OF SUSPENDED SOLIDS ORIGINATED FROM THE BLACK SEA INTO THE NORTH AEGEAN COASTAL AREA

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ABSTRACT

The current paper deals with the study of the transport, accumulation and settlement of the suspended solids, that transport from the Black Sea into the North Aegean through the Dardanelles Straits, using the hydrodynamic model ELCOM and the environmental model CAEDYM. Climatological factors, such as air temperature, relative humidity, wind speed, wind direction, solar radiation, atmospheric pressure and rainfall that affect the water circulation and subsequently the suspended soil distribution in the North Aegean as well as the Coriolis force effect, are taken into account. The discharge, the salinity and the water temperature from the Dardanelles are taken to be seasonally varied. The simulation was conducted for suspended solids (SSOL) of 2μm diameter. The results indicate that the suspended solids are transported by the Dardanelles surface water plume in the North Aegean and are distributed and accumulated in its water column. The region of the North Aegean that is more affected by the presence of the Black Sea suspended solids is the Thracian Coastal Area.

Keywords
Dardanelles; North Aegean; Black Sea; surface buoyant plume; Coriolis; hydrodynamic simulation; suspended solids

1. INTRODUCTION

The water exchange between the Mediterranean Sea and the Black Sea occurs within the Dardanelles Straits. The upper surface layer of 10m depth which originates from the Black Sea and is directed to the Aegean Sea presents low salinity and temperature values, while the lower layers which are situated from 10m to 55m depth contains water masses of high salinity, which are originated from the Aegean Sea and are directed to the Black Sea. This physical mechanism, that has been created since the ancient years in the Dardanelles Straits constitute one of the most important factors that influence the hydrodynamic and the biochemical characteristics of the North Aegean water column.

The Black Sea is a basin area of 1,800,000 km^2. The environmental degradation of this basin is enforced by its natural and geographical characteristics. The anthropogenic activities from 17 countries with total population of 165.000.000 influence the ecological parameters of the Black Sea. Nowadays, the main problems of the Black Sea include the progressive degradation of the coastal environment due to ground erosion, the continue degradation of the water quality due to the progressive eutrophication, the extension of the hypoxic and the anoxic regions, the enrichment of the eutrophic regions with H_2S, and the continue accumulation of pollutants originated from land and air including and quantities of radionuclides (Sur et al, 1994; Sur et al, 1996; Buesseler, 1987; Buesseler and Osvath, 1999; Kourafalou and Stanev, 2001).

The N.Aegean is characterized as an oligotrophic region despite the fact that it is the receiver of important water masses from the Black Sea basin which are rich in nutrients that can modify its trophic condition to mesotrophic or oligotrofic. Furthermore, the suspended solid particles that outflow in the N.Aegean can transfer harmful substances which can lead to the N.Aegean water quality degradation.

The aim of this paper is to investigate the movement, the dispersion and the accumulation of the suspended solids (SSOL) that originated from the Black Sea and outflow in the water surface layers of the North Aegean Coastal Area through the Dardanelles Straits, using suitable numerical models such as the 3D hydrodynamic model ELCOM (Estuary and Lake Computer Model) and the aquatic ecological model CAEDYM (Computational Aquatic Ecosystem Dynamics Model). The hydrodynamic ELCOM and the environmental CAEDYM, were developed in the Center of Water Research in the Western Australia University and are used for the numerical simulation of lakes, estuaries and enclosed oceans.

2. DESCRIPTION OF THE HYDRODYNAMIC MODEL ELCOM AND THE AQUATIC ECOLOGICAL MODEL CAEDYM

The ELCOM that is used for the numerical simulation of the present paper, is a three-dimensional hydrodynamic model for estuaries, lakes and enclosed seas, and is mainly used to predict the variation of water temperature and salinity in space and time (Hodges, 2000). It applies hydrodynamic and thermodynamic models to simulate the temporal behavior of stratified water bodies with environmental forcing. The hydrodynamic simulation method solves the unsteady, viscous Navier-Stokes equations for incompressible flow using the hydrostatic assumption for pressure. Modelled and simulated processes include baroclinic and barotropic responses, rotational effects, tidal forcing, wind stresses, surface thermal forcing, inflows, outflows, and transport of salt, heat and passive scalars. The hydrodynamic algorithms are a semi-implicit, finite-difference approach based on a second-order Euler-Lagrange advection of momentum with an implicit solution of the free surface evolution. Passive and active scalars (i.e. tracers, salinity and temperature) are advected using the conservative ULTIMATE QUICKEST discretization. The transport equations are the unsteady Reynolds-averaged Navier-Stokes (RANS) as well as scalar transport equations, using the Boussinesq approximation and neglecting the non-hydrostatic pressure terms. The free surface evolution is governed by a vertical integration of the continuity equation applied to the Reynolds-averaged kinematic boundary condition. The user is required to supply meteorological information (e.g. solar radiation, wind-speed and direction, humidity and air temperature) and inflow and outflow volume fluxes.

CAEDYM is an aquatic ecological model that may be run independently or coupled with hydrodynamic model ELCOM. CAEDYM consists of a series of mathematical equations representing the major biogeochemical processes influencing water quality. CAEDYM incorporates set of library subroutines that contain process descriptions for primary production, secondary production, nutrient and metal cycling, and oxygen dynamics as well as the movement of sediment. By simulating several state variables at the species level, CAEDYM can be used to support the understanding and management of a system. In addition, the model can be coupled to the three-dimensional hydrodynamic model ELCOM for studies of the seasonal, annual or decadal variation in water quality. To maximize speed and memory requirements CAEDYM shares a common internal data structure with ELCOM. They also use common output data storage formats, and share common Graphical User Interface (GUI) and visualization routines for model configuration and results interpretation.

3. MODEL INPUTS AND SET UP

The selected region of the North Aegean Sea that is used for the numerical simulation of the present investigation is depicted in Figure 1. As it can be seen it is bounded to the north and west by the Greek mainland and to the east by the Turkish coastline. The south open sea boundary is located before the south end of Chios Island. A rectangular computational grid was constructed, consisting of uniformly distributed horizontal cells with a breadth and width of 4 km, (Figure 1). In the vertical direction 200 layers of 5m thickness each, were used. Therefore, the first 1000m depth are taken into account for the simulation. To avoid numerical diffusion during the calculations the constructed numerical grid is rotated 17.48 degrees clockwise from the north, in order for the Dardanelles outflow to be parallel to the horizontal grid lines.

The selected time step for the calculations is 3min and a total real flow time of 6 years is simulated. The starting date for the simulation is selected to be the beginning of winter on 1 January 2005, when the water column was well-mixed and freshwater inputs were confined to the eastern margins. The corresponding ending date is selected to be on 31 December 2010. Winter is defined as December-February, spring as March-May, summer as June-August and autumn as September-November. The Black Sea Water (BSW) entering the model domain via the Dardanelles Straits and the water of the North Aegean Sea exiting the model domain at the Hellespont, are simulated as point sources. The river inflows in the North Aegean Sea are neglected, as they can be considered negligible in relation to the massive mean annual discharge from the Dardanelles Straits. Daily discharges, available in the literature, are used for inflows and outflows at the Dardanelles exit to the North Aegean (Figure 2).

The maximum and minimum discharges in the upper layer occur in winter and summer, respectively. Mean annual values of the discharges at the Aegean exit are at about 38820 m^3/s in the upper layer (from the Dardanelles into the Aegean) and 30000 m^3/s in the bottom layer (from the Aegean into the Dardanelles). The seasonal variability of volume fluxes in the bottom layer of the Aegean exit is 9600 m^3/s. The variability of the discharges in the upper layer is much weaker (about 6115 m^3/s). These differences could be explained by the contribution of the baroclinic component that is caused by the density difference between the two basins (Unluata et al, 1990, Kanarska and Maderich, 2008). The water inflow (from the Dardanelles into the Aegean) takes place within the first 10m depth, while the water outflow (from the Aegean into the Dardanelles) takes place from 10m to 55m depth.

4. INITIAL CONDITIONS, BOUNDARY CONDITIONS AND FORCING FIELDS

Initial conditions over the whole model domain were set as varying temperature and homogeneous salinity profile that were derived from literature sources (Kanarska and Maderich, 2008) as it is shown in Figure 2b. Since the simulation begins on January of 2005 the initial condition for the water temperature according to Figure 2b is assumed to be 14.5°C.

The open boundary condition for the model domain was selected at the boundary between the Northern and Southern basins (Figure 1), to minimize boundary-forcing effects on the main area of interest, in the Dardanelles outflow as well as in the circulation patterns of the North Aegean Sea. Model inputs for this boundary included homogeneous profiles of temperature and salinity derived from field measurements at stations in the Island of Mykonos by the Poseidon system of the Hellenic Centre of Marine Research. Typical salinity and temperature profile values used as open southern boundary forcing conditions, for 3 years of simulation (2008-2010), are depicted in Figures 3a, 3b.

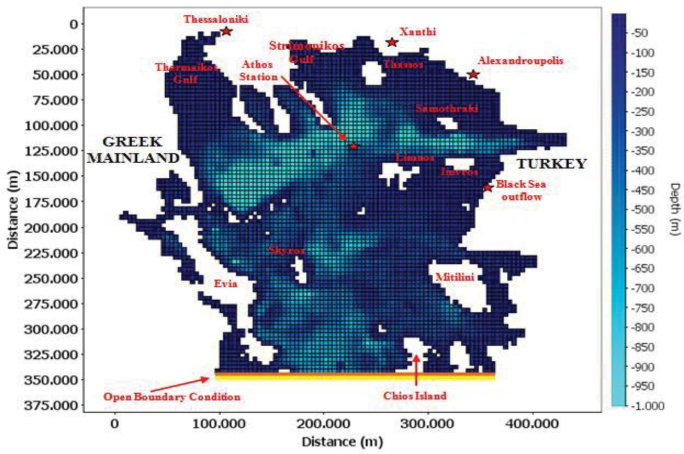
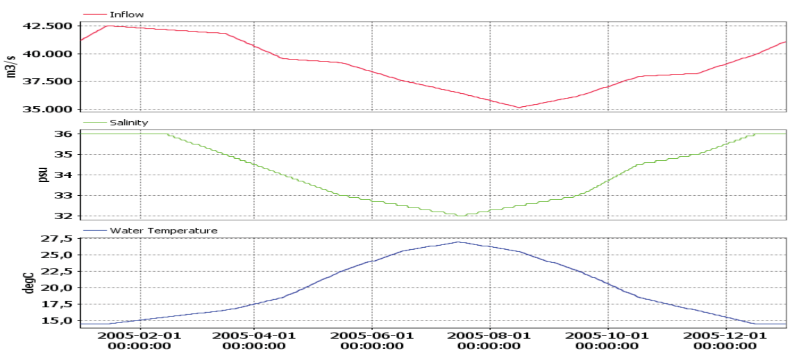
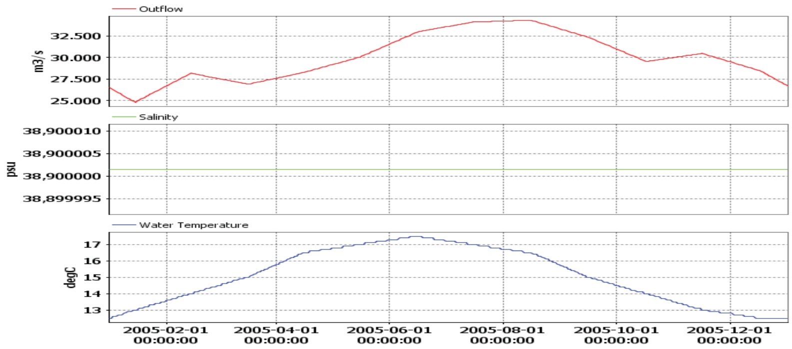


Figure 1. North Aegean Sea bathymetry and horizontal computational grid that were used for the simulation of the present paper.



(a)



(b)

Figure 2. Used seasonal variability of the discharge, salinity and water temperature at the North Aegean exit of the Dardanelles Straits for the year 2005, (a) in the upper (inflow) and (b) bottom (outflow) layer respectively (Kanarska and Maderich, 2008; MEDAR Group, 2002).

The salinity and temperature of the inflowing and outflowing water that were applied at the Dardanelles exit to the North Aegean are depicted in Figures 2a, 2b. The two-layer exchange flow at Dardanelles is primarily controlled by mixing and friction at much shorter time scale. Therefore, the magnitude of Dardanelles outflow alters weekly in response to local environmental conditions, such as the short term wind episodes. In order to approach more realistically the impact of the Dardanelles outflow in the North Aegean, a high frequency (daily) superimposed forcing was applied for the outflow and inflow boundary conditions.

A 6 year period (2005-2010) of meteorological data consisting of 10 minutes frequency readings of solar radiation, air pressure, air temperature, relative humidity, wind direction and wind velocity measured at the Genisea meteorological station at North Greece, were applied over the whole domain for the corresponding simulation period (2005-2010). The Genisea station is stated in the city of Xanthi and belongs to the authority of the Democritus University of Thrace. The prevailing wind situation is characterised by wind speeds varying from 3m/s to 7.5m/s, with strong northerly winds prevalent in summer and even strongest (up to 16m/s wind speed) northeasterly winds in winter (Poulos et al, 1997). Typical values of meteorological data used for the present study from Genisea station are given in Figure 4 indicatively for the year 2008.

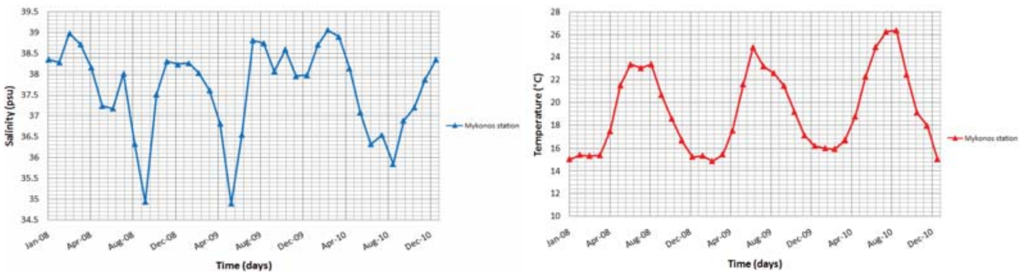
The ELCOM and CAEDYM models were successfully coupled to simulate the suspended solids distribution in the N.Aegean water column by using a series of data concerning their physical characteristics such as density, diameter, settling velocity etc. Additional data was used by field measurement that found in the literature and concern the average monthly outflow of the suspended solid particles at the Dardanelles Straits. The suspended solids (smectites) that used for the present simulation they have diameter 2.5μm and density 2650kg/m^3 (Post 1989 and Douglas 1990). Figure 5 illustrates the suspended solids outflow from the Dardanelles Straits into the N.Aegean in 2009 (Turkoglou, 2010b; Turkoglou, 2010c and Ehrmann et al, 2007). The same initial condition regarding suspended solids input are also used for the previous years of the simulation.

5. MODELS SIMULATION

ELCOM and CAEDYM models have been successfully calibrated and validated for the North Aegean in the PhD Thesis of Kopasakis (2012). An investigation regarding to the N.Aegean water circulation was initially conducted, which is described in the following subsection (Subsection 5.1), followed by the study of the suspended solids movement in the N.Aegean basin (Subsection 3.2).

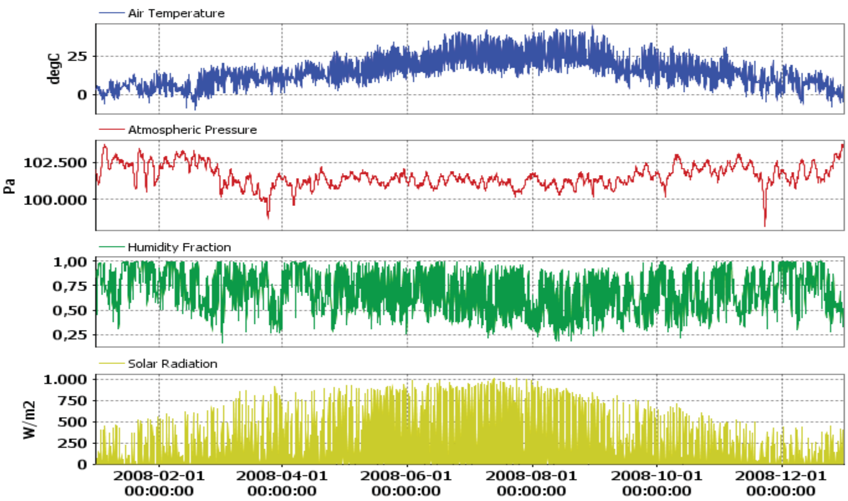
5.1. North Aegean water circulation

The main feature of the circulation in the North Aegean Sea is the BSW current, with surface velocities up to 0.8 m/sec. The Dardanelles water plume, during summer, after its entrance in the North Aegean, is diverted north passing through Limnos and Imvros islands and reaches the east part of Samothraki Island where it enforces the strong anticyclonic eddy (Figure 6a). Figure 6b, shows that the Dardanelles water plume, during autumn, splits in two different flows. The first flow reaches the east part of Limnos Island and is diverted to the north with velocities up to 0.6m/sec, while the second flow moves southwest to Limnos Island forming an anticyclonic eddy. This flow pattern that reaches the south part of Athos basin sets up one of the strongest currents in the North Aegean domain during that period with current velocities up to 0.7m/sec (Figure 6b). During winter the Dardanelles plume appears to be less energetic, with maximum current velocities just up to 0.3m/sec.



(a) (b)

Figure 3. Open southern boundary forcing conditions for ELCOM, from Mykonos station for (a)salinity and (b)water temperature.



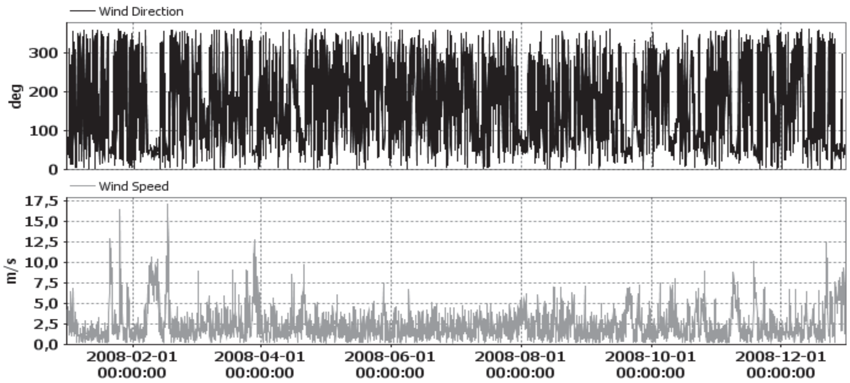


Figure 4. Typical time series of meteorological data recorded at the Genisea station in 2008.

5.2. Simulation of the suspended solids movement in the N.Aegean

The inorganic suspended sediment particles that are simulated in the present study with the use of ELCOM and CAEDYM models are clay suspended solid particles SSOL that are transferred from the Black Sea into the N.Aegean through the Dardanelles Straits. These clay minerals that outflow in the N.Aegean are mostly smectites according to Ehrmann et al, (2007) and Bayhan et al, (2001). In general, the suspended solids are used for studying the transportation paths within the oceans and the semi-enclosed seas, because they transferred and dispersed with the aid of water sea currents.

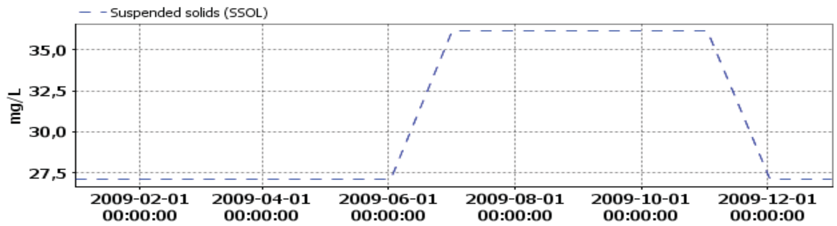
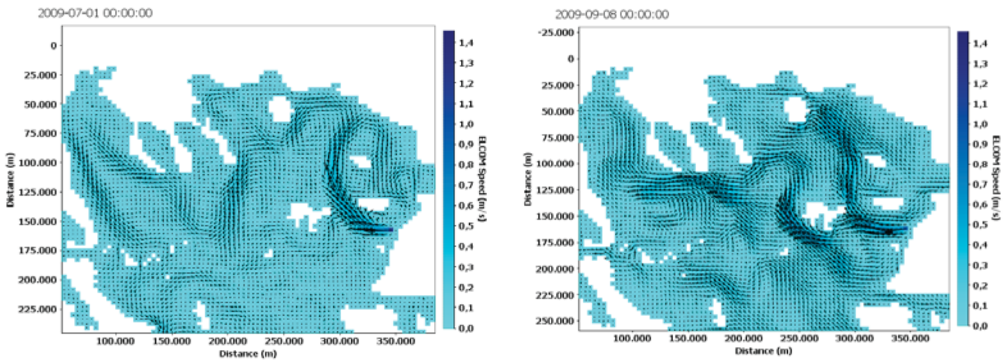


Figure 5. Black Sea suspended solids outflow in the N.Aegean Sea

The suspended solid particles that are formed from inorganic processes remain in suspension for a long time absorbing toxic metals such as nickel (Ni) and zinc (Zn) on their surface area (Premovic et al, 2007). Thus, these metals can be transferred via the surface currents in the N.Aegean coastal areas, where they settle in the lower water layers and causing water quality degradation.



(a) (b)

Figure 6. Surface water circulation of the N.Aegean for (a) 01/07/2009 and (b) 08/09/2009

According to Figure 7a, in January, the SSOL after their entrance to the N.Aegean from the Dardanelles Straits are transported by three flow regimes. The first flow regime, under the influence of the Coriolis force is directed along the coastal area (Turkish coastline) that is situated above the Dardanelles outflow region. The second flow regime forms an anticyclonic eddy between the Limnos and Imvros islands and the third flow regime reaches the south part of Limnos Island and then is diverted to the north, approaching the west part Limnos basin. During June, the flow of the suspended solids is more energetic, due to the high solid particles discharge at the Dardanelles outflow and involves a relatively wide set of velocity vectors with the same direction. The flow moves between Limnos and Imvros islands then reaches the south part of Thassos Island and diffused in the surface area of the Thracian Sea, regarding to Figure 7b. In September, the SSOL split in two paths. The first path includes an anticyclonic eddy that is formed around the Imvros Island while the second path includes a semi anticyclonic eddy that is formed around the Limnos Island (Figure 7c). Finally, in November the SSOL flow is moved less energetic between Limnos and Imvros islands and forms a meandric path up to the Thracian coastal area (Figure 7d).

The accumulation of the suspended solids in the bottom layer of the N.Aegean coastal area and more specific in the area situated from the Gulf of Xiros to the Gulf of Kavala and the north coastal area of Thassos Island is achieved during the summer period, when the thermal stratification occurrs in the N.Aegean water column. The increase of the suspended solids concentration in the proposed coastal area is due to the enrichment of the bottom layer with nutrients of phosphorus and nitrogen which leads to the increase of the phytoplanktonic mass and the chlorophyll-a concentration (Kopasakis, 2012). Quantities of phytoplankton that settled to the lower layers due to their decomposition, drag along, transfer and cause the accumulation of suspended solids at the bottom layer of the above areas.

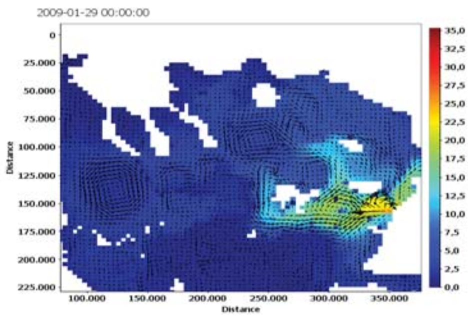
6. CONCLUSSION

The present study is an attempt to investigate interactions between the Black Sea outflows, the climate forcing, the surface water circulation and the Black Sea suspended solids movements, over a range of time and space scales in the North Aegean Sea. The main objective is to quantify these effects using a dynamic modeling and mass balance approach. It is the first approach of modeling the Black Sea surface plume in the North Aegean using a seasonal Dardanelles discharge that differs from previous studies and it is based in the work of Kanarska and Maderich (2008) approach, of the water exchange in the Dardanelles straits. Moreover, according to the authors' best knowledge, it is the first time that apart from the hydrodynamic characteristics of the proposed phenomenon (velocity field, salinity and temperature distributions), the long term fate and accumulation of suspended solids that are transported from the Black Sea into the North Aegean Sea, is numerically predicted. The main conclusions and findings of the present numerical investigation are summarized below:

1. Physical processes such as brackish buoyant Black sea water inputs, vertical mixing and basin scale circulation, are delicately balanced.
2. The use of a 3D physical-hydrodynamic model such as ELCOM coupled with an aquatic ecological model such as CAEDYM, is necessary to capture the large scale physical processes of the Black Sea suspended solids in the N.Aegean and to estimate the mass fluxes in this system with a high degree of spatial and temporal variability.
3. The main factor that influences the North Aegean water circulation is the surface buoyant mega plume that is formed from the brackish waters discharging from the Dardanelles Straits, under the effect of the Coriolis force and the wind stresses.
4. The Black Sea suspended solids that outflow in the N.Aegean disperse on the Thracian Sea surface and during summer, when thermal stratification occurrs in the N.Aegean water column, accumulate and settle at the bottom see-water layers.

5. Increased concentration of Black Sea suspended solids appears during summer at the bottom layer of the N.Aegean in the coastal areas of the east part of Limnos Island, the Imvros and Samothraki islands, the east and west part of Thassos Island and the coastal area between Alexandroupolis and Strimonikos Gulf, with values varying from 7.5 mg/l to 13.5 mg/l.

6. The flow of suspended solids that originate from the Black Sea is more energetic in the N.Aegean surface during summer, when a thermal stratification occurs in the water column. After their entrance in the N.Aegean from the Dardanelles Straits they are diverted to the north between the Imvros and Limnos islands under the effect of the Coriolis force, and reach the north part of Thasos Island.



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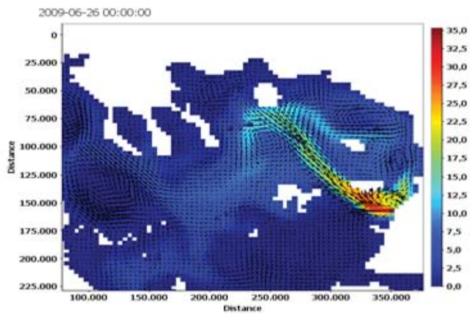

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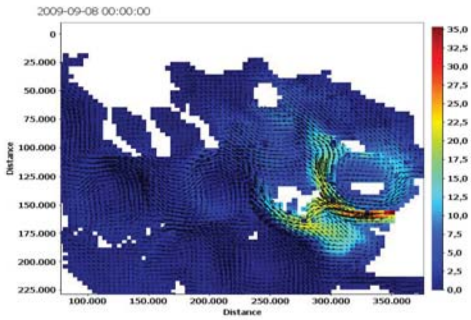

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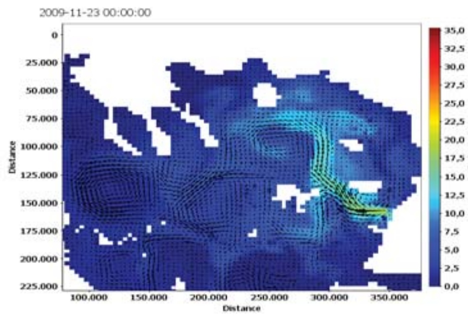
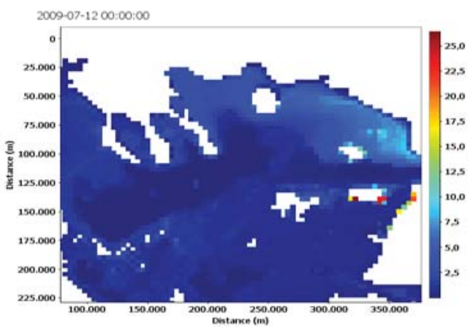


(d)

Figure 7. Black Sea suspended solids distribution in the N.Aegean surface layer for (a) 29/1/2009, (b) 23/11/2009, (c) 8/9/2009 and (d) 23/11/2009.



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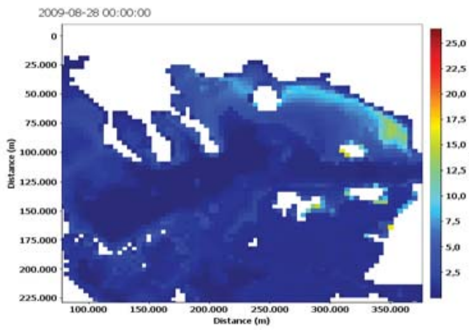

(b)

Figure 8. Black Sea suspended solids distribution in the N.Aegean bottom layer for (a) 12/7/2009 and (b) 28/8/2009.

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