To my family

Contents

1 Introduction

The increasing knowledge in ocean dynamics, the development of new numerical models and the improving performance of the computational platforms provide new instruments for physical oceanography. Numerical simulations are useful tools for studying many relevant oceanographic phenomena at different spatial and time scales, from large-scale open sea dynamics down to coastal areas management and local environmental defense problems.

This study aims at analyzing the hydrodynamic features of small-scale coastal areas using a state of the art numerical model. In particular, the analysis is focused on the Gulf of Trieste (Northern Adriatic Sea, Figure 1), a shallow embayment strongly influenced by the local meteorological conditions and by the freshwater input of the rivers flowing into it [for a more thorough review of the main characteristics of coastal areas and the Gulf of Trieste see Appendix A (INTRODUCTION) and Appendix C (sections 1, 2, 3)].

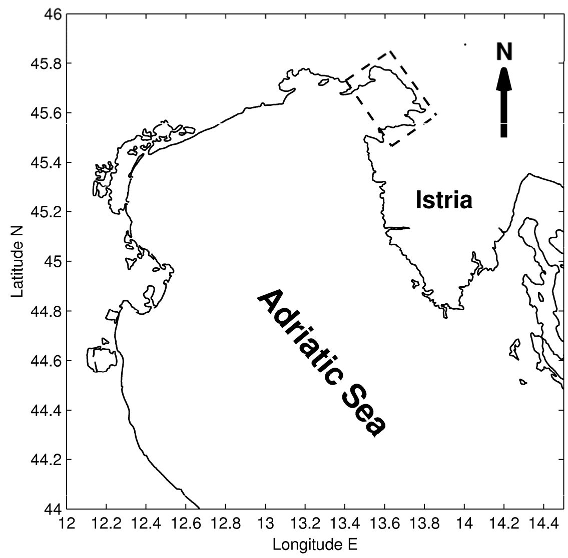

Figure 1 – The Northern Adriatic Sea. The Gulf of Trieste is indicated by the dashed rectangle.

The complex hydrologic and hydrodynamic features that characterize the Gulf of Trieste and the relevant anthropic pressure applied by the cities located along its coast (mainly Trieste on the Italian side and Koper on the Slovenian side, Figure 2) make this basin a very interesting natural laboratory for marine investigations.

Nowadays it is important to have a monitoring system able to help in facing the problems related to and caused by the human activity. Such a kind of monitoring system should not only investigate and simulate the environmental conditions (hindcast), but also give real-time predictions of the dynamics of the area (forecast).

This study is focused on the hydrologic/hydrodynamic features of the Gulf of Trieste and has been carried out in the framework of this type of operational system. Its final task is to produce short term oceanographic forecasts of the main physical properties (currents, density, temperature and salinity) of the basin.

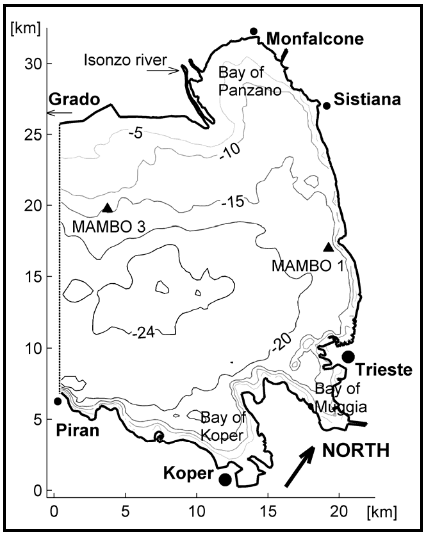

Figure 2 – The Gulf of Trieste.

The numerical model implemented is based on the MITgcm code, developed at the Massachusetts Institute of Technology (Boston, USA). It is customized to fit the Gulf of Trieste features, with particular concern about the forcing acting on it. Experimental data sets are used to simulate realistic environmental conditions. The model domain, the initial conditions and the boundary conditions derive from these observed data. The model was first tested solving simple theoretical problems and then it was tuned simulating real case studies. The model output showed good agreement with both the analytical solution of theoretical problems and the results of field campaigns. Therefore, it was chosen to be the core of the hydrodynamic operational system, which is still being developed in the framework of the ADRIANE project (Fondo Trieste contract). The deliverables of this project will be short term (48 hours) forecasts of the main hydrodynamic features (i.e.: currents, density, temperature and salinity) of the basin.

The thesis is structured as follows: chapter 2 is a short overview of the numerical model and its implementation for the Gulf of Trieste case studies. Chapter 3 presents the main issue examined in this numerical study: the influence of wind forcing and riverine freshwater input on the dynamics of the basin. The dissertation closes with the discussion of the most significant results and with the concluding remarks.

Appendix A, B and C present three papers published during the PhD course. The first one is a study on the wind driven circulation both in idealized (Ekman's theory) and realistic (measured initial and boundary conditions) case studies. The second paper briefly shows the effects of wind forcing, river freshwater discharge and their reciprocal interaction on the dynamics of the Gulf of Trieste. The third paper analyzes two particular case studies in which wind forcing and river freshwater input play a dominant role on the dynamics of the basin. The model output is checked against the results of a nondimensional scale analysis and against buoy and satellite observed data. These comparisons show a good correlation, validating the numerical simulations for the two case studies. An evaluation of the time required for the water renewal in the basin (residence time) is also performed.

2 Materials and methods

This study was carried out customizing an open-source numerical code and using experimental data to create the computational domain and to initialize and force the model. The observed data were also compared with the model output to obtain a validation of the numerical results. [An exhaustive description of the experimental data set is given in Appendix C (subsection 4.2).]

The following section is an overview of the main features of the MITgcm numerical code.

Section 2.2 describes the customization of the model. The original code was modified and configured for running high resolution simulations of coastal areas. In particular, the implementation of the domain, the vertical turbulent parametrization, the transport of generic passive tracers, the open boundary problem, and the simulation of riverine freshwater input are presented. This customized version of the model was applied to the Gulf of Trieste case studies.

2.1 The MITgcm model

The MITgcm is a three dimensional GFD (Geophysical Fluid Dynamics) numerical model. Its main features are listed below:

- ✓ the code is open source (freely available at http://mitgcm.org/);
- ✓ it can be used to study both atmospheric and oceanic phenomena. One hydrodynamical kernel is used to drive forward both atmospheric and oceanic models;
- ✓ it has a non-hydrostatic capability and so can be used to study also small-scale processes, where the hydrostatic assumption does not hold (Figure 3);
- ✓ finite volume techniques are employed yielding an intuitive discretization and support for the treatment of irregular geometries;
- ✓ it is developed to perform efficiently on a wide variety of computational platforms.

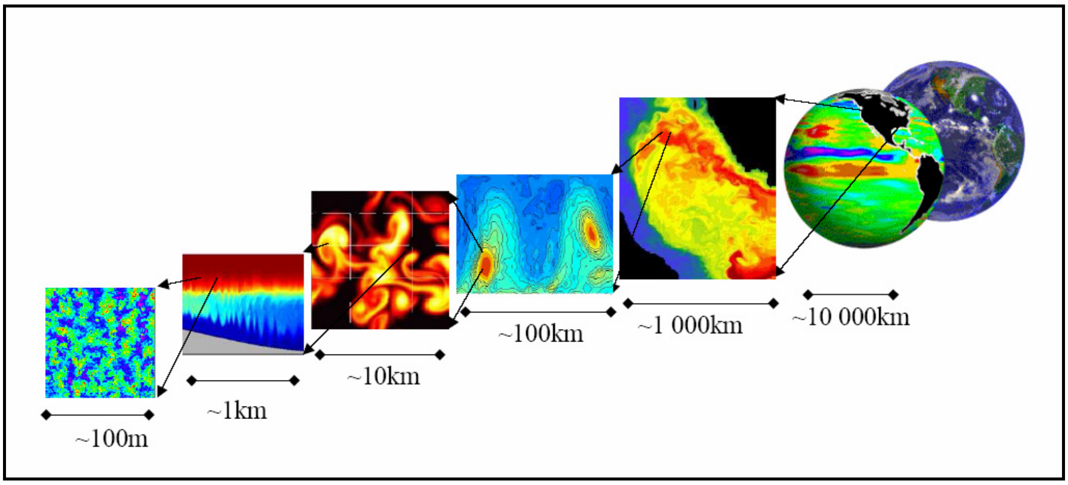

Figure 3 - Range of phenomena that can be studied using the MITgcm model: from convection (left) to global circulation patterns (right). Image taken from the MITgcm online user manual.

2.1.1 Software architecture

The software architecture consists of a core set of numerical and support code with optional "pluggable" packages (Figure 4). This allows a simple use of the many options implemented in the model and a high portability on several platforms. The packages (containing for example mixed-layer schemes, biogeochemical schemes, air-sea interaction physics) are used both to overlay alternate dynamics and to introduce specialized physical content onto the core numerical code.

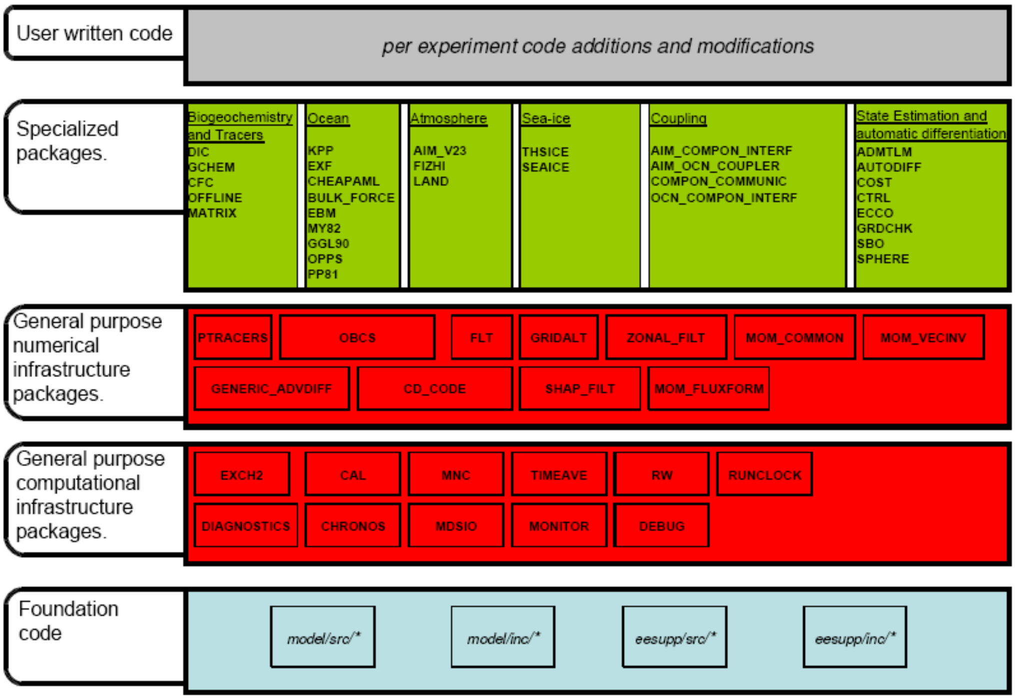

Figure 4 - Hierarchy of code layers that are assembled to make up a MITgcm simulation. Image taken from the MITgcm online user manual.

The core numerics and pluggable packages operate within a support framework called WRAPPER (Wrappable Application Parallel Programming Environment Resource), which is a software interface between the model and the various computational platforms (Figure 5).

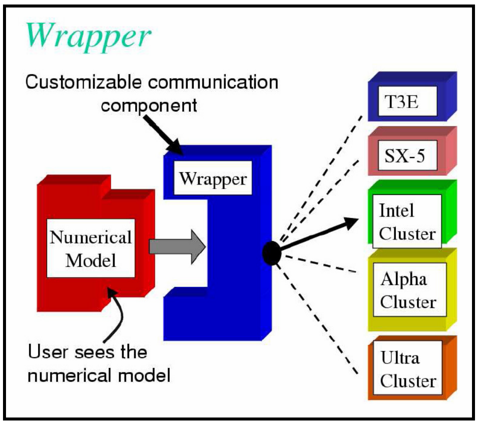

Figure 5 - Numerical code is written to fit within a software support infrastructure called WRAPPER. Image taken from the MITgcm online user manual.

Some bugs were also fixed and new features were successfully customized and tested while setting up the final model configuration for the Gulf of Trieste.

2.2 Model implementation

2.2.1 Model domain

The bathymetry of the Gulf of Trieste is obtained by kriging interpolation from maritime charts and is rotated $30°$ clockwise to better fit the grid space. The domain is a Cartesian Arakawa-C grid (128×88 cells), with horizontal resolution of 250 m, and vertical resolution of 1 m (25 levels) for the experiments described in Appendix A, and of 0.5 m for the 6 upper levels and 1.0 m for the other 22 levels for the experiments described in Appendix B and C. The model adopts a typical mid-latitude constant (f-plane approximation) Coriolis parameter ($1\cdot10^{-4}\ 1/s$).

2.2.2 Vertical mixing: the nonlocal K-Profile Parametrization (KPP)

The MITgcm model can parametrize vertical turbulence either via constant coefficients of vertical eddy viscosity and diffusivity or using the KPP (K-Profile Parametrization) technique.

The KPP scheme is common in many ocean models. It unifies the treatment of a variety of unresolved processes involved in vertical mixing. It deals with distinct mixing processes in the ocean's surface boundary layer and in the ocean's interior:

- ✓ mixing in the interior is governed by shear instability, internal wave activity, and double-diffusion. Shear instability is modeled as function of the local gradient Richardson number, internal wave activity is assumed constant, and double diffusion is not implemented in the model;
- ✓ a boundary layer depth is determined at each grid point, based on a critical value of turbulent processes parameterized by a bulk Richardson number;
- ✓ mixing is strongly enhanced in the boundary layer under the stabilizing or destabilizing influence of surface forcing (buoyancy and momentum) enabling boundary layer properties to penetrate well into the thermocline. Mixing is represented through a polynomial profile whose coeffcients are subject to several constraints;
- ✓ where the water column is unstable, mixing is enhanced by "a non-local" term which is independent of the vertical property gradient.

Appendix A (RESULTS AND DISCUSSION) shows the implementation of a numerical experiment aimed at reproducing the theoretical surface boundary layer studied by Ekman. The conditions assumed by Ekman are constant and uniform wind forcing, and constant vertical eddy coefficients on an idealized, laterally unbounded domain. When the model is run under the same conditions as the theoretical case, the results match exactly the analytic solution and they do not depend on the initial thermohaline condition (uniform or stratified water column). Conversely, the velocity field obtained using the KPP parametrization is different from the theoretical case and the vertical profile of velocity depends on the thermohaline stratification.

This simple case study points out the importance of a realistic parametrization of the vertical turbulent processes.

2.2.3 Tracer transport

The choice of a correct numerical scheme for tracer advection is a further critical point. This section shows the comparison between 2nd and 3rd order advection schemes. Figure 6 shows two dimensional advection of a generic gaussian feature (example taken from the MITgcm online user manual). The following two pictures show the advection of an initial surface spot of a generic passive tracer released near Trieste (1 km off the coast) which has been moved and stretched by the currents induced by the Bora (ENE) wind. In Figure 7 and in Figure 8, a centered 2nd order scheme (upper-left plot of figure 6) and a 3rd order DST (Direct Space Time) scheme with flux limiter (bottom center plot of figure 6) are used, respectively. A strong analogy between the ideal case and the Gulf of Trieste simulations can be noted for both the 2nd and 3rd order schemes: in particular, the 2nd order scheme (the default of the model) give raise to an anomalous and noisy advection of the tracer. To avoid this noise all the experiments were run using the 3rd order DST scheme.

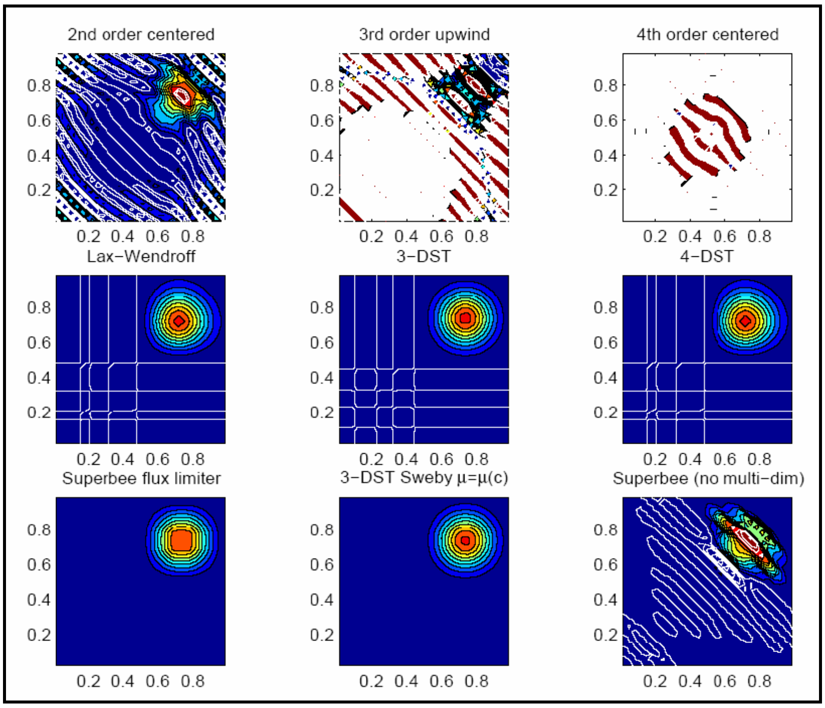

Figure 6 – Tracers: 2D advection of a generic gaussian feature. Comparison between 2nd (left column), 3rd (central column) and 4th (right column) order advection schemes. Image taken from the MITgcm online user manual.

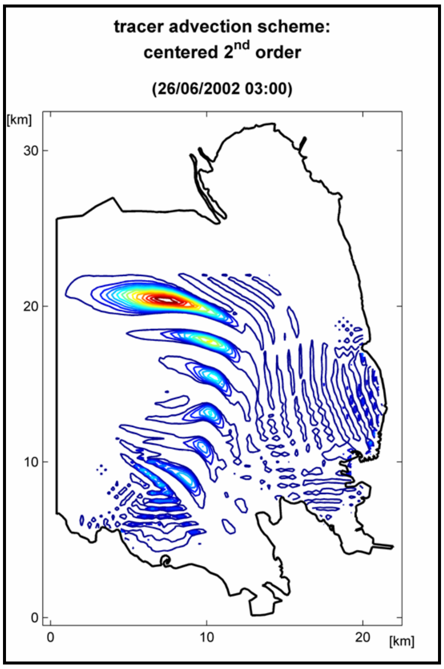

Figure 7 - Advection-diffusion of an initially concentrated generic passive tracer. The numerical noise is due to the centered 2nd order advection sheme.

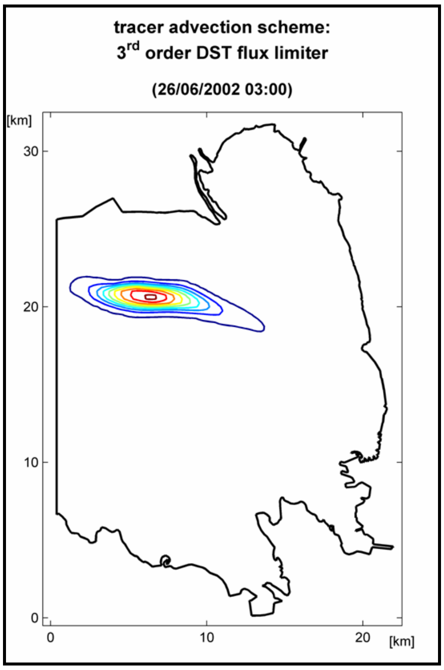

Figure 8 - Advection-diffusion of an initially concentrated generic passive tracer. The initial spot is moved and stretched by the wind without numerical noise.

2.2.4 The open boundary conditions problem

The conditioning of the open boundary is an important aspect when simulating open or semi-enclosed basins [*Palma and Matano*, 1998, 2000].

An exhaustive discussion on the open boundary conditions (OBCs) is carried out in Appendix C (subsection 4.2.4.). The three following paragraphs are a first overview on the accuracy and the limits of three kinds of OBCs applied to the Gulf of Trieste case study. Particular attention is paid to their relation with the other boundary conditions (in particular the wind stress). The three cases analyzed below were set up using the same initial conditions and forcing. The only difference is in the implementation of the momentum and thermohaline conditions at the OB of the domain (i.e.: the vertical plane between Grado (Italy) and Piran (Slovenia)). Figures 9, 10, and 11 show instantaneous snapshots of the horizontal velocity fields at various depths during a strong summer Bora wind event, starting from stratified initial conditions.

Closed boundary

The simplest, but roughest approximation is considering a closed boundary (no fluxes of both momentum and tracers). Plot a) shows how velocity vectors are aligned with the direction of the Bora wind (ENE) near the eastern coast, veer to the right due to the Coriolis effect in the center of the basin and, finally, hit the solid western boundary, giving rise to unrealistic meridional components of velocity. The same western boundary constraint is also evident in plot b) and c).

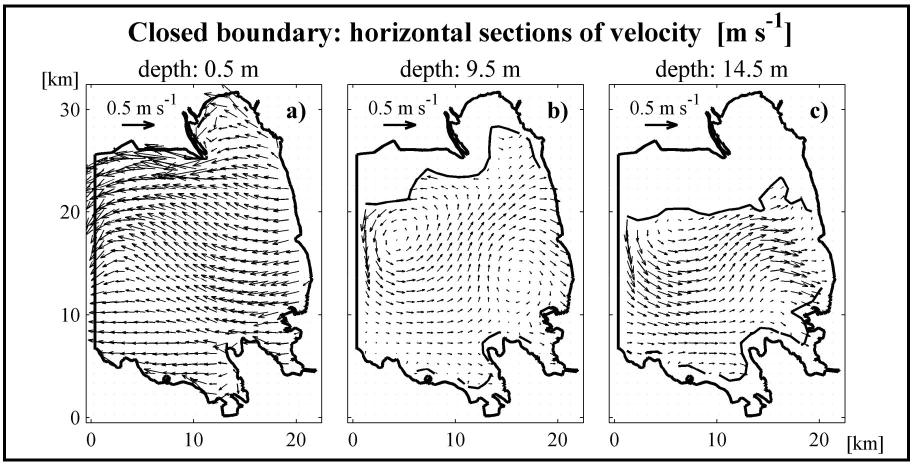

Figure 9 – Horizontal sections of velocity using a closed western boundary.

Orlanski radiation condition

The circulation pattern remarkably changes if the Orlanski radiation condition is prescribed at the boundary. In this case, the surface layer is allowed to leave the domain under the effect of wind forcing, while a bottom countercurrent balances the surface outflow (Figure 10). Such a kind of OBC can be used only for short integrations and when the remote forcing of the Northern Adriatic Sea is negligible if compared with the other forcing. Another problem is the mass conservation in the basin: the radiation condition, in fact, does not impose any constraint on the balance of fluxes across the boundary. In this particular case, the sea level rises of several centimeters (bottom countercurrent is overstated by the model).

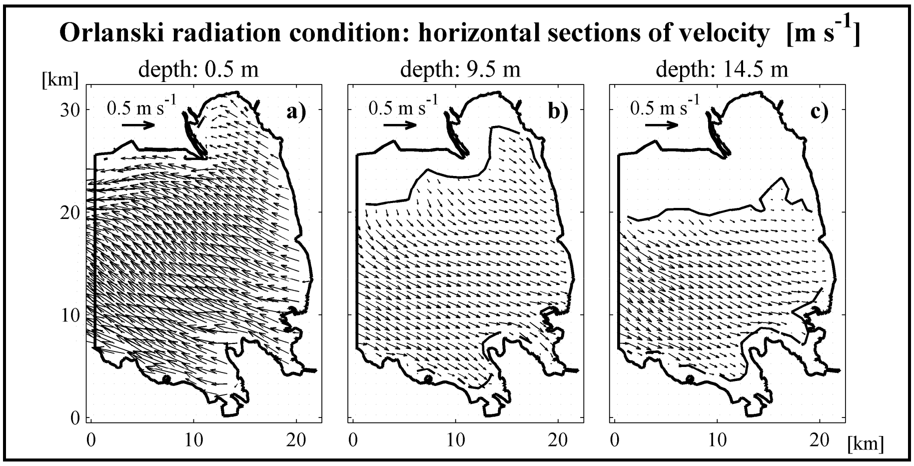

Figure 10 - Horizontal sections of velocity using radiating boundary conditions.

Nudging layer

In this last case, an active OBC is imposed. A nudging layer is implemented to allow internal perturbations to propagate outside the domain: the nudging layer thickness (2500 m, i.e.: 10 grid cells) and the relaxation time control the relations between the inner and the outer values of velocity and scalars. Figure 11 shows the velocity fields obtained imposing a boundary inflow along the Istrian coast and outflow along the Italian coast. The imposed boundary velocity is vertically uniform, constant in time and varies linearly from Piran (inflow: $10\,\mathrm{cm/s}$) to Grado (outflow: $10\,\mathrm{cm/s}$). In the absence of wind forcing, OB values are dominant (not shown). When strong Bora blows, the inner dynamics prevail over the external weak forcing. It must be pointed out that, in this case, there is a control on the mass balance across the boundary. A comparison between plot b) and c) of figure 10 and figure 11 shows that bottom velocities in the active OBC case are weaker than in the Orlanski case. Then, the overstatement of bottom velocities has been removed: this eliminates the anomalous increase of the sea level observed in the previous case.

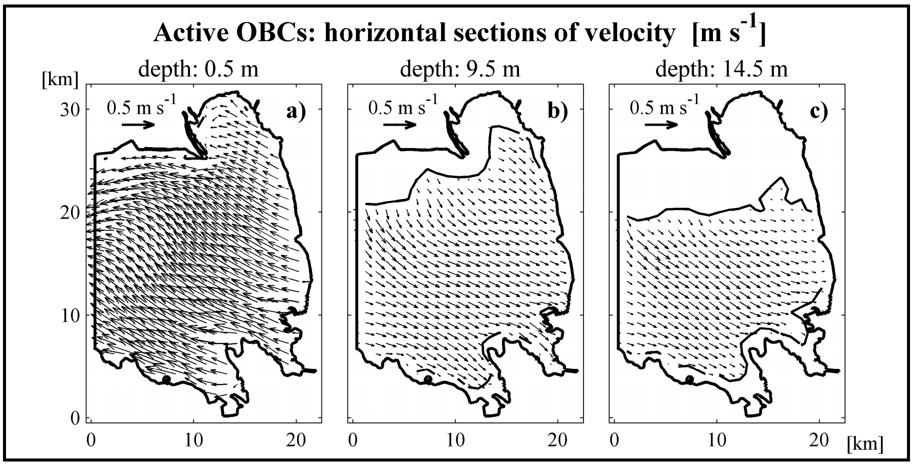

Figure 11 - Horizontal sections of velocity applying a nudging layer to the open boundary.

The choice of correct OBCs strongly depends on the spatial and time scales of the model, and on the availability of forcing data at the boundaries. The best solution must be found each time, for each particular case study, as shown in Appendix A (Boundary Conditions) and C (subsection 4.2.4).

2.2.5 Implementation of riverine freshwater input

The model is configured to simulate the Isonzo river (Figure 12), which supplies the largest freshwater contribution to the Gulf of Trieste (yearly average discharge rate of about $150\,\mathrm{m}^3/\mathrm{s}$). The modelization of the river input is made considering the riverbed as a part of the bathymetry of the model. A 3 m deep channel has been added to the bathymetry. Also the morphology of the mouth has been reproduced interpolating the topographic data taken from a high resolution map. River discharge rates and thermohaline properties are imposed as boundary conditions, using the time series of experimental observations. This kind of modelization allows to simulate the contributions of both momentum (discharge rate) and buoyancy (freshwater thermohaline properties). This approach is much more realistic than the classical method, where only the salinity variation is considered. It must be noted that, despite the presence of high velocities along the channel and abrupt changes of riverbed direction, the model proves to be numerically stable also with relevant flow rates (discharge rates higher than $500\,\mathrm{m}^3/\mathrm{s}$).

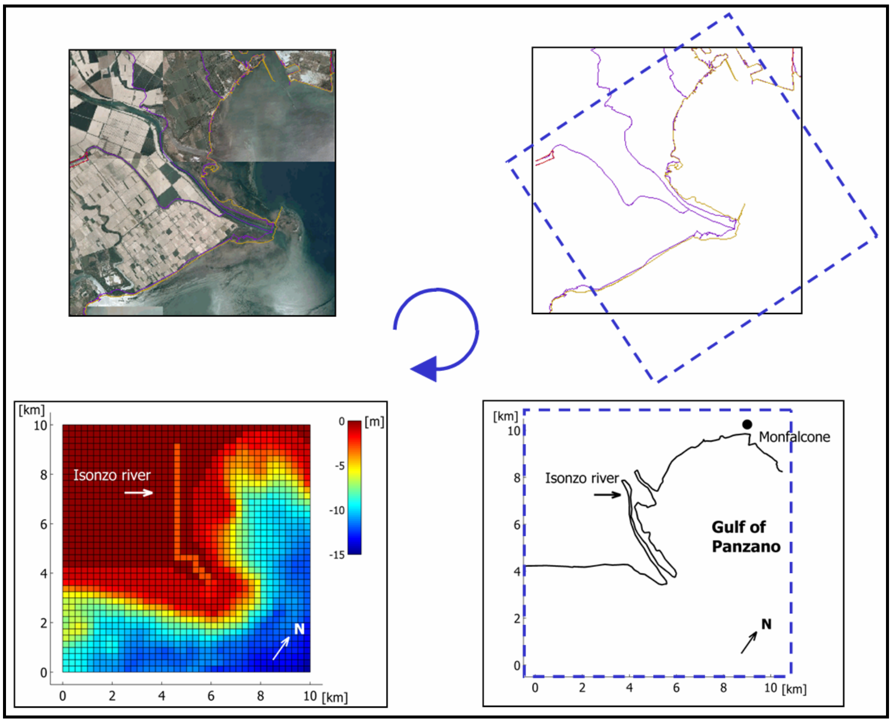

Figure 12 – Modification of the bathymetry to include the Isonzo riverbed.

3 Influence of wind forcing and riverine freshwater input

This chapter introduces the study of the effect of wind forcing and river discharge on the dynamics of the Gulf of Trieste. Particular attention is devoted to the analysis of the thermohaline structure and of the circulation of the basin. Both the river flow and the wind data used in the simulations are derived from in situ measurements. The wind forcing is assumed spatially uniform over the basin. The paper in Appendix B presents an overview of this study while Appendix C contains a detailed analysis and discussion of this topic.

The first case study highlights the influence of wind forcing on the circulation of the Gulf of Trieste. Wind driven circulation can be dominant during strong episodes of Bora and Scirocco, which are the prevalent winds that blow over the basin. In particular, intense summertime Bora events can break the typical initial thermohaline stratification and mix the entire water column in a few hours, especially near the shores where relevant upwelling phenomena can occur. In fact, when the water column is stratified, the offshore drift of the light surface layer, causes the upwelling along the eastern coasts. Such strong wind-driven currents can flush the whole basin in almost 3 days.

The second case study shows the effect of the Isonzo river on the circulation and the thermohaline structure of the basin, especially in the absence of severe atmospheric events. River floods affect mainly the upper layer, down to 5 m, increasing the stratification and reducing the ventilation of the bottom layers of the Gulf. The plume spreads over the basin, creating a freshwater layer that floats over the dense (salty) ambient water. This buoyancy driven estuarine circulation is much weaker than the wind driven circulation.

Appendix B gives only a qualitative assessment of the influence of wind, of river discharge and of their combined effect.

Appendix C investigates in detail the role of these two main forcings on the Gulf of Trieste. First, a nondimensional scale analysis give a general description of freshwater plume dynamics. Then, the attention is focused on a transient response of the basin to the dominant wind (Bora) and on the effects of the major freshwater discharge (Isonzo River) during the stratification season (spring and summer).

4 Discussion and conclusions

This study describes the set up, testing and validation of a three dimensional hydrodynamic model for coastal areas. This numerical analysis is the first step towards the implementation of a fully operational monitoring system for the Gulf of Trieste.

The model set up consists of several phases: the discretization of the domain, the choice of a realistic parametrization of turbulence and of a stable (but not damping) numerical scheme for the advection of tracers, the implementation of both passive (radiating) and active (nudging layer) boundary conditions, and the realistic modelization of the river freshwater input.

The model was tested comparing its output to the analytical solutions of idealized case studies. Then it was used to analyze real events recorded in the Gulf of Trieste, since it is will be the core of an operational system applied to this area. The model simulates correctly the strong wind events and the river floods that occur during the stratification season.

Summer Bora episodes affect the circulation of the entire basin. When the water column is stratified, the offshore drift of the light surface layer causes an upwelling along the eastern coasts. The bottom dense water is lifted up to the surface and an incoming bottom current originates to keep the mass balance.

These summer events are the main mechanisms for the renewal of the bottom water and, consequently, for avoiding anoxia and other bio-geochemical phenomena that pose environmental concerns in the Northern Adriatic Sea and, in particular, in the Gulf of Trieste. These circulation processes are also critical for the pollutant dispersion in the Gulf.

Conversely, buoyancy driven estuarine circulation is much weaker. Riverine freshwater efficiently replaces only the northern part of the surface layer in a few days, while the Northern Adriatic Sea general circulation is supposed to bring a relevant contribution to the renewal of the intermediate and bottom water masses.

Previous researches have already studied these processes, analyzing the results of several field campaigns in the Gulf of Trieste and using numerical simulations. The study presented here is based on a numerical code but it is also implemented and validated using measured data sets. Such a kind of high resolution numerical approach has never been applied to this area.

Although the model reproduces correctly several observed phenomena, it has also some limits. It neglects the effect of tides and it is not forced by a larger scale nesting model at the boundary. The former aspect should not cause significant errors since tidal currents are not very strong in the area investigated and the relative residual currents are also weak ($\sim 1\,\mathrm{cm/s}$). The lack of a nesting model as a forcing at the open boundary can lead to unreliable results in case of long term simulations (two weeks or longer). Also surface wave motion is neglected: this is another source of error since waves are responsible for the turbulent processes in the surface mixed layer and determine alongshore currents near the coasts.

The Gulf of Trieste is also one of the areas of dense water formation of the Mediterranean Sea [*Vested et al.*, 1998]. This is a typical winter phenomenon and occurs when the water column is homogeneous. It is caused mainly by strong heat loss induced by the meteorological conditions and low freshwater contribution due to snow heap on the watershed. The study of the generation of these cold and salty water masses (which involves not only the Gulf of Trieste but a wider area of the

Northern Adriatic Sea) is beyond the scope of the work presented here but must be considered to have a complete overview on the dynamics of the area.

At present, the model is still in its pre-operational stage, but gives reasonable results for short term (up to 20 days) diagnostic runs. In particular, since it simulates correctly the response of the basin to the main external forcings (wind, heat fluxes, river discharge) it is suitable for operational applications.

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Appendix A

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Appendix B

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Appendix C

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