Modelling circulation in a Southern Italy coastal basin

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Abstract

The purpose of the present work is the study of particular hydrodynamic aspects of Mar Piccolo, a basin located in the Northern side of the Gulf of Taranto in the Ionio Sea (Italy), by means of mathematical modelling. A first analysis has been driven, thus realizing a test case with simple hypothesis, referring to data from the literature, in order to validate two 3D hydrodynamic models, i.e. the Princeton Ocean Model and the MIKE 3. Once a quite good agreement was observed between the outputs of the tested models, a further comparison was considered. The results of the two models have been compared with some circulation structures proposed in the literature, in analogous conditions. Successively, both models have been forced by a further input, in order to observe the response of the circulation to input modifications. The direct comparison between simulation results and field measurements collected during surveys is the future development of the ongoing research.  
Keywords: tidal circulation, wind-induced circulation, circulation structures.

1 Introduction

The Mar Piccolo is a coastal basin of about 21.7 km², the basin being about 200 thousand m³ and the average depth about 7.0 m (Figure 1). It is divided into two interconnected embayments, through the channel of the Punta Penna Bridge, whose width of 500 m in reality is reduced by surrounding shoals and mussel-farms. The western (first) embayment takes up about 9 km² and has a maximum depth of about 13 m. It is connected with the open sea through two channels. The first one, the Canale Navigabile, is an artificial channel, 58 m wide and 12 m deep and the second one, the Canale Porta Napoli, is natural and it is 150 m
wide and 2.5 m deep. The eastern (second) embayment extends over a surface area of about 12.7 km² and its maximum depth is 10 m.

Because of its peculiar hydrographical features, influenced by freshwaters coming from small tributary rivers and freshwaters springs called *citri*, the basin can be compared to a brackish lake [3]. Moreover its aquatic ecosystem is subjected to human activities and urban discharge which affect it, giving origin to a compromised environmental equilibrium.

As a result of different European monitoring and research programmes, a certain amount of biological, physical and chemical data, describing the qualitative status of the Mar Piccolo, is available, whereas information about its hydrodynamic circulation patterns are not widely present in bibliography. For this reason, the present work means to examine its peculiar hydrodynamics, by numerical modelling, though generated by some selected forcings.

Two finite difference hydrodynamic models have been used: the MIKE 3, an engineering software, and the Princeton Ocean Model, a sigma coordinate, free surface, ocean model. The tests are executed in two different barotropic scenarios and they highlight a good agreement between the results of the adopted models. Besides, the outputs of each model show a quite good agreement with some reproductions proposed in literature, as a result of analogous input conditions.

Figure 1: The Mar Piccolo of Taranto (from chart no. 1643 published by Admiralty Charts and Publications in 1985 under the superintendence of Rear Admiral R.O. Morris, Hydrographer of the Navy, United Kingdom, and the Hydrographic Office of Italy).
2 Description of POM and MIKE 3 models

The first numerical model implemented in this research is the POM (Princeton Ocean Model), a 3-D, free surface, finite difference ocean circulation model developed by Blumberg and Mellor [1] and widely described in De Serio and Petrillo [4]. It is based on the classical hydrodynamic equations of mass, momentum, temperature, salinity and kinetic energy conservation, and on the UNESCO state equation modified by Mellor [7]. It also uses the Bussinesq and hydrostatic approximations regarding density and pressure respectively.

The finite difference discretization of the equations is done on the Arakawa-C grid and the horizontal time differencing is explicit, whereas the vertical differencing is implicit. The vertical structure of the model is represented by a bottom-following, sigma coordinate system which can simulate bottom boundary layers as well as the surface Ekman layers [5]. In this case the vertical discretization is made by twelve sigma levels. The horizontal grid is defined on rectangular orthogonal coordinates and for the examined tests it is set with a resolution of 80 m, to avoid computational instability.

The POM model incorporates the Mellor and Yamada [8] turbulent closure scheme to provide a time and space-dependent parameterization of vertical turbulent mixing. The horizontal diffusion terms are calculated using the Smagorinsky formulation [1] in which horizontal viscosity coefficients depend on the grid size and horizontal velocity gradients. The numerical scheme makes use of the split time-step technique, where the external (or barotropic) mode solves the vertically integrated momentum equations, while the internal (or baroclinic) mode solves the three-dimensional momentum equations. Leapfrog time stepping is employed for both the barotropic and the baroclinic modes.

The second model used in the research is the MIKE 3 (by the Danish Hydraulic Institute), a professional engineering software package for three-dimensional free-surface flows, designed in a modular structure and applicable to simulations of hydraulics, water quality and sediment transport in water bodies. This study required the application of the hydrodynamic module, which solves the time-dependent conservation equations of mass and momentum in three dimensions (the so-called Reynolds-Averaged Navier-Stokes equations). The closure problem has been solved in the turbulence module through the Boussinesq eddy viscosity concept relating the Reynolds stresses to the mean velocity field. The Smagorinsky subgrid scale model has been applied in the tests. The MIKE 3 horizontal calculation grid allowed a finer resolution than POM model, with cells of 20 m side, thus providing a detailed analysis of circulation patterns. The vertical domain is divided into twelve horizontal layers, distant among each other 1 m.

3 Numerical tests: results and discussion

The currents in the Mar Piccolo are essentially due to the action of the tidal waves and to climatic factors, especially wind. For this reason, in the first test,
both models have been forced by a sinusoidal variation of elevation, representing tide, at the two open boundaries of the domain, Canale Porta Napoli and Canale Navigabile. This simplified tidal wave is characterized by 0.18 m amplitude and 12 hours period, representative values for Mar Piccolo basin, according to I.I.M. (Istituto Idrografico della Marina) tide tables. Moreover, the same values were adopted by Casulli and Notarnicola [2], who simulated the hydrodynamic structure of the basin, by means of a semi-implicit finite difference 2D model, adopting a rectangular grid with a resolution of 100 m. In the following, it will be called CN model. Another not negligible input force is taken into account in the experiments, i.e. the existence of a man made channel on the north-western coast of the western inlet, which supplies seawater to a cooling plant in a nearby steel factory, with a flow rate of 34 m$^3$s$^{-1}$. No other fluxes (inflow/outflow), neither thermohaline, have been considered. As the dynamical steady state is reached after approximately five tidal cycles in barotropic conditions, a simulation period of three days has been used.

The results of POM and MIKE 3 models put in evidence a quite good agreement in qualitative terms, that is, both models in the same temporal interval give origin to similar dynamical structures and trends. It has to be underlined that in both cases a good vertical homogeneity has been observed. So, the further comparison of the superficial fields by POM (Figure 2) and MIKE 3 (Figure 3) with the 2D circulation of the CN model (Figure 4) seems justified and it confirms the principal jets and eddies induced by the same input forcings and conditions.

Figure 2, Figure 3 and Figure 4 refer to the latest tide cycle (the 6th cycle) and they show the temporal variation of the tidal circulation, at time intervals of three hours. In particular, on the top left page the circulation three hours after low tide (ALT) has been plotted, while the circulation at high tide (HT) has been plotted on the bottom left page. On the top right page the circulation three hours after high tide (AHT) has been plotted, finally the circulation at low tide (LT) has been plotted on the bottom right page.

A comparison among model reproductions highlights that simulations with MIKE 3, because of its finer resolution, are greatly influenced by batimetry and consequently they induce some local vortical trends, quite invariant during the wave cycle, which are reproduced neither by POM and by CN model, both characterized by a coarser resolution. Therefore the homogeneous circulation in POM and CN simulations, particularly evident in the eastern inlet, can be explained taking into account that they are less affected by bed topography and that the most effects of tide and outflow is visible in the first inlet.

The analysis of Figure 2.a, Figure 3.a and Figure 4.a shows that all models, in ALT condition, originate two intense jets entering the western basin from the openings and feeding an anticyclonic trend directed to the eastern inlet. Also the effect of the scooping machine seems to contribute partially to this pattern in the first inlet. Confirming what just argued, a quite uniform superficial circulation is reached in the second embayment with CN and POM model.
Figure 2: Tidal surface circulation in Mar Piccolo by Casulli and Notarnicola (1988): a. three hours After Low Tide; b. at High Tide; c. three hours After High Tide; d. at Low Tide.
Figure 3: Tidal surface circulation in Mar Piccolo modelled by POM at: a. three hours After Low Tide; b. High Tide; c. three hours After High Tide; d. Low Tide.
In HT condition the southern inflowing jet is still evident in CN (Figure 2.b) and MIKE 3 (Figure 4.b) outputs, while it is less relevant in POM output (Figure 3.b). A further agreement between CN and POM model is observed; in fact Figure 2.b and Figure 3.b show the western anticyclonic trend of the ALT condition, closing now into a vortex. Local effects, inducing eddies along the communicating channel, are evident both in CN and MIKE 3 circulations.

The AHT condition is characterized by two outflows through the open boundaries. Figure 2.c and Figure 3.c show that the southern outflow leaves the anticyclonic vortex, while the western outflow derives from a near cyclonic trend. MIKE 3 higher velocities contribute to a less organized structure (Figure 4.c), even if the presence of opposite circulations can be observed. A westward current in the communicating channel is present in all the three cases.

The cyclonic and anticyclonic vortexes in the first inlet are still present in the LT condition, both for POM (Figure 3.d) and MIKE 3 (Figure 4.d), while the CN model differs from the previous ones, simulating just the anticyclone (Figure 2.d). The topographic effect originates a small cyclone near the communicating channel, visible both in Figure 2.d and in Figure 4.d.

Comparing the time-varying velocity fields reproduced by CN, POM and MIKE 3, it can be observed that velocities have the same order of magnitude, even if MIKE 3 model lightly overestimates them.

Once validated the two models in qualitative terms, in the second test the number of input forcings has been increased, adding a homogeneous northerly wind field with an intensity of 5 ms$^{-1}$. The amplitude of the tidal wave forcing the open boundaries has been reduced to 0.09 m. These particular values have been derived from some data recorded in quite not stratified vertical conditions during a measurement spring survey (April 2002) carried out by the research group of the Department of Water Engineering and Chemistry of the Technical University of Bari [6]. In this way, in a future development, it will be possible to compare directly models results and field measurements.

For the sake of brevity, only circulations reproduced by POM and MIKE 3 at the intermediate depth of 5.5 m from free surface, and relative to High Tide condition, are shown in the following. It can be pointed out that wind action induces remarkable modifications to those trends generated by tide and scooping machine, also in deeper layers. It is also evident that the homogeneous condition along the vertical direction can no more be supposed, thus justifying the necessity of a 3D model to describe the currents system.

Regarding each model, the circulation shows a quite uniform trend in the eastern inlet, directed towards north, north-east, thus clockwise rotated respect to the wind direction, according to the Ekman theory for stationary wind induced currents.

About the first inlet, from POM results (Figure 5) it can be observed that the two inflowing jets from open boundaries convey to form a northward trend which also feeds the outflow to cooling plants. Moreover two opposite local eddies are evident near the openings and an anticyclone establishes upstream the communicating channel.
Figure 4: Tidal surface circulation in Mar Piccolo modelled by MIKE3 at: a. three hours After Low Tide; b. High Tide; c. three hours After High Tide; d. Low Tide.
Referring to MIKE 3 results (Figure 6) only the inflowing flow from the southern opening is evident and the structure in the first inlet is characterized by more sinuous trends in the central region, which seem to disturb the velocity field, giving origin to less organized structures.
4 Conclusions

In this paper some test cases have been illustrated in order to explain typical features of Mar Piccolo hydrodynamics, when forced by tidal and wind forcings. Also the effect of the outflow to some cooling plants has been considered. Two numerical model have been used, the POM and the MIKE 3 models.

The first test, carried out in absence of the wind field, shows a quite homogenous circulation along the vertical direction, so a comparison of the 3D models results with the 2D model by Casulli and Notarnicola [2] has been carried out. It highlights a substantial agreement among the three models outputs.

By superimposing the wind forcing to the steady tidal circulation, a modification in the vertical structure has been observed. Consequently the comparison has been limited to POM and MIKE 3 results at an intermediate depth. It shows a similar trend for both models referring to the second inlet. About the first inlet, POM output highlights the presence of fluxes and eddies in the typical tidal pattern, while in MIKE 3 output the effect of wind seems to induce more sinuous and less organized structures.

References


