Mediterranean Marine Science

Vol 5, No 1 (2004)

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doi: 10.12681/mms.205

Mediterranean Marine Science
Vol. 5/1, 2004, 05-18

Modeling of the upwelling hydrodynamics in the Aegean Sea

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Abstract

The special features of the hydrodynamic circulation in the Aegean Sea referring to the development of regional upwelling coastal zones are studied by means of a mathematical model. The modeling effort is focused on the tracing of coastal areas, where upwelling events are frequently observed during the summer meteorological conditions. These areas are characterized by the enrichment of surface waters with nutrients and, consequently, increased fish production. The phenomenon is studied by the use of a two-layer mathematical model comprising the surface heated zone and the rest of the water column. The numerical solution of the model is based on the finite differences method. The wind shear applied over the stratified basin, with predefined density stratification and initial water-layers thickness, and the gravity and Coriolis forces taken into account, constitute the basic external factors for the generation of the hydrodynamic circulation in the area of the Aegean Sea. The calibration and the validation of the model are performed by the comparison of the model output to the data and observations reported in valid scientific sources. The aim of the paper is to demonstrate the significant contribution of numerical models to the better understanding of the hydrodynamics governing the Aegean water circulation as well as the tracing of upwelling zones.

Keywords: Aegean Sea; Mathematical modeling; Hydrodynamic circulation; Stratified flow; Upwelling zones.

Introduction

The water circulation in the Sea environment has constituted one of the most significant scientific issues of oceanography during the last decades. Mathematical modeling constitutes a very useful and valuable tool for the prediction of the hydrodynamics as well as sediment and pollutants transport in the sea. Many successful modeling works have been done up to now, by CHRISTODOULOU (1974), BLUMBERG & MELLOR (1987),

KOUTITAS & O'CONNOR (1980), KOUTITAS (1987, 1988), AL-RABEN *et al.* (1989), VALIOULIS & KRESTENITIS (1994), DRAKOPOULOS & LASKARATOS (1999), KRESTENITIS *et al.* (1997, 2000), KOURAFALOU (1999, 2001), SAVVIDIS *et al.*, (2000, 2001), DODOU *et al.* (2001), KOURAFALOU *et al.* (2004) as well as many other researchers.

An important point of modeling the hydrodynamics in the marine environment is the fact that the simulations can contribute significantly to the detection of upwelling zones. The term 'upwelling' is used to express the physical phenomenon of the seawater upward movement from the deep layers of the sea up to the surface. This process constitutes a physical mechanism of the surface seawaters' enrichment with nutrients and it is considered to be of vital importance for the fishery and generally the life in the sea. The upwelling phenomenon is of special biological importance, which is briefly described in the following lines. Life in deeper layers of the sea is limited in comparison to life in the surface waters, therefore, there are large quantities of nutrients due to the absence of living organisms that might have consumed them. When deep and cold waters, enriched with nutrients, move to the surface, they enhance biological activity, making these coastal waters of the surface layers very rich in fish-productivity. It is very important to note that the highest amount of the fishery all over the oceans comes from regional zones where upwelling events occur, although those regions constitute only 3% of the world oceans (ALBANAKIS, 1999). Relevant information, referring to the high amount of nutrients in relation to the upwelling currents, can be found available on the following Internet site: http://virga.sfsu.edu/courses/geol103/2/labs/upwelling/world-wide.html. On some coasts, like the Pacific coast in South America, upwelling is fairly steady and takes place over an extended geographical area. In other cases, like the coast of California, upwelling processes tend to occur as localized and short-lived events (CASTRO & HUBER, 1997). As far as the Greek Seas are concerned, upwelling regions have been traced on the eastern coasts of the Aegean and Ionian Sea, during the summer period, when northern winds blow along the coasts (ALBANAKIS, 1999). The special upwelling process, described above, refers to the generalized case of the continental shelf seawaters, where the wind blows parallel to the coast, with the coastline on the left side of the wind direction in the case of the northern hemisphere or on the right side of the wind direction in the case of the southern hemisphere. However, for the shallow waters of the inner part of a continental shelf, the most favorable winds for upwelling events are mainly the ones that blow normally to the coast, with direction to the open sea.

The aim of this paper is to study the general features of the hydrodynamic circulation in the Aegean Sea with specific emphasis on the upwelling dynamics and the tracing of upwelling zones with the contribution of mathematical modeling. In detail, the study is based on the application of a two-layer hydrodynamic mathematical model and concerns the case of the stratified Aegean marine basin with a characteristic seasonal thermocline on the mixed surface layer, which is a typical case especially during the summer period. More specifically, the hydrodynamics and the tracing of upwelling zones are studied by the use of a mathematical model, applied on a two-layer marine basin, consisting of the surface heated zone and the rest of the water column.

It is, of course, well known that 3D baroclinic (even non hydrostatic) models have been used for the analysis of the hydrodynamism of the Aegean Sea. Such examples include the modeling works of VALIOULIS & KRESTENITIS (1994) and KORRES & LASKARATOS (2003). Those models are based on the well-known Princeton Ocean Model (POM), which was initially developed and presented by BLUMBERG & MELLOR (1987). However, due to the surfacial character of the wind induced upwelling phenomenon, especially in the Aegean Sea characterized by a surface layer of 50 m versus its average depth of more than 500 m, the use of a 2-layer or even of a reduced gravity (one layer) model, is considered realistic. Successful examples of such models (reduced gravity models) have been given by ARANGO & REID (1991), as well as WANG *et al.* (2003). The use of a 2-layer model, as a prognostic tool, based on the aforementioned point of view, is the working hypothesis of this paper. Furthermore, the aim of this work is an overall approach of the hydrodynamics related to the upwelling dynamics in the Aegean Sea and not a detailed analysis of the currents climatology. This macroscopic approach gives, on the other hand, very satisfactory information of the real phenomenon.

Modeling studies, based on the 2-layer approach, have been conducted by MINATO (1992) and JUNGCLAUS & BACKHAUS (1994) or more recently by IZQUIERDO *et al.* (2001), CAI *et al.* (2002) and ANDERSSON & VERONIS (2004). Furthermore, works by THEOHARIS *et al.* (1999), ENNET *et al.* (2000) and SONG & CHAO (2004) refer to upwelling studies theoretically or mathematically.

Focusing on the Aegean Sea, some of the important research studies, carried out up to now, concerning the extended area of the Aegean Sea or regional basins of that sea, include works by LYKOUSIS *et al.* (1981), CHRISTOPOULOS & KOUTITAS (1991), CHRISTOPOULOS (1997), LASKARATOS (1992), GEORGOPOULOS *et al.* (1992), VALIOULIS & KRESTENITIS (1994), KRESTENITIS & VALIOULIS (1994), THEOCHARIS *et al.* (1990, 1999), NITTIS & LASKARATOS (1999), GEORGOPOULOS (2002), KORRES & LASKARATOS (2003) and KOURAFALOU *et al.* (2004).

The Aegean Sea is located in the eastern Mediterranean Sea and constitutes one of the eastern Mediterranean sub-basins, with quite complex bathymetry and coastlines. In detail, the Aegean Sea is located between the Greek and the Turkish coasts of Asia Minor, concerning the west-east geographical orientation-direction, and also between the northern part of Continental Greece and the southern islands of Crete and Rhodes, concerning the north-south geographical axis. A great number of islands are dispersed in this sea. The depths and generally the geomorphology of the Aegean is complicated, varying from very shallow depths in the coastal areas and the zones around the islands, reaching quite large depths of 2500 m in local regions north of Crete, as well as 1000 and 1500m south of Mount Athos (northern Greece) and in the Sporades Basin respectively (Fig. 1a). A coarse map with the bathymetry of the Aegean is given in the Figure 1b. Although the grid and the coastline are not shown in detail (fine resolution), the main features of the geological formation of the bottom anaglyph are quite well depicted (Fig 1a, 1b).

Materials and Methods

External forces that influence the hydrodynamics in the Aegean

The hydrodynamic circulation in the Aegean is mainly wind generated. The commonest winds, blowing over the whole Aegean Sea are the so-called Etesians (VALIOULIS & KRESTENITIS, 1994; GEORGOPOULOS, 2002), which are characterized by important north wind components. More specifically these winds are north-eastern over the northern area of the Aegean Sea turning gradually to north-western over the southern areas of the Sea.

The tidal signal, in the Mediterranean and in the Aegean Sea is generally weak, with a mean tidal height of about 25 cm (KRESTENITIS *et al.*, 1997; DODOU *et al.* 2002). Consequently the tide, as an external force on the seawater masses, does not influence the circulation much and it is, therefore, neglected in the present study.

The density differences constitute an important parameter that influences quite significantly the hydrodynamics of the Aegean waters - especially during the summer period. This characteristic parameter has been studied during the last decades by VALIOULIS & KRESTENITIS (1994), KRESTENITIS & VALIOULIS (1994) and THEOCHARIS *et al.*, (1999). Focusing on the summer meteorological conditions, it should be noted that the density differences along the depth of the stratified water column of the Aegean Sea are mainly due to thermal differences. This thermal influence on the water masses results in the

Fig. 1a: Aegean Sea (VALIOULIS & KRESTENITIS, 1994).

Fig. 1b: A coarse map of the Aegean topography.

formation of two different layers, i.e. the one on the surface, which constitutes the surface heated zone, which is known as the mixed surface layer and the second deep layer, which constitutes the rest of the water column.

The above characteristic elements, related to the structure of the seawater column and the relevant dynamics, are studied by a two-layer mathematical model, which is described below.

The mathematical structure

The mathematical structure of the model is based on the application of the well-known equations of momentum and mass conservation for each layer separately. The river discharges have not been taken into account since their influence, on the summer water circulation in the Aegean Sea, is not important. The differential equations, which constitute the mathematical structure of the model, are written in terms of the upper and lower layer average depths ho, hu and the correspondent depth-average velocity components Uo, Vo, Uu, Vu. As far as their validity is concerned, the model equations require two simplifying assumptions, the one of the non-mixing on the two layers interface and that of the flow horizontality. The first assumption is realistic, provided that for small density differences $\Delta\varrho/\varrho = 5$ ‰, which are the commonest in nature, turbulence in the two fluids interface is minimized, so that limited mixing happens there. The second assumption is also realistic for fields with horizontal dimensions much larger than the vertical ones and can be translated into a consequent hydrostatic pressure distribution assumption.

The principle of mass conservation is given by the following mathematical relationships for the upper and lower layer respectively:

Upper layer:

$$\frac{\partial h_o}{\partial t} + \frac{\partial}{\partial x}(U_o h_o) + \frac{\partial}{\partial y}(V_o h_o) = 0$$

Lower layer:

$$\frac{\partial h_u}{\partial t} + \frac{\partial}{\partial x}(U_u h_u) + \frac{\partial}{\partial y}(V_u h_u) = 0$$

The principle of momentum conservation is given by the following mathematical relationships for the upper and lower layer respectively:

Upper layer – x-axis:

$$\frac{\partial U_o}{\partial t} + U_o\frac{\partial U_o}{\partial x} + V_o\frac{\partial U_o}{\partial y} = -g\frac{\partial}{\partial x}(h_o + h_u + z_b) + \frac{\tau_{sx}}{\rho_o h_o} - \frac{\tau_{ix}}{\rho_o h_o} + A_h\frac{\partial^2 U_o}{\partial x^2} + A_h\frac{\partial^2 U_o}{\partial y^2} + fV_o$$

Upper layer – y-axis:

$$\frac{\partial V_o}{\partial t} + U_o\frac{\partial V_o}{\partial x} + V_o\frac{\partial V_o}{\partial y} = -g\frac{\partial}{\partial y}(h_o + h_u + z_b) + \frac{\tau_{sy}}{\rho_o h_o} - \frac{\tau_{iy}}{\rho_o h_o} + A_h\frac{\partial^2 V_o}{\partial x^2} + A_h\frac{\partial^2 V_o}{\partial y^2} - fU_o$$

Lower layer – x-axis:

$$\frac{\partial U_u}{\partial t} + U_u\frac{\partial U_u}{\partial x} + V_u\frac{\partial U_u}{\partial y} = -g\frac{\partial}{\partial x}(h_u + z_b) - g\left(1 - \frac{\Delta\rho}{\rho}\right)\frac{\partial h_o}{\partial x} + \frac{\tau_{ix}}{\rho_o h_o} - \frac{\tau_{bx}}{\rho_o h_u} + A_h\frac{\partial^2 U_u}{\partial x^2} + A_h\frac{\partial^2 U_u}{\partial y^2} + fV_u$$

Lower layer – y-axis:

$$\frac{\partial V_u}{\partial t} + U_u \frac{\partial V_u}{\partial x} + V_u \frac{\partial V_u}{\partial y} =$$
$$-g \frac{\partial}{\partial y}(h_u + z_b) - g\left(1 - \frac{\Delta\rho}{\rho}\right)\frac{\partial h_o}{\partial y}$$
$$+ \frac{\tau_{iy}}{\rho_o h_u} - \frac{\tau_{by}}{\rho_o h_u} +$$
$$+ A_h \frac{\partial^2 V_u}{\partial x^2} + A_h \frac{\partial^2 V_u}{\partial y^2} - f U_u$$

where U_o, U_u are the velocity components along x axis of the upper and lower layer respectively and V_o, V_u are the velocity components along y axis of the upper and lower layer respectively, h_o, h_u the thicknesses of the upper and lower layer respectively, z_b is the seabed distance from a reference level, ϱ_o, ϱ_u are the mean seawater densities of the upper and lower layer respectively, $\Delta\varrho/\varrho = (\varrho_u - \varrho_o)/\varrho_u$ is the relative density and $1-(\Delta\varrho/\varrho) = \varrho_o/\varrho_u$, g is the gravity acceleration, τ_{sx} and τ_{sy} are the wind shear stresses along x and y axis, τ_{ix} and τ_{iy} are the shear stresses in the interface of the two layers along x and y axis, τ_{bx} and τ_{by} are the seabed shear stresses along x and y axis, A_h is the horizontal momentum turbulent eddy diffusion coefficient, as a function of the velocity gradients according to Smagorinski scheme, and f is the Coriolis parameter.

The numerical solution of the hydrodynamic model consisting of the above-presented equations is accomplished by an explicit, centered in space, finite differences scheme for the cyclical computations of the U, V and h distributions along the flow domain, for each layer, every time step, starting from a 'cold start' and advancing the solution in time. The time discretisation was based on a 'forward' finite differences scheme. The computational field (as far as the spatial discretisation is concerned), was discretised by a nearly orthogonal grid of 46×46 cells with grid size $\Delta y = 18520$ m (10 nautical miles) along y-axis and a variable Δx, as a function of Δy according to the relationship $\Delta x = \Delta y \times \cos(\varphi)$, where φ is the geographical latitude of each grid cell. The velocity components U and V are computed on the sides of the grid cells and the layer thickness h in the center of each grid cell. The time-step, Δt, was selected according to the Courant criterion.

More details about the model structure, the equations as well as the boundary conditions can be found in KOUTITAS *et al.* (1994) as well as in KOUTITAS (1988).

Results

The mathematical model described above, has been applied to the Aegean Sea in order to simulate the hydrodynamic circulation in the Aegean Sea basin under stratification conditions that constitute a characteristic feature of the Aegean water column, especially during the summer period. In more detail, the density stratification of the water masses of the Aegean Sea depends mainly on the temperature differences between the surface heated layer and the lower cooler one. However, the seawater density gradients depends also on the salinity differences due to the water masses originating from the Black Sea, coming from the northeast areas of the Aegean Sea and the Levantine waters coming from the southeast areas, as well as the water masses coming from the central and western Mediterranean Sea. The deeper water layers are usually separated from the upper surface mixed layer by a characteristic pycnocline.

For the application of the model, it was assumed that the surface layer has an initial mean thickness of 25 m, with density difference between the two layers $\Delta\varrho/\varrho = 5‰$. The values of the initial upper layer as well as the mean density difference between the upper and the lower layer were based on GEORGOPOULOS (2002), who studied in detail the physical and dynamic characteristics of the Aegean water masses, with special emphasis on the north Aegean seawater masses. More specifically, according to the research of GEORGOPOULOS (2002), the thickness of the surface mixed layer, in summer conditions, is about 25 meters (the pressure is approx. 25 decibars), while the density differences between the surface and bottom layers vary between 5‰ and 6‰ (GEORGOPOULOS, 2002). As far as the wind forcing is concerned, the Etesian winds, which form a system of northeastern winds (northeasterlies) north of the study area varying gradually to northwestern winds (northwesterlies) in the south, were taken into account. The wind speed used in the simulation was 10 m/sec, corresponding to relatively strong wind events. Figure 2 depicts the field of the winds that blow over the extended area of the Aegean Sea (Fig 2).

As it is obvious, the wind velocity vectors (showing the wind direction and speed) form a characteristic curl, with northeasterly wind components prevailing over the northern areas of the Aegean Sea, northerly wind components prevailing over the central areas and northwesterly winds prevailing over the southern areas of the Aegean. This general wind regime represents the commonest meteorological conditions as far as the blowing winds over the Aegean Sea are concerned. The

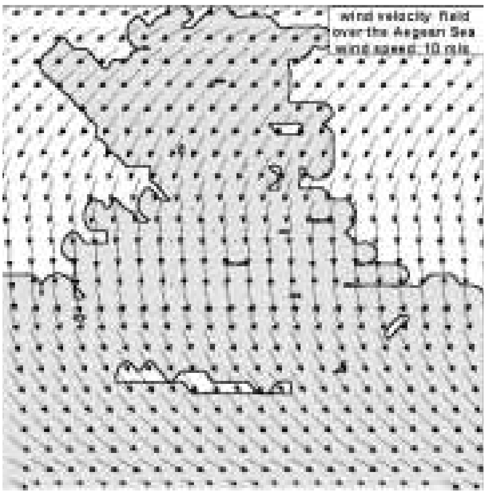

Fig. 2: Wind velocity field (wind speed 10 m/s).

velocity field and the layers' thickness, resulting from the model runs, constituted the main work of this paper. It was considered that the hydrodynamic circulation in the Aegean Sea was generated by the wind forcing of the Etesians. The current velocities, resulting from the model runs, are given in the following figures (Figures 3a, 3b, 4a and 4b), which show the velocity field and the thickness of the upper and lower layer respectively. It is interesting to note the output of the model runs, concerning the tracing of the upwelling coastal zones, that have been developed along the eastern coasts of the Aegean Sea under the influence of the Etesians for 3 and 6 days respectively (Figures 3a, 3b). Upwelling zones have also been developed along the southwestern coasts of Crete.

The fact that there are not any current velocity vectors on the narrow coastal strip of the eastern coasts of the Aegean Sea, depicted in Figures 4a and 4b as well as the disappearance, in this area, of the upper layer in figures 3a and 3b, clearly indicate upwelling coastal zones. More analytically, the upwelling mechanism brings the deep-water masses to the surface causing, in this way, the disappearance of the initial upper layer. These findings, as a result of the numerical modeling, are in agreement with recent reports found in national and international valid scientific sources. More analytically, VALIOULIS & KRESTENITIS (1994) and ALBANAKIS (1999) report that upwelling events take place along the eastern coasts of the Aegean Sea. In addition, according to GEORGOPOULOS (2002), there are also satellite observations, which indicate upwelling processes along the marine coastal strip of Asia Minor (Fig. 5).

Upwelling events in the area south of the Dardanelles, during the summer period, are also reported by ZERVOUDAKI *et al.* (1999). Similar reports are found in JONSSON & ZODIATIS (1999). The evolution in time of the upper layer thickness, corresponding to 2 local sites of the eastern coasts of the Aegean Sea resulting from the model runs, are given in the

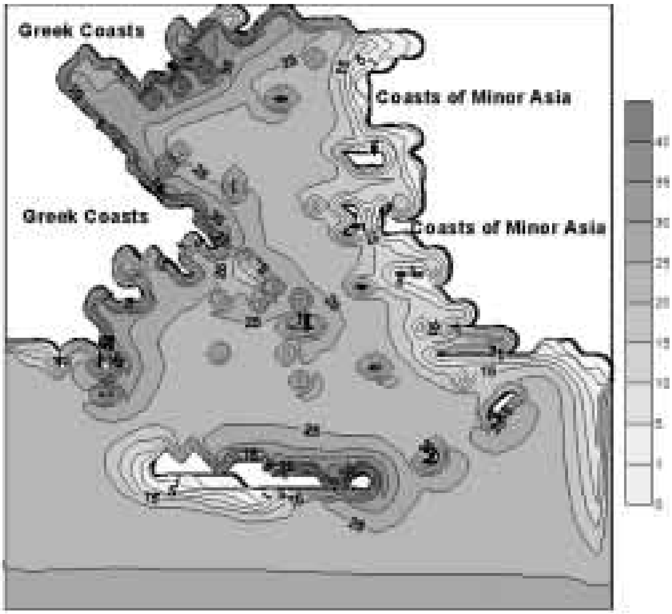

Fig. 3a: Thickness of the upper layer under the influence of the Etesians for 3 days (thickness in m).

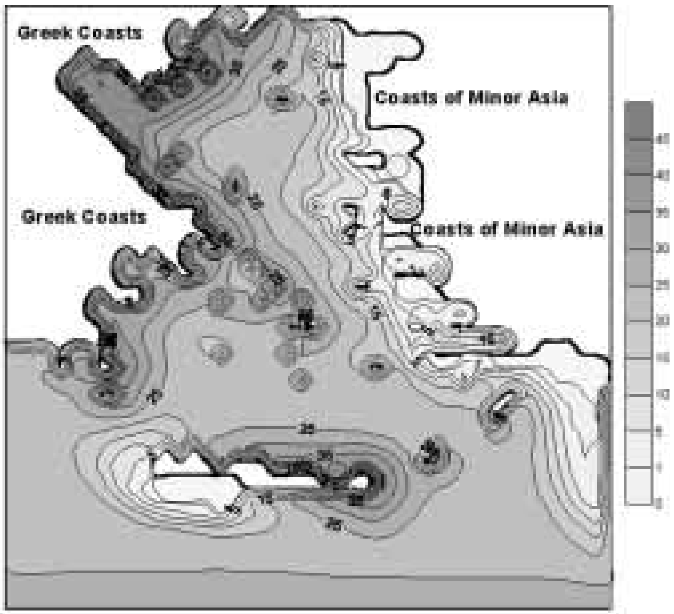

Fig. 3b: Thickness of the upper layer under the influence of the Etesians for 6 days (thickness in m).

Fig. 4a: Current velocities of the upper layer under the Etesians for 3 days (ref vectors in m/s).

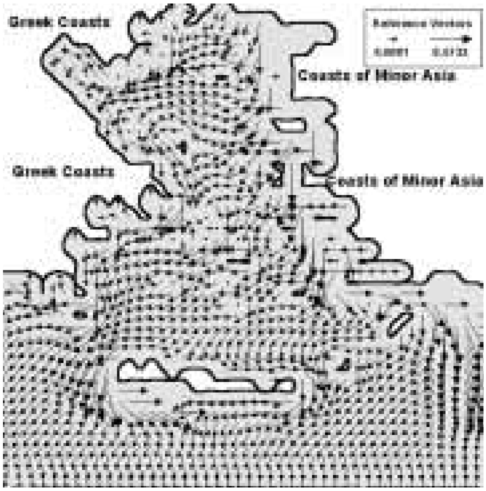

Fig. 4b: Current velocities of the upper layer under the Etesians for 6 days (ref vectors in m/s).

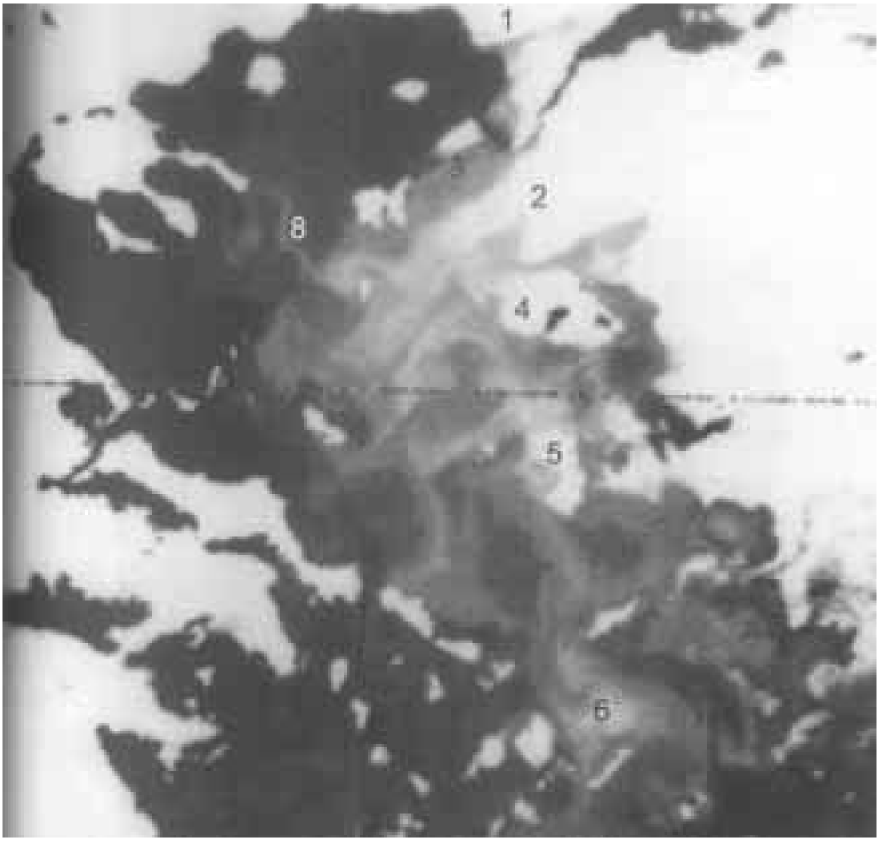

Fig. 5: Thermography of 19-8-1986 NOAA 9 (GEORGOPOULOS, 2002) (1), (2), (4) and (5) upwellings.

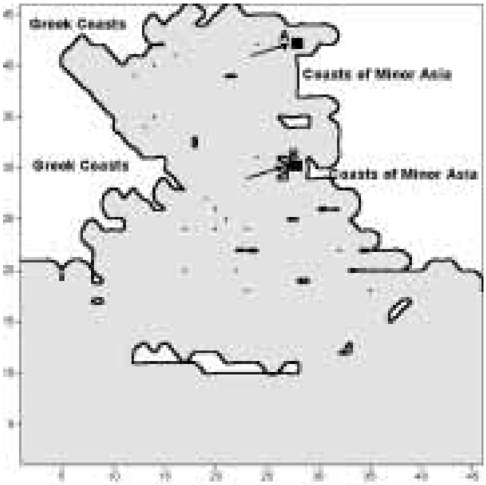

Fig. 6a: Position of two sites near the Coasts of Minor Asia.

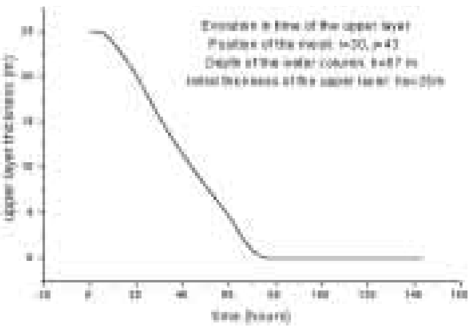

Fig. 6b: Evolution in time of the upper layer thickness (position A).

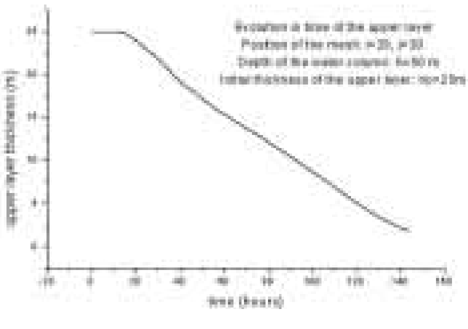

Fig. 6c: Evolution in time of the upper layer thickness (position B).

resulting from the model runs, are given in the Figures 6a, 6b and 6c (positions A and B).

Furthermore, the major southward movement of the waters, along the western coasts of the Aegean Sea, which is formed between the Aegean and the Greek mainland (Figures 4a, 4b), constitutes another important finding of the simulation. This model output is in line with the work of VALIOULIS & KRESTENITIS (1994). As far as the upper layer is concerned, the model runs show that a characteristic coastal strip along the eastern coasts of the Aegean Sea seems to develop where the lower layer has obviously come up to the surface, occupying the entire water column, from the bottom up to the surface. It is obvious, that in this case, no upper layer exists and refreshment processes by the substitution of the surface waters with deep-layer waters take place. Figures 7a, 7b, 8a and 8b given below, depict the velocity field and the thickness of the lower layer, respectively, due to the Etesians. It is pointed out that the simulations were based on the existence of an initial surface layer of thickness equal to 25 m. Consequently, in areas with depths less than 25 m, like coastal zones around the islands or along continental coasts, which can not accommodate a lower layer, only the upper layer initially exists. Furthermore, the lack of the lower layer and the suppression of the velocity field imply downwelling processes only for water depths larger than 25 m (Fig 7a, 7b, 8a, 8b).

Conclusions

The special features of the hydrodynamics related to the upwelling dynamics in the marine basin of the Aegean Sea (East Mediterranean Sea) have been studied with the development and application of a two-layer hydrodynamic mathematical model. The wind shear, applied over the stratified basin of the Aegean Sea, with predefined density stratification and initial water-layers thickness, as well as the gravity and Coriolis forces, were taken into account,

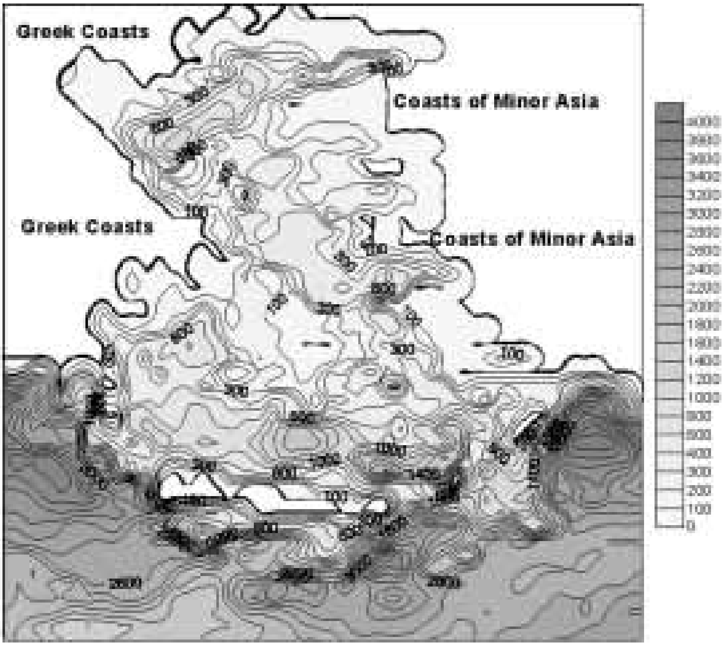

Fig. 7a: Thickness of the lower layer under the influence of the Etesians for 3 days (thickness in m).

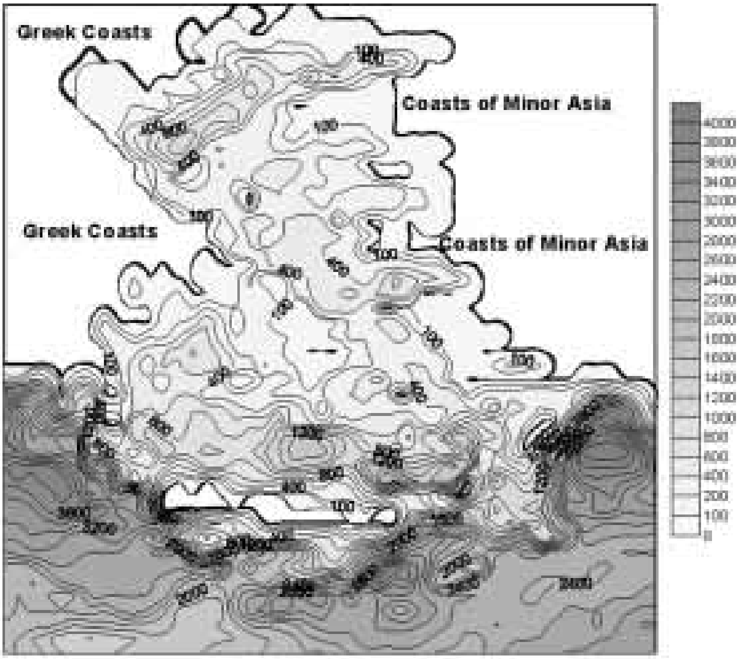

Fig. 7b: Thickness of the lower layer under the influence of the Etesians for 6 days (thickness in m).

Fig. 8a: Current velocities of the lower layer under the Etesians for 3 days (ref vectors in m/s).

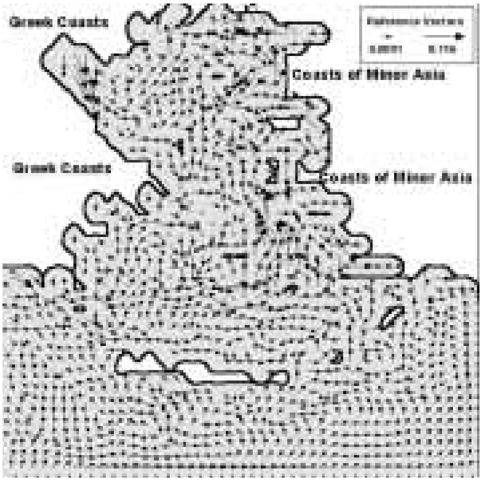

Fig. 8b: Current velocities of the lower layer under the Etesians for 6 days (ref vectors in m/s).

for the generation of the hydrodynamic circulation in the Aegean Sea. The special conditions concerning the prevailing wind forcing over the extended Aegean and the density stratification of the water column, which constitutes a characteristic feature of the Aegean seawater masses in summer conditions, is found to cause upwelling episodes, especially on the eastern coasts of the basin. The model output was in line with the generalized theory according to which, the coastal upwelling processes, along continental shelf regions, take place under the influence of winds parallel to the coastline, with the coastline on the left of the wind direction, in the northern hemisphere. Concerning the Aegean Sea, the northern winds (northerlies), and generally the winds with important north components, like the Etesians, constitute the main feature of the meteorological conditions over the whole domain. This external forcing was taken into account in the present study that was implemented by the application of the two-layer hydrodynamic model in the real topography of the Aegean Sea. The validity of the model was further confirmed by the comparison of the model output with observations and reports of valid scientific sources. The simulations revealed that, in the case of the Etesians, applied over the whole Aegean basin, with wind speed of 10 m/s, upwelling processes started to develop during a period of a few days. Obviously, stronger winds than 10 m/s cause upwelling events during smaller time periods. Summarizing, the simulations helped significantly with the interpretation of the hydrodynamics in the Aegean Sea, concerning especially the upper surface mixed layer and the tracing of upwelling zones. This modeling work can be used as a prognostic tool for the study of the hydrodynamics and upwelling dynamics in different cases of the world's marine basins.

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