INFLUENCE OF WIND AND FRESHWATER ON THE CURRENT CIRCULATION ALONG THE ROMANIAN BLACK SEA COAST

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Abstract. The main aim of this study is the understanding on how winds and freshwater inputs influence the currents circulation along the Romanian coast. It is a "sensitivity" study of how the Romanian coastal circulation varies changing the main forcings acting on it. In order to do this, a finite element model of the entire Black Sea was used, having a high resolution mesh near the Romanian coast and the Danube distributaries. Several theoretical simulations were carried out in order to understand the influence of the Danube discharge and of the wind on the coastal current. The obtained results show that the water discharge from the Danube influences the current along the entire Romanian Black Sea coast, generating a longshore current mainly in the surface layers. This current occurs even at low discharges and is evident both at low and high wind velocity.

Key words: current, coastal dynamics, wind, discharge, flux

1. INTRODUCTION

The Romanian Black Sea coastal dynamics is strongly influenced by the water and sediment input from the Danube distributaries. The Romanian littoral can be divided into two sub-units (fig. 1), the northern one in front of the Danube Delta and the southern one, from Mamaia Bay to the border with Bulgaria (Panin, 2005). The two units are separated by Cape Midia, which represents an impermeable boundary in sediment transport, due to the presence of the Midia Harbor jetties. These jetties, with a length of 5 km offshore, have interrupted the littoral sediment drift originating from the Danube and going southwards (Spătaru, 1990; Ungureanu and Stănică, 2000; Stănică, 2003). South of the Danube Delta coast, the coastal currents are influenced by human structures, harbor defense works, coastal protection measures for tourist beaches, artificially designed pocket beaches etc. (Kuroki *et al.*, 2007). The influence of the Danube inputs of alluvia on the northwestern coast of the Black Sea was analyzed, among others, by Panin and Jipa (2002). Panin (1998), Giosan *et al.* (1999), Ungureanu and Stănică (2000), Stănică *et al.* (2007), Vespremeanu-Stroe *et al.* (2007) and Dan *et al.* (2007; 2009), among others, analyzed the coastal dynamics in front of the Danube Delta.

The available information was synthesized in order to be integrated in a 3D hydrodynamic model of the whole Black Sea, thus improving the understanding of the coastal currents formation along the Romanian Black Sea coast. The model is named SHYFEM (Shallow Water HYdrodynamic Finite Element Model) and it was first used in this zone by Tescari *et al.* in 2006, focusing on the Romanian coast in front of the Danube Delta.

As the purpose of this study was to detect the influence of wind and Danube discharge on the coastal currents formation, several hydrodynamic simulations were made using different initial conditions to simulate the sea state in cold and warm seasons. Theoretical wind blowing from various directions, with low and high velocity and differing values of Danube discharge were used.

No detailed current simulation along the coast (e.g. long shore currents by radiation stress due to waves) is intended, but the overall current patterns are reproduced. The resolution is not enough to catch rip and long shore currents near the shore, but it is sufficient to resolve coastal current due to meteorological forcing and to freshwater discharge.

This paper presents the results of the simulations without wind (calm conditions) and for wind blowing from northeast and southwest. Wind from northeast has the highest frequency and it is usually responsible for storms, according to data from the Romanian National Administration for Meteorology (Bondar *et al.*, 1973; Bondar and Panin, 2001; Bondar, 2006). The southwest direction is also important, as about 8 – 12% of the wind comes from there, sometimes with velocities higher than 28 m/s (Bondar *et al.*, 1973). Results are extracted on several cross-sections, perpendicular on the coast and with the same length.

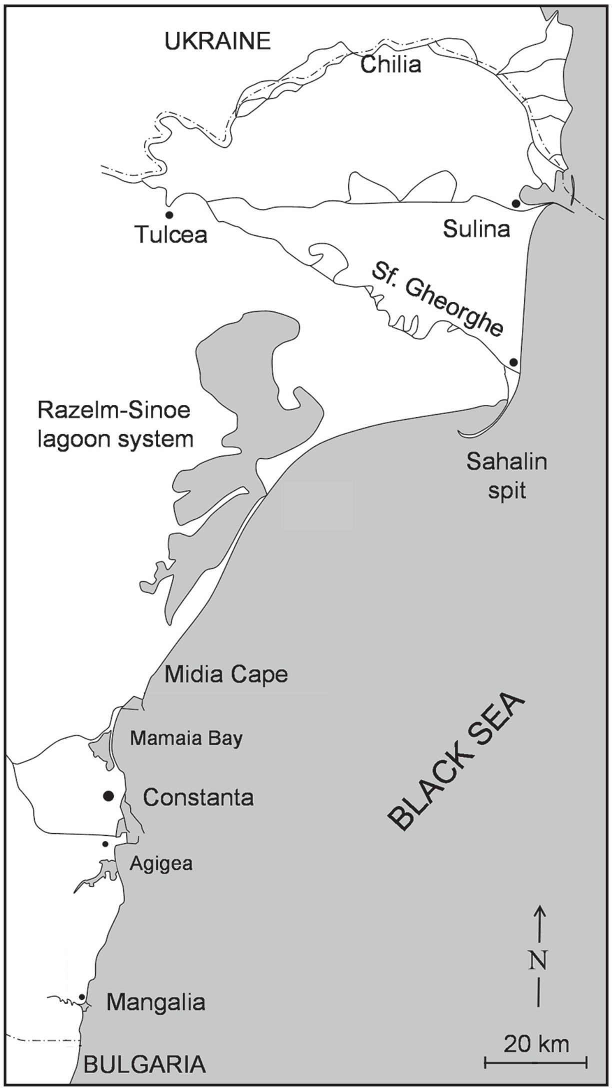


Fig. 1 Sketch of the Romanian Black Sea coast

2. MATERIALS AND METHODS

Model setup

The SHYFEM model (Umgiesser *et al.*, 2004; Umgiesser, 2010) is developed at the Institute of Marine Sciences in Venice and it is based on the method of the finite elements to solve the hydrodynamic equations in lagoons, coastal seas, estuaries and lakes. The model was applied in several cases (see e.g. Ferrarin and Umgiesser, 2005; Bellafiore *et al.*, 2008; Ferrarin *et al.*, 2008; De Pascalis *et al.* 2009, Bajo and Umgiesser, 2010).

The model was implemented on the entire Black Sea and it is focused on the Romanian coast and the Danube delta with a resolution gradually increasing towards the shoreline.

The model is multilayered and it provides a 3D representation of the basin. The model uses a staggered grid, defined by 11668 nodes and 21667 triangular elements (fig. 2), and a semi-implicit algorithm for the integration in time. The water level is specified in the nodes, while the velocities are specified in the element centers. The bathymetry is specified in each element.

The mean distance between nodes is about 50 m near the coast and about 20 km in the central part of the Black Sea. Open boundary conditions are specified at the Bosphorus Strait and for the main rivers.

The water column is divided into 27 layers, 1 being the surface layer and 27 the bottom layer. The layer thicknesses can be set by the user and are constant, except for the surface layer, which involves the variation due to the water level ζ. The thickness of the model layers goes from 2 m, for the first 10 m of the water column to 500 m, for the last layer, located in the centre of the Black Sea. The shallow water equations are:

$$\frac{dU_\ell}{dt} - fV_\ell + h_\ell\left[g\frac{\partial\zeta}{\partial x} + \frac{g}{\rho_0}\frac{\partial}{\partial x}\int_{-h_\ell}^{\zeta}\rho' dz + \frac{1}{\rho_0}\frac{\partial p_a}{\partial x}\right] - \frac{1}{\rho_0}\left(\tau_x^{\ell-1} - \tau_x^{\ell}\right) - A_H \Delta U_\ell = 0$$

$$\frac{dV_\ell}{dt} + fU_\ell + h_\ell\left[g\frac{\partial\zeta}{\partial y} + \frac{g}{\rho_0}\frac{\partial}{\partial y}\int_{-h_\ell}^{\zeta}\rho' dz + \frac{1}{\rho_0}\frac{\partial p_a}{\partial y}\right] - \frac{1}{\rho_0}\left(\tau_y^{\ell-1} - \tau_y^{\ell}\right) - A_H \Delta V_\ell = 0$$

$$\frac{\partial\zeta}{\partial t} + \sum_\ell \frac{\partial U_\ell}{\partial x} + \sum_\ell \frac{\partial V_\ell}{\partial y} = 0$$

where ζ is the water level [L], $U_\ell = h_\ell u_\ell$ and $V_\ell = h_\ell v_\ell$ are the vertically-integrated velocities (total transports) for the layer ℓ [LT^{-1}], t is the time [T]; g is the gravity acceleration [LT^{-2}], p is the atmospheric pressure at the mean sea level [$ML^{-1}T^{-2}$]; ρ_0 is the undisturbed water density [ML^{-3}]; ρ' is the water density [ML^{-3}]; p_a is the air pressure; h_ℓ is the thickness of the layer ℓ [L]; f is the variable Coriolis parameter [T^{-1}]; τ_x^ℓ and τ_y^ℓ, $\tau_x^{\ell-1}$ and $\tau_y^{\ell-1}$ are the stress components at the lower interface of the layers ℓ and $\ell-1$ [$ML^{-1}T^{-2}$]; A_H is the horizontal diffusion parameter [L^2T^{-1}].

On the uppermost layer, the wind stress components are specified using the Smith and Banke formulation (Smith and Banke, 1975):

$$\tau^x = \rho_a c_D |u| u^x \quad \text{and} \quad \tau^y = \rho_a c_D |u| u^y$$

where ρ_a is the air density (1.225 kg/m^3), c_D is a dimensionless drag coefficient, varying between 1.5×10^{-3} and 3.2×10^{-3} and $|u|$, u^x, u^y are the module and the components of the wind velocity in the *x* and *y* directions (Umgiesser, 2010).

On the lowermost layer, the bottom stress has the following formulation:

$$\tau_b = \frac{\lambda}{H} |U_L| U_L$$

where λ is a dimensionless friction parameter equal to 0.0025, H is the total depth and U_L is the velocity in the last layer (Umgiesser, 2010).

We modeled part of the Danube river, in order to set up the momentum that the Danube has when it discharges into the Black Sea. The freshwater inputs are spread among the border elements. Discharge is prescribed and horizontal velocities are computed by the model.

The coastline used for the mesh is a merge of the Romanian coastline provided by GeoEcoMar, a coarser coastline of the Black Sea provided by NOAA (http://rimmer.ngdc.noaa.gov/mgg/coast/getcoast.html), and a coastline extracted from Google Earth (http://earth.google.com/).

The bathymetry near the Romanian coast was measured and provided by GeoEcoMar, while for the other parts of the Black Sea, the data were obtained from the NOAA free online service (http://www.ngdc.noaa.gov/mgg/gdas/gd_designagrid.html

The water discharge subdivision for the three distributaries of the Danube was introduced taking into account the percentages provided by Bondar and Panin, 2001: Chilia 58%, Sulina 19% and Sfântu Gheorghe 23%. Other discharge values introduced in the model represent the rivers Dnepr, Dnestr and South Bug and were found in Yankovsky *et al.* (2004).

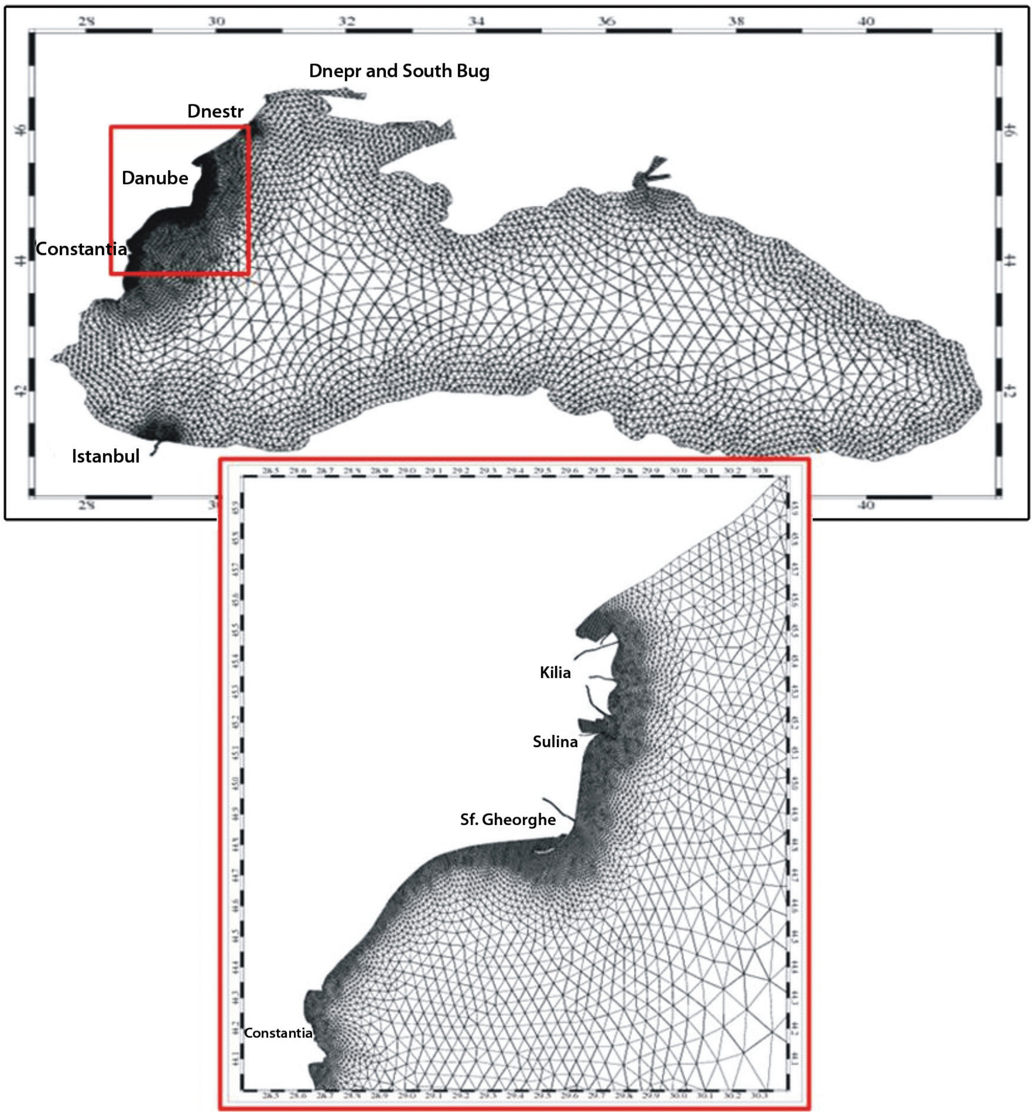


Fig. 2 The computational grid

SIMULATIONS SETUP

We made simulations in low wind conditions (5 m/s) and high wind conditions (10 m/s). The wind is at 10 m height, as normally used.

These values were established based on the available data from the Romanian National Meteorological Administration (Bondar, 2006).

The total average Danube discharge is of 6500 m^3/s (Panin and Jipa, 2002). Simulations were made imposing a low discharge value of 4000 m^3/s and a high discharge value of 9000 m^3/s (Bondar *et al.*, 1991). The discharges of the rivers Dnepr, Dnestr and South Bug were modified as well, in order to agree to the decrease or increase of the total Danube discharge.

Initial temperature and salinity conditions for the cold and warm seasons were provided by using climatological data from the Mediterranean Data Archiving and Rescue (MEDAR) project (http://medar.ieo.es). This project provides monthly average fields of temperature and salinity for the Mediterranean and the Black Sea obtained from processed observations. The average distributions from January and May were considered as typical for the winter and summer periods and MEDAR fields were interpolated onto our grid.

The analysis presented in this paper was carried out comparing the results of the simulations performed under the following conditions, both with the initial state for January and May:

1. calm (no wind) and medium Danube discharge, of 6500 m^3/s;
2. wind from NE with low velocity, of 5 m/s, and low Danube discharge, of 4000 m^3/s;
3. wind from NE with high velocity, of 10 m/s, and high Danube discharge, of 9000 m^3/s;
4. wind from SW with low velocity, of 5 m/s, and low Danube discharge, of 4000 m^3/s;
5. wind from SW with high velocity, of 10 m/s, and high Danube discharge, of 9000 m^3/s.

Seven cross-sections were chosen for the comparison of the fluxes calculated for each simulation. Their locations (fig. 3) were established in order to be significant with respect to the Danube discharge and the morphology of the coast. All the cross-sections have extends seaward about 25 km, going to water depths between 35 m for the northernmost one and 175 m for the southernmost one. The first cross-section is situated south of the Sulina mouth of the Danube, the second one being south of Sf. Gheorghe mouth, towards the southern tip of Sahalin spit. The following two intermediate cross-sections are located, from north to south, in Perişor area and in front of the barrier beach separating the Razelm and Sinoe lakes. One cross-section is located north of Midia Harbor, while the last one on Romanian territory is placed north of Mangalia (southernmost town along the Romanian coast). The last cross-section considered in this study is on the Bulgarian coast, close to Cape Kaliakra.

The cross-sections were created along adjacent elements of the grid, in order to be perpendicular on the shoreline. This is why they don't appear like straight lines (fig. 3). The velocity vectors on the cross-sections are interpolated to the nodes from their element values.

Both for winter and summer conditions, the first simulations, without wind, were carried out for a 45 days period, for low, medium and high discharge. Then wind forcing was applied, with constant velocity and direction for two days.

Results are exposed through surface current maps and cross-sections (figs. 4 – 8 and 10 – 14) and salinity cross-sections in various conditions (figs. 9 and 15). Calculated fluxes versus discharge on the 7 cross-sections were compared for the cold and warm seasons (figs. 16 – 18).

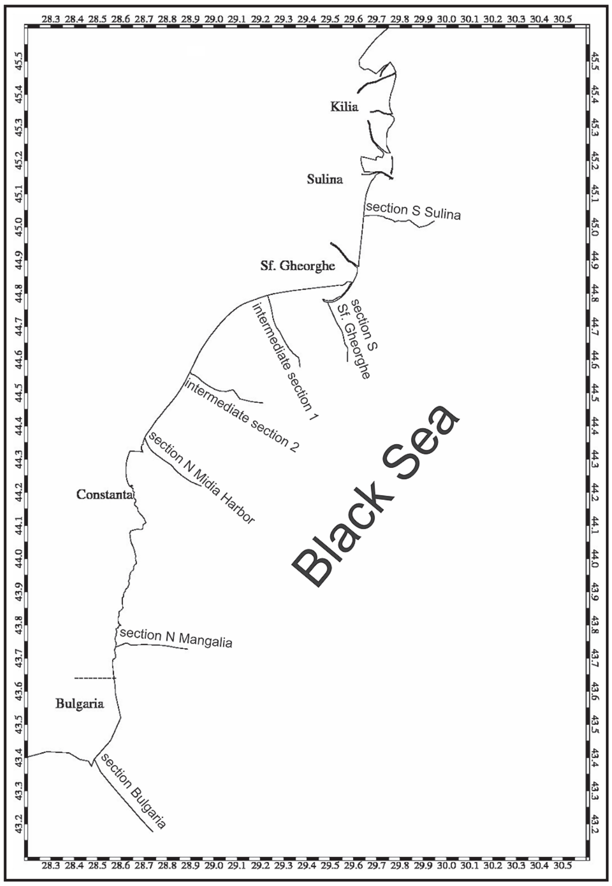


Fig. 3 Location of the cross-sections used in the analysis

3. RESULTS AND DISCUSSION

3.1. CURRENTS

In the absence of wind, a longshore current is formed along the Romanian Black Sea coast (figs. 4, 10). The longshore current flows on the surface and is formed by the Danube freshwater that has a higher buoyancy than the salty Black Sea water. The current is stronger during the cold season. Eddy-like currents, due to the discharge of the Danube distributaries and to the presence of the Sulina jetties (Panin,

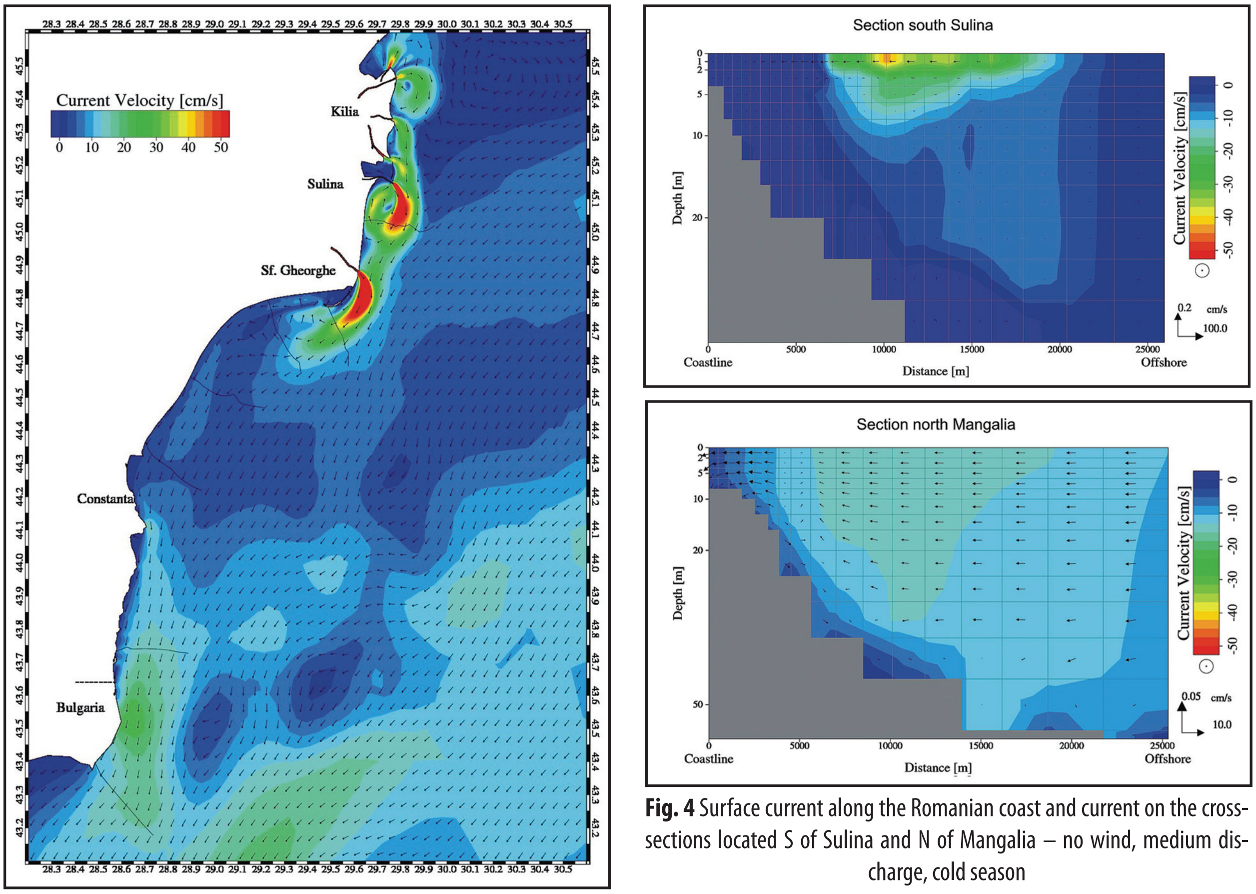


Fig. 4 Surface current along the Romanian coast and current on the cross-sections located S of Sulina and N of Mangalia – no wind, medium discharge, cold season

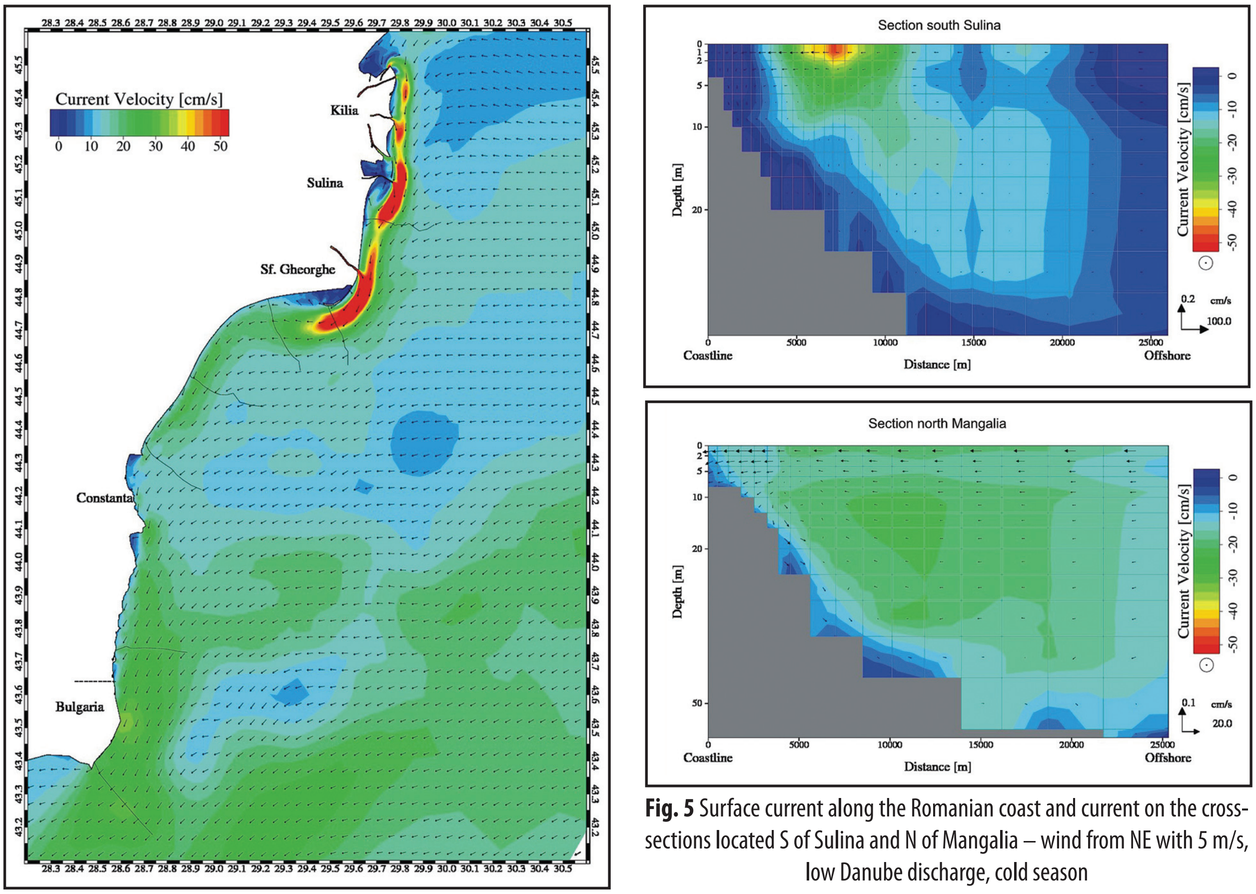


Fig. 5 Surface current along the Romanian coast and current on the cross-sections located S of Sulina and N of Mangalia – wind from NE with 5 m/s, low Danube discharge, cold season

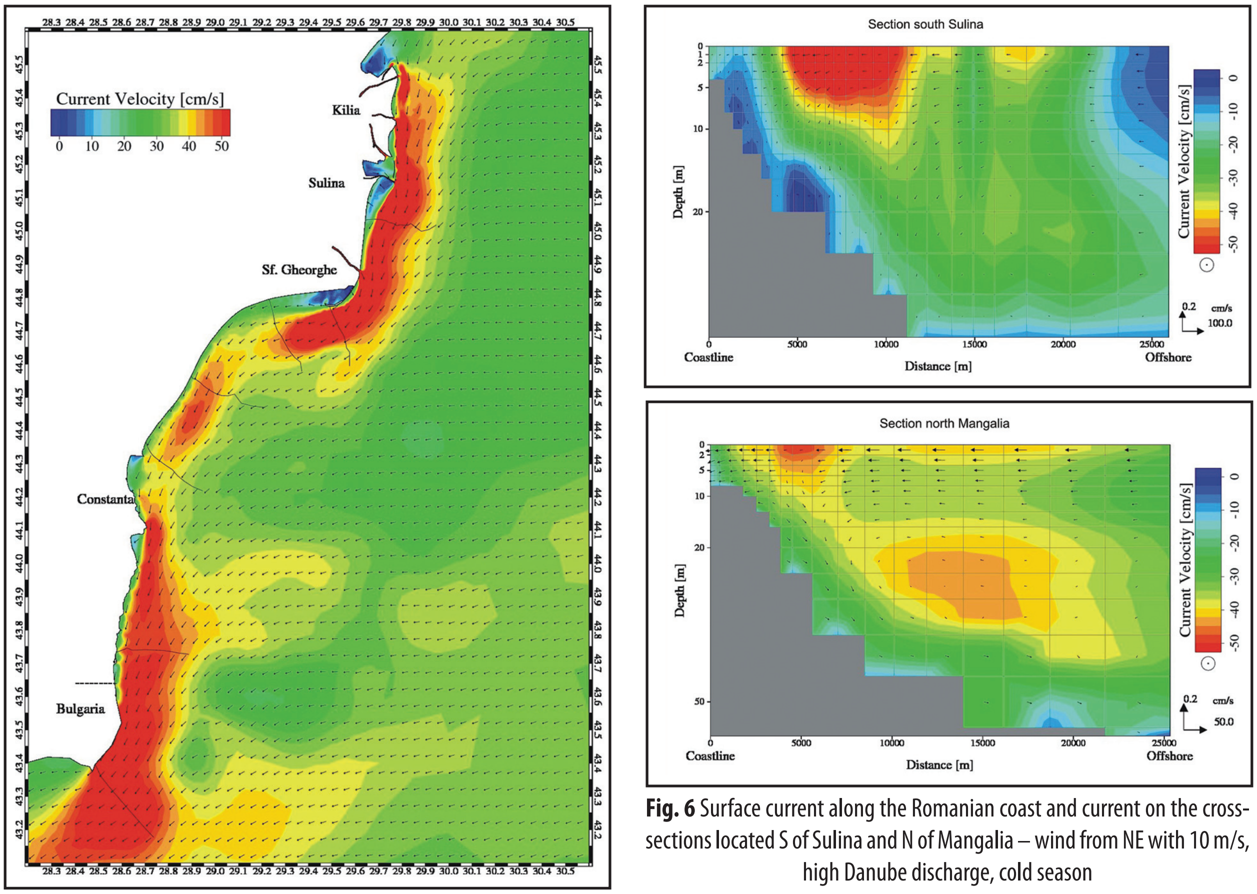


Fig. 6 Surface current along the Romanian coast and current on the cross-sections located S of Sulina and N of Mangalia – wind from NE with 10 m/s, high Danube discharge, cold season

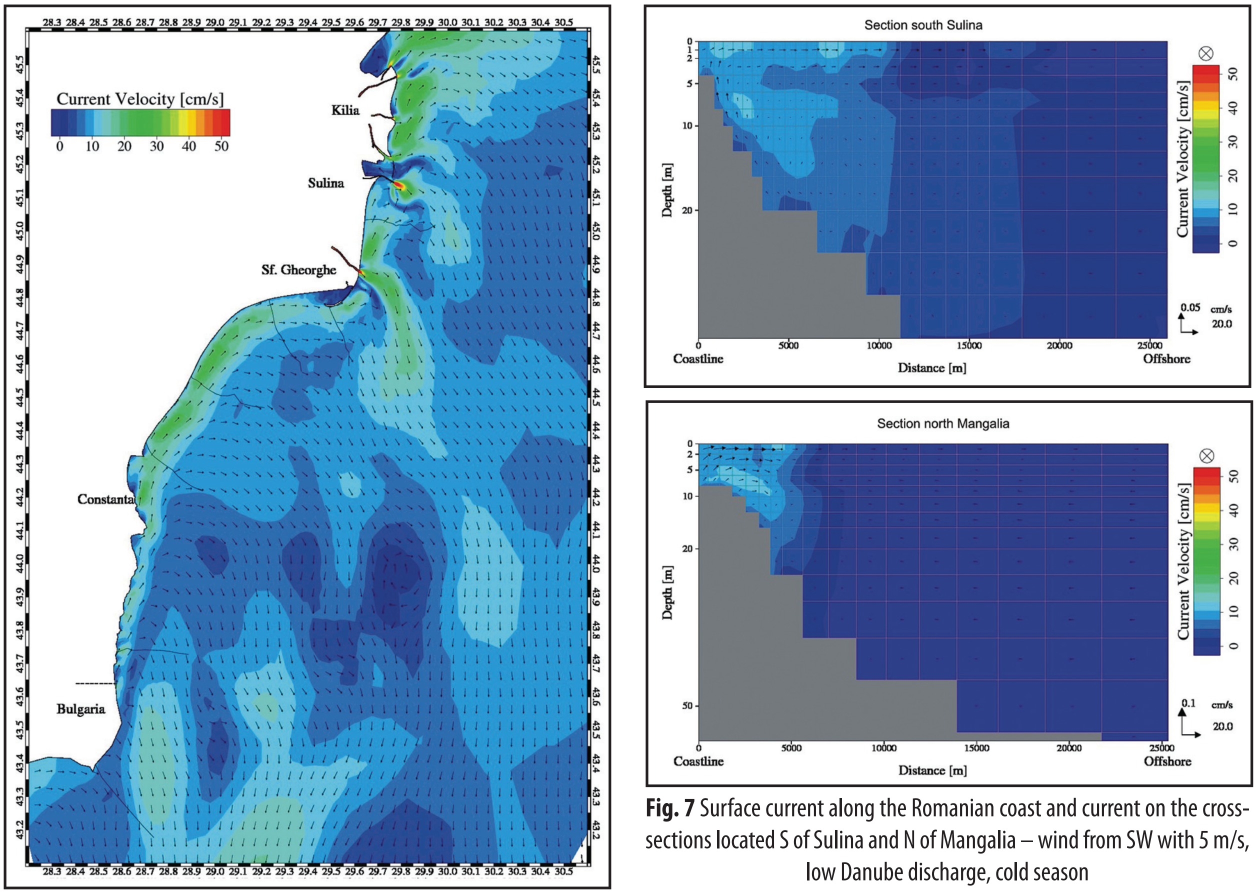
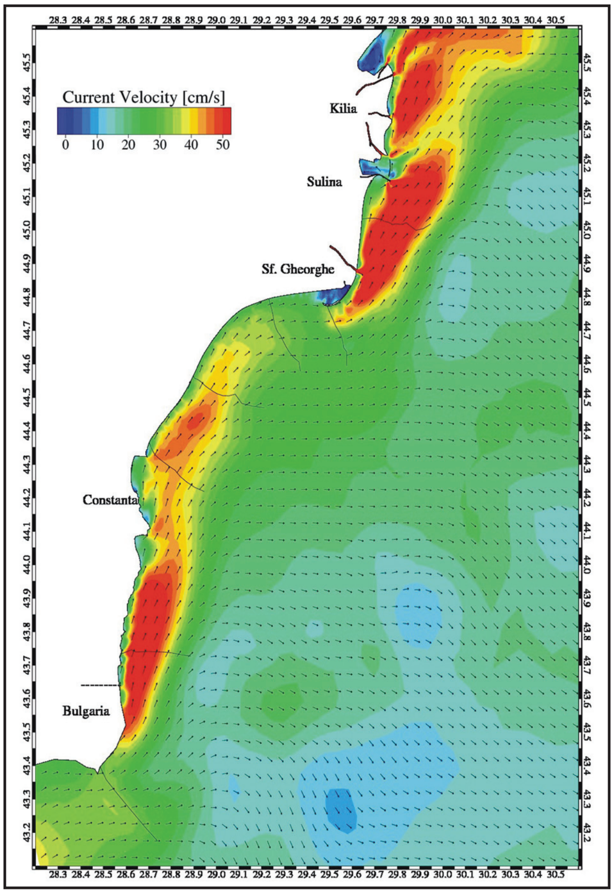


Fig. 7 Surface current along the Romanian coast and current on the cross-sections located S of Sulina and N of Mangalia – wind from SW with 5 m/s, low Danube discharge, cold season



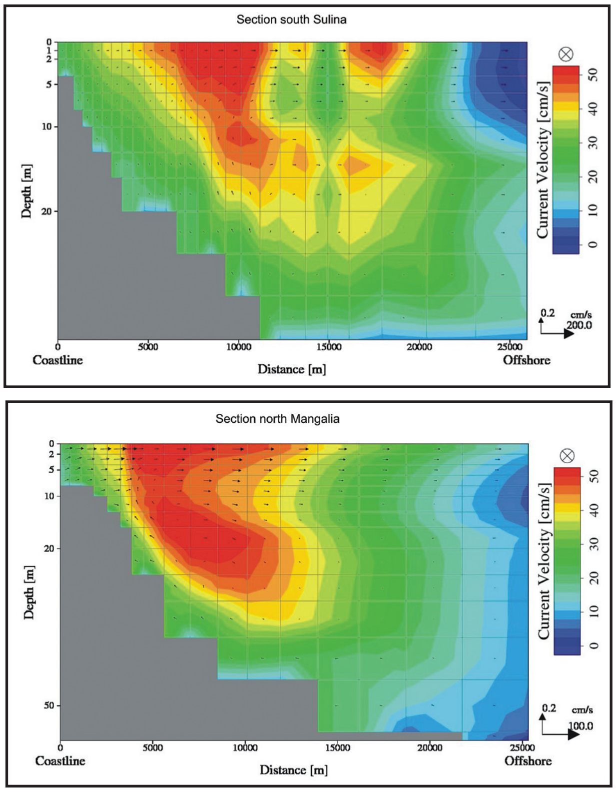
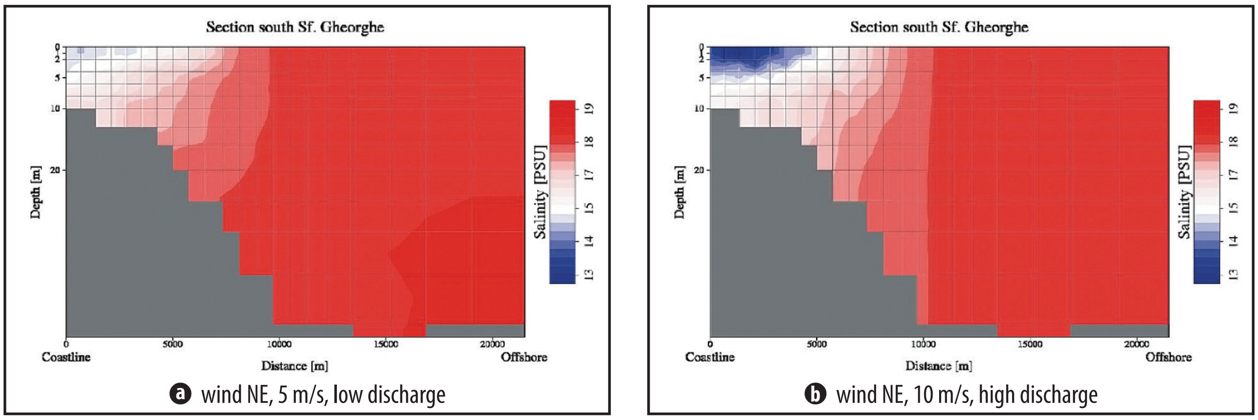
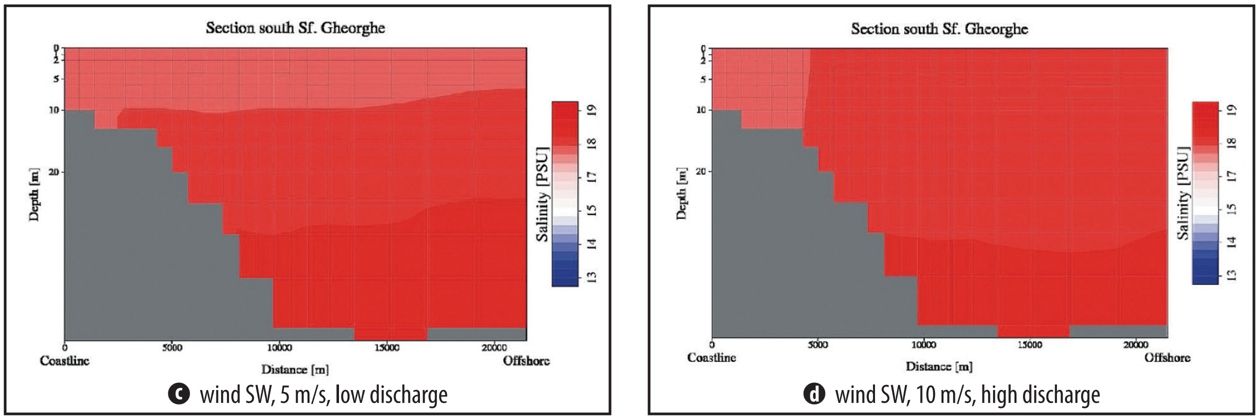


Fig. 8 Surface current along the Romanian coast and current on the cross-sections located S of Sulina and N of Mangalia – wind from SW with 10 m/s, high Danube discharge, cold season



ⓐ wind NE, 5 m/s, low discharge ⓑ wind NE, 10 m/s, high discharge



ⓒ wind SW, 5 m/s, low discharge ⓓ wind SW, 10 m/s, high discharge

Fig. 9 Salinity on the cross-section located S of Sf. Gheorghe, various conditions, cold season

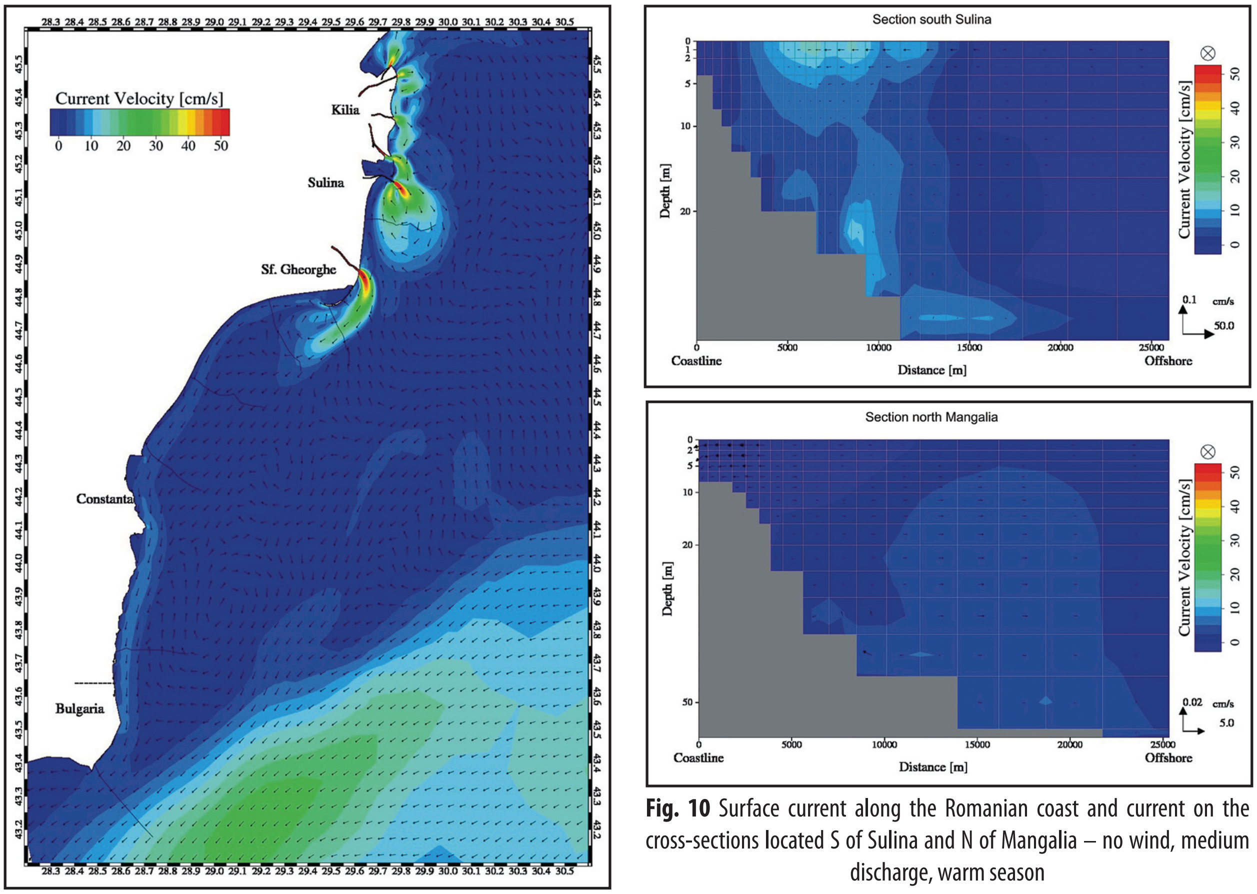


Fig. 10 Surface current along the Romanian coast and current on the cross-sections located S of Sulina and N of Mangalia – no wind, medium discharge, warm season

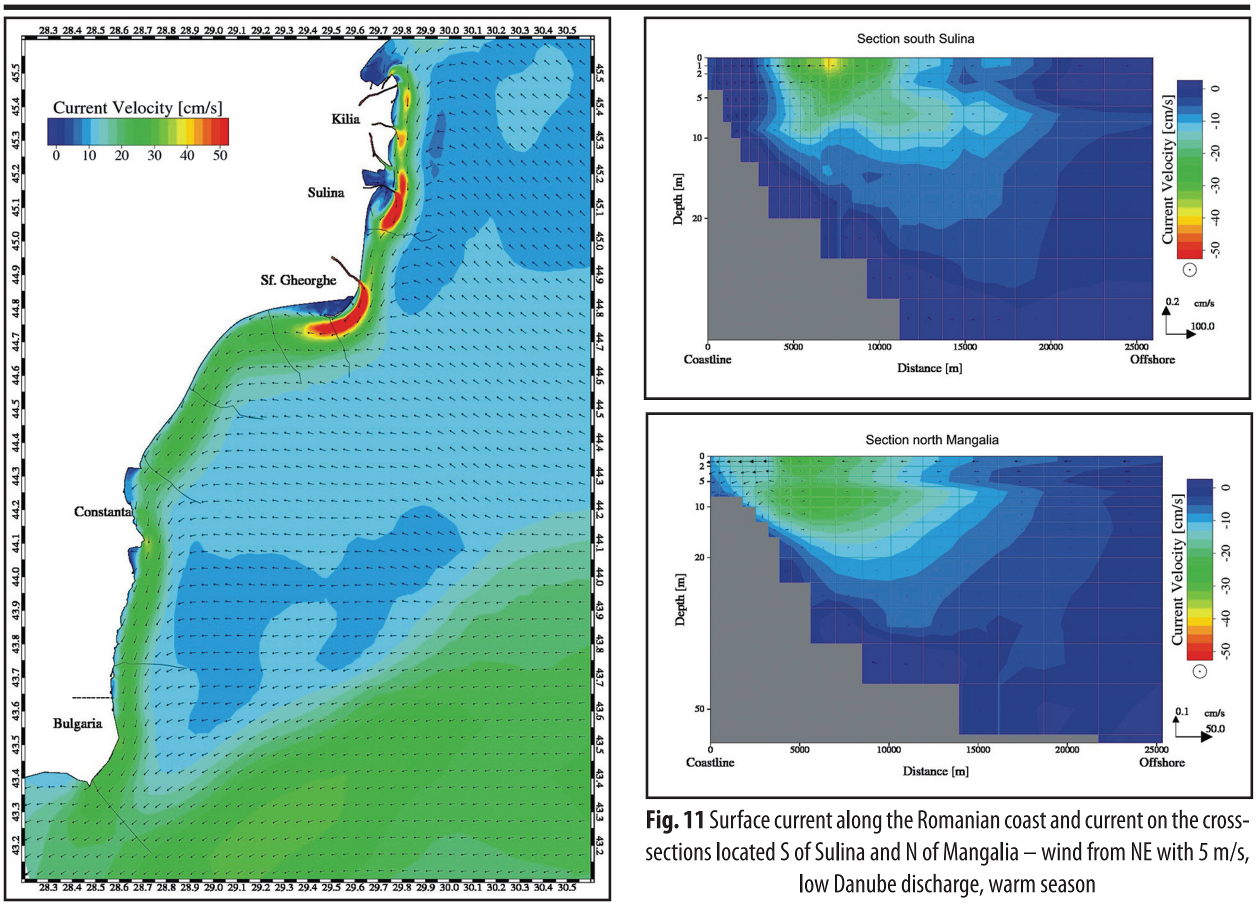


Fig. 11 Surface current along the Romanian coast and current on the cross-sections located S of Sulina and N of Mangalia – wind from NE with 5 m/s, low Danube discharge, warm season

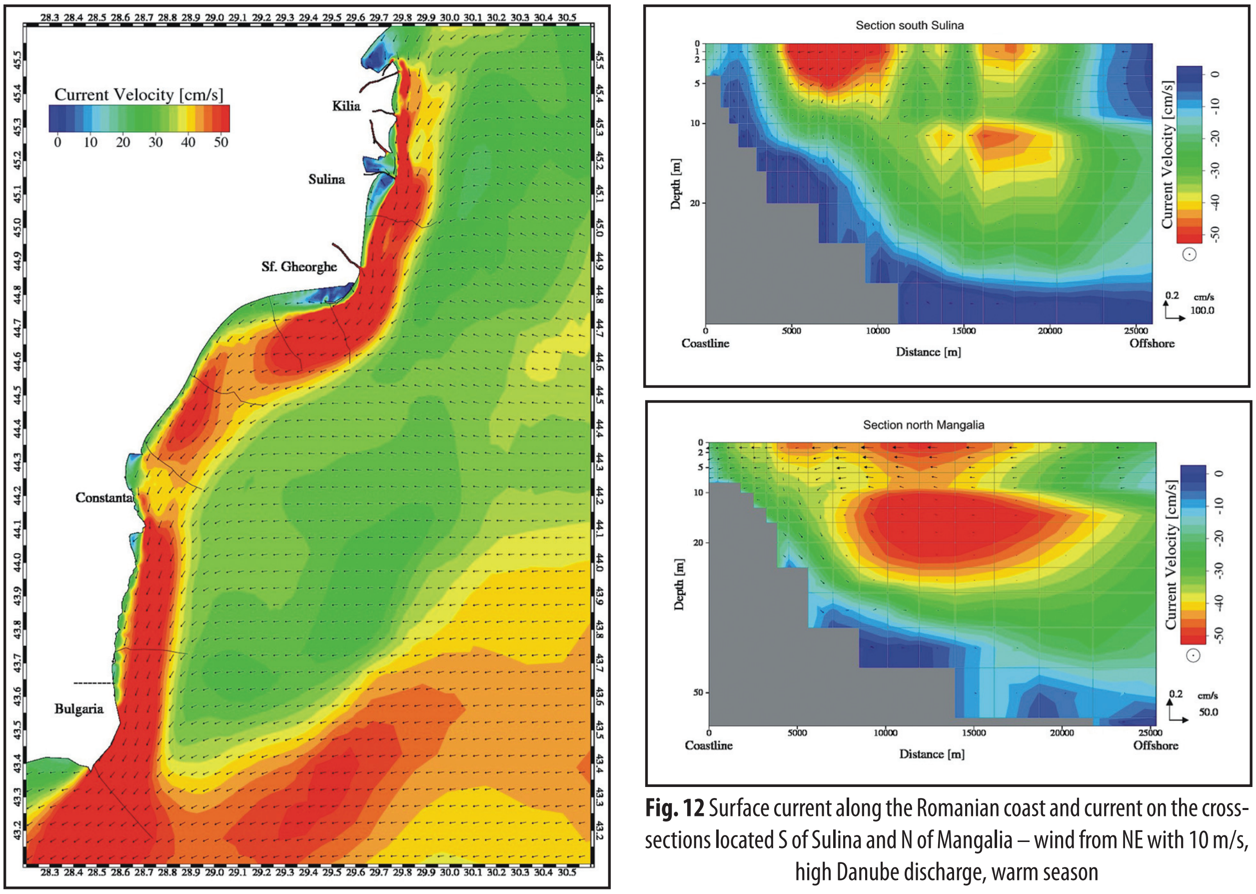


Fig. 12 Surface current along the Romanian coast and current on the cross-sections located S of Sulina and N of Mangalia – wind from NE with 10 m/s, high Danube discharge, warm season

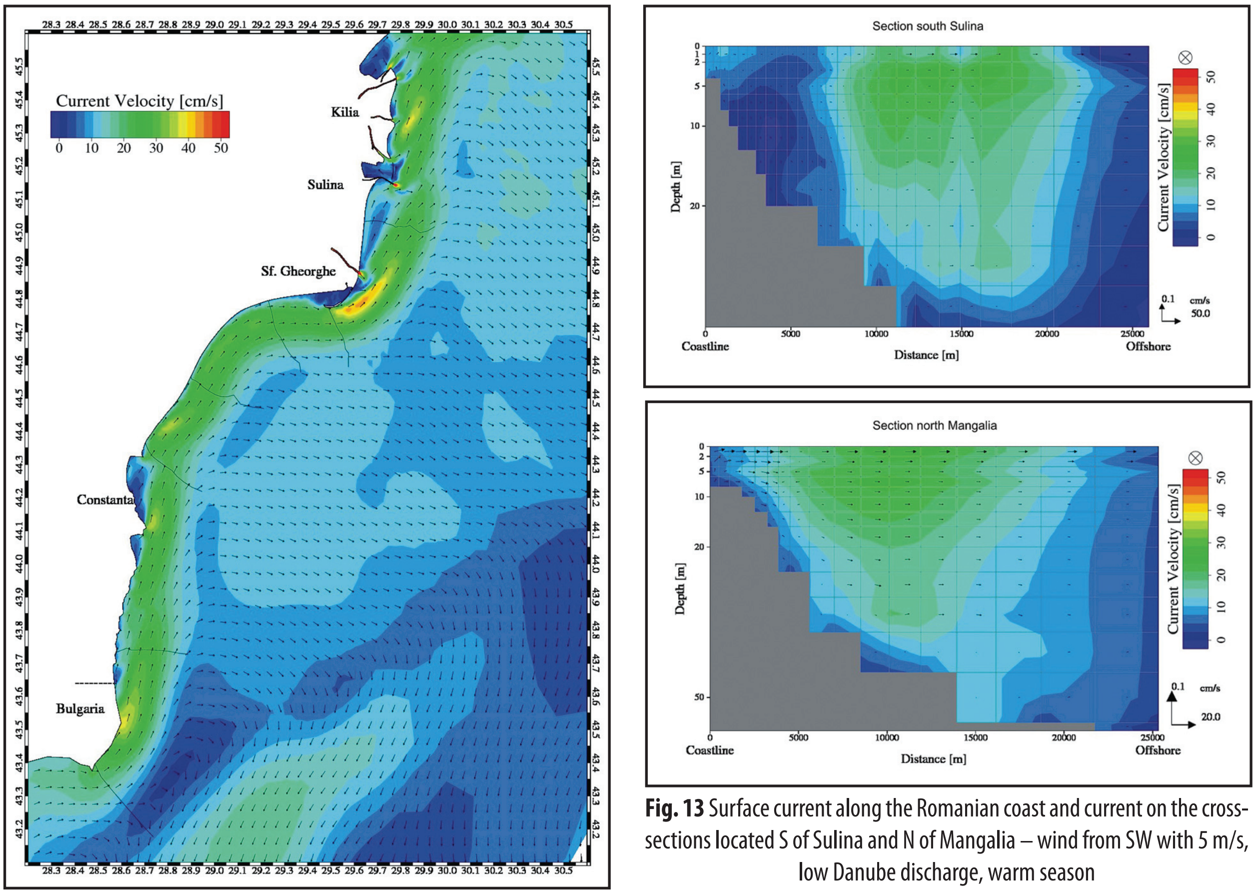
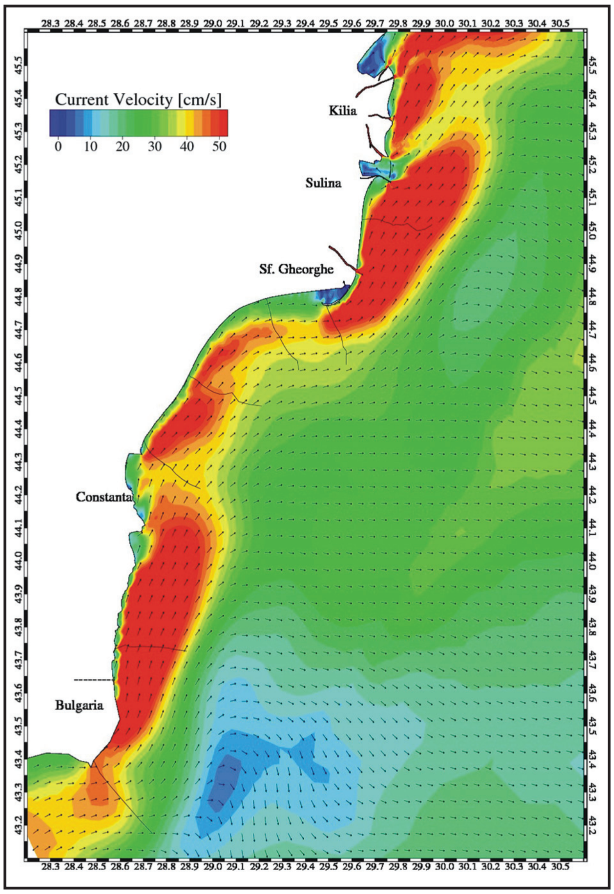


Fig. 13 Surface current along the Romanian coast and current on the cross-sections located S of Sulina and N of Mangalia – wind from SW with 5 m/s, low Danube discharge, warm season



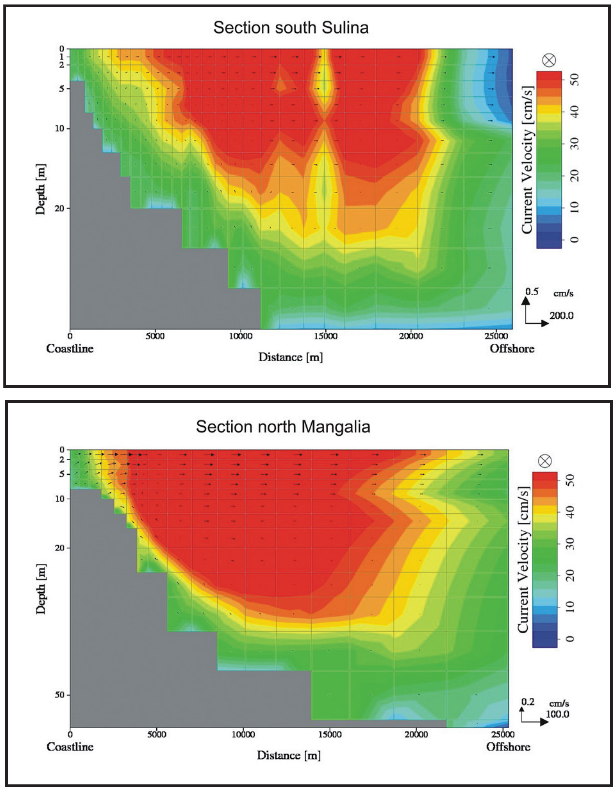
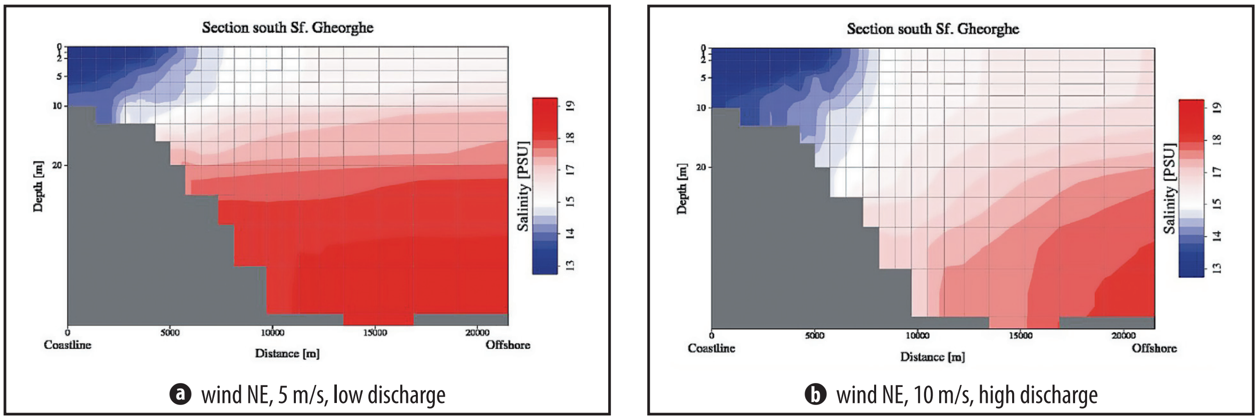
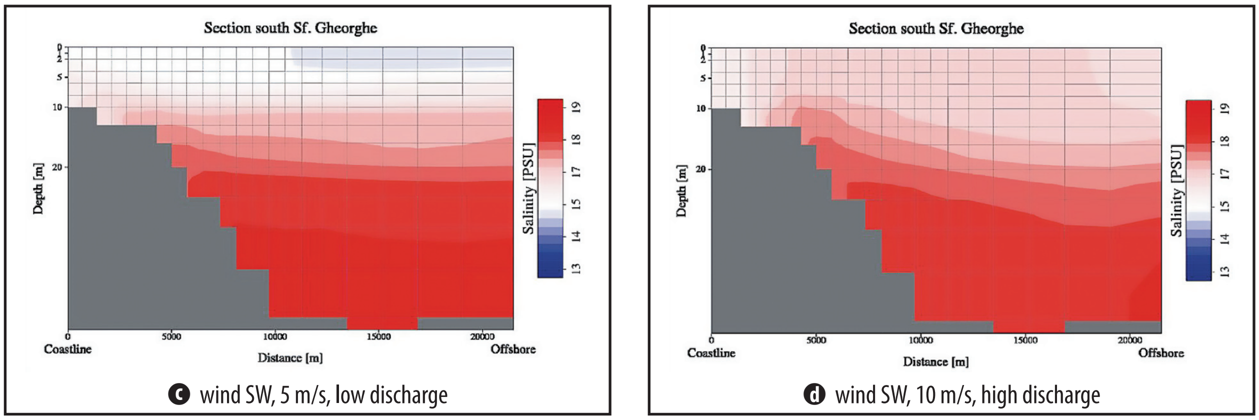


Fig. 14 Surface current along the Romanian coast and current on the cross-sections located S of Sulina and N of Mangalia – wind from SW with 10 m/s, high Danube discharge, warm season



ⓐ wind NE, 5 m/s, low discharge

ⓑ wind NE, 10 m/s, high discharge



ⓒ wind SW, 5 m/s, low discharge

ⓓ wind SW, 10 m/s, high discharge

Fig. 15 Salinity on the cross-section located S of Sf. Gheorghe, various conditions, warm season

1998, Giosan *et al.*, 1999, Tescari *et al.*, 2006, Stănică and Panin, 2009 among others), are emphasized in the absence of the wind (figs. 4 and 10).

Wind blowing constantly from NE or SW determines the main direction of the surface current, especially at higher velocity (figs. 5 – 8 and 11 – 14). Thus, the eddy-like currents that occur near the Sulina distributary in the absence of wind, with both initial conditions of temperature and salinity (figs. 4 and 10), disappear after two days of constant wind.

The analysis of the cross-sections shows that the influence of wind can reach 30 m deep, with the higher wind velocity.

In order to analyze the current through the cross-sections, we divided the data in positive (northward) and negative (southward). Negative currents are shown on the cross-sections from figs. 4 – 6, for cold season simulations, and from figs. 11 and 12, for warm season simulations. Positive currents are shown on the cross-sections from figs. 7 and 8, for cold season simulations, and from figs. 10, 13 and 14, for warm season simulations.

3.2. SALINITY

Salinity was analysed on the cross-section located south of the Sf. Gheorghe distributary, for the simulations with wind from NE and SW, with low and high values of velocity, both for cold season (fig. 9) and warm season (fig. 15). This cross-section was chosen because, with wind from NE, it takes over directly a significant part of the Danube discharge, from all three distributaries.

Looking at the figs. 9 (for the cold season) and 15 (for the warm season), it is possible to note the Danube freshwater kept closer to the coast with NE wind, while with SW wind it flows far from the coast. When wind blows from SW, this causes the push of the Danube freshwater offshore and its mixing to the more salty water.

The same trend is observed for the cold and warm seasons. The stratification due to temperature gradients is more accentuated in May. This is normal, taking into account the fact that temperature rises in the surface layer due to a higher solar radiation. In fact, the temperature stratification is due only to the initial condition. The stratification influences the surface current which, under the same conditions of wind and discharge, is stronger during the warm season.

The temperature and salinity fields determine distortions of the surface currents with respect to the main directions, induced by wind.

3.3. FLUXES

The SHYFEM model provides the fluxes calculated on the chosen cross-sections. The cold season and warm season fluxes were compared on all the cross-sections for various conditions – calm, wind from NE and wind from SW.

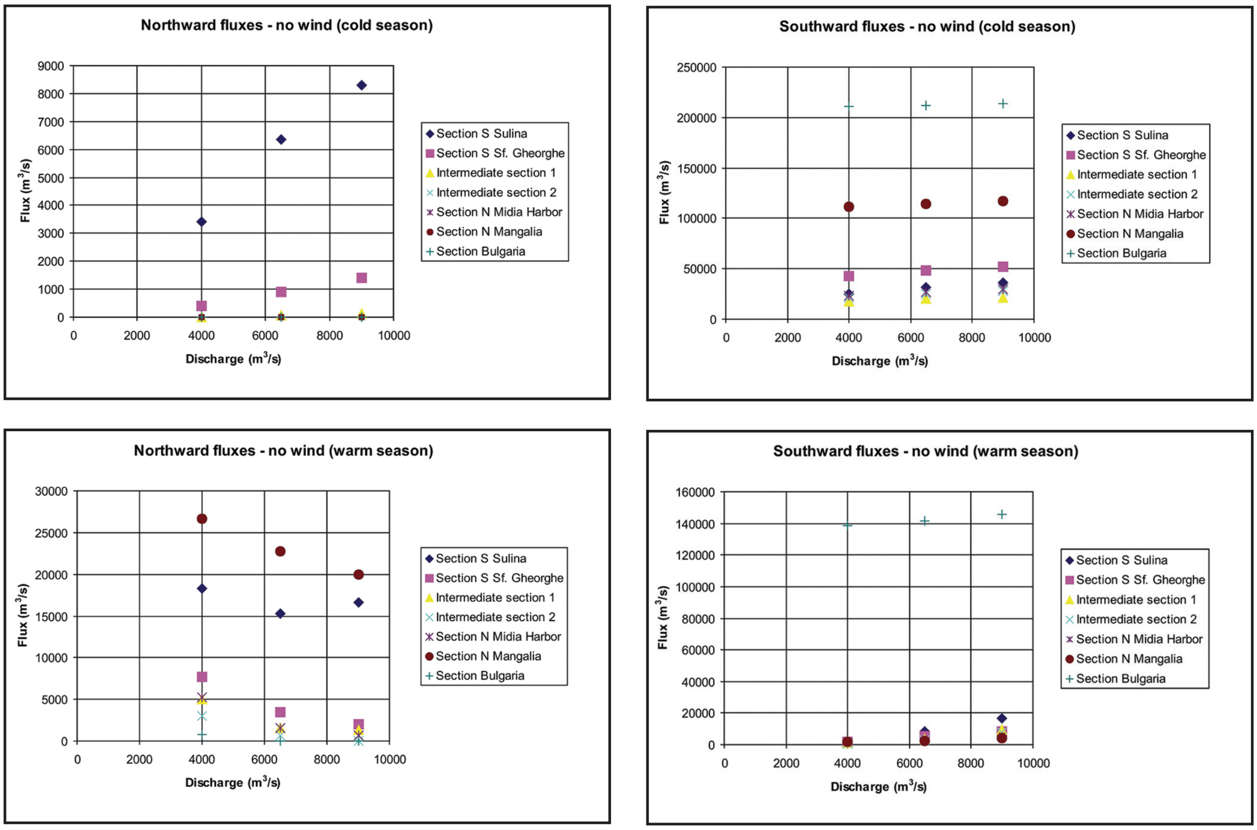


Fig. 16 Fluxes on cross-sections – no wind forcing

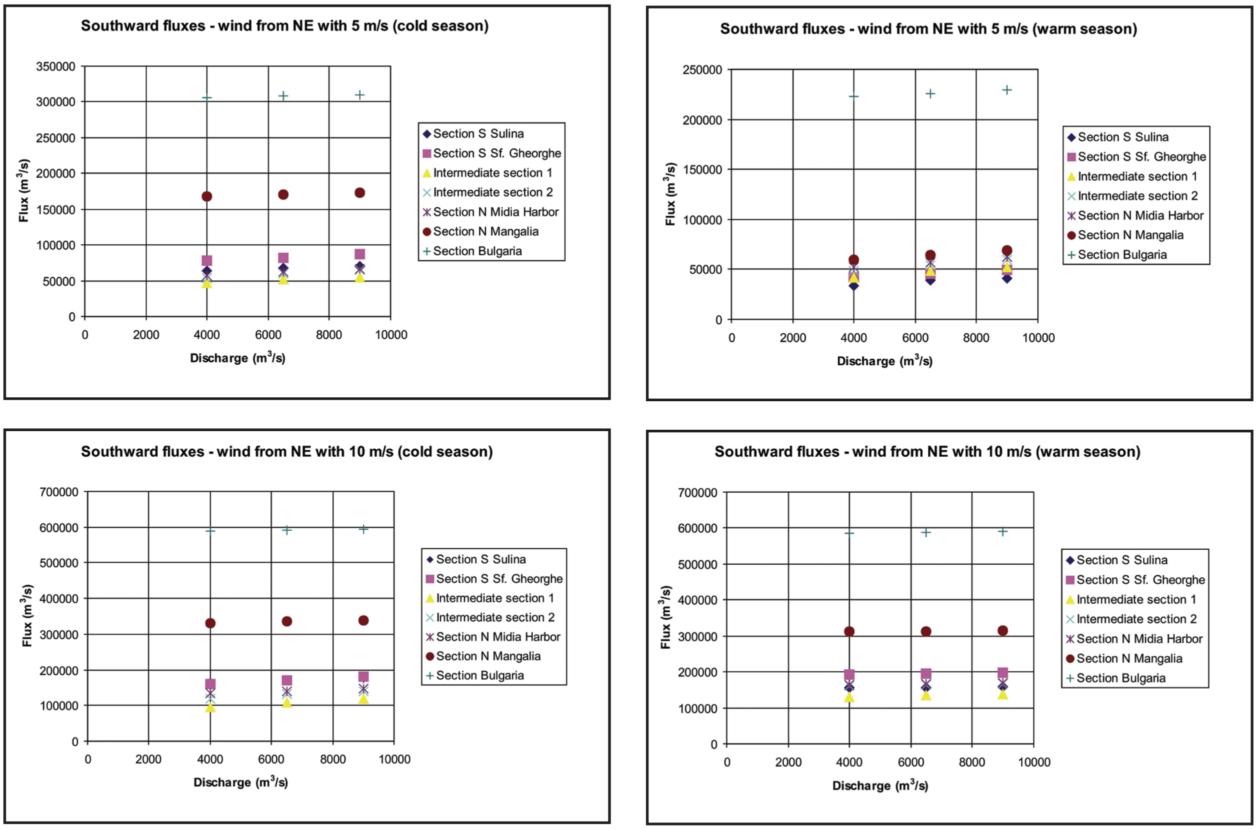


Fig. 17 Fluxes on cross-sections – forcing by wind from NE

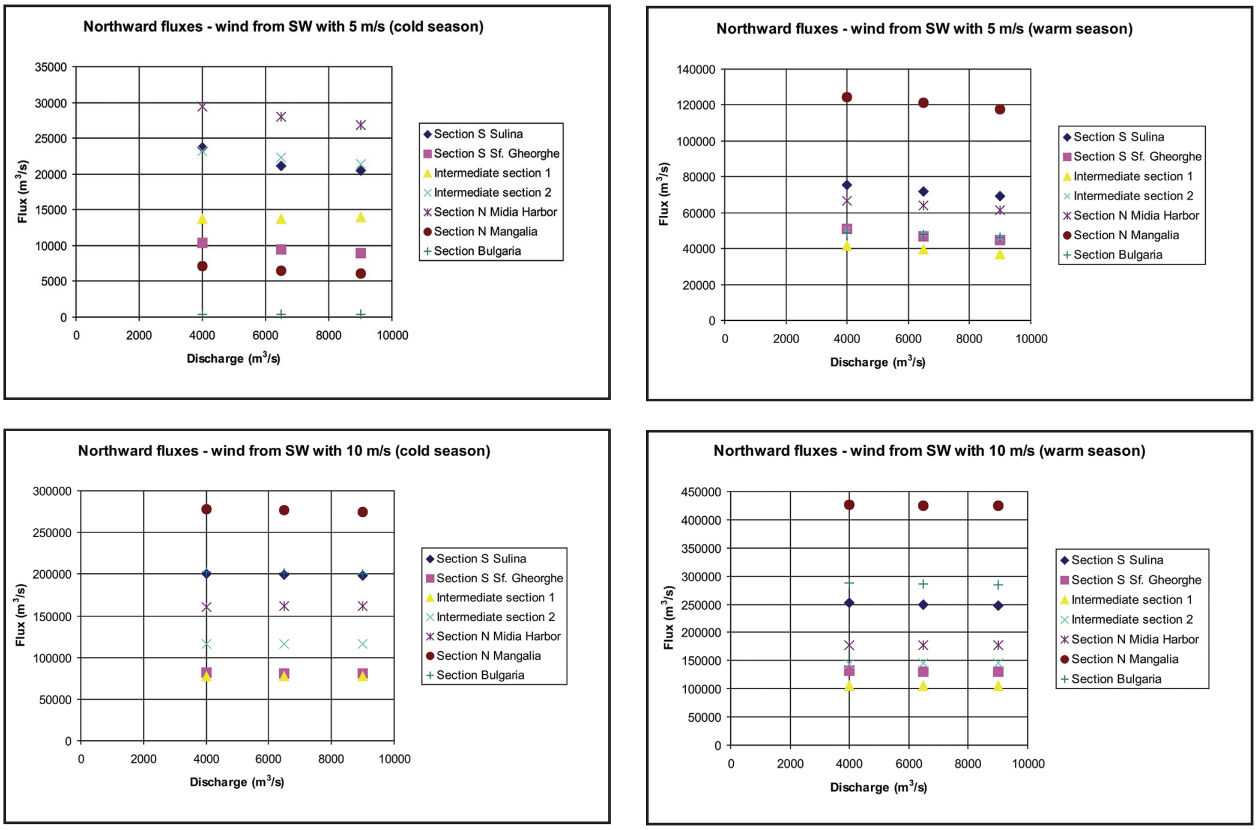


Fig. 18 Fluxes on cross-sections – forcing by wind from SW

There are significant changes between cold season and warm season fluxes on the cross-sections, showing that the influence of temperature and salinity fields is important. In calm conditions (fig. 16), the northward fluxes on the cross-sections located south of both Sulina and Sf. Gheorghe show an increasing trend with respect to discharge during the cold season and an almost decreasing trend during the warm season. The northward fluxes on the section located north of Mangalia are rather high during the warm season and show a decreasing tendency with respect to discharge. During the cold season, there is no northward flux of this cross-section.

The northward fluxes are higher during the warm season, while the southward fluxes are much higher during the cold season. This is normal, because the southward current is stronger in the wintertime.

Wind blowing from NE with 5 m/s leads to higher southward fluxes in the cold season than in the warm season (fig. 17).

When the velocity of NE wind is increased at 10 m/s, there is no significant difference between the cold season and the warm season fluxes. This shows that wind has a stronger influence on the flux at higher velocity, regardless of the temperature and salinity distribution.

Wind blowing from SW with 5 m/s leads to higher northward fluxes in the warm season than in the cold season (fig. 18). There are significant differences between the cold season and warm season fluxes on the cross-sections, due to the differing fields of temperature and salinity. For example, the flux calculated on the cross-section located north of Mangalia is the lowest one in wintertime and the highest one in summertime.

When the velocity of SW wind is increased at 10 m/s, the northward fluxes are higher in the warm season. But the tendency is the same for the winter and summer conditions simulated. This suggests again that, at higher velocity, wind becomes a dominant factor controlling the flux, with a stronger influence than the distribution of temperature and salinity.

4. CONCLUSIONS

An analysis of the wind and freshwater inputs on the marine circulation along the Romanian Black Sea coast was performed, using the open-source 3D numerical model SHYFEM. Several simulations were carried out, varying the main forcings, which are the wind velocity and direction and the Danube discharge.

Air-sea interactions are complex. We used just one formulation of the stress that does not require a wave model.

The results obtained in conditions of calm, low and strong winds from NE and from SW with different initial states are discussed in this study.

In the absence of wind, a longshore current, stronger in wintertime, occurs. This current is caused mainly by the change in salinity induced by the Danube freshwater.

Constantly blowing wind becomes a significant factor responsible for the formation of coastal currents, both in the cold and warm seasons.

This work does not apply to the currents nearest to the shoreline, that are mainly generated by bottom induced wave breaking.

The stratification due to temperature and salinity influences the surface current driven by wind, which, under the same conditions of wind and discharge, is stronger during the warm season.

Wind blowing from NE enhances the change in salinity induced by the Danube distributaries, as it keeps the freshwater near the coast.

Calculated fluxes across several cross-sections of about 25 km long, plotted against discharge, show significant differences between the cold and warm seasons, which are due to the differing fields of temperature and salinity. The differences between cold season and warm season fluxes become smaller for stronger winds from NE. This shows again that, at higher velocity, wind is the main factor controlling the coastal overall water circulation.

This study is a first step towards the development of a fully operational oceanographic model for the northwestern part of the Black Sea. Future developments of this Black Sea model include the use of real meteorological forcing to study the average circulation, the calibration on measured current velocities, the representation of some stormy events, modeling of the sediment transport and of the waves.

5. ACKNOWLEDGEMENTS

This work was performed within the research project CLASS, contract 32-130/2008, funded by ANCS, the Romanian Authority for Scientific Research.

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