SIMULATION OF THE DISCHARGE OF BRACKISH WATERS FROM THE DARDANELLES INTO THE NORTH AEGEAN

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Abstract

Nowadays, one of the most important sources of pollution for the North Aegean Sea is the water inflow from the Dardanelles straits and by extension from the Black Sea. The main aim of the current work is the study of the surface buoyant plume that is formed from the discharge of the brackish waters from the Dardanelles into the North Aegean Sea taking into account the effect of the Coriolis force in the root and dispersion pattern of the proposed plume. The study is carried out using both an experimental and a numerical model. For the experimental work a physical model of the North Aegean Sea constructed in a rotating tank is used and the experiments are carried out following the method of Flow Visualization. A comparison is made with properly processed satellite data in order to validate the experimental results. The numerical simulation of the proposed phenomenon is carried out using the ELCOM hydrodynamic model. From the comparison of the experimental, satellite and numerical data, it is concluded that the North Aegean Sea, is highly influenced by the Dardanelles outflow.

Keywords: Dardanelles, North Aegean, Black Sea, Plume, Coriolis

1. Introduction

Nowadays, one of the most important sources of pollution for the North Aegean Sea is the water inflow from the Dardanelles straits and by extension from the Black Sea which water quality has been highly aggravated within the last 30 years. As it is highlighted by many researchers, Black Sea is daily used as a disposal receiver for great amounts of industrial, agricultural, residential wastes that are produced by the activity of 160 million people that live in 16 countries around the Black Sea. The oil pollution in the Black Sea is estimated to be more than 100000 tones per year, without taking into account the illegal disposals from the oil tankers that seem to be a common secret in the area (Hatzikonstantinu A. et al., 2005). Despite the fact that the North Aegean Sea is deep enough with depths of up to 1200 meters, the topology and bottom morphology does not allow the exchange of water between North Aegean Sea and South Aegean Sea for depths greater than 200 meters.

The main aim of the current work is the study of the surface buoyant plume that is formed from the discharge of the brackish waters from the Dardanelles into the North Aegean Sea taking into account the effect of the Coriolis force in the path and dispersion pattern. The study is carried out using both an experimental and a numerical model. The experimental simulation is carried out using a physical 3d model of the North Aegean Sea constructed in a rotating tank with a diameter of 5 meters were a series of flow visualization experiments are performed. For the numerical approach the 3d hydrodynamic simulation of the proposed phenomenon is done using the hydrodynamic model ELCOM. Finally, the experimental and numerical results are compared with properly processed satellite images that indicate the proposed phenomenon and some valuable, qualitative and quantitative results are withdrawn.

2. Experimental Simulation

2.1 Construction of the North Aegean Sea physical model in the rotating tank

For the construction of the physical model, due to the finite dimensions of the available rotating tank, the technique of the distorted scale model was applied. Hence, the applied horizontal length scale was $k_{hor} = 10^{-5}$ and the corresponding vertical one was $k_{ver} = 10^{-3}$. All the necessary modeling scales are derived using dimensionless analysis and specifically Froude and Rosby number similarity. For the bathymetry of the North Aegean Sea physical model, that was constructed for the aims of the current work, a naval map of the North Aegean Sea was used which was obtained from the Hydrographic Service of the Military Navy in Greece. The laboratory model simulated the detailed shoreline, the isobaths as well as the bathymetry of the North Aegean.

2.2 Description of experimental set up and procedure

The rotating tank that is available at the Laboratory of Hydraulics in the department of Civil Engineering in the Democritus University of Thrace, where the physical model of the north Aegean Sea was constructed, has a diameter of 5.2 meters and its main characteristics are shown in the following figure (*Figure 1*).

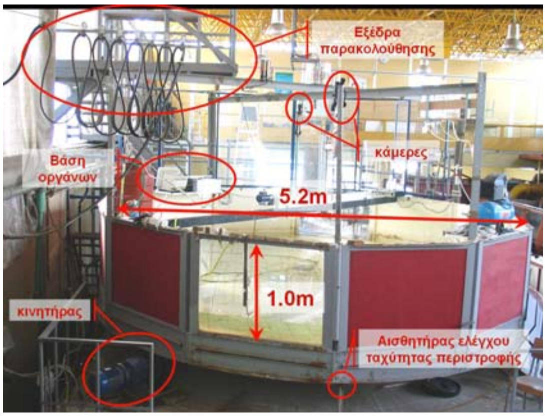


Figure 1. *Main characteristics of the rotating tank*

The experimental set-up used for the laboratory experiments consists of the rotating tank where the physical model of the North Aegean Sea was constructed, the video cameras used for the filming of the experiments, the head lamps that were used as lighting sources, the fresh water discharge apparatus (Dardanelles straits discharge), the fresh water storage tank, the fresh water coloring apparatus, the salinity meter in order to control the salinity of the saline water in the model (North Aegean receiving basin), the remote controls for all the electronic devises in the rotating tank and finally the apparatus for the saline water preparation and the filling up of the rotating tank before the beginning of each experiment. Fresh water was used to simulate in the model the discharge of Dardanelles straits into the rotating tank (Aegean Sea), taking care the salinity difference in the physical model between the discharge and the ambient water to be the same as the existing salinity difference in the prototype (Dardanelles straits-North Aegean Sea). For the experiments the flow visualization method was used using the coloring apparatus mentioned previously. A total of 6 experiments were conducted with tank rotation, and one without activating the rotating mechanism in order to investigate the alteration of the path and the dispersion pattern of the plume without the effect of the Coriolis force.

2.3 Experimental results

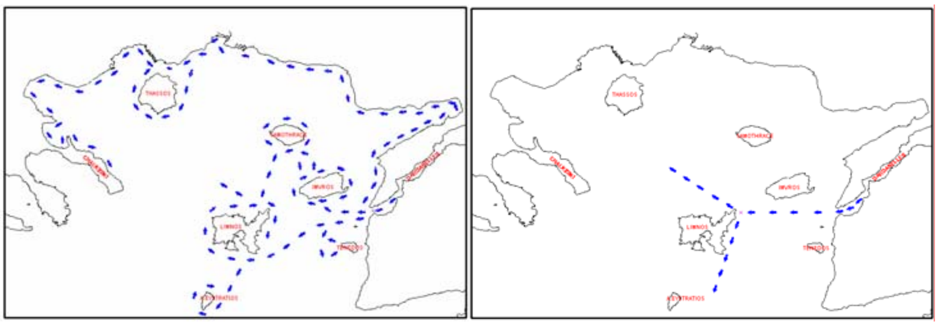
In *Figure 2* some indicative frames from the post-possessed experimental videos with all the appropriate details are illustrated. The grid shown in the frames corresponds to 10x10 km real distance (prototype).

Figure 2. *Indicative frames from the 2nd experiment*

The study and the comparison of the videos taken from the experiments that were conducted in a rotational environment, lead to the conclusion that the rotation produces cyclonic and anti-cyclonic movements in the path and the general dispersion pattern of the colored fresh water that discharges from the discharge apparatus (Dardanelles straits) into the saline water of the receiving basin in the rotating tank (North Aegean Basin).

In more detail, immediately after the start of the discharge from the Dardanelles straits and for a short time interval the colored fresh water (simulation of Dardanelles outflow) is moving straightforward forming an almost circular spot that gradually increases in all directions. After a while, the Dardanelles outflow is deflected to the right (North) and the circular spot is transformed in an almost elliptic one with its long axis almost perpendicular to the direction of the initial discharge. Then, one part of the Dardanelles outflow that was deflected to the north is heading to the south coasts of Imvros Island where it is divided into 2 sub-parts. One sub-part is spreading anti-cyclonically around the coastline of Imvros island and the other sub-part is heading north-east of Imvros Island and is spreading in a narrow zone along the continental coastline which is located to the right of the discharge point (Dardanelles). Simultaneously in the same time period a small cyclone is formed at the south of the discharge point in the area to the west of Tenedos Island. It should also be mentioned that another small cyclone is formed in the area between Imvos Island and Samothrace Island. Afterwards, for a long time period a new part of flow is formed that is heading to the south coasts of Limnos Island ant then starts to spread anti-cyclonically around it. At the end of this time period one sub-part of the part of the flow that spreads anti-cyclonically around Limnos island, is changing direction and heads towards the east of the island of Agios Eustratios were it starts spreading anti-cyclonically around the island. At the same time, two additional flow patterns are formed. One of them starts to spread anti-cyclonically around Samothrace Island and the other one is heading north-west until it reaches the south coasts of Thassos Island. The results from the experiment that was conducted without rotation present a substantial difference .The spreading pattern of the Dardanelles surface plume without the effect of the Coriolis force is completely different from the one described previously ,without any cyclonic and anticyclonic movements. In the following figures (*Figures 3a and 3b*) the general circulation patterns observed in the experiments are illustrated schematically for the experiments with and without rotation respectively.

The experimental observation that the plume from the Dardanelles Straits into the Aegean Sea, after some distance from the outflow is basically deflected to the north due to the effect of the Coriolis force, is in agreement with findings of Grigoriadou V. et al., 2005 , regarding the deflection of the surface buoyant plume from rivers outflows to sea .



a) b)

Figure 3. *Circulation of the water discharge from the Dardanelles straits into the North Aegean Sea: a) with rotation of the tank, b) without rotation of the tank*

3. Numerical Simulation

3.1 Description of the hydrodynamic numerical model ELCOM

The hydrodynamic model ELCOM was used for the numerical simulation. ELCOM (Estuarine and Lake Computer Model) has been developed in the Center for Water Research of the University of West Australia and constitutes a 3d hydrodynamic finite difference model, suitable for the simulation of lakes and enclosed sea basins. The main equations solved are the Reynolds equations for rotating systems (use of the Coriolis term), using the Boussinesq approximation and neglecting the non hydrostatic pressure terms. For the horizontal direction the turbulence is treated using a stable turbulent viscosity coefficient while for the vertical direction an energy model of layer mixture is applied. Density is calculated from the salinity and temperature through an algebraic equation, while the salinity and temperature are calculated through a differential equation of diffusion transport (Hodges B., 2000 & Hodges B. and Dallimore C., 2001).

3.2 North Aegean Simulation results

The Dardanelles outflow was simulated under simplified conditions so that the results to be directly comparable with the experimental results that where discussed previously. Hence, the discharge from the Dardanelles straits into the North Aegean Sea was considered to be steady while the variations of Dardanelles discharge due to the possible effect of the wind, the evaporation, the sun radiation or the effect of the precipitation were not taken into account. The meshing used consists of 4x4 km² horizontal grids with

20 horizontal layers of 5 meter depth each in the vertical direction. Hence, the maximum depth for the Aegean Sea is assumed to be 100 meters, which is satisfactory because, as it has been conformed from the experimental and numerical results, the syncline is formed up to a maximum depth of 50 meters. For the bottom a turbulent benthic boundary condition was applied, adopting a constant friction coefficient. It should also be mentioned that the total number of cells used was 140000. Sections A-A' and B-B' as well as the bathymetry of the North Aegean Sea that was used in the numerical model are illustrated in Figure 4 below.

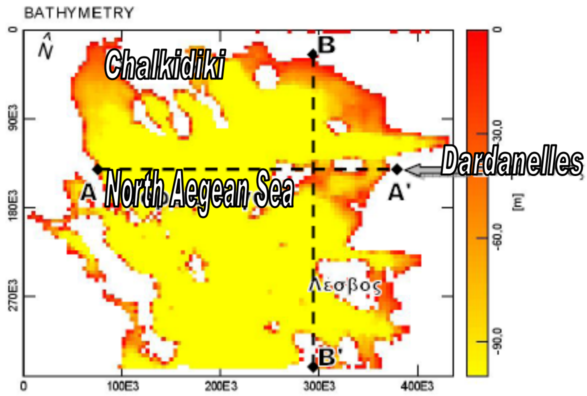


Figure 4. *North Aegean Sea Bathymetry and sections A-A' & B-B'*

The time step adopted for the calculations was 10 minutes (real time). The initial salinity of the ambient sea water in North Aegean was equal to 38.6 ppt and the initial sea water temperature was equal to 15.0 ºC that correspond to a sea water density value of 1028.75 kg/m³. The discharge width at the Dardanelles straits exit was taken to be 4 km while the corresponding discharge depth was taken to be 10 m. The Dardanelles outflow discharge was assumed to be constant and equal to the average annual discharge of 40000 m³/sec with a constant salinity of 29.6 ppt and a constant temperature of 14 ºC that yield a density of 1022.00 kg/m³ (Unluata U. et al., 1990). At the south edge of the control field, which was defined as the axis from the south of Chios Island to the north of Andros Island, an open boundary condition was applied with a constant water level of 0 meters that allowed passively the inflow or outflow of water from every cell according to the flow needs. During the inflow from the open boundary the same water properties were used as these used at the initial condition for the ambient water. A total of two tracers (TRACER_1 for the Dardanelles and TRACER_10 for the open boundary) were assumed to be contained into the water inflow from the Dardanelles straits to the North Aegean Sea and for the water inflow from the open boundary respectively. These tracers had a dimensionless concentration equal to 1 and could be assumed to be passive, diluted and conservative substances, or pollutants. The reason for using two tracers was to investigate the origin of the water contained in each cell of the control field and the corresponding mixing with the ambient water, during the simulation. The total simulation time was 3.5 years. After the first 3 years of simulation an almost steady state was achieved in the North Aegean and a new tracer (TRACER_9) was introduced to the water inflow from the Dardanelles straits into the north Aegean Sea. Using this tracer, the path and the dispersion pattern are obtained after a form of dynamic balance has been reached in the general circulation of the system, under the sole driving force of Dardanelles input. As it is shown in Figure 5 after a simulation time of 2.5 rears the average concentration of TRACER_1 obtains asymptotically a constant value, which is about 17% of the value of the TRACER_1 at Dardanelles exit. This means that North Aegean accumulate a considerable amount of the pollutants which outflow to Aegean from the Dardanelles.

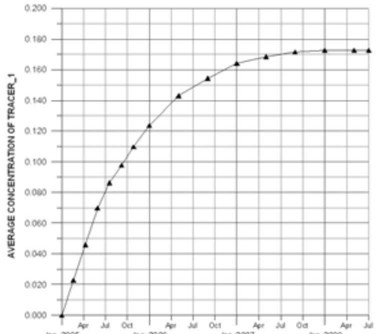


Figure 5. *Average concentration of TRACER_ 1 (entire control field)*

The basic numerical results at the surface layer of sea density, pollutant retention time, TRACER_ 1 and TRACER_10 dimensionless concentrations after 3 years of simulation are shown in figures 6(a), 6(b), 6(c) and 6(d) respectively. In figures, 7 & 8 the corresponding fields for the sections A-A΄ και B-B΄ of figure 4 are illustrated. The time evolution of the path and dispersion of TRACER_9, introduced at the Dardanelles straits three years after the start of the simulation, is illustrated in Figure 9.

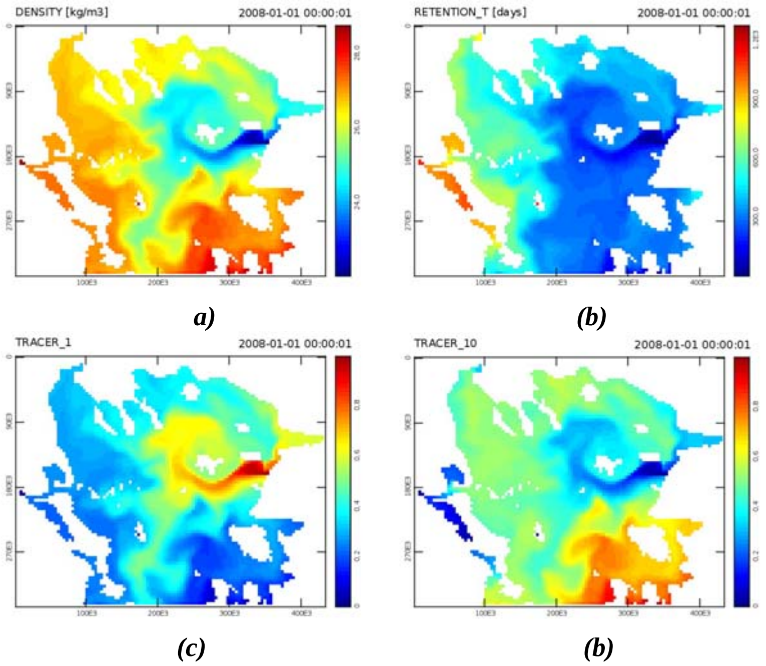


Figure 6. *Surface layer, 3 years from the start of the simulation: Distributions of (a) density, (b) retention time, (c) dimensionless concentration of TRACER_1 (originating from the Dardanelles straits) and (d) dimensionless concentration of TRACER_10 (originating from the open boundary).*

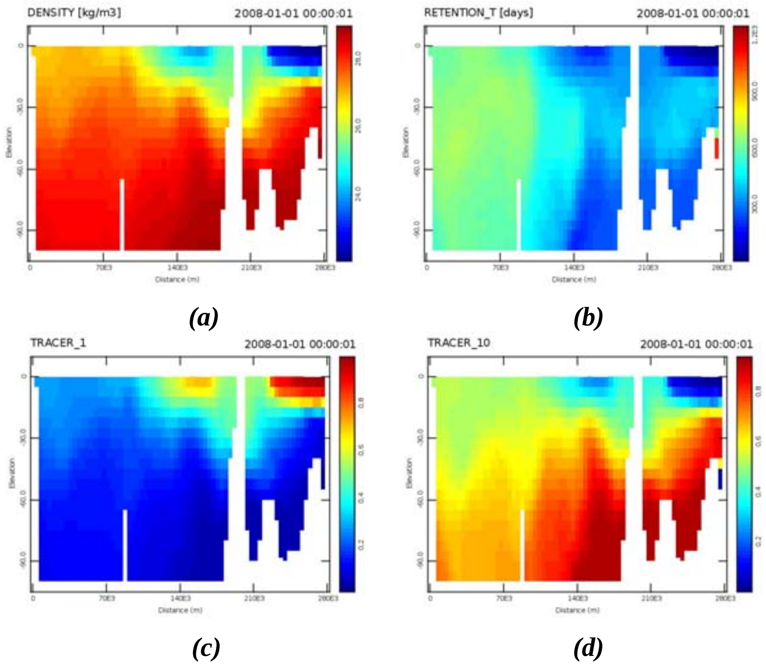
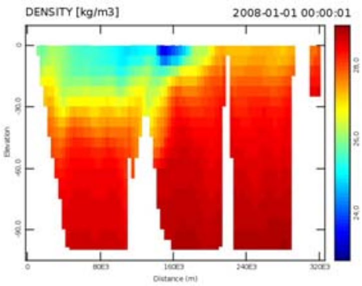
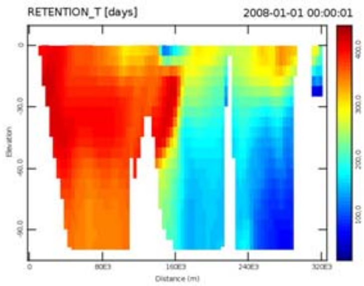
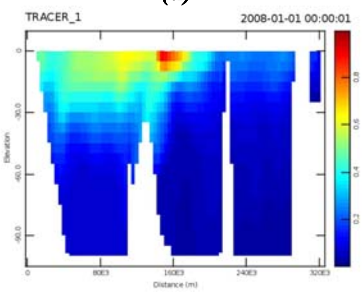


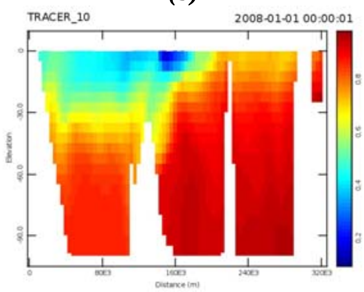
Figure 7. *Section A-A΄, 3 years from the start of the simulation: Distributions of (a) density, (b) retention time, (c) dimensionless concentration of TRACER_1 (originating from the Dardanelles straits) and (d) dimensionless concentration of TRACER_10 (originating from the open boundary).*





(a) ***(b)***





(c) ***(d)***

Figure 8. *Section B-B΄, 3 years from the start of the simulation: Distributions of (a) density, (b) retention time, (c) dimensionless concentration of TRACER_1 (originating from the Dardanelles straits) and (d) dimensionless concentration of TRACER_10 (originating from the open boundary).*

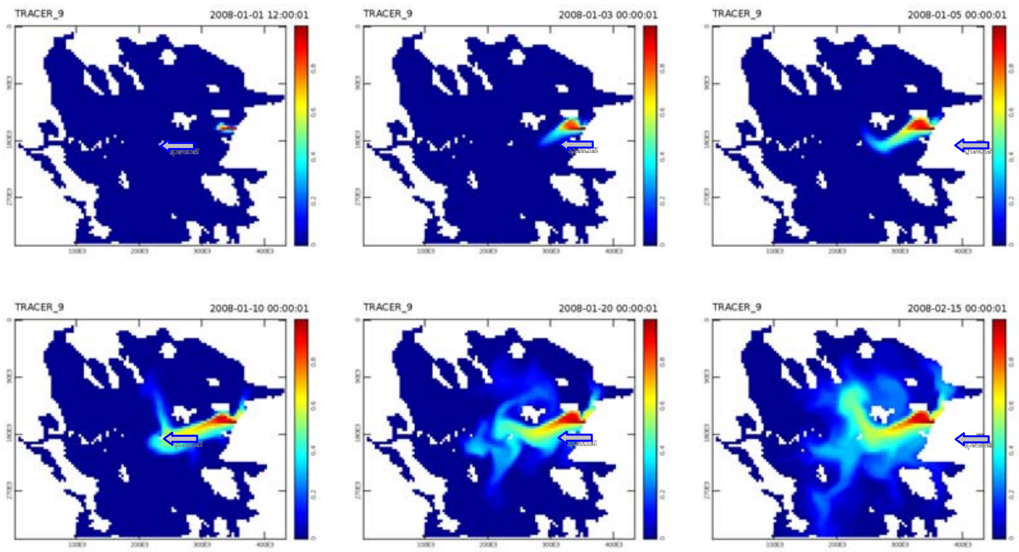


Figure 9. *Time evolution of the root and disperse pattern of TRACER_9 (originating from the Dardanelles straits, 3 years after the start of the simulation) in the surface layer.*

The numerical simulation indicated that, after 2½ years from the start of the simulation, the main regimes of the water situation remain stable (with small fluctuations). It is found that the main current from the Dardanelles straits is heading to the west, south of Limnos island, passes from the west of Limnos island and deviates its course to the north, heading to the Thracian Sea. In this region, the concentration of TRACER_1 (proportional to the pollutant load from Dardanelles) is found to be high enough (60% of the Dardanelles values). A secondary current originating from the Dardanelles straits deviates immediately to the right of the discharge point in the Dardanelles straits, following a path parallel to the coastline in the Xiros Golf and reaching the Greek coasts of Thrace and Macedonia. Another secondary current is traced southwest of Limnos Island, heading south-southwest and exiting the flow field to the east of the south edge of Evoia. Following TRACER_1 , it is observed that at the west of the south open boundary, part of Dardanelles water leaves the North Aegean, while following TRACER_10, at the east of the south open boundary, inflow of water from South Aegean is observed (Figure 6). This leads to the conclusion that that the inflow of water from the Levantine Sea into the East Aegean Sea (which has been observed in the past by many researchers) is basically driven by the hydrodynamic circulation that is caused in the North Aegean Sea from the Dardanelles straits outflow. Moreover, as it is obvious from the concentrations of TRACER_10 in sections A-A’ and BB’, the water inflow from the open boundary reaches up to the Thracian Sea in the lowest layers beneath the water originating from the Dardanelles straits (Figures 7 & 8). Sections A-A’ and BB’ also indicate that in the North Aegean the Dardanelles surface plume is dispersed in a “thin” surface layer , so that the pycnocline is formed at depths not greater than 50-60 meters (Figures 7 and 8). From the distribution of the retention time of surface water (sections A-A’ and BB’) , it is concluded that there is a region in the axis formed between Chalkidiki and Evoia, where east of which the retention times have low values (up to 400 days) (figures 6,7 & 8) . This is due to the fact that in the north part water enters to the flow field from the Dardanelles straights and in the south part water enters to the flow field from the open boundary.

By observing in Figure 9 the path of TRACER_9, it is found that the main current from the Dardanelles outflow reaches within five days the straits between Limnos and Agios Eustratios islands and is then heading to the north- northwest, reaching the south edge of Athos after 10 days. TRACER_9 visualizes also the secondary current, which deviates immediately to the north moving parallel to the Turkish and Thracian coasts up to Evros river mouth (North of Samothrace island) after 1½ month. Moreover, after 1½ month the part of the flow that is heading to the north-west has reached south Evoia and finally exits the flow field. The maximum concentrations are traced in the main current exactly as in the case of TRACE_1. The dispersion times of TRACER_9 have particular interest as they give information for the dispersion times of a pollutant that originates from the Dardanelles outflow.

4. Satellite Images

In order to validate the experimental and numerical results a comparison is made with properly processed satellite images of the path of Dardanelles water (Jonsson L., 2001 & NASA-Visible Earth, 2003). In Figure 10 below, three different kinds of satellite images that show the path and dispersion pattern of the Dardanelles straits water into the North Aegean Sea are shown.

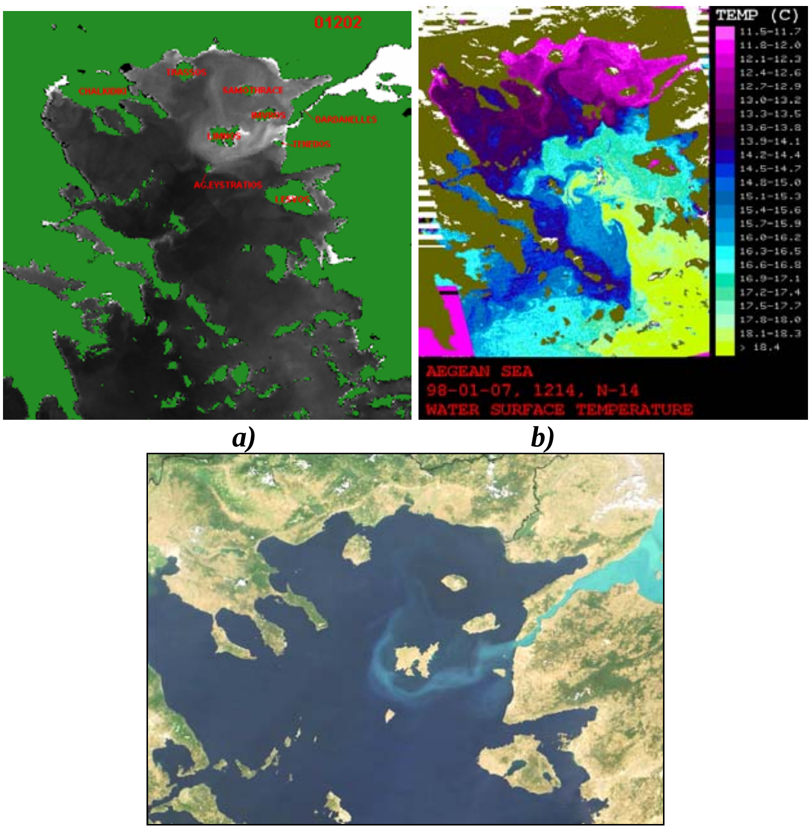


Figure 10. *Satellite images showing the phenomenon of the brackish water discharge from the Dardanelles Straights into the North Aegean Sea. a) Chlorophyll Map (Jonsson L., 2001), b) Sea Surface Temperature image (Jonsson L., 2001), c) Satellite image showing an eutrophication event in Propontida at summer of 2003(NASA-Visible Earth, 2003).*

It is obvious that the main and secondary currents revealed during both the experimental and numerical results are also evident in the satellite images.

5. Conclusions

In this paper the time evolution and the macroscopic circulation in North Aegean Sea induced by the huge buoyant surface plume that is formed from the discharge of brackish water from the Dardanelles, is studied. The study has been accomplished using an experimental and a numerical model. The comparison of the experimental with the numerical results as well as with properly processed satellite images showed a high degree of agreement, which leads to the conclusion that the most important factor that define the surface water circulation in this region is the discharge of the brackish waters from the Dardanelles straits. In addition, it was found that due to the Coriolis force the Dardanelles outflow is deflected basically to the North. From the environmental point of view, it should be mentioned that the fact that the water that discharges from the Dardanelles Straits into the Aegean Sea, after some distance from the outflow, is deflected to the north reaching the coasts of Thrace and Macedonia, implies that a substantial percentage of Dardanelles pollutants accumulate in the North part of the Aegean Sea .

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