# Flow regimes study within the Strait of Gibraltar using an high performance numerical model.

G. Sannino(1), A. Carillo(1), V. Artale(1), V. Ruggiero(2) and P. Lanucara(2)

(1) *Global Climate Project - C.R. ENEA Casaccia, Rome.*
(2) *CASPUR - Rome*

**Summary.** — A three-dimensional sigma coordinate free-surface high performance model is used to investigate the flow regimes within the Strait of Gibraltar. High performances are achieved through a directive based, MPI like, parallelization of the code, obtained using SMS tool. The model makes use of a coastal-following, curvilinear orthogonal grid, that includes the Gulf of Cadiz and the Alboran Sea, reaching very high resolution in the Strait. Four experiments with different initial salinity conditions representing the present and possible future climate conditions over the Mediterranean basin have been performed. Model results, analysed by means of the three-layer composite Froude number theory, have shown two different possible regimes within the strait; for the present climate condition the strait is subjected to a sub-maximal regime while for possible future climate conditions a maximal regime can be reached.

PACS 92.10.-c – Physics of the oceans.

## 1. – Introduction

The narrow and shallow Strait of Gibraltar connects the Atlantic Ocean with the Mediterranean Sea. It is about 60 Km long and about 20 Km wide with a minimum width of 15 Km near Tarifa and a shallow sill located near Camarinal (west of Tarifa) with a minimum depth of less than 300 m. The mean circulation, is characterized by two counterflowing currents: in the upper layer Atlantic Water flows eastward spreading into the Mediterranean Sea and in the lower layer flows westward toward the Atlantic Ocean.

As initially suggested by Bryden and Stommel [1] the mean circulation is in sub-maximum regime,i.e. the two-layer flow is topographically controlled at Camarinal Sill while within the narrow region east of Tarifa both experimental data [2] and numerical model [3] do not show any control region.

Recent data analysis in the Gulf of Cadiz (west of Gibraltar) shows a relatively marked salinity increase of Mediterranean outflow waters from 1955 to 1993 due to an increase of E-P (evaporation - precipitaion) over the whole Mediterranean basin [4]. Thus, in order to understand if the strait of Gibraltar can exibit a maximal exchange regime [5], i.e. a two-layer flow controlled both at Camarinal Sill and Tarifa Narrow, three numerical experiments have been performed.

The numerical model used for all these three experiments is the Princeton Ocean Model (POM) [6] in a very high-resolution configuration (Δx, Δy <500 m) in order to represent all the dominant topographic features of the strait. However with the aim to speed-up the time performances of this model configuration, an MPI version of the standard POM (downloadable via web at: http://www.aos.princeton.edu/WWW/PUBLIC/htdocs.pom/) has been developed.

The paper is organized as follow: a description of model geometry, initial and boundary conditions is presented in section 2, parallelization details are reported in section 3, finally model results and conclusions are described in section 4 and 5 respectively.

## 2. – Model Description

The numerical model used for this study is based on the three-dimensional POM model developed by Blumber and Mellor [7] and modified by Sannino et al. [3]. POM is a free-surface model that solves the primitive equations using the sigma vertical discretization. The model numerically solves the momentum, continuity and tracers (temperature and salinity) equations in finite difference form. The two tracers are coupled to the fluid velocity through a nonlinear equation of state for density [8]. Horizontal (along sigma coordinates) and vertical turbulent mixing processes are parameterized via the Smagorinsky [9] and the Mellor and Yamada [10] schemes respectively. An explicit leapfrog scheme is used for time stepping, except for vertical diffusion terms, which are solved through an implicit scheme. The free surface is computed explicitly with a small time step (1 sec. in our study), however for computer time economy the 3D-equations are solved with a larger time step (60 sec), using a time splitting technique. Model variables are staggered following the standard Arakawa-C scheme in order to conserve linear and quadratic quantities like mass and energy.

Model grid and bathymetry, as well as boundary and initial conditions are the same as [3], so in the following we focus only on the principal model characteristics. The curvilinear orthogonal model grid has a variable resolution and covers a geographical region extending from the Gulf of Cadiz (11°W, 36°N) to Ibiza Island (3°E, 37°N). The maximum resolution is reached in the Strait of Gibraltar (< 500 m) while it degrades to about 10 Km and 15 Km at the eastern and western edges respectively.

In the present model configuration 32 vertical sigma levels, logaritmically distributed at the surface and at the bottom are used. As in [3] the model topography has been obtained by merging the high-resolution (< 1 km) topographic data set of the Strait of Gibraltar provided by the Laboratoire d'Oceanographie Dynamique et de Climatologie with the relatively low-resolution (5 min) U.S. Navy Digital Bathymetric Data Base-5 data set (available from U.S. Naval Oceanographic Office, Bay St. Louis, Mississippi at http://128.160.23.42/dbdbv/dbdbv.html) for the Alboran Sea and the Gulf of Cadiz. The resulting model topography in the region of the strait is shown in figure 1, where the dominant topographic features of the strait are well represented; in particular from west to east it is possible to recognize Spartel Sill (Sp), Tanger Basin, Camarinal Sill (Cm) and Tarifa Narrows.

In the vicinity of the eastern and western ends of the computational domain two open boundaries are defined: an Orlanski radiation condition [11] for the depth-dependent

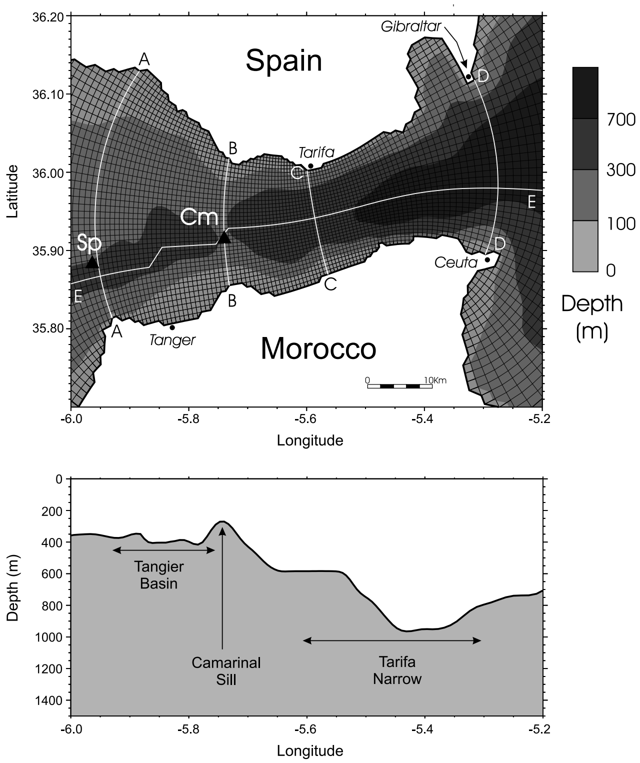

Fig. 1. – (Upper) Model bathymetry, computational grid, and transects for the presentation of model results within the Strait of Gibraltar. The gray levels indicate the water depths. The points Cm and Sp mark the points where are located Spartel Sill and Camarinal Sill respectively. (Lower) Bathymetry along the longitudinal section E

velocity, a flow relaxation scheme [12] for the depth-integrated velocity, and a Newtonian restoring for the two active tracers, with a damping timescale of 5 days.

Four numerical experiments have been performed (EXP0, EXP1, EXP2, EXP3), they are characterized by different salinity initial conditions; in particular EXP0 is initialized with climatological data obtained by a horizontal average of the spring MODB data (available at http://modb.oce.ilg.ac.be/modb) and the spring Levitus data [13] for the Alboran Sea and the Gulf of Cadiz respectively.

The initial difference between the two salinity profiles is 1.5 psu. For EXP1, EXP2 and EXP3 the initial temperatures are the same as in EXP0 while salinity in the Alboran Sea is increased uniformely at all vertical levels by .5, 0.7 and 1. psu respectively.

## 3. – Parallelization details

In order to develop a parallel code which is easy to create/maintain, efficient and portable, the SMS (Scalable Modeling System) tool has been used. SMS has been recently developed by the Advanced Computing Branch of the Forecast Systems Laboratory at NOAA (National Oceanic and Atmospheric Administration) [14]. In this section we recall only the principal SMS features used to parallelize our POM implementation, while a

Table I. – *Time (in milliseconds) and speed-up of the full code and for the principal routines referred to a single time step*

| | **Time(ms)** | **Speed-up** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| CPUs | 1 | 4 | 8 | 12 | 16 | 20 | 24 | 28 | 32 |
| full code | 14900 | 4.1 | 7.7 | 10.8 | 13.3 | 15.1 | 17.5 | 19.5 | 21.2 |
| profq | 1610 | 4.3 | 8.4 | 12 | 15.5 | 17.9 | 20.9 | 23 | 23.7 |
| proft | 720 | 4.2 | 8.8 | 13 | 17.1 | 21.2 | 24.8 | 26.6 | 31.3 |
| advct | 717 | 4.5 | 7.9 | 11.4 | 13.8 | 16.3 | 19.4 | 21.7 | 22.4 |
| dens | 632 | 4.3 | 11.1 | 18 | 23.4 | 28.7 | 35.1 | 39.5 | 45.1 |
| denst | 511 | 4.5 | 12.8 | 21.3 | 28.4 | 35.7 | 42.5 | 51.1 | 53.8 |
| advq | 428 | 5.1 | 9.9 | 14.3 | 17.5 | 20.4 | 21.9 | 23.1 | 26.7 |
| profs | 248 | 4.3 | 8.5 | 11.8 | 16.5 | 17.7 | 20.7 | 22.5 | 24.8 |
| profu | 242 | 4.2 | 7.8 | 11.5 | 15.1 | 18.6 | 22 | 26.9 | 28.5 |
| profv | 240 | 4.4 | 8.3 | 11.5 | 15.5 | 20.2 | 22 | 26.3 | 26.4 |
| baropg | 175 | 4.2 | 7.6 | 12.1 | 12.1 | 12.5 | 15.1 | 15.3 | 16.1 |
| vertvl | 146 | 4.7 | 9.1 | 11.7 | 14.6 | 14.7 | 15.4 | 15.5 | 15.7 |
| advave | 128 | 4.3 | 8.3 | 12.2 | 16 | 19.4 | 21.7 | 27.3 | 28.4 |

complete overview of SMS can be found at http://www-ad.fsl.noaa.gov/ac/SMS_UsersGuide_v2.8.pdf.

It makes use of a set of directives (about 20) that users have to add to their code in form of comments. SMS translates the code and directives into a parallel version which runs efficiently on both shared and distributed memory high performance computing platforms; in particular it uses a source-to-source translation technique to generate different parallel target codes from a single source code. The advantage of the SMS approach is that no complicated compiler-generated communication statements have to be included in the code, moreover SMS contains a number of features to speed up the debugging process and to support incremental parallelization. Further, no code changes are required when porting the SMS serial version to other shared and distributed memory machines. As in [15] the parallelization strategy used for POM follows the well known domain decomposition technique, applied to the two horizontal coordinates, which is automatically achieved by SMS.

The resulting SMS version of POM includes only 3% more code lines respect to the original serial code, while the speed-up obtained for our implementation of POM is about 21 using 32 IBM Power4 CPUs (1.3 Ghz clock and 64 Gb). In Table I speed-up details for the principal routines are shown.

## 4. – Model Results

The model starts from rest for all the experiments. The flow within the strait adjusts to a quasi-steady two-layer system after 200 days of integration reaching a mean transport in both layers of 0.72, 0.86, 0.89 and 0.93 Sv ($10^6 m^3 s^{-1}$) for EXP0,EXP1,EXP2 and EXP3 respectively.

These transports have been computed integrating the along-strait velocity vertically, from the bottom up to the surface, and then laterally across section $\mathsf{C}$ (refer to model grid in Figure 1):

$$Q_M(t) = \int_C ds \int_{z=bottom}^{z=surface} u_{in}(z,t)dz \tag{1}$$

$$Q_A(t) = \int_C ds \int_{z=bottom}^{z=surface} u_{out}(z,t)dz, \tag{2}$$

where $Q_A$ and $u_{out}$ are the transport and velocity toward the Atlantic while $Q_M$ and $u_{in}$ represent the transport and velocity toward the Mediterranean. The above transport values are in reasonable agreement with the last experimental estimates [16], [17].

In order to evaluate which kind of flow regime the strait of Gibraltar exhibits under the four different initial conditions, the composite Froude number has been computed in the whole strait. As argued by [18] e [3] the better way to represent the flow within the strait region is considering the flow as a three-layer system, with a surface inflowing layer, a deep outflowing layer and a thin intermediate layer in between. Thus, applying the formulaes developed by [3] for a three-layer system, the composite Froude number has been computed as:

$$G^2 \equiv F_1^2 + F_2^2 + F_3^2 \tag{3}$$

where

$$F_1^2 = \frac{\bar{u}_1^2}{h_1 g(1-r_{1,2})}, \quad F_2^2 = \frac{\bar{u}_2^2(1-r_{1,3})}{h_2 g(1-r_{1,2})(1-r_{2,3})}, \quad F_3^2 = \frac{\bar{u}_3^2}{h_3 g(1-r_{2,3})}, \tag{4}$$

where $G$ is the composite Froude number, g is gravity, $F_i$, $\bar{u}_i$ and $h_i$ represent respectively the layer Froude number, mean velocity and thickness for the three layers and $r_{i,j}$ is the density ratio $\bar{\rho}_i/\bar{\rho}_j$.

The Froude numbers obtained for the four experiments are shown in Figure 2; here it is evident that the flow over Camarinal Sill is always controlled (i.e. G $>$ 1), while in Tarifa Narrow the region controlled increases with salinity difference. In particular for EXP0 (Figure 2a) the strait exhibits a sub-maximal behaviour with an unique control over Camarinal Sill, EXP1 still shows a sub-maximal regime, but in this case some controlled regions appear on the northern shore east of Tarifa (Figure 2b), however they are not sufficient to control the entire cross-strait region. When the salinity difference reaches a value of $\Delta$S =2.2 the flow starts to show a maximal regime, i.e. two hydraulic control regions are simultaneously present within the strait, one over Camarinal Sill and the other east of Tarifa Narrow (Figure 2c). The same regime is achieved also for EXP3 when the salinity difference is increased to $\Delta$S =2.5 (Figure 2d).

Different regimes within the strait have a deep influence on the three-layer system. The principal effect is certainly on the volume transport that does not increase linearly with salinity difference when the flow switches from sub-maximal to maximal regime. This is particularly clear in Figure 3 where the transport within the strait is plotted against the salinity difference for the four experiments. Here one can see a discontinuity in the trend of the transport just at $\Delta$S =2., that corresponds to the flow transition from sub-maximal to maximal.

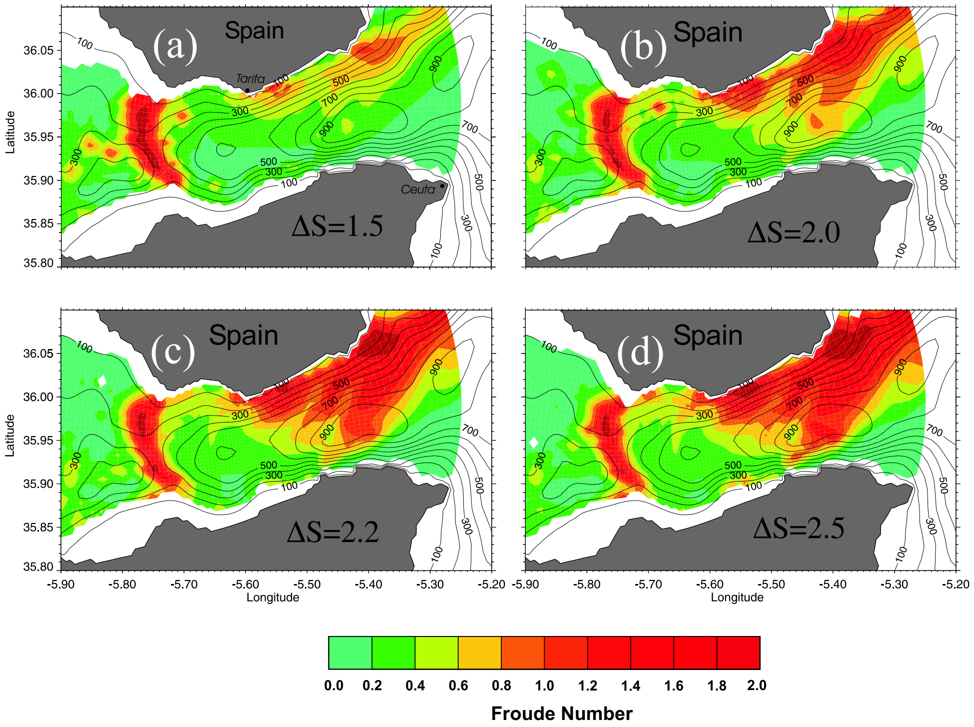

Fig. 2. – Three-layer composite Froude number for EXP0 (a), EXP1 (b), EXP2 (c) and EXP3 (d), calculated using the three-layer composite Froude number theory. Contour lines represent the bathymetry.

## 5. – Summary and Conclusions

One of the most controversial point about the water circulation within the Strait of Gibraltar is the kind of flow regime that the strait can exhibit. In order to study this problem, in the last twenty years two big experimental campaigns were conducted within

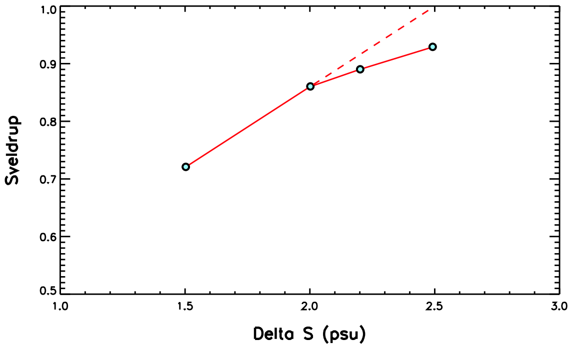

Fig. 3. – Predicted transport through the strait for the four experiments versus the salinity difference.

the Strait of Gibraltar: the Gibraltar experiment [19] and the CANIGO experiment [20]. However, due to the complexity of the problem, the uncertainity still remains and two different opinions exist: one is inclined to think that the strait is always in a sub-maximal regime while the other thinks that the strait can switch between a sub-maximal and a maximal regime with a seasonal frequency (see for example [2] [21]). In order to improve knowledge about this problem four numerical experiments have been performed in this study; the model used is based on the Princeton Ocean Model (POM) parallelized using SMS tool, that is a powerful semiautomatic translator ables to convert a serial code into an MPI version. The experiments differ only for the salinity initial condition, in particular EXP0 is initialized with climatological data, while EXP1, EXP2 and EXP3 with an increased salinity difference between the Atlantic and the Mediterranean waters, motivated by recent climate results [4] that show an increment of salinity production in the Mediterranean Sea. Applying to the results of all the experiments the three-layer Froude number theory has been possible to evaluate the flow regime within the strait. For EXP0, that can be considered as the present climate condition, the flow regime simulated by the model is sub-maximal, i.e. there is only a region, over Camarinal Sill, where the composite Froude number is greater than 1 (Figure 2a). EXP1, that is characterized by an increased salinity difference of 0.5 psu respect to EXP0, shows a sub-maximal regime. In this case, some regions, limited to the northern shore eastern of Tarifa, begin to be controlled; however these regions are not sufficient to control the whole flow (Figure 2b). A marked modification of the flow regime is evident only in EXP2 and EXP3, which are characterized by an increased salinity difference of 0.7 and 2. psu respect to EXP0. For both experiments two well established regions, one on Camarinal Sill and the other in the eastern part of Tarifa Narrow are interested by a composite Froude number greater than 1. One of the most evident effect of the maximal flow regime is on the volume transport across the strait that shows a different trend respect to the one exhibited between EXP0 and EXP1. Thus one can conclude that the Strait of Gibraltar can exhibite both regimes but in the present climate condition the flow within the strait can be only in sub-maximal regime. However should be stressed that these simulations neglect both the subinertial (due to meteorological forcing) and tidal variability that can modify on shorter time scale (respect to climate scale) the sub-maximal regime. Finally, in spite of these limitations, this model represents the first numerical effort towards a more realistic model of the Strait of Gibraltar.

* * *

## REFERENCES

[1] Bryden H. L. and Stommel H. M., *Limiting processes that determine basic features of the circulation in the Mediterranean Sea* in *Oceanol. Acta* 7 1984 289

[2] Lafuente J.G., Delgado J., Vargas J.M., Vargas M., Plaza F. and Sarhan T., *Low-frequency variability of the exchanged flows through the strait of Gibraltar during CANIGO* in *Deep Sea Res. II* 49 2002 4051

[3] Sannino G., Bargagli A. and Artale V., *Numerical modeling of the mean exchange through the Strait of Gibraltar* in *J. Geophys. Res.* 107(C8) 2002 3094

[4] Potter R.A. and Lozier M.S., *On the warming and salinification of the Mediterranean outflow waters in the North Atlantic* in *Geoph. Res. Letters* 31 2004 L01202,doi:10.1029/2003/GL/018161

[5] Garrett C., Bormans M. and Thompson K., *Is the exchange through the Strait of Gibraltar maximal or submaximal?* in *The Physical Oceanography of Sea Straits* edited by L. J. Pratt, Kluwer Acad., Noerwell, Mass. 1990 271-294

[6] Blumberg A.F. and Mellor G.L., *A description of a three-dimensional coastal ocean circulation model* in *Three-Dimensional Coastal Ocean Models, Coastal Estuarine Science* edited by N. S. Heaps, Ed., Amer. Geophys. Union 1987 1-16

[7] Blumberg A. F. and Mellor G. L., *A description of a three-dimensional coastal ocean circulation model* in *Three-Dimensional Coastal Ocean Models, Coastal Estuarine Science* edited by S. Heaps, Ed., Amer. Geophys. Union 1987, pp. 1-16.

[8] Mellor G. L., *An equation of state for numerical models of oceans and estuaries.* in *J. Atmos. Oceanic Technol.* 8 1991 609

[9] Smagorinsky J., *General circulation experiments with primitive equations. I: the basic experiment* in *Mon. Weather Rev.* 91 1963 99.

[10] Mellor G. L. and Yamada T., *Development of a turbulent closure model for geophysical fluid problems* in *Rev. Geophys.* 20 1982 851

[11] Orlanski I., *A simple boundary condition for unbounded hyperbolic flows* in *J. of Computational Physics* 21 1976 251

[12] Martinsen E.A. and Engedahl H., *Implementation and testing of a lateral boundary scheme as an open boundary condition in a barotropic ocean model* in *Coastal Eng* 11 1987 603

[13] Levitus S., *Climatological Atlas of the World Ocean* in *NOAA Prof. Paper 13* edited by U.S. Govt. Printing Office 1982, pp. 173.

[14] Govett M., Hart L.,Henderson T., Middlecoff J. and Schaffer D., *The Scalable Modeling System: Directive-Based Code Parallelization for Distributed and Shared Memory Computers* in *J. of Parallel Computing* 29 2003 995

[15] Sannino G., Artale V. and Lanucara P., *An hybrid OpenMp/MPI parallelization of the Princeton Ocean Model* in *Parallel computing, advances and current issues* edited by Imperial College 2001 222

[16] Bryden H. L., Candela J. and Kinder T. H., *Exchange through the Strait of Gibraltar Prog. Oceanogr.*, **33** (1994) 201

[17] Lafuente J. G.,Vargas J. M., Plaza F., Sarhan T., Candela J. and Bascheck B., *Tide at the eastern section of the Strait of Gibraltar J. Geophys. Res.*, **105(C6)** (2000) 14,197

[18] Bray N. A., Ochoa J. and Kinder T. H., *The role of the interface in exchange through the Strait of Gibraltar* in *J. Geophys. Res.* 100 1995 10755

[19] Bryden H. L. and Kinder T. H., *The Gibraltar Experiment: A plan for dynamic and kinematic investigations of strait mixing, exchange and turbulence Oceanol. Acta*, **9** (1988) 29

[20] Parrilla G., Neuer S., Le Traon P.Y. and Fernadez E., *Deep Sea Res.*, **P** (a) rt II 49 2002 3951

[21] Bormans M., Garrett C. and Thompson K.R., *Seasonal variability of the surface inflow through the Strait of Gibraltar* in *Oceanol. Acta* 9 1986 403