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МОДЕЛИРОВАНИЕ ГИБРАЛТАРСКОГО ПРОЛИВА: ОТ ОПЕРАТИВНОЙ ОКЕАНОГРАФИИ ДО ВЗАИМОДЕЙСТВИЯ МАСШТАБОВ

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Сделан обзор работ, посвящённых моделированию океанологических процессов в Гибралтарском проливе. Это район, в котором поверхностные Атлантические воды поступают в Средиземное море, а вытекающие Средиземноморские воды распространяются на средних глубинах Северной Атлантики, формируя значительную термохалинную аномалию. Кроме среднего водообмена рассматриваются и другие процессы, такие как приливы, внутренние волны высокой амплитуды, субинерциальные колебания, вызванные метеорологическими явлениями синоптического масштаба, перемешивание и широкий спектр пространственно-временных масштабов. Значительный прогресс, достигнутый в понимании и моделировании океанологических процессов в Гибралтарском проливе, позволяет отвечать на новые общественные запросы и ставить новые научные задачи. Одним из социоэкономических требований является увеличивающаяся потребность в оперативной океанографической информации для использования в процессе принятия решений в районе, который является одним из наиболее интенсивных судоходных проливов в мире, и в результате этого подвергается повышенному риску морских происшествий и загрязнения окружающей среды. В статье описывается Оперативная Океанографическая Система для Гибралтарского пролива, отвечающая вышеуказанным требованиям. Новые научные задачи вызывают необходимость в развитии модельных исследований, учитывающих процессы и взаимодействие между разными масштабами. Используя глобальную модель циркуляции океана с регионально увеличенным пространственным разрешением вокруг Иберийского полуострова, мы смогли разрешить процессы локальных масштабов в Гибралтарском проливе и Кадисском заливе, в то же время учитывая процессы происходящие в масштабах всего Атлантического океана. Нами было обнаружено, что вызванные приливами процессы локального масштаба в Гибралтарском проливе и Кадисском заливе оказывают существенный вклад в распределение средиземноморских вод в Атлантическом океане.

Ключевые слова: Гибралтарский пролив, Кадисский залив, средиземноморские воды, численное моделирование, оперативная океанография, взаимодействия масштабов, приливы.

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MODELLING IN THE STRAIT OF GIBRALTAR: FROM OPERATIONAL OCEANOGRAPHY TO SCALE INTERACTIONS

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We make a review on the modelling efforts devoted to better understand the complex oceanography of the Strait of Gibraltar, where Atlantic waters enter the Mediterranean Sea as a surface flow, and Mediterranean outflowing waters spread into the interior of the North Atlantic forming a prominent basin-scale termohaline anomaly at mid-depths. Besides the mean exchange flows relevant phenomena include tides, high amplitude internal waves, meteorologically forced subinertial oscillations, mixing, and involve a wide-range of spatio-temporal scales. The remarkable progress achieved

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in understanding and modelling the ocean processes in the Strait of Gibraltar allows now undertaking new societal demands and scientific challenges. One societal demand is given by the increasing need of operational oceanographic information as a support tool for decision-makers in an area considered as one of world's busiest shipping lanes, with an increased risk of maritime accidents and environmental pollution. We present an Operational Oceanography system for the Strait of Gibraltar responding to that demand. On the other hand, new scientific challenges call for the need of developing perspective-modelling studies accounting for process and scale interactions. Using a global ocean general circulation model with regional high resolution around the Iberian Peninsula we are able to resolve the local-scale at the Strait of Gibraltar and the Gulf of Cádiz while focusing on the basin scale. As a result, we find that tidally-induced local-scale processes in the Strait and in the Gulf of Cádiz appear to have a drastic impact on the distribution of Mediterranean outflow waters in the Atlantic basin.

Key words: the Strait of Gibraltar, the Gulf of Cadiz, Mediterranean Outflow, Numerical modelling, Operational oceanography, scale interactions, tides.

The Strait of Gibraltar has been a challenge and an opportunity for mankind along its existence. There is not yet an agreement whether it served more as a barrier or a bridge for human groups in prehistoric times [1, 2]. Now it is evident that the Strait works as a barrier or a bridge depending on the complex evolution of the geopolitical situation and economic interests. Whatever its role, it is clear that the Strait of Gibraltar, due to its relevance in the European and North-African history and to its geostrategic importance, is a paradigmatic example of what a strait means.

According to Luzón-Nogué [3] there were people who dared to cross the Strait of Gibraltar in the 2nd millennium BC, before the Phoenicians. The Odyssey describes how Odysseus (Ulysses), after sailing away from Calypso's island (often identified as modern Ceuta) aboard a rickety raft headed into the Mediterranean Sea. This could well be an ancient depiction of the strong eastward surface currents dominating the eastern part of the strait (although Homer gave all the merit to the warm and fair wind Calypso summoned for him). This is only one example of the many early historical descriptions of the oceanography of the Strait of Gibraltar. With the development of navigation it became a well-established fact that the surface currents in the Strait of Gibraltar were permanently flowing eastward. But what was the fate of this uninterrupted flow of water entering the Mediterranean? It was probably von Waitz in 1755 (see [4]) the first who was able of giving a scientific explanation of how a compensating counter flowing undercurrent should be maintained in the Strait due to the excess evaporation in the Mediterranean basin and the salinity differences between the Atlantic and the Mediterranean waters. Waitz (1755) argued that a similar water exchange must take place between the equatorial and polar regions of the ocean. As Deacon [4] explicitly notes, Waitz (1755) work on the Strait of Gibraltar allowed him to setup an early theory of ocean circulation, which would be further developed by other authors.

Besides this oceanographic significance, the Strait of Gibraltar presents an enormous geostrategic value, being a key location during the Battle of Trafalgar and during WWII, and an overwhelming economic importance. In fact, it is considered one of the world’s busiest shipping lanes: around 110,000 vessels per year traveling through the Strait moving half of the world’s trade. This high traffic density, including oil tankers, settles a high risk of collision and posses a thread to navigation safety and pollution in an extremely vulnerable ecosystem. At the same time the dramatic increase in world inequality has triggered a desperate immigrant flow through the Strait in the last decades with the tragic death toll of several thousands human beings [5]. As the inequality causing that migration flow seems not to vanish in the years to come it is of vital importance the efficient development of search and rescue (SAR) operations. The efficiency of the fight against marine pollution and SAR operations partly relies on an appropriate meteorological and oceanographic support to decision-making.

The amount of scientific literature regarding the Strait of Gibraltar is huge and increasing, a clear testimony of the paradigmatic interest to the oceanography in the Strait. Nevertheless our focus is not on a complete review of the Strait of Gibraltar oceanography, but on the advancement in ocean numerical modelling within the Strait, which have been very useful in filling the gaps left behind by the inherent simplicity of analytical solutions and the forced incompleteness of observational data sets. This scientific progress has allowed to successfully enfacing some societal demands, simultaneously opening new scientific challenges. This paper is structured as follows: A short geographic and oceanographic description of the Strait of Gibraltar is given in Section 2. Section 3 presents a review on ocean numerical modelling efforts carried out in the Strait. These efforts have contributed to the development of an Operational Oceanography System for the Strait of Gibraltar run at the University of Cádiz (UCA) and described in Section 4.1. The Section 4.2 introduces a new modelling approach with allowance for scale interactions and presents an assessment of the impact of tidally-induced local processes on the Mediterranean Outflow waters spreading in the North Atlantic. Finally, the conclusions are presented in Section 5.

The Strait of Gibraltar: a short description. The Strait of Gibraltar, placed between North Africa and the Iberian Peninsula, is the only nexus connecting the Atlantic Ocean and the Mediterranean Sea. It is located at a mean latitude of 35º 58' N with its longitudinal axis almost E-W aligned along 60 km between the imaginary meridional lines connecting Punta Almina and Punta Europa at the east and Cabo Espartel and Cabo Trafalgar at the west (fig. 1). Its minimum width is 14 km at Tarifa Narrows widening up to 44 km at the western end. The Strait was formed in the Lower Pliocene as result of the Zanclean flood once the Gibraltar Arc, blocking the gap between the Atlantic Ocean and Mediterranean Sea, was breached. This catastrophic flood put an end to the Messinian salinity crisis [6]. The result is an irregular coastline and a complex bathymetry characterized by a succession of sills and basins. The most prominent morphometric features, from west to east, are the shallow Spartel sill, the Western basin (~600 m), the shallow (a maximum depth of 300 m) Camarinal Sill and the deep Tarifa Narrows. North of Punta Cires the Strait presents the maximum depth (1181 m), and near the eastern boundary the Algeciras submarine canyon crosses the northern part of the strait (see fig. 1).

The oceanographic characteristics of the Strait of Gibraltar are basically determined for the fact of being the nexus between two ocean basins of distinct nature and with different water properties, being accepted values of $\sigma_\theta = 29$ and $\sigma_\theta = 26.5$ as characteristic for the Mediterranean and Atlantic exchanged waters [7].

Lighter Atlantic waters flow into the Mediterranean, becoming denser due to the excess evaporation and winter cooling and eventually sinking to form intermediate and deep Mediterranean water masses, which flow back to the Atlantic as an undercurrent called the Mediterranean Outflow (MO). Thus in the Strait of Gibraltar it is established an inverse estuarine circulation. This two-layer exchange is of great importance as it is necessary to close the Mediterranean Sea water and salt balance. Bryden and Stommel [8] proposed an overmixing model for the Mediterranean basin, where the Atlantic-Mediterranean salinity difference is minimum and the magnitude of the two-layer flow is maximum consistent with the internal hydraulic control at the Strait. Armi and Farmer [9, 10] and Farmer and Armi [11] explained this and other features of the flow through the Strait within the framework of the two-layer internal hydraulics theory and making use of available data sets.

Different processes affect this mean two-layer exchange. Lacombe & Richez [12] analysed a comprehensive data set and characterized in detail the hydrodynamic regime of the Strait distinguishing three fundamental scales of variability: long period, subinertial and tidal. The long period variability is related to seasonal, interannual and longer period fluctuations in the two-layer exchange. The subinertial variability comprises periods ranging from few days to few months, and it is associated to the exchange flows modulation caused by meteorological forcing [13]. Tides are by far the most energetic process in the Strait and present an essentially semidiurnal character, although diurnal current velocities are not negligible, especially in the eastern part

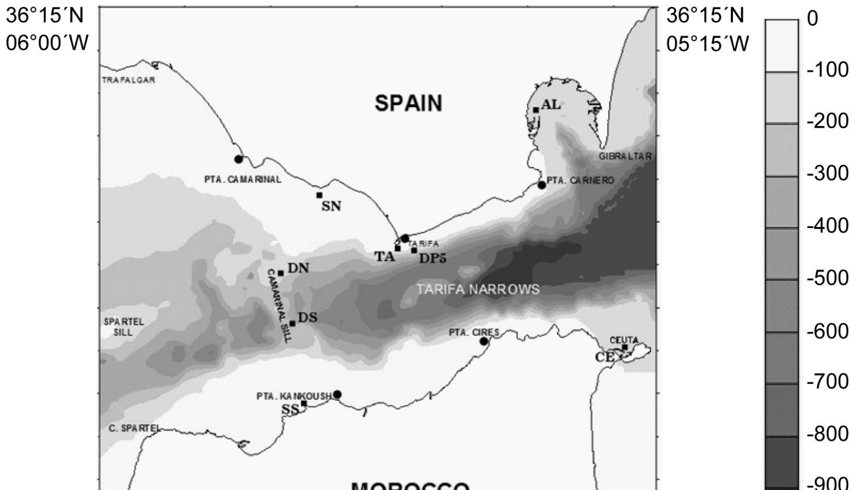

Fig. 1. Bathymetry map of the Strait of Gibraltar. Also shown coastal tide gauges (solid circles) and bottom pressure stations (solid squares) referred to in table.

Comparison of O_1 modelled amplitudes and phases with data from tide gauges and bottom pressure measurements. Observed data are taken from [14] and [22]

Station	Latitude	Longitude	Observed		Predicted	
	North	East	Amplitude, cm	Phase, deg.	Amplitude, cm	Phase, deg.
Pta. Gracia	36º05.4'	05º48.6'	1:8 ±0:2	313 ±8	3.4	282.8
DN	35º58'	05º46'	1.5	291.7	2.5	286.8
DS	35º54'	05º44'	2.8	335.7	2.2	299.6
SN	36º03'	05º43'	0.7	298.0	2.2	288.2
SS	35º50'	05º43'	3.8	332.0	2.7	327.4
Kankoush	35º50.5'	05º41.0'	2:9 ±0:4	343± 8	1.7	281.0
Tarifa	36º00.2'	05º36.4'	0.5±0.2	165±25	1.3	266.1
TA	36º01'	05º36'	1.2	104.7	1.3	257.5
Dp5	36º00'	05º34'	1.7	225.3	0.7	234.6
Pta. Cires	35º54.7'	5º28.8'	1:2 ± 0:2	81 ± 10	0.6	34.1
AL	36º08'	05º26'	1.1	106.9	1.5	147.8
Pta. Carnero	36º04.3'	05º25.7'	0:7 ± 0:2	181 ±17	1.2	121.5
CE	35º53'	05º18'	2.0	102.7	1.6	99.8

of the Strait. In the vicinity of Camarinal Sill tidal current velocities are strong enough to periodically reverse the flow in both layers [14]. It is precisely at Camarinal Sill where the interaction of the strong barotropic tidal forcing with the sill originates a transfer of energy to internal dynamics as observed and reported [15—17]. According to [10] and [11] it begins with the formation of an interfacial depression over the western edge of the Camarinal Sill near low water at Tarifa, when both layers over the sill crest move west. During one hour before high water, when the lower layer at the sill continues to move west, an internal bore with amplitude as high as 100 m is released from the Camarinal Sill and starts to travel east, gradually disintegrating into a train of solitary waves. Naturally, tides and internal wave dynamics will have a notorious contribution to the mixing processes in the Strait of Gibraltar.

This intertwined panoply of ocean processes with widely different space-time scales makes it an ambitious challenge to ultimately model them allowing for their interactions. Traditionally, different processes were modelled in an isolated way, and quite often with strong limitations imposed by the spatial resolution. Fortunately, the continuous increase in computing power and advances in numerical modelling techniques has made it more affordable a complex approach at higher resolution, enriching our knowledge of the processes taking place in Strait of Gibraltar and making operational forecasts possible. The drawback, however, is that the output of complex 3D numerical models is not that readily interpretable and easy to analyse.

Numerical models: a brief review. This review does not pretend to be exhaustive. Rather we will focus on those models we consider represented an outstanding advance or innovation.

Barotropic tides (2D models). To our knowledge the first attempt in modelling surface tides was [18], using a nonlinear, finite-difference model with prescribed values of tidal elevation at open boundaries and a grid spatial resolution of 2.5 km. Later on [19] employed a nonlinear, finite-element model with prescribed values of tidal elevation at open boundaries and a nominal spatial resolution of 2.0 km. Both models reproduced the observed features of the simulated tidal harmonics (M_2, S_2, N_2, K_1) obtaining a reasonable agreement with observed data. Namely, for the semidiurnal tides a twofold decrease in amplitudes from the western to eastern end of the strait as well as small variations in phases within the strait with a southward propagation and a nearly 90º phase difference between tidal velocity and elevation. The diurnal wave K_1 presented a clear wave propagation towards the east and an increase in amplitudes towards the southern coast. However, the nature of these features remained unexplored. Moreover, the energetics of the semidiurnal surface tides in the Strait of Gibraltar was not discussed, and the model results were not sufficiently verified.

In two successive works Tejedor et al. [20, 21] simulated the dynamics and energetics of the main semidiurnal (M_2 and S_2) and diurnal (O_1 and K_1) tidal waves employing a 2D high-resolution (0.5 km) boundary-fitted

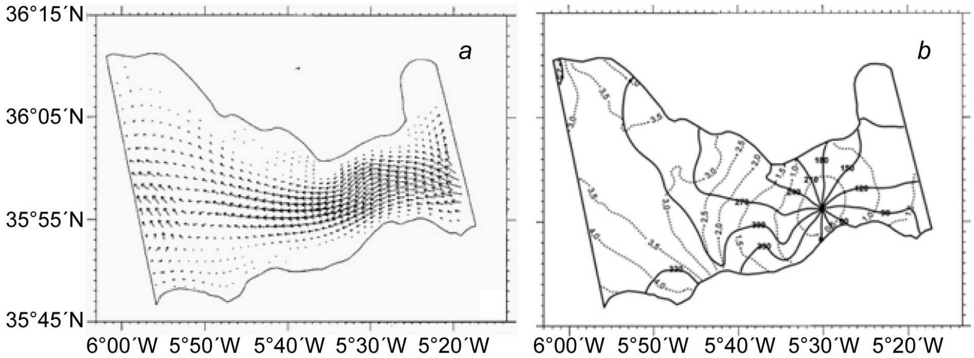

Fig. 2. *a* — M_2 tidal energy flux; *b* — O_1 cotidal chart.

coordinate model. The model reproduced all their known features and highlighted some new ones. They found a general direction of the M_2 and S_2 mean tidal energy fluxes to the west in accordance with the observed cotidal charts. This semidiurnal tidal energy flux (fig. 2, *a*) and the existence of a vast area with ~90º phase difference between tidal velocity and elevation was attributed to both end and topographic funnelling effects. The role of Camarinal Sill in determining the bulk of total tidal energy dissipation within the Strait of Gibraltar was highlighted [21]. Regarding the diurnal tides it was showed for the first time the presence of an O_1 amphidrome with anticlockwise rotation in the Tarifa Narrows, likely related to the superposition of two opposed Kelvin waves [20] (fig. 2, *b*). The existence of this amphidromic point is confirmed by the harmonic analysis of coastal tidal gauge and bottom pressure measurements (see table), where the anticlockwise rotation of cotidal lines is evident as well. The agreement between observed and simulated O_1 is satisfactory but worse than for the semidiurnal tidal waves. This is caused by the O_1 strong sensitivity to small variations in morphometry due to its small amplitude, but also to the fact that the energy content of the diurnal spectral band is within the noise limits produced by internal tidal waves, therefore the estimation of O_1 harmonic constants from bottom pressure measurements must be taken with caution [14].

Internal dynamics (vertical 2D, two-layer 1D and 2D, horizontal 2D). Pierini [23] used a horizontally two-dimensional, nonlinear dispersive model to successfully reproduce the evolution and propagation of internal solitary waves observed in the Alboran Sea, accounting for the important 2D spreading effects. It was a propagation model based on the Kadomtsev-Petviashvili equation, in which the internal tide in the Strait of Gibraltar was prescribed as a given time-dependent boundary condition. Longo et al. [24] used a one-dimensional, hydrostatic, nonlinear, two-layer model to simulate the internal bore generation by the combined action of mean and barotropic tidal flow over the Camarinal Sill. The joint modelling of the generation and propagation of internal waves was first undertaken by [25]. They used a weakly non-hydrostatic, two-layer numerical model based on the Boussinesq equations to describe both, the generation of internal hydraulic jumps inside the strait and the development and propagation of internal bores as well as their disintegration into trains of internal solitary waves. Although their model was depending on the along-strait coordinate only, it retained several 3D features by including a realistic bottom profile, a variable channel width, and a trapezoidal channel cross-section. Rotation, however, was not included.

Sein et al. [26] developed a two-dimensional, two-layer, boundary-fitted coordinate model based on the hydrostatic nonlinear shallow-water equations on an f-plane for the simulation of the flow exchange and tidally-induced dynamics of the Strait of Gibraltar.

A similar model was later employed by [27] to study the time–space variability of hydraulic controls and the development and evolution of internal bores in the Strait of Gibraltar. Their results showed that geometric spreading markedly affects the development of internal bores in the Strait of Gibraltar, and provided the internal bore travel times between different parts of the Strait reaching a good agreement with observations (fig. 3). However, the hydrostatic assumption precluded the bore disintegration into internal solitary wave trains.

Morozov et al. [28] applied a two-dimensional, along-strait, multilayer numerical model considering a continuously stratified rotating ocean of variable depth incorporating non-hydrostatic effects. Their modelling results agreed well with the observations from the 1985-86 Gibraltar Experiment [29]. They showed the formation of an undular bore east of the sill and a weak undular bore west of it and demonstrated the importance of the outflowing current in forming the undular bore and of the velocity shear in the intensification of the internal bore and wave packets in the upper layer.

Vázquez et al. [30] applied a high resolution (50 m horizontal and 140 vertical σ-levels) fully nonlinear, non-hydrostatic, laterally averaged numerical model to reproduce at higher detail the baroclinic tide generated over the Camarinal Sill and its propagation. Their results revealed a complex multimodal structure in the baroclinic tide, consisting at least of two types of large-amplitude internal waves. The first one, a packet of large amplitude internal solitary waves resulting from the disintegration of the first-mode baroclinic bore generated by tidal flow over Camarinal Sill and propagating towards the Mediterranean. The second system of waves (behind the first) propagates slower and has relatively larger length scale, presenting the characteristics of higher baroclinic mode internal waves trapped by the flood flux just over the sill. They concluded that in a general balance of mixing processes in the strait the higher mode baroclinic disturbances should be taken into account in addition to the first-mode internal waves.

3D models. The absolute forerunner of 3D modelling applied to the Strait of Gibraltar was Wang [31], who studied the combined mean and tidal circulation using a 3D primitive equation model. He started from a lock-exchange problem, adding later a spring semidiurnal tidal flow at the open boundaries. Such a way he was able of obtaining reasonable water exchange, tidal velocities and linear internal tide characteristics. Wang [32] accounted, using the same model, for the spring-neap tidal cycle and the diurnal inequality. His results were consistent with observations. However, the price to pay for precocity was coarse resolution (4—5 km horizontal and 50 m vertical resolution), which strongly limited the possibilities of obtaining a full 3D picture and a deeper insight into the hydraulic behaviour of the Strait. A decade later Androsov et al. [33] applied a 3D, boundary-fitted coordinate model with vertical σ-levels to simulate the M2 tide and the associated baroclinic dynamics and hydraulic control in good agreement with observations and hydraulic theory predictions.

Saninno et al. [34] used the three-dimensional Princeton Ocean Model with a horizontal resolution of 500 m and 25 σ-levels in the vertical to investigate the mean flow and the hydraulic regime in the Strait of Gibraltar. Their results offered an unprecedented detailed picture of the mean circulation patterns in the Strait. Sannino et al. [35] added semidiurnal tidal forcing to the previous model to study the effect of the semidiurnal tides on the rectified mean water exchange in the Strait of Gibraltar, and Sannino et al. [36] used it to describe the interfacial layer impact on strait exchange and hydraulics.

Vlasenko et al. [37] applied for the first time a fully non-linear, non-hydrostatic numerical model (MITgcm) to investigate the large-amplitude internal waves propagating in the Strait of Gibraltar. They found those waves to have a remarkable three-dimensional behaviour appearing a non-rank-ordered wave structure as a result of the energy transfer within the wave train. Recently, the influence of hydrostaticity has been assessed in several works [38, 39].

Meteorological forcing. The atmospheric component is lacking in the above review although it is known to have an effect in the sea level and flows in the Strait [40—42]. Meteorological forcing has been long disregarded in numerical modelling of the Strait probably due to the overwhelming interest of the ocean-alone processes.

To our knowledge Peliz et al. [43] first forced a Strait of Gibraltar model (ROMS) with surface winds from a 10 km resolution WRF output to investigate the cold filament generation by gap wind events in the Strait. Reyes-Reyes et al. [44] used a specially developed high-resolution nested MM5 model to provide meteorological

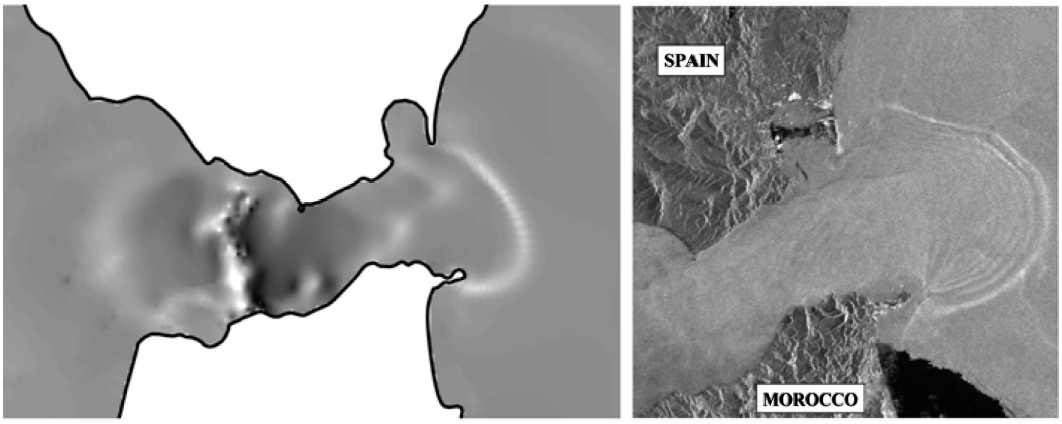

Fig. 3. Spatial structure of internal bore in the Strait of Gibraltar. The left panel shows the model predictions of the surface strain. The right panel is an ERS-1 SAR image (6-Feb-1992, 1104 UTC, orbit 2929, frames 2871/2889) of surface signatures of an eastward-travelling internal bore. Lighter shading shows the bore front.

forcing to a 2.5D ocean model of the Strait of Gibraltar [27] within an operational framework. That configuration was used as a basis for a storm early warning system in the Strait of Gibraltar and the Gulf of Cádiz [45].

This section, not being exhaustive, demonstrates a clear evolution: numerical models first focused on separated processes under idealised conditions, then the conditions were approaching the real ones, finally the advent of 3D high-resolution modelling made it possible simulating together different processes under quasi-real conditions. This fast advance open new challenges to confront. Two of them are (1) the establishment of sound local operational oceanography system (OOS) to respond to societal needs, and (2) to address the scientific issue of scale-interactions.

Facing the challenges

Operational Oceanography System in the Strait of Gibraltar. The modelling module of the Strait of Gibraltar OOS (http://oceand.uca.es/prediccion) consists of an atmospheric MM5 setup [46] implemented in Andalusia with maximum resolution reached in the Strait of Gibraltar. The MM5 configuration relies on a one-way active nested non-hydrostatic run with three refining grids (30, 10 and 3 km resolution), all of them with 35 vertical levels. The MM5 mother domain (30 km) is fed with output from the Atlantic regional WRF-ARW run by Meteogalicia at 36 km. In turn, this WRF domain takes boundary conditions from the NCEP GFS operational forecast, with 1º spatial resolution. The MM5 outputs have been successfully compared against meteorological data from Deep Sea Buoys located in the Gulf of Cadiz and Cape of Gata and from automatic weather stations [44].

The ocean is represented by the 2D [47] 2.5D [27] and 3D [48, 49] models having different spatial coverage and resolution but covering most of the Andalusian coast: the Gulf of Cadiz, the Strait of Gibraltar and the Alboran Sea. Wind fields supplied by the MM5 atmosphere with a prediction time of 72 hours drive the ocean models, following the scheme presented in fig. 4.

The Operational Oceanography System is run at the University of Cádiz (UCA) daily. Results form all models are available in real time within OceansMAP-UCA (http://ocean1.uca.es/oceansmap), a web-based met-ocean data and emergency response simulation system accessible for registered users. This user-friendly interface does not only display maps of the relevant met-ocean variables, but also allows the user to realize basic data analysis and simulations. The system has been applied in the real case of the oil spill released by the tanker Fedra in the Bay of Algeciras in 2008 and is currently used for the Search and Rescue Spanish Service [50].

Scale interactions. While it is accepted that the scarce 1 Sv of MO waters at the Strait of Gibraltar makes a contribution to the relatively high salinity of subsurface waters of the Nordic Seas and plays a role in the deep water formation, the extent of that influence is a matter of scientific dispute. Reid [51] concluded that MO waters are advected northward from the Gulf of Cádiz as a poleward eastern boundary undercurrent along the European continental slope penetrating to the Nordic seas. In turn, McCartney and Mauritzen [52] defended that the influence of MO on subpolar waters is indirect via mixing with North Atlantic Central Waters (NACW).

But the question turns even more complex if we consider the wide range of spatial and temporal scales involved in the fate of the MO at the Strait of Gibraltar and the Gulf of Cadiz, where the MO core has a width

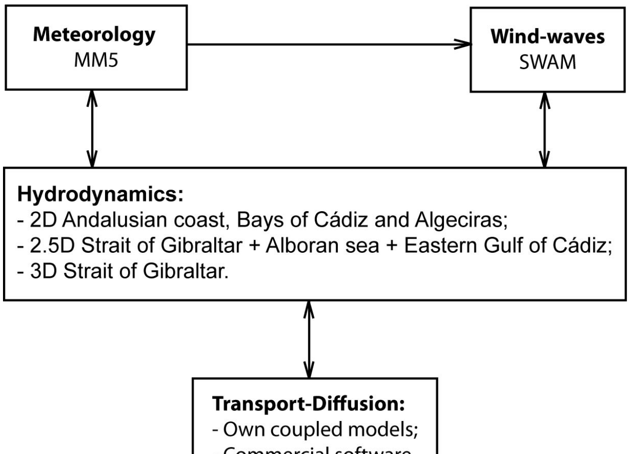

Fig. 4. Scheme of the Operational Oceanography system for the Strait of Gibraltar.

of just a few tens of km. It has been postulated that changes in the characteristics of Atlantic and/or Mediterranean water masses could affect the exchange flows through the Strait, and also the fluxes of salt, heat and other properties [53]. Tidal forcing substantially modifies the amount of exchanged salt and water due to the high correlation over the tidal period between the depth of the interface and the strength of the inflowing currents [54]. This oscillatory flow, in turn, originates internal waveforms, which are providers of energy for mixing at the Strait of Gibraltar, and are likely to determine at some extent the volume and characteristics of the MO. Therefore, there is a need of understanding if and to what extent the tidally-induced local-scale processes at the Strait and the Gulf of Cádiz have an impact on MO waters properties and spreading.

We show here the first steps of an integral approach to resolve both the local-scale processes at the Strait and the Gulf of Cádiz as well as the larger-scale processes, which may influence the North Atlantic and Mediterranean climate (fig. 5, see an insert), using an efficient global coupled AOGCM with regional high resolution in the vicinity of the Iberian Peninsula suitable for long-term runs. We employ a special setup of the Max Planck Institute Ocean Model (MPIOM), developed at the Max Planck Institute for Meteorology [55—57]. MPIOM is a free surface, primitive equations ocean model, which uses the Boussinesq and incompressibility approximations. The model is formulated on an orthogonal curvilinear Arakawa C-grid with z-level vertical discretization. An important advantage of the curvilinear grid is that high resolution in the region of interest can be reached, while maintaining a global domain. This avoids the problems associated with open boundaries in a regional ocean model.

The ocean grid (SPAN10, fig. 6, see an insert) places one pole in the Iberian Peninsula, the other in South America, allowing 4 km resolution at the Strait of Gibraltar (mean global resolution 1.0°). To check the influence of tides on the MO water spreading we run MPIOM in uncoupled mode, using as surface forcing the OMIP climatology [58]. The model has 80 vertical levels with increasing level thicknesses, allowing a fair vertical resolution and keeping the implicit vertical numerical diffusivity small. The inclusion of the tides shortens significantly the ocean model time step, being of 432 s. The SPAN10 setup includes the explicit exchange through a realistic Strait of Gibraltar and tidal forcing, as well as a good resolution of the most relevant topographic features at the Strait and the Gulf of Cádiz (fig. 6).

Here we present two baseline experiments. In experiment TIDE the full ephimeridic luni-solar tidal potential is activated, in experiment NOTIDE not. Surface forcing, parameterizations, numerical coefficients and time step are identical for both experiments. Both experiments were first run for 12 years, in order to erase the memory of the initial conditions and let the modelled processes shape the oceanographic fields in the eastern North Atlantic. Figure 7 (see an insert) shows the salinity field at approximately the MO water depth for both experiments and the GDEM climatology. Starting from the same initial conditions both experiments reproduce the MO water core. However, while the TIDE run resembles the GDEM climatology, the NOTIDE run produces a too salty tongue and an unrealistic southward salt flux (fig. 7, *c*), which does not resemble the MO spreading pathways established from observations [59]. The salinity distribution in the TIDE run shows a pattern more dominated by advective processes to the north and more diffusive spreading to the south (see the separation of the isohalines). This is in agreement with previously described MO water spreading mechanisms.

This striking difference in the spreading pattern of MO water over the North Atlantic is fully attributable to the inclusion of the tidal generating potential in the TIDE control experiment, highlighting how local-scale processes in an overflow region may have a drastic impact on the basin scale.

Conclusions. In this work we have tried to present a review on the ocean modelling developments achieved in the oceanographic research of the Strait of Gibraltar. The Strait is itself a natural geophysical laboratory where processes of a wide range of spatial and temporal scales interact. The contribution of ocean numerical modelling to a better comprehension of the phenomena occurring in the Strait of Gibraltar waters has been enormous, narrowing the gap left by observations and contributing to test and develop new theoretical approaches. While successfully modelling and better understanding many of the ocean processes relevant in the Strait of Gibraltar, the progress in modelling and the increasing computing and observational capabilities set new challenges up. Such a new challenge is the issue of scales interaction. Without any doubt the Strait of Gibraltar plays a role in the formation of the climate of the North Atlantic Ocean and the Mediterranean Sea, and that impact should be related to the properties and amount of the water exchanged. In turn, ocean and atmospheric large-scale processes may have an effect in the exchanged waters. Therefore we propose a global modelling approach with locally high resolution at the Strait of Gibraltar to account for the impact of local-scale processes on the North Atlantic and Mediterranean Sea without loosing the larger scale ocean and atmosphere feedbacks. As a first step we demonstrate in a series of climatology-forced experiments that tidally-induced local processes have a remarkable effect on the Mediterranean Outflow Water spreading in the North Atlantic. While the concrete mechanism (-s) involved are still not revealed, this result opens a direction for further research.

But the scientific progress is as well a necessary tool to satisfy society demands. The vertiginous advance in IT technologies, in remote observation techniques and in ocean numerical modelling has made it possible to provide timely, continuous and accurate information on the meteorological and oceanographic conditions in the Strait of Gibraltar. In the Strait, due to its geostrategic location, intense marine traffic and environmental value such information is of vital importance. We briefly present such an Operational Oceanography system designed to be used in marine safety, search and rescue operations and spillage of hazardous and noxious substances.

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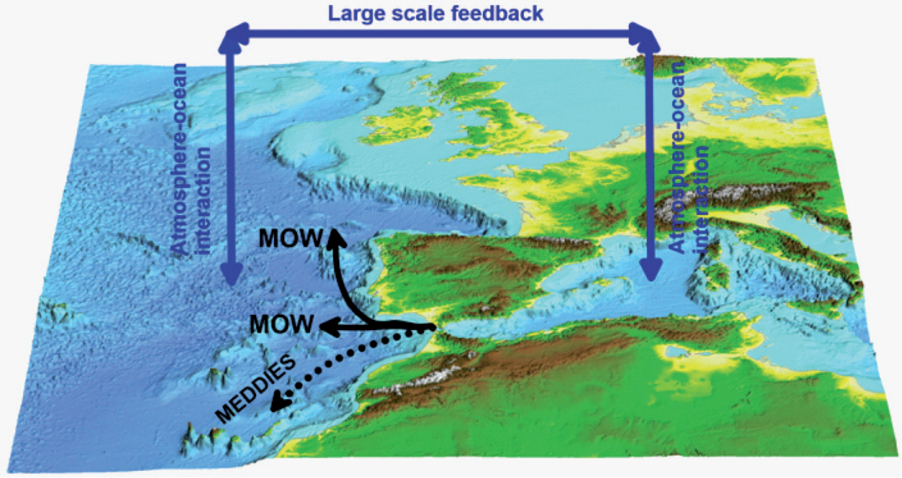

Fig. 5. Scheme of the Mediterranean Outflow water spreading paths and the large scale feedbacks.

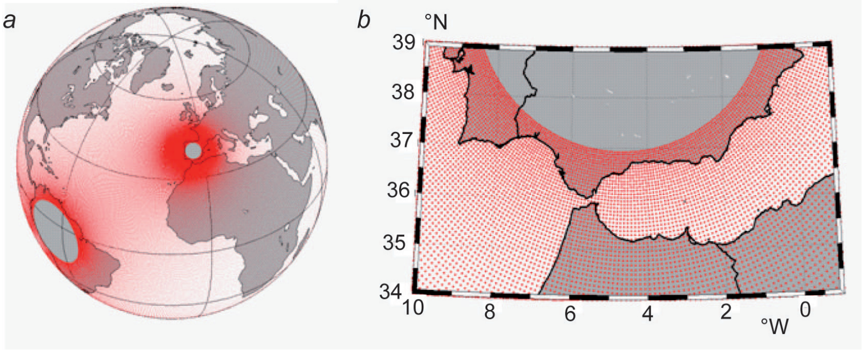

Fig. 6. *a* — MPIOM SPAN10 global grid; *b* — detail around the Iberian Peninsula.

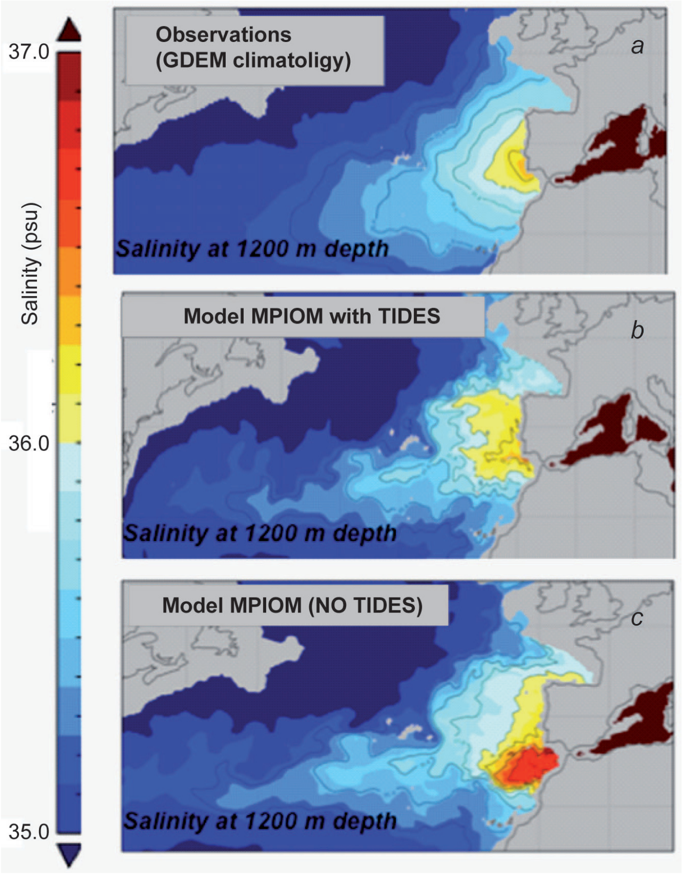

Fig. 7. Salinity fields at 1200 m depth for GDEM climatology (*a*), TIDE experiment (*b*), NOTIDE experiment (*c*).