell'Ambiente Marino of CNEN in Fiascherino (La Spezia) during selected periods from June 1976 to June 1977.

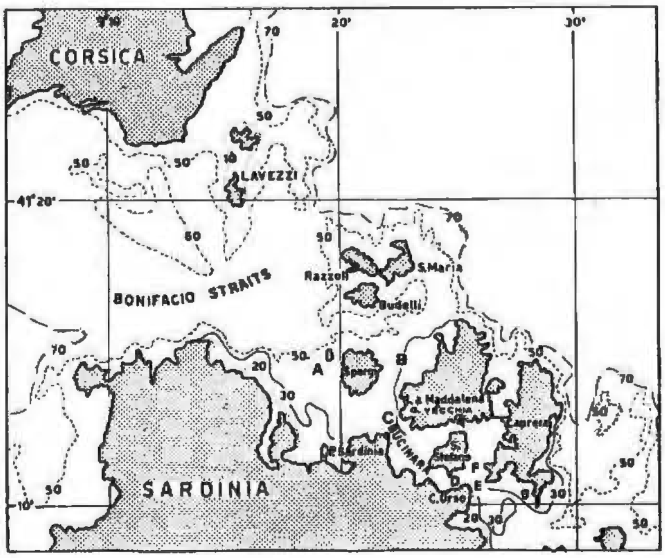

Figure 1
The Archipelago of La Maddalena: bottom topography and mooring positions.

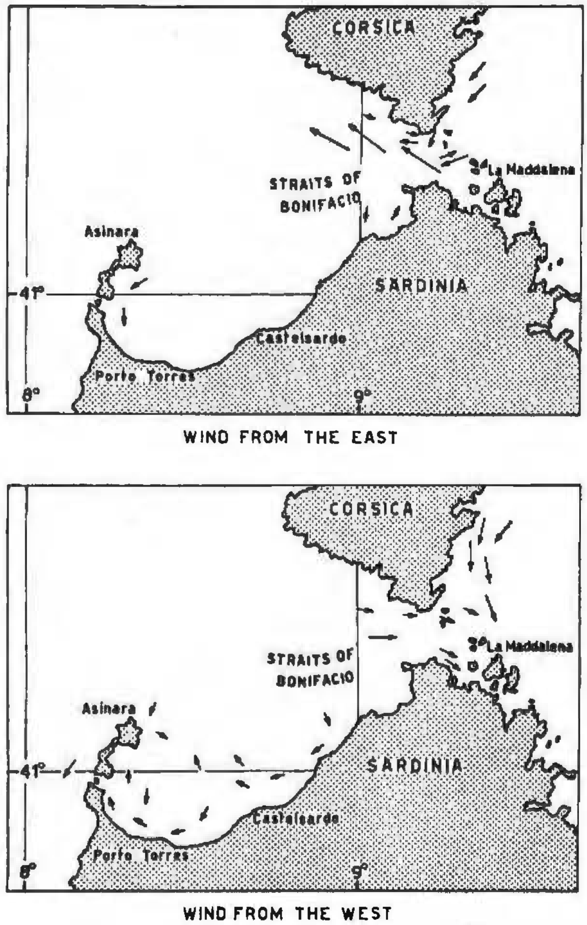

Figure 2
Surface currents in the Straits of Bonifacio (redrawn from Canò, Stocchino, 1966; with the permission of the authors).

Previous current measurements in the Straits of Bonifacio have been made by Canò and Stocchino (1966) and Romanovsky (1958). Surface currents due to a wind from the West and from the East, reported by Canò and Stocchino (1966) are shown here in Figure 2. Analysis of wind data (Baldacci *et al.*, 1961) has shown the prevailing winds to be in the east-west direction, and that the winds can be steady for periods of several days. Under these conditions the wind-driven currents were observed to reach a steady state, which was then maintained for some days.

The investigation described in this report has used a numerical model in an attempt to reproduce the dominant features of the wind-driven circulation in the Straits of Bonifacio (Fig. 2) and in the Archipelago of La Maddalena (Fig. 1) under the action of a wind from the west. Many numerical investigations of the circulation and surface elevation in seas with simplified topography can be found in the literature (e. g. Nihoul, 1975). However, the present investigation differs in that it was complicated by the presence of several islands, separated by narrow channels, and a major goal was to determine whether the wind-driven currents could be modelled successfully in such a region. A two-dimensional depth-averaged hydrodynamic model has been used in the present study; this enables us to estimate the effects of wind driving, bottom topography, bottom friction and dispersion. Since the area considered includes islands and narrow channels, we may expect the horizontal gradients of the velocity field to be significant; therefore the advective terms have been included in the model equations.

One of the major difficulties in such a study lies in obtaining adequate field data. Wind stress distributions and lateral boundary conditions were not available in any systematic form, and it has been necessary to resort to mean or typical values for many of the input conditions. For a preliminary study of the steady state circulation, however, this is thought to be adequate. Thus in this paper we present and discuss the results of numerical experiments to predict steady state currents due to a constant wind stress distribution. A series of numerical experiments have been performed in order to evaluate the effects of the bottom topography, the boundary conditions on the open sea frontiers, the advective terms, and the Coriolis acceleration. Two models were developed: the first used a coarse grid to predict the flow through the Straits of Bonifacio, the second was a near-field model of the area near La Maddalena which used the output from the large-scale model as its boundary conditions.

WIND-DRIVEN CIRCULATION

The channel running east-west between Corsica and Sardinia, the Straits of Bonifacio, has a strong influence on the local winds and causes the dominant winds to be east-west in the region of the Archipelago of La Maddalena. Analysis of wind data from the observatory in Guardiavecchia (146 m above sea level) during the period 1975-1977 has shown the prevailing winds to be east-west. The frequency distribution of the wind direction is given in Table 1 and Figure 3.

Current and temperature measurements were made, during selected periods from June 1976 to June 1977, using moored current meters; the mooring locations are shown in Figure 1. The instruments were Aanderaa RCM-4 current meters with a sampling interval of 10 minutes. The data were initially averaged to obtain 3-hourly values so as to be compatible with the wind data measured at Guardiavecchia. The surface currents, measured at a depth of 10-15 m, were resolved

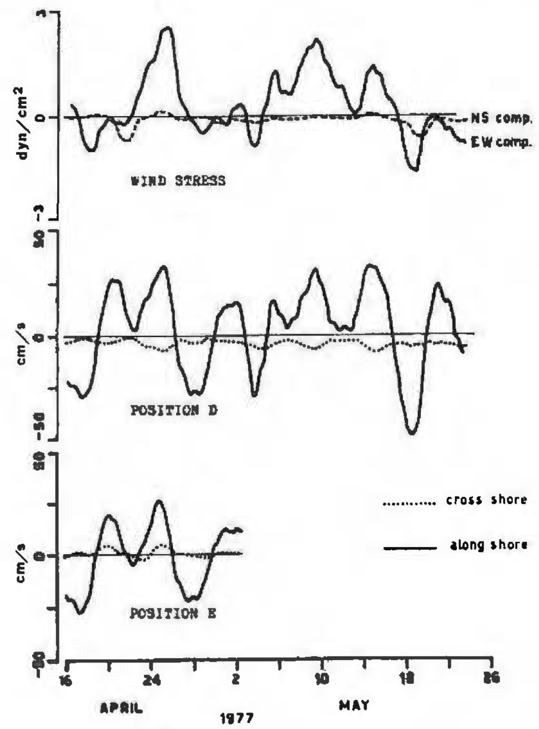

Figure 4
Wind stress and currents at location D *and* F *during April and May,* 1977.

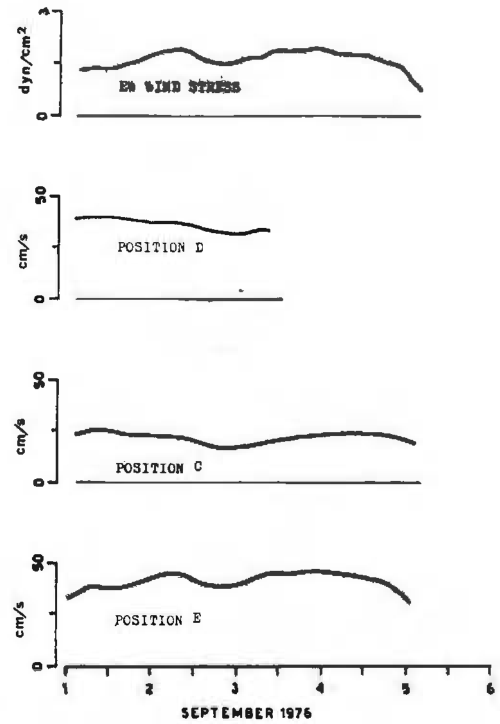

Figure 5
EW wind stress and alongshore currents at location C, D, E *from* 1 *to* 5 *September* 1976.

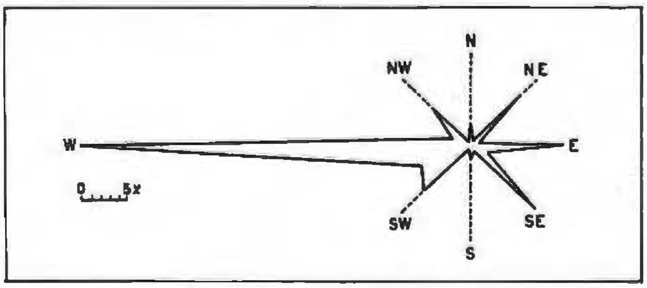

Figure 3
Wind direction during the period 1946-1960 *(from Baldacci* et al., 1961; *with the permission of the authors).*

Table 1
Percent values of the wind direction.

Years	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Calm
1901-1905	1.8	1.3	9.2	1.9	8.8	1.9	7.2	0.3	0.2	0.1	3.1	2.1	41.5	1.7	3.1	0.2	15.6
1946-1960	2.2	0.4	6.5	0.7	8.5	1.5	8.3	0.4	1.4	0.2	5.8	4.8	35.0	1.5	4.8	0.2	17.7
1975-1977	2.1	3.5	4.8	4.1	8.8	6.3	2.4	0.7	0.3	0.6	1.0	6.5	32.7	9.1	4.2	1.7	11.3

into along-shore (u) and cross-shore (v) components, the wind stress into east-west (τ_{EW}) and north-south (τ_{NS}) components. These components were smoothed (low-pass filtered) by calculating the running means over 13 readings (36 hours) in order to study the low-frequency (<0.6 cpd) fluctuations in current and wind stress. The cross-shore components were much smaller than the along-shore components. As an example, the EW and NS wind stresses and the along-shore and cross-shore currents at location D and E, during the period April-May 1977, are plotted in Figure 4.

During the period from June 1976 to June 1977 the prevailing east-west winds were observed to persist for several days, the wind direction frequently remaining steady for up to 3 days and often for as long as 10 days. As an example, Figure 5 shows the EW wind stress and the along-shore currents at the mooring position C, D, E from 1 to 5 September, 1976.

The linear regression function $u = a\,\tau_{EW} + b$ between u and τ_{EW}, and the correlation coefficient, r, were computed for all data sets (current measurements were made in different periods from June 1976 to June 1977) and the results are shown in Table 2. The coherence squared between u and τ_{EW} for three different periods of measurements are plotted in Figure 6 and show that, in general, there was high coherence at low frequencies for the locations in the Bucinara Channel. In contrast, the NS wind stress was neither significantly correlated nor coherent with the alongshore current. On the basis of the regression analysis we may conclude that about 50-60% of the along-shore current variance can be related directly to the EW wind stress.

Table 2

Linear regression and correlation coefficients computed for all data sets.

Mooring location	a	b	r
C	11.32	3.28	0.79
D	14.90	−0.52	0.73
E	9.63	2.21	0.56

MODEL EQUATIONS AND GRID REPRESENTATION OF THE STUDY AREA

The basic equations, in rectangular coordinates for a depth-averaged hydrodynamic model are:

$$\frac{\partial\eta}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} = 0,$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} - fv = -g\frac{\partial\eta}{\partial x} + N\nabla^2 u + \frac{1}{h}(F_{xs} - F_{xb}),$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + fu = -g\frac{\partial\eta}{\partial y} + N\nabla^2 v + \frac{1}{h}(F_{ys} - F_{yb}),$$

where η is the surface elevation, $h = D + \eta$ is the total depth and D the bottom depth, (u, v) is the depth-

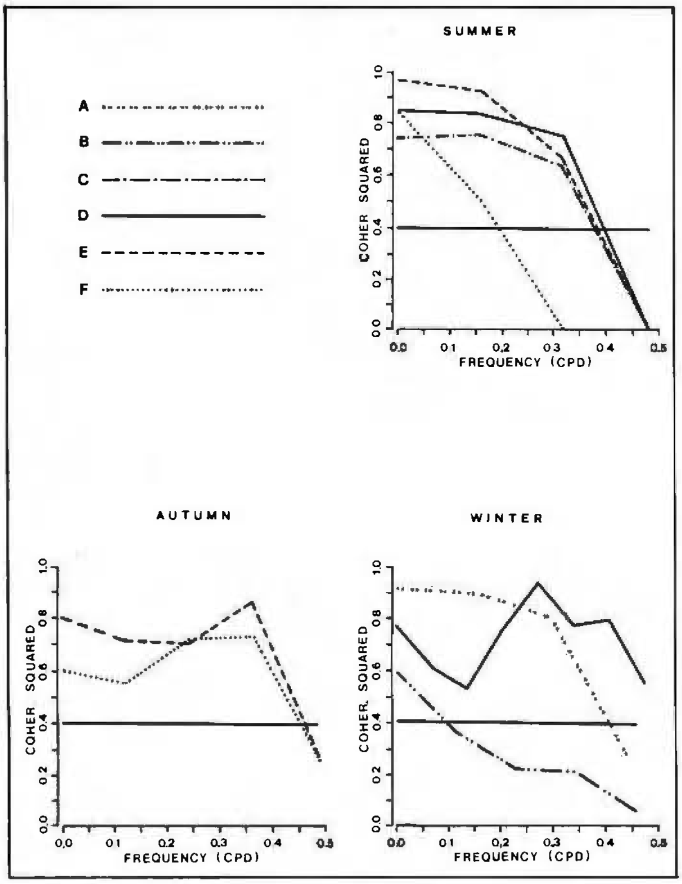

Figure 6

Coherence squared between EW wind stress and alongshore currents (the 95% significance level is shown).

averaged velocity, (F_{xs}, F_{ys}) and (F_{xb}, F_{yb}) represent the surface and bottom stresses associated with the flux of momentum at the air-sea interface and at the bottom; these have been calculated using:

$$F_{xs} = k_s W_x \sqrt{W_x^2 + W_y^2},$$

$$F_{ys} = k_s W_y \sqrt{W_x^2 + W_y^2},$$

$$F_{xb} = k_b u \sqrt{u^2 + v^2},$$

$$F_{yb} = k_b v \sqrt{u^2 + v^2},$$

where (W_x, W_y) is the wind velocity and k_s and k_b are the appropriate drag coefficients. It is assumed that the sea is a homogeneous layer of constant density and that the gravity force is balanced by the pressure gradient. Details of the basic concepts, approximations and equations of a depth-averaged model can be found in Nihoul (1975).

Along the coastal boundaries zero normal flow is assumed; thus, at coastal points, $u_n = 0$, where u_n is the component of the flow perpendicular to the coast. Along the open boundaries values of the surface elevation are specified; thus at the open-sea boundary points, $\eta = \eta^*$, where η^* is known or can be calculated using a radiation condition (Heaps, 1974). It is assumed that the sea was initially at rest, so that the initial conditions were $\eta = 0$, $u = 0$, $v = 0$ at time $t = 0$ everywhere.

The diffusion coefficient was obtained by diffusion experiments made in the area (Astraldi *et al.*, 1978), while the coefficients k_s and k_b were taken from the literature. In all the numerical experiments we have assumed the following parameters in the equations (Blackford, 1978; Hamilton, Rattray, 1978; Elliott, 1979).

$N = 10^4\, cm^2.sec^{-1}$; $k_s = 1.50 \times 10^{-3}$; $k_b = 2.50 \times 10^{-3}$.

Around the open boundary the pressure gradient appeared to be balanced by the wind stress (this was determined by inspecting the model output and estimating the terms in the equation of motion), therefore the bottom friction is likely to be less important than the other terms.

The initial boundary value problem was solved numerically by using the finite difference method with a staggered grid. The η points alternate with the u points in the x-direction and with the v points in the y-direction. It should be noted that an upwind scheme was used for the advective terms and that the time derivatives were evaluated by using an explicit leapfrog scheme with lagged friction and diffusion. The derivation of the standard condition for non-rotating flow:

$$\Delta t \leqq 2\,\Delta x/(g \max_{x,y} D)^{1/2},$$

relates to simplified hydrodynamic equations, but provides an indication to stability.

The area of the Straits of Bonifacio was covered with the grid of 34 × 14 mesh points shown in Figure 7. In the figure the bottom depths are given in meters at the points of the grid where the surface elevation was calculated. The mesh size was assumed constant with:

$$\Delta x = \Delta y = 2 \text{ km}.$$

The open boundaries to the north and to the south of the Straits (dashed lines in Fig. 7) were assumed to be closed. It seems reasonable that a steady state circulation pattern *in the inner region* should not be influenced by this assumption.

As shown in Figure 7, the Archipelago of La Maddalena was considered as a single island. However, because of the assumed mesh size, the breadth of the Bucinara Channel was not realistic. Thus the model area in Figure 7 gives an idealized picture of the actual topography of the Straits of Bonifacio, represented as a channel with a narrow section and an island in the middle of the channel. For a preliminary study of the steady state situation this is felt to be adequate. As the channel is

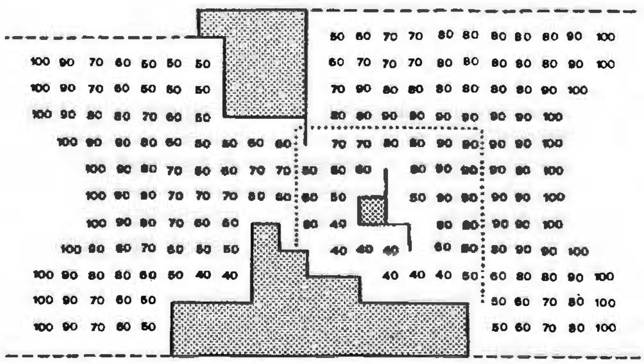

Figure 7
Schematic grid with bottom depths (m) for the Straits of Bonifacio (depth equals 100 m where not labelled).

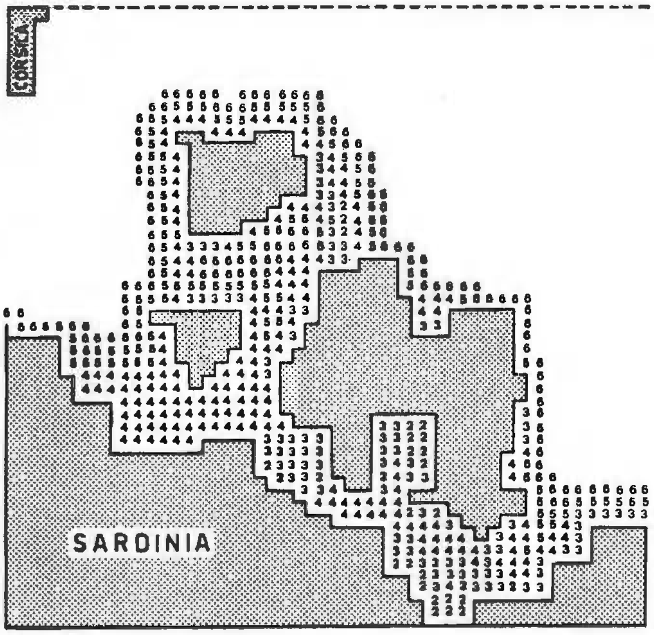

Figure 8
Schematic grid with bottom depths (10 × m) for the region of the Archipelago of La Maddalena (depth equals 60 m where not labelled).

relatively shallow and its open boundaries lie in deep water, the surface elevation was set to zero along those boundaries.

A second model was developed to give detailed predictions of the nearfield conditions by covering the area of the Archipelago of La Maddalena (region bounded by a dotted line in Fig. 7) with the grid of 50 × 50 mesh points shown in Figure 8. In this figure the bottom depths in tens of meters are given at the points of the grid where the surface elevations were calculated. The mesh size was assumed constant with:

$$\Delta x = \Delta y = 0.25 \text{ km}.$$

The islands of La Maddalena, Caprera and San Stefano have been considered as a single island; this is justified since in practice there is no flow of water between La Maddalena and Caprera (Passo della Moneta) and between La Maddalena and San Stefano. The steady state circulation patterns were then calculated for a constant wind stress. The wind was taken to be from the west with a speed of 10 m/sec. A time step of $\Delta t = 30$ seconds was used for the region of the Straits of Bonifacio, and $\Delta t = 5$ seconds was used for the Archipelago of La Maddalena.

NUMERICAL RESULTS

The first step was to calculate the steady state circulation in the Straits of Bonifacio (Fig. 7) assuming the surface elevation to be equal to zero on the open sea boundaries and neglecting the Coriolis force. Numerical experiments were made for different values of the number N_x of the mesh points in the east-west direction and with a flat bottom topography near the open boundaries. The calculation showed that for $N_x \geq 34$ the computed results

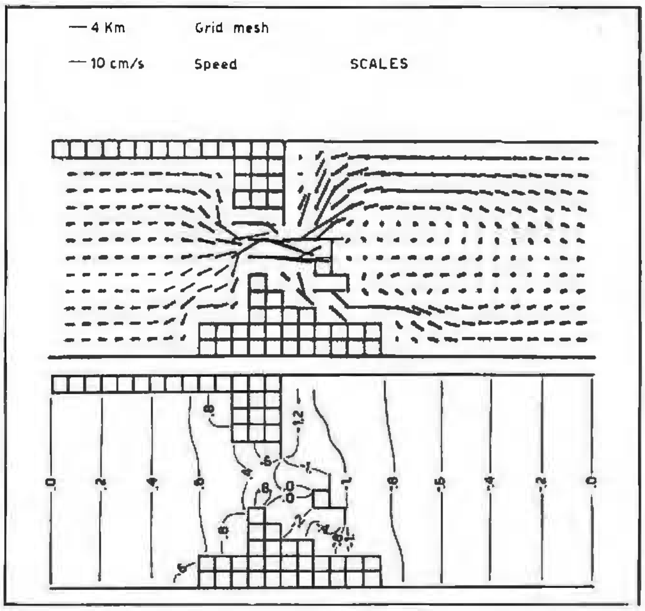

Figure 9
Circulation and surface elevation patterns in the Straits of Bonifacio after 288 hours. $\eta^*=0$; Coriolis acceleration neglected; wind from west.

in the inner region were independent of N_x and so we chose $N_x=34$ for economy. From rest the steady state was reached in about 6 days.

The velocity field and the surface elevation are shown in Figure 9. The vectors $[1/2\,(u_{i-1\,j}+u_{ij}),\ 1/2\,(v_{i,\,j-1}+v_{ij})]$ are drawn at the η-points (marked by dots) of coordinates $x_i=(i-1)\,2\,\Delta x$ and $y_j=(j-1)\,2\,\Delta y$, ($i=1, 2, \ldots, N_x$; $j=1, 2, \ldots, N_y$). Strong currents (30-40 cm/sec.) were generated in the Straits between Corsica and Sardinia. Further experiments were performed to evaluate the effects of the Coriolis acceleration, and the resulting circulation pattern is shown in Figure 10. In all the cases the circulation was influenced by the geometry of the area, which caused a funnelling of the water through the Bonifacio Straits.

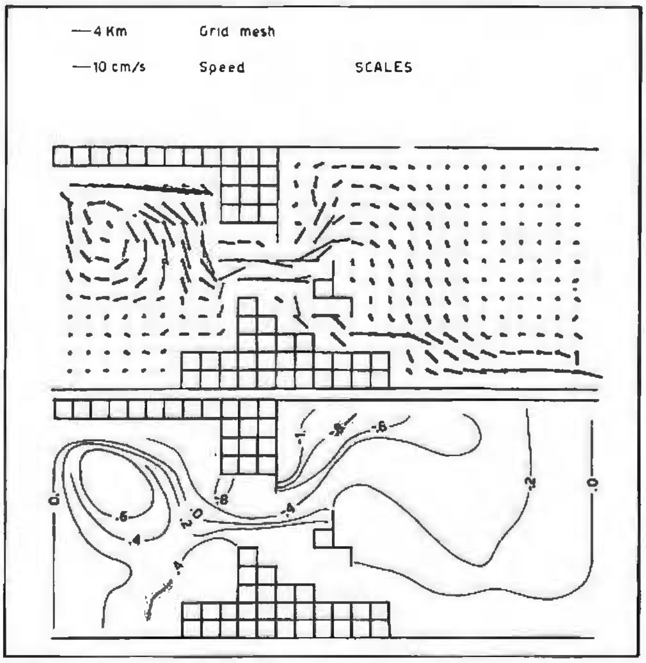

Figure 10
Circulation and surface elevation patterns in the Straits of Bonifacio after 204 hours. $\eta^*=0$, with Coriolis acceleration; wind from west.

When the Coriolis force was included, some countercurrents were generated, as in the observed circulation (Fig. 2), but an unrealistic gyre was created near the western boundary. As a consequence the velocity in the straits was about a half of the value without Coriolis.

The two-dimensional model was then applied to the region of the Archipelago of La Maddalena (Fig. 8). A flat bottom topography, with a depth of 60 m, was imposed outside the region of the Archipelago and the wind was taken to be from the west with a constant speed of 10 m/sec. The surface elevations computed by the large-scale model were used to specify the function η^* on the open boundaries. The values of η^* were obtained by averaging the values of the surface elevation on the two rows or columns of the grid adjacent to the dotted lines in Figure 7 and by linearly interpolating these averaged values along the dotted lines. When the Coriolis acceleration is neglected, the wind driven circulation pattern is shown in Figure 11. The currents in the Straits

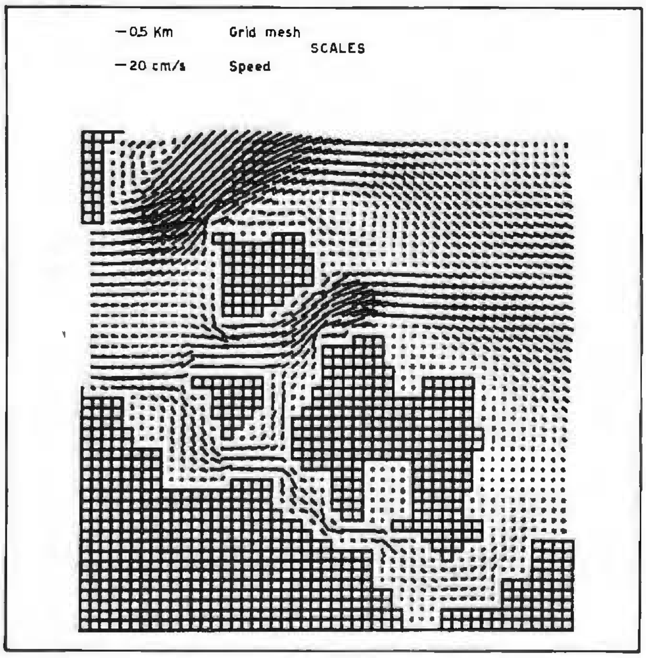

Figure 11
Circulation pattern in the region of the Archipelago of La Maddalena. η^* from the large-scale model shown in Figure 9; Coriolis acceleration neglected.

of Bonifacio resemble the currents computed by the coarse grid model. The big gyre behind the Archipelago in Figure 10 was split (Fig. 11) into two small gyres by the channel in the middle of the Archipelago. The inclusion of the Coriolis acceleration gave the results shown in Figure 12.

In order to compare the computed and experimental results, the computed velocities were averaged over a small region around each mooring location. For the experimental results we have taken the speed computed by the linear regression function between the alongshore current u at each mooring location and τ_{EW} for a wind speed of 10 m/sec. The results are given in Table 3. Surprisingly, better results were obtained when the Coriolis acceleration was omitted. This may be due to the narrowness of the channels in which the measurements were taken, but it is more likely to be an artifact due to the

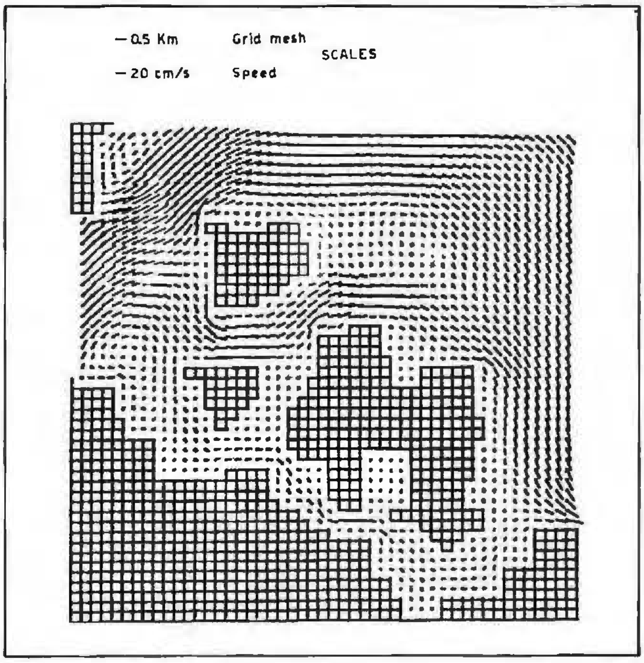

Figure 12

Circulation pattern in the region of the Archipelago of La Maddalena. η from the large-scale model shown in Figure 10; Coriolis acceleration included.*

way in which the elevation boundary conditions have been chosen. The results suggest that the model is capable of giving good predictions but that the boundary conditions need to be better defined.

DISCUSSION

This work was motivated by the need to predict the dispersion and flushing characteristics of the bays and channels that form the Archipelago of La Maddalena. Consequently, it was only a part of a much larger project which involved chemical and biological studies of the area. The predictions of the flow around and between the islands that have been made using the small scale inner model should permit an estimate to be made of the residence time for a pollutant introduced into the channels around La Maddalena. The flow patterns around the islands (Fig. 11, 12) appear reasonable and the experimental data suggest that it should be possible to calibrate the model so that meaningful results can be obtained (Table 3).

In common with many other modelling investigations this study lacks adequate observations of the relevant parameters. In particular, the farfield boundary conditions need to be better defined, and these can probably best be obtained by using offshore tide gauges.

Table 3

Comparison between the inner model results and the observational data (cm/sec.).

Mooring position	Two-dimensional model-Coriolis neglected	Two-dimensional model-with Coriolis	Experimental results
A	20.0	11.2	21.9
B	8.8	3.0	6.2
C	21.1	15.1	21.0
D	23.5	17.4	23.0
E	15.8	19.4	17.2

The encouraging aspect of this study is that there are probably very few locations in the world where the assumption of a constant wind has such relevance. Consequently, in view of the steady wind regime, it should be possible to continue the work and obtain realistic current predictions if additional field measurements can be made.

Acknowledgements

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FIRST INTERNATIONAL CONFERENCE ON METEOROLOGY AND AIR/SEA INTERACTION OF THE COASTAL ZONE

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In the week of 10 to 14 May 1982, the American Meteorological Society and the Royal Netherlands Meteorological Institute will co-sponsor the First International Conference on Meteorology and Air/Sea Interaction of the Coastal Zone. For present purposes the coastal zone is considered to be the domain from 500 km offshore to 500 km inland, i. e. where air-land-sea effects are significant. The Conference will be held in The Hague, within 45 minutes of Amsterdam.

Contributions on subjects of great contemporary interest for both meteorologists and physical oceanographers concerned with atmospheric processes and effects in the coastal zone are anticipated; topics of emphasis include, but are not restricted to:

- air/sea interaction;
- synoptic meteorology;
- fog and stratus;
- marine inversion;
- mesoscale processes and modelling;
- adjustment processes;
- air and water quality;
- cold air outbreaks;
- marine air invasions;
- climatology;
- wind driven circulation shelves (including storm surges);
- wind waves and swell on shallow water;
- the upper ocean mixed layer;
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- cooperative experiments;
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- applications, problems and products;
- operational meteorology and oceanography.

The Conference is co-convened by Pr. Hendrik Tennekes, Director of Research, Koninklijk Nederlands Meteorologisch Instituut, De Bilt, the Netherlands and Pr. Christopher N. K. Mooers, Chairman, Department of Oceanography, Naval Postgraduate School, Monterey, California, USA.