Simulation of coastal currents and river discharges in the south-eastern Black Sea

*Ercan Köse, Coşkun Erüz, Abdulaziz Güneroğlu, Sebnem Erkebay & Yasar Gulten
Faculty of Marine Science, Karadeniz Technical University, Trabzon, Turkey
* [E-mail: ekose@ktu.edu.tr ]

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In this study, development and evaluation of buoyant river plumes under the influence of the coastal currents and the guidance of topography in the south eastern Black Sea coast (Solaklı and Sürmene) rivers were analyzed. For simulation, the rivers are inputted as source of zero salinity in computer based simulation model CARDINAL, which uses depth averaged shallow water equation for two-dimensional conditions and the equations of non-steady boundary layer for three-dimensional conditions. The river plumes are examined with realistic topography and idealized wind conditions. In order to check accuracy of the simulation, temperature, salinity, current speed and directions were measured in 22 stations and then density was calculated by using UNESCO formulae. Comparison of the measurements and modeling of currents showed good agreement. When both buoyancy and wind are employed as external forcing, the circulation is influenced by the opposing tendencies for stratification. The present findings suggest that transport of low salinity waters depends on buoyancy in the vicinity of rivers and wind components away from river mouths.

[Key words: Black Sea, coastal currents, river discharge]

There are many causes leading to pollution in coastal areas and rivers. Added to the effluents from municipal and industrial sources is the pollution from natural causes, such as the carry-over of nutrients and sediments in river deltas. Agricultural activities may overload soils with fertilizers and pesticides. Washing off of the soil by rainfall produce high concentrations of nitrates, phosphorus and toxic chemicals in rivers and coastal waters. Traditionally, assessment of environmental quality is based on monitoring results, but there is increased recognition that this data is often insufficient to answer all the questions being posed. Considering the large area of Black Sea, monitoring programs are limited both spatially and temporally. Computer models can help by providing a means of integrating monitoring data in both space and time, and making predictions. In addition, model results can be used to optimize monitoring programs in terms of identifying important sampling locations and time scale.

The coastal waters are the recipients of fresh water and land drained materials that are primarily brought in through river discharges. From dynamical point of view the discharge site (river mouth) can be considered the source of momentum and buoyancy, produced by the release of light fluid into more dense ambient.

Several investigators have discussed distribution of a river plume. Earlier studies recognized the importance of non-linearity, coriolis and friction in the development of the buoyant plume. Chao & Boicourt applied a three dimensional primitive equation model to study the establishment of an estuarine plume by discharge of fresh water into the upper reaches of a model estuary adjacent to an enclosed basin.

A three dimensional, primitive equations, time dependent, σ co-ordinate free surface, eustarine and coastal ocean circulation model was developed by Blumberg & Mellor. The model performance has been tested in variety of applications such as coastal circulations simulation of tides in Chesapeake Bay, simulation of coastal circulation off Long Island, New York and general circulation in the Middle Atlantic.

Recent oceanographic studies, model simulations and satellite data have added significant details to our knowledge of the Black Sea circulation. Some mesoscale eddies have been revealed. For example, several anticyclonic eddies have been observed. The most prominent sub-basin scale feature is perhaps the quasi-permanent Batumi eddy located eastern most basin of Black Sea.

Similarly, Köse et al. investigated the effect of bottom topography on coastal currents and measured riverine suspended sediment distribution in the coastal waters. To our knowledge, no extensive analyses of coastal current and river plume dynamics have been carried out in previous Black Sea modeling studies.
This research aims to demonstrate that by using a numerical model, adapted to coast of Black Sea, one can simulate the coastal current and river plumes. Our aim is not to describe yet another new model of Black Sea, but rather to present new results obtained from the modeling system CARDINAL. The study herein has not attempted an ecological analysis that would include biological, chemical and geological considerations, such as the influence of fresh water discharge on marine life, dilution rates of the important pollutants in the study area.

Materials and Methods

Study area

The in situ measurements were made monthly (March 1998 to December 1999) in 20 marine and 2 river stations. (Fig. 1). In this study, 5 line perpendicular to coast (Arakh, Surmene, Yeniay, of, lyidere) and 4 stations (1 km, 2.5 km, 5 km, 10 km) on this line were selected. Co-ordinates of these stations were fixed by using Magellan NAV 5000D GPS. Water samplings were conducted between 10:00 and 16:00 hours and from surface and 25 m depth. Basic parameters (temperature, salinity, and conductivity) were measured up to 200 m depth. Temperature and salinity were measured by using Aanderaa RCM 9. Then density was calculated by using UNESCO formulae.

Meteorologic and hydrographic data

Some of the data used in this study were obtained from different sources. Flow rates of rivers were taken from state water organization (Table 1). Precipitation and wind data were obtained from State Meteorological Office. However, wind measurements from land stations underestimate the magnitude of wind above sea surface. This is mainly due to differences in characteristics of the atmospheric planetary boundary layer over land and water. Wind speed over sea surface was found as:

\[ U_{sea} = 3.0(U_{land})^{0.67} \]

where, \( U_{sea} \) = wind speed over sea surface (m/s) and \( U_{land} \) = measured wind speed (m/s). Analysis of this wind data showed that direction of wind is mostly NNW in Trabzon. Monthly averaged wind speed is shown in Fig. 2.

Mathematical modeling

CARDINAL system allows to create computer models of different water objects and to simulate non-steady water dynamics, dispersion of pollutants, and transport of sediments using curvilinear co-ordinates with options for two-dimensional or three-dimensional conditions. It simulates the long wave dynamics and dispersion of pollutants in any complicated area using the depth-averaged shallow water equations for two-dimensional conditions and the equations of a non-steady boundary layer for three-dimensional conditions. The framework of the model is produced by the means of boundary-fitted curvilinear co-ordinates (BFC) and mapping of a

| Table 1 — Monthly averaged flow rates of Solaklı and Sürmene Rivers (m³/s) (1999) |
|------------------|---|---|---|---|---|---|---|---|---|---|---|---|
|                | J | F | M | A | M | J | J | A | S | O | N | D |
| Solaklı         | 7 | 7 | 12 | 22 | 41 | 38 | 23 | 13 | 11 | 11 | 10 | 9 |
| Sürmene         | 4 | 4 | 8  | 15 | 36 | 33 | 21 | 10 | 8  | 7  | 7  | 3 |

Fig. 1 — Study Area and Locations of Stations
given domain onto one rectangle or a system of rectangles. The BFC method may achieve a fine grid resolution in important regions and more accurate solutions than using the rectangular grids. The equation of dispersion of pollutants is solved by the third and first order implicit up-stream conservative finite-differences. This solution method does not diffuse pollutants much, but does prevent numerical oscillations.

Geometry and bathymetry of the area of computation, locations of the open boundaries and boundary conditions, loading of pollutants, time/space variable wind and atmospheric pressure fields, bottom roughness field, relations for empirical coefficients, initial conditions were inputted.

CARDINAL is capable to compute the vertical structure of the flow. All you need is to set horizons: their number and the relative distances between them. Sigma-transformation is used, so all layers will be inside computational domain.

In 3D approach the next system of equations is solved in the CARDINAL modeling system

\[
\begin{align*}
\rho \frac{\partial u}{\partial x} + \rho \frac{\partial v}{\partial y} + \rho \frac{\partial w}{\partial z} &= \frac{\partial P}{\partial x} + \rho g \zeta, \\
\frac{\partial P}{\partial z} &= \left[ f_y \right]_{\xi} = \rho g \zeta, \\
u_x + u_x v_x + v_y w_x + w_z = -\frac{\partial P}{\partial x} + f_x + K(u_{xx} + u_{yy}) + (k_x), \\
u_y + v_x v_y + v_y w_y = -\frac{\partial P}{\partial y} + f_y + K(u_{xx} + u_{yy}) + (k_y), \\
u_z + w_x w_z + w_y w_y = -\frac{\partial P}{\partial z} + f_z + K(u_{xx} + u_{yy}) + (k_z),
\end{align*}
\]

where, \( \zeta \) is water volume, which comes from internal sources in the unit volume per second; \( c_s \) is concentration in sources; \( \lambda \) is the unconservativity coefficient; \( k_c, K_c \) are the coefficients of diffusion in the vertical and the horizontal directions; \( w_0 \) is the vertical velocity due to the buoyancy force; \( K \) and \( k \) are the coefficients of eddy viscosity in the vertical and the horizontal directions; \( P_A \) is the atmospheric pressure; \( U \) and \( V \) are full fluxes; \( f_b \) is the bottom friction coefficient. The equations are solved after turning to curvilinear boundary-fitted co-ordinates (Fig. 3.)

The model computed realistic flow patterns for the variety of dynamical processes that were combined herein. The model exhibited the ability to accommodate various scales, both in space (shallow coastal and deeper shelf) and in time.

\[
U = \int u \, dz, \quad V = \int v \, dz, \quad H = h + \zeta
\]

In 2D approach the equations take the form

\[
\begin{align*}
U_x + \frac{U^2}{H} + \frac{U V}{H} &= -g H \zeta - \frac{g H^2}{2 \rho_r} - \frac{H}{H} \frac{\partial P}{\partial \xi} \\
&+ f V + K \Delta U + C_D \frac{\rho_w}{\rho_0} W_{(x)} |\overline{W}| - f_b \frac{U |\overline{V}|}{H^2} \\
V_y + \frac{U V}{H} + \frac{V^2}{H} &= -g H \zeta - \frac{g H^2}{2 \rho_r} \\
&- \frac{H}{\rho_0} \frac{\partial P}{\partial \eta} + f U + K \Delta V + C_D \frac{\rho_w}{\rho_0} W_{(y)} |\overline{W}| - f_b \frac{V |\overline{V}|}{H^2} \\
\zeta_x + U_x + V_y &= w_x \\
(\overline{\zeta} H)_x + (U \overline{\zeta})_y + (V \overline{\zeta})_y &= K \overline{\zeta} - \lambda \overline{\zeta} H + \overline{\zeta} w_z - f_z
\end{align*}
\]

where, \( w_x \) is water volume, which comes from internal sources in the unit volume per second; \( c_s \) is concentration in sources; \( \lambda \) is the unconservativity coefficient; \( k_c, K_c \) are the coefficients of diffusion in the vertical and the horizontal directions; \( w_0 \) is the vertical velocity due to the buoyancy force; \( K \) and \( k \) are the coefficients of eddy viscosity in the vertical and the horizontal directions; \( P_A \) is the atmospheric pressure; \( U \) and \( V \) are full fluxes; \( f_b \) is the bottom friction coefficient. The equations are solved after turning to curvilinear boundary-fitted co-ordinates (Fig. 3.)

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Fig. 3 — Seasonal Sigma-t, Salinity and Temperature Distribution in the Eastern Black Sea; a) Spring b) Summer c) Autumn d) Winter
velocity vector with components $w_x$ and $w_y$, and $f_b$ is the bottom friction coefficient.

For solving these equations in an arbitrary water domain a transformation to curvilinear boundary-fitted co-ordinates $\xi = \xi(x, y)$, $\eta = \eta(x, y)$ is made. Along the lateral boundaries one of the co-ordinates is fixed and other is distributed arbitrarily, but monotonously. Transformation to curvilinear co-ordinates makes it possible to increase considerably the accuracy of computations. The computational domain is mapped on a rectangle or on a system of rectangles. The curvilinear grid generated by solving a set of elliptical equations. A deficiency of using the Cartesian velocity components in curvilinear co-ordinates is the interpretation of zero normal component of velocity vector at solid lateral boundaries, which leads to a cumbersome averaging procedure. For the simplification of boundary conditions the contravariant components of velocity vector instead Cartesian ones are introduced. The transformed equations are solved with a semi-implicit numerical method with a non restrictive stability condition. It should be noted that the numerical scheme used in the model becomes unstable when water velocities exceed the super critical values.

**Boundary and initial conditions**

Open boundaries in this program may be of four types. For the *discharge type* (D) open boundaries the time dependent discharges should be defined. The *discharge type* open boundary may be used for the river mouths, which run into the computational area (seas, lakes) or come out from it (lakes), or for two cross-sectional boundaries of computational domain, which presents a river part. For the *level type* (L) open boundaries the time dependent surface levels should be defined. Discharges through these boundaries will be computed using values of level. The *level type* may be used for sea open boundary where measurements of sea level oscillations are often available or for the cross-sectional boundaries of a river. For the *free exit type* (F) the so called radiation condition is used.

$$ u = \sqrt{\frac{g}{h}} \zeta $$ \hspace{1cm} \ldots (9)$$

where $u =$ velocity; $h =$ depth; $\zeta =$ level.

Through the sections of open boundaries of this type water disturbances may exit the area of computation. The free exit type also may be used for the lower cross-sectional boundary of a river if there are positive values of surface levels - for the negative ones this boundary condition gives ingoing fluxes. The main application of the free exit boundary type is for problems with open boundaries through which water level disturbances should leave the computational domain. The free exit relation is precise for one-dimensional linear waves, for two-dimensional waves this relation is an approximation. It is not correct to assign this boundary type for the boundaries through which ingoing fluxes are expected, for example due to wind action. The last type of the open boundary *Forecasted discharges* is rather specific one and it is used to import in the model forecasts of water discharges from an outer model.

A reasonable value of the time step for computations of water dynamics is connected with the time of propagation of the gravitational waves across a grid cell. This time is proportional to the grid size and inverse proportional to the depth in a grid cell, and is determined by the *Courant-Friedrich-Lewy*, CFL condition (Eq. 10). The program uses implicit numerical scheme for the gravitational mode, so the stable condition here permits any value for the time step but if its value is too large the numerical oscillation may appear in the solution.

If the advection terms are turned on in the Dynamics window, then the time step is restricted by the condition indicated as Eq. 11. Note that computations become unstable if water velocity exceeds velocity of gravitational waves (Eq. 12), but for such ('super critical') motions calculation without advection terms has no meaning:

$$ \Delta t < \frac{\Delta x}{\sqrt{gh}} $$ \hspace{1cm} \ldots (10)$$

$$ \Delta t < \frac{\Delta x}{v} $$ \hspace{1cm} \ldots (11)$$

$$ v < \sqrt{gh} $$ \hspace{1cm} \ldots (12)$$

where $\Delta t =$ timestep; $\Delta x =$ grid step; $v =$ water velocity; $g =$9.81 m/s$^2$; $h =$ depth; $\sqrt{gh} =$ velocity of long wave.

**Results and Discussion**

The fresh water that is brought to the continental shelf by rivers is both medium for a number of land-drained tracers of various lifetimes and a relatively long lived tracers itself. The path that water of river
origin follows can thus be viewed as an indication of the predominant circulation pattern. The pathway that river borne materials most likely to follow is examined here based on the forcing mechanism that are the focus of the present study, namely river runoff, wind stress. The purpose of this exercise is to offer an application of the understanding of the model computed circulation patterns aimed towards the understanding of the extent of impact that land drainage (which is largely controlled by man-related activities) might have on the coastal waters.

In order to model circulation characteristic, initial values of temperature, salinity, and density ($\sigma_t$), were needed. Therefore, these values were measured monthly since 1997 (Fig. 4).

At first, the Solaklı and Sürmene rivers were considered as the only source of fresh water to the study area. Annual mean of ~17 and 13 m$^3$/s for Solaklı and Sürmene rivers were specified as discharge rate (Table 1).

Although, simulations were done for several different conditions, only three results were given here. These results were to simulate dry and rainy seasons. The first simulation was done for the May 1999. Input values for this run are as follows, river discharge rate 41 m$^3$/s, 34 m$^3$/s for Solaklı and Sürmene rivers respectively, (monthly averaged), wind speed is 10 m/s NNW.

The measured velocity values are shown in Fig. 5A and modeled velocity distribution is illustrated in Fig. 5B. As seen from these figures, a flow pattern of jet like offshore “streamers” was observed in the vicinity of rivers. This tongue like distribution of coastal waters happens during spring as a transient rather than persistent pattern$^{23}$. This is simulated by our simulation, which showed that the streamers formed only during the high discharge conditions that characterize the spring season (due to high precipitation and snow melting). This agrees with the simulations were done by Kourafalou$^{24}$ on the part of the continental margin that extends from approximately West Palm Beach to Cape Hatteras, North Carolina. It is seen from Fig. 6A. that, surface current is affected by wind. First, currents at river months are towards the North, then turns to east under the effect of wind forcing.

Simulation for February 1999 was done by integrating with 10 m/s westward wind forcing, typical of a wind event during winter. As seen from Fig. 7 A,B and 6 B cross shore development was considerable diminished, and the plume occupied the shallowest part of the shelf. Northward spreading of the head was totally eliminated. Kourafalou$^{22}$ simulated river plume at North Adriatic Sea and Northwestern Agean Sea, and showed that under favourable conditions, river plume occurs close the shelf. Same forcing mechanism occurred here. When general circulation of Blacksea combined with westerly wind and low flow rate of the river, plume developed to close the shelf.

![Fig. 4 — Grid points of the study area](image)

![Fig. 5 — A) Measured current speed, B) Calculated current speed for May 1999](image)
Figure 8 A and B presents measured and the model-computed, near surface current field during July period. The high river discharge created the large amounts of low-density water that are found near major rivers. The atmospheric conditions, however, were not favorable for offshore removal of this water due to small magnitude of wind stress vector. The low-salinity band was thus contained within inner shelf and the current were mainly buoyancy driven, exhibits a strong offshore component near the river months and eastward (alongshore) flow (Fig. 6 C).

When the buoyancy driven Northward flow is forced by westerly wind force, the change of coastal current direction and the timescale of this flow adjustment are determined by the relative magnitude of wind and buoyancy forcing. Thus, while light wind (>5 m/s) have a minimal effect on strong plumes,
moderate to strong wind (5-10 m/s) may fully change
the direction of buoyancy driven current within a few
hours (depending on the flux rate, “plume strength”).

The shelf response to the combined input river
runoff and wind stress will be determined by the
relative strength of the outflow, the rivers location,
and the magnitude, direction and duration of wind
stress. The seasonal variability of the two forcing will
therefore, influence the removal of low salinity waters
from inner shelf.

During the simulation of wind stress and fresh
water discharge forcing, the followings are derived.
The shelf response to the input of river flow and wind
stress will be determined by the strength of the
outflow, the river location, and magnitude and
duration of the wind. The seasonal variability of two
forcing will therefore influence the distribution of low
salinity water. During the wind reversals and
relaxation of wind field (which could allow plume to
strengthen), it is possible to have opposite alongshore
flows in the vicinity of rivers.

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