TRACING UPWELLING COASTAL ZONES BASED ON MATHEMATICAL SIMULATIONS

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Abstract

A two layer hydrodynamic model for stratified flows is presented in this paper. The model has been developed and applied to the Thermaikos Gulf, aiming in the study of hydrodynamic circulation of the gulf as well as the tracing of upwelling zones. That special upwelling phenomenon constitutes a very important issue for fishery since coastal zones with upwelling events are characterized by enrichment of surface waters with nutrients, indicating in this way, increased fish production. The mathematical simulation was based on the finite difference method. Wind and Coriolis forces constituted the main parameters for the study of the hydrodynamic circulation under stratification conditions. As far as the basic features of the seawater circulation are concerned, the results of the model were in line with field measurements, collected during the period of earlier studies in the gulf. The successful tracing of upwelling regions resulted from the dominant winds over the coastal domain was one of the most important findings of the model.

Keywords: mathematical models, hydrodynamic circulation, stratified flow, upwelling, biological productivity, fish production

ΑΝΙΧΝΕΥΣΗ ΠΑΡΑΚΤΙΩΝ ΖΩΝΩΝ ΑΝΑΔΥΣΗΣ ΜΕ ΤΗ ΒΟΗΘΕΙΑ ΜΑΘΗΜΑΤΙΚΗΣ ΠΡΟΣΟΜΟΙΩΣΗΣ

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Περίληψη

Στην εργασία αυτή παρουσιάζεται ένα υδροδυναμικό μοντέλο δύο στοιβάδων για στρωματωμένες ροές το οποίο αναπτύχθηκε και εφαρμόστηκε με στόχο τη μελέτη της θαλάσσιας κυκλοφορίας στο Θερμαϊκό κόλπο και την ανίχνευση – εντοπισμό περιοχών ανάδυσης. Το φαινόμενο της ανάδυσης αποτελεί ένα σημαντικό κεφάλαιο για την αλιεία, αφού παράκτιες ζώνες στις οποίες παρατηρείται το φαινόμενο αυτό χαρακτηρίζονται από εμπλουτισμό των επιφανειακών στρωμάτων σε θρεπτικές ουσίες, γεγονός που υποδηλώνει αυξημένη ιχθυοπαραγωγή. Η μαθηματική προσομοίωση βασίστηκε στη μέθοδο των πεπερασμένων διαφορών. Ο άνεμος και οι δυνάμεις Coriolis αποτέλεσαν τις βασικές παραμέτρους για τη μελέτη της κυκλοφορίας στον κόλπο κάτω από συνθήκες στρωμάτωσης. Τα αποτελέσματα του μοντέλου, σε ό,τι αφορά τη γενική μορφή της κυκλοφορίας στον κόλπο, ήταν σε συμφωνία με τιμές πεδίου οι οποίες συλλέχτηκαν στο πλαίσιο προηγούμενων μελετών στην περιοχή. Ένα από τα σημαντικότερα εξαγόμενα του μοντέλου που αποτέλεσε και την εκπλήρωση του στόχου της εργασίας ήταν ο επιτυχής εντοπισμός περιοχών ανάδυσης σε σχέση με τους επικρατέστερους ανέμους στην περιοχή.

Λέξεις-κλειδιά: μαθηματικά μοντέλα, υδροδυναμική κυκλοφορία, στρωματωμένη ροή, ανάδυση, βιολογική παραγωγικότητα, ιχθυοπαραγωγή

1. Introduction

The hydrodynamic circulation of the seawater masses has constituted a subject of research during the last decades. The use of mathematical simulation contributed significantly to the progress of this research and various mathematical models were developed for the simulation of hydrodynamic circulation of the seawaters (Koutitas 1987, Blumberg et al. 1987, Krestenitis et al. 1997, Drakopoulos et al. 1999, Dodou 2001) as well as for the dispersion of pollutants and suspended sediments in the marine environment (Koutitas et al. 1980, Al-Raben et al. 1989, Savvidis et al. 2000, Mpimpas et al. 2001). The successful application of the aforementioned mathematical models can give useful information for the study of issues related to aquaculture and fishery.

Especially, in the case where the wind forces, Coriolis forces and forces due to horizontal pressure gradients constitute the prevailing factors for the generation of hydrodynamic circulation, the well-known process of upwelling is taking place. The term “upwelling” is used to express the physical phenomenon of upward movement of the waters, which move from the deep layers of the sea up to the surface. This special process constitutes a physical mechanism of enrichment of the surface waters with nutrients and it is considered to be of vital importance for the fishery and generally the life in the sea. The process of upwelling and its importance is described in the following paragraphs.

Life in deeper layers of the sea is limited in comparison to life in surface waters therefore there are large quantities of nutrients due to the absence of living organisms which could consume them. When deep waters enriched with nutrients move to the surface they enhance biological activity, making, marine zones, where upwelling events are present, very rich in fish-productivity. It is quite characteristic that the highest amount of the fishery on a universal scale comes from regional zones where upwelling events occur, although those regions constitute only the 3% of the oceans (Albanakis, 1999).

On some coasts, like the Pacific coast of South America, upwelling is fairly steady and it takes place over a geographical area. On other coasts, like the coast of California, upwelling tends to occur as localized and short-lived events (Castro et al. 1997).

As far as the Greek Seas are concerned, upwelling regions were traced on the eastern coasts of the Aegean and Ionian Sea, during the summer period, when northerly winds blow along the coasts (Albanakis, 1999).

The special upwelling process, described above, refers to the generalized case of the middle continental shelf seawaters, where the wind blows parallel to the coast, with the coastline on the left side of the wind direction for the case of north hemisphere or on the right side of the wind direction for the case of south hemisphere. However, when the waters are shallow, like the waters of the inner part of the continental shelf, the most favorite winds for upwelling events are the ones blowing normally to the coast. The case of the hydrodynamic circulation in the Thermaikos Gulf (Northern Greece), mainly in summer conditions, due to wind forcing and density differences constitutes a characteristic example for the occurrence of the aforementioned upwelling events.

Figure 1.1 illustrates the Thermaikos Gulf and its sub-zones as follows: a) the Bay of Thessaloniki, occupying the northern part of the Thermaikos Gulf, and extending southwards to the line ‘cape Micro Emvolo – Galikos river mouth’, b) the Gulf of Thessaloniki, which extends from the line ‘cape Micro Emvolo – Galikos river mouth’, to the line ‘cape Epanomi – cape Atherida’ and c) the outer Thermaikos Gulf extending south from the Thessaloniki Gulf reaching the southern boundary line ‘cap Posidi – cap Platamonas’.

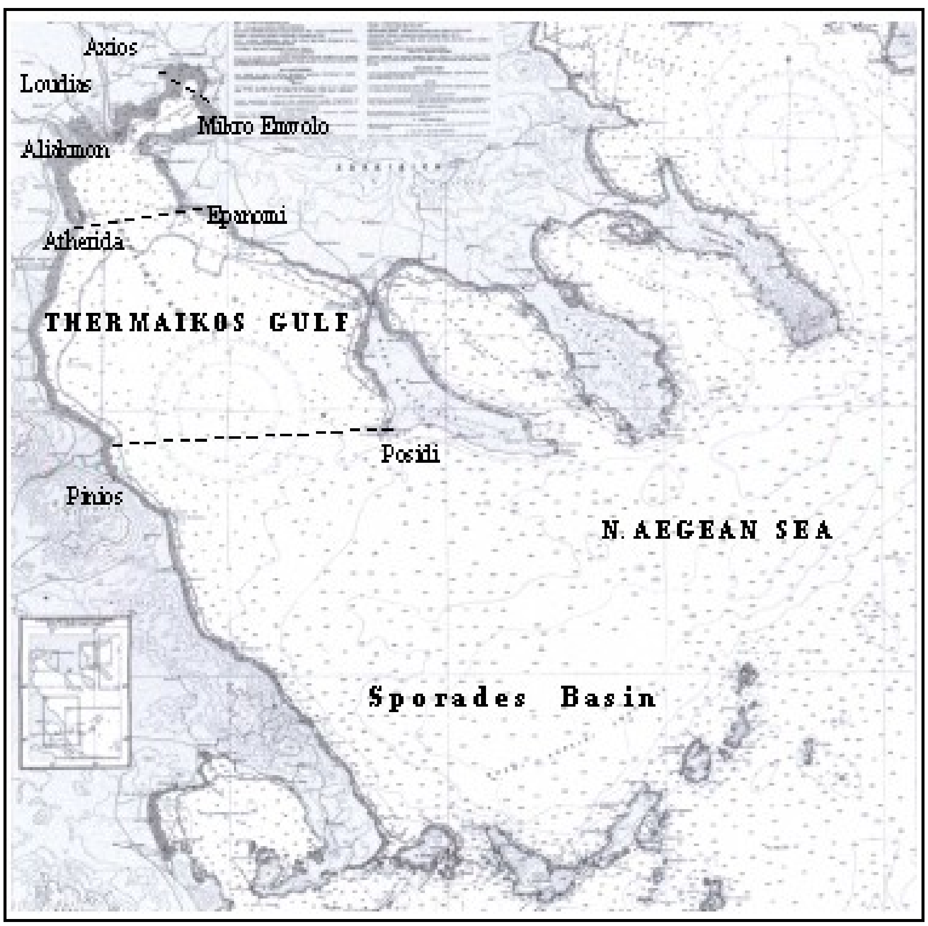

Figure 1.1 Thermaikos Gulf and zonation of the area

As far as the bathymetry of the Gulf is concerned, the basin extends from the shallow nearshore coastal areas to the deep offshore sea with depths, reaching 100 m (Figure 1.2). Axios, Loudias and Aliakmonas (Pinos southern but just outside from the computational domain) are the main rivers, which outflow into the west coasts of the Thermaikos Gulf (Figure 1.1).

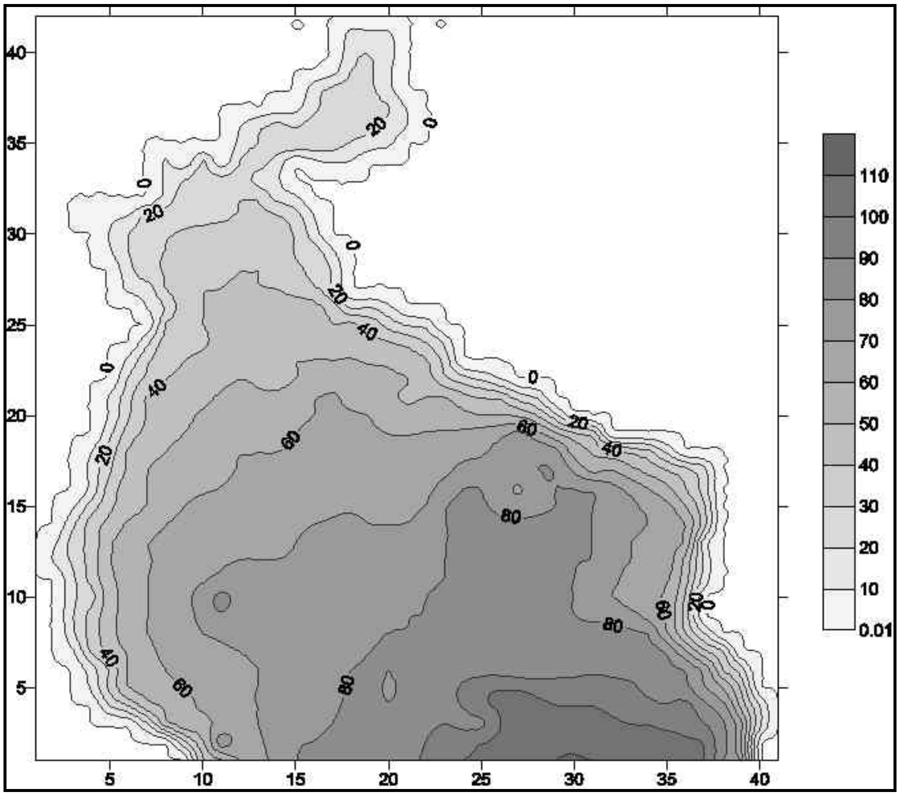

Figure 1.2 Bathymetry of Thermaikos Gulf
(the isobaths are in meters and the horizontal and vertical axis in nautical miles)

2. Material and Methods

2.1 The mathematical model of the two layer hydrodynamic circulation

In the case of vertical stratification of density, successive models of depth average flow for each separate fluid layer are applied. Given that those measurements prove the existence of a pycnocline, we can consider that the fluid is two layered (with densities ρ_o και ρ_u for the upper and lower layer respectively) and write the equations of equilibrium and mass conservation for each layer separately. The unknown variables of the differential equations are average depths h_o, h_u of upper and lower layer and the respective depth average velocity components U_o, V_o, $U_{\underline{u}}$, V_u (Figure 2.1).

The formation of stratified flow model equations requires the following simplifying assumptions: a) the consideration of two non-mixing homogeneous fluid layers and b) the assumption of horizontal flow. The first assumption is realistic, provided that for small density differences $\Delta\rho/\rho = 5$ ‰ -the commonest in nature- turbulence in the interface of the two fluids is minimized and limited mixing happens there. The second assumption is also realistic for fields with horizontal dimensions much larger than the vertical ones and consequently so is that of hydrostatic pressure distribution.

2.2 Model Equations

The equations of mass and momentum conservation were solved, according to the finite difference method, as follows:

Equation of mass conservation
According to that principle of mass conservation no mass can be generated or lost in a system, therefore the total amount of mass remains the same (without any changes). The equation, which describes the principle of mass conservation, is given by the following mathematical relationships for the upper and lower layer respectively:

Upper Layer

$$\frac{\partial h_o}{\partial t} + \frac{\partial}{\partial x}(U_o h_o) + \frac{\partial}{\partial y}(V_o h_o) = 0 \qquad (2.1)$$

Lower Layer

$$\frac{\partial h_u}{\partial t} + \frac{\partial}{\partial x}(U_u h_u) + \frac{\partial}{\partial y}(V_u h_u) = 0 \qquad (2.2)$$

Equation of momentum conservation - Equilibrium equations
According to the principle of momentum conservation (equilibrium equations), every moving object cannot gain or loose momentum unless an external force exerts on it. The equations, which describe the principle of momentum conservation, are given by the following mathematical relationships for the upper and lower layer respectively:

Upper Layer
along x axis:

$$\frac{\partial U_o}{\partial t} + U_o \frac{\partial U_o}{\partial x} + V_o \frac{\partial U_o}{\partial y} = -g\frac{\partial}{\partial x}(h_o + h_u + z_b) + \frac{\tau_{sx}}{\rho_o h_o} - \frac{\tau_{ix}}{\rho_o h_o} + A_h \nabla_h^2 U_o + f V_o \qquad (2.3)$$

along y axis:

$$\frac{\partial V_o}{\partial t} + U_o \frac{\partial V_o}{\partial x} + V_o \frac{\partial V_o}{\partial y} = -g\frac{\partial}{\partial y}(h_o + h_u + z_b) + \frac{\tau_{sy}}{\rho_o h_o} - \frac{\tau_{iy}}{\rho_o h_o} + A_h \nabla_h^2 V_o - f U_o \qquad (2.4)$$

Lower Layer
along x axis:

$$\frac{\partial U_u}{\partial t} + U_u \frac{\partial U_u}{\partial x} + V_u \frac{\partial U_u}{\partial y} =$$

$$-g\frac{\partial}{\partial x}(h_o + h_u + z_b) - g\frac{\Delta\rho}{\rho}\frac{\partial h_o}{\partial x} + \frac{\tau_{ix}}{\rho_u h_u} - \frac{\tau_{bx}}{\rho_u h_u} + A_h \nabla_h^2 U_u + f V_u \qquad (2.5)$$

along y axis:

$$\frac{\partial V_u}{\partial t} + U_u \frac{\partial V_u}{\partial x} + V_u \frac{\partial V_u}{\partial y} =$$

$$- g \frac{\partial}{\partial y}(h_o + h_u + z_b) - g \frac{\Delta\rho}{\rho}\frac{\partial h_o}{\partial y} + \frac{\tau_{ix}}{\rho_u h_u} - \frac{\tau_{by}}{\rho_u h_u} + A_h \nabla_h^2 V_u - f U_u \qquad (2.6)$$

where U_o, U_u the velocity components along x axis of the upper and lower layer, V_o, V_u the velocity components along y axis of the upper and lower layer respectively, h_o, h_u the thickness of the upper and lower layer respectively, z_b the absolute seabed height, ρ_o, ρ_u the densities of the upper and lower layer respectively, g the gravity acceleration, τ_{sx}, τ_{sy} the wind shear stresses along x and y axis, τ_{ix}, τ_{iy} the shear stresses in the interface of the two layers along x and y axis, τ_{bx}, τ_{by} the seabed shear stresses along x and y axis, A_h the momentum turbulent eddy viscosity coefficient and f the Coriolis parameter.

More details concerning the model structure as well as the boundary conditions, applied, can be found in Koutitas et al. (1994).

3. Results

The above described mathematical model of a completely stratified, two layered field has been applied to simulate the baroclinic circulation regime in the Thermaikos Gulf which is characterized by a surface mixed layer overlying a steep pycnocline. That was the case of July and August 1994, as it is obvious from the typical density profiles (Figures 3.2, 3.3) based on measurements realized at station TP26 (Figure 3.1), in the framework of a research coordinated by Proudman Oceanographic Laboratory (P.O.L).

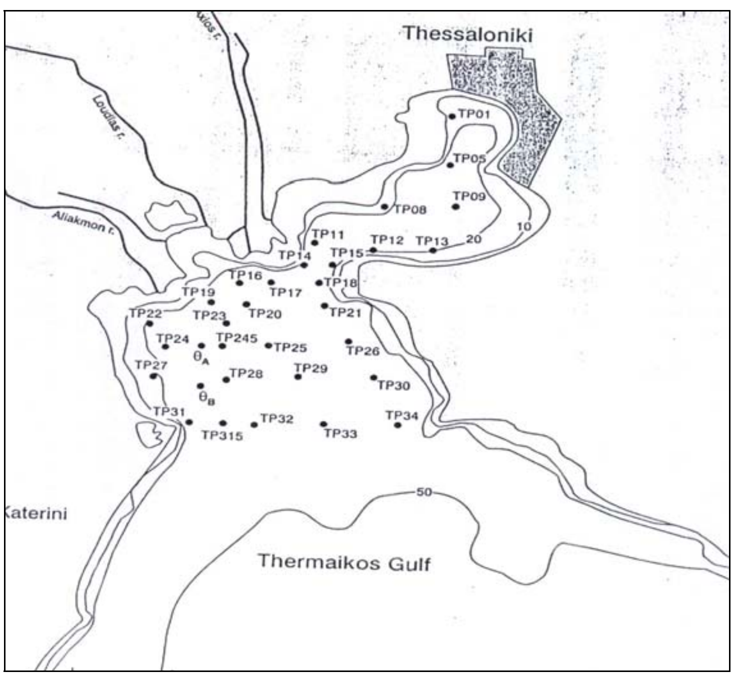

Figure 3.1 A chart of the bathymetry over the survey area showing moorings THA, THB and survey stations TP01-34 (Proudman Oceanographic Laboratory, 1997)

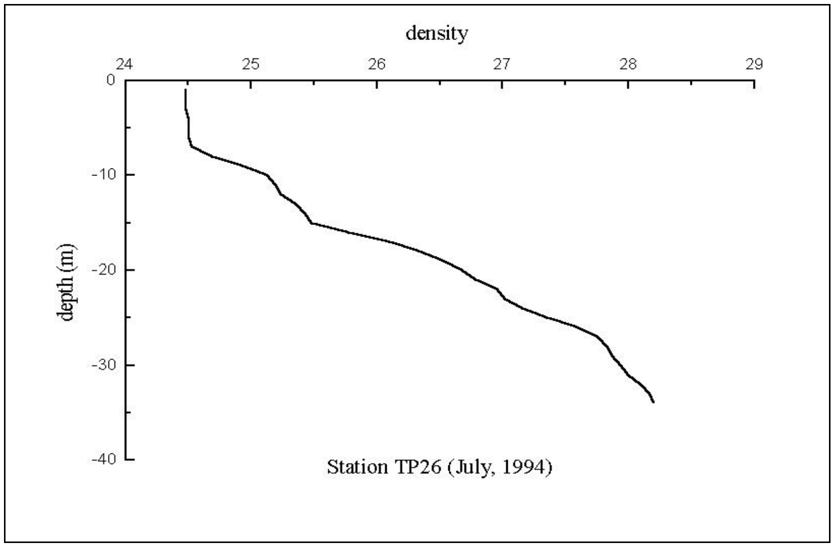

Figure 3.2 Depth distribution of σ_θ density, measured at station TP26 in July 1994

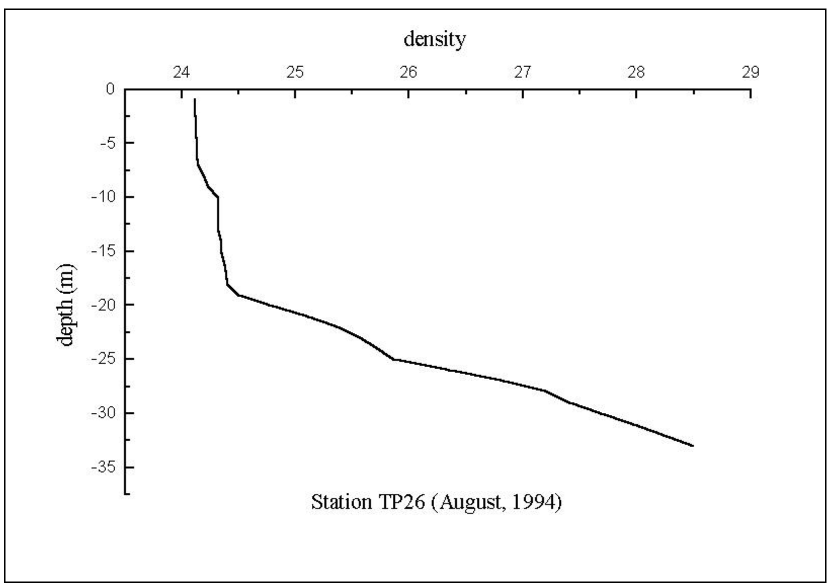

Figure 3.3 Depth distribution of σ_θ density, measured at station TP26 in August 1994

For the application of the model, it was considered that the surface layer had developed a satisfactory thickness of 20 m, while the pycnocline was steep corresponding to a pycnometric difference of about 5 $‰$, as it arises from density profiles in Figures 3.2 and 3.3.

As far as the wind forcing is concerned, the two following cases have been examined. a) The case of a NW wind of intensity 7 m/sec and b) the case of a SE wind of intensity 7 m/sec also, which are the commonest winds in the region, as it is obvious from the histogram in Figure 3.4.

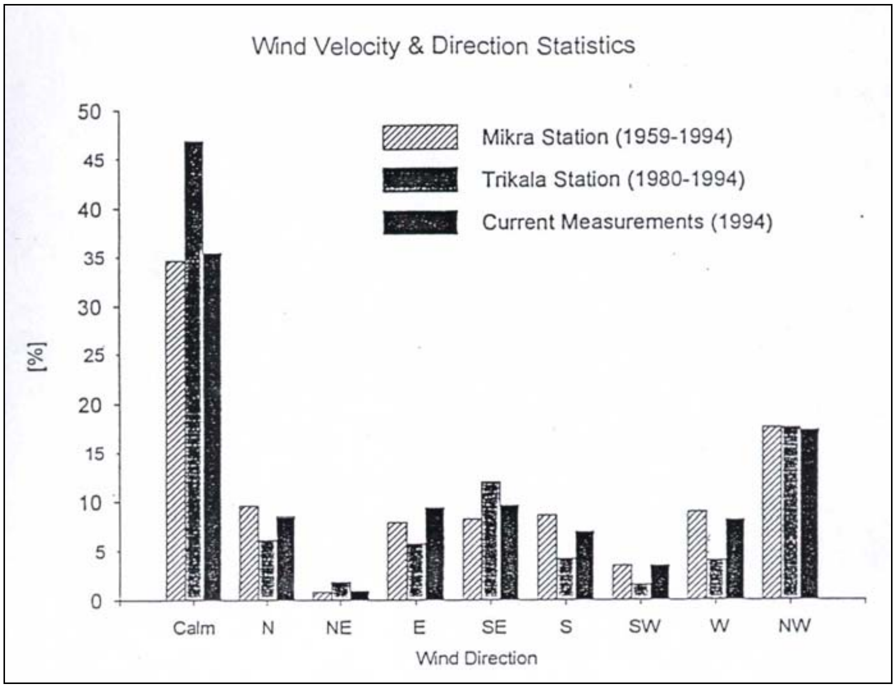

Figure 3.4 Wind statistics as histograms

For the numerical solution of the model, the computational field, which includes the region of Thermaikos Gulf, with southern limit the cross section "Platamonas – Posidi", was discretized. The discretization of the model area was performed by a cartesian grid of 41 × 42 meshes. The horizontal grid size was $\Delta x = \Delta y = 1852$ m. Concerning the vertical direction, the computational field was extended to the depth contour of 100 m, so we selected a time step of 25 sec in order to satisfy the Courant criterion:

$$\Delta t < \frac{\Delta x}{\sqrt{g h_{max}}}$$

The solution results are shown in the diagrams of the following figures that follow (Figures 3.5 – 3.12) representing the depth contours which indicate the thickness of every layer and the velocities fields corresponding to steady flow conditions (x and y axes are in nautical miles NM, where 1 NM ≈ 1852 m).

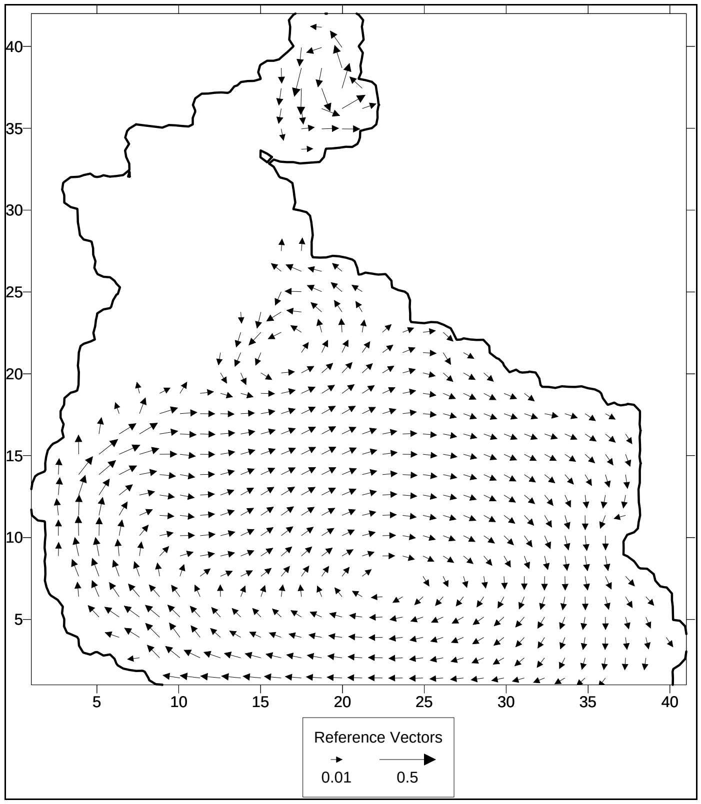

Figure 3.5 Velocity field of the upper layer under the influence of NW wind (velocities in m/s)

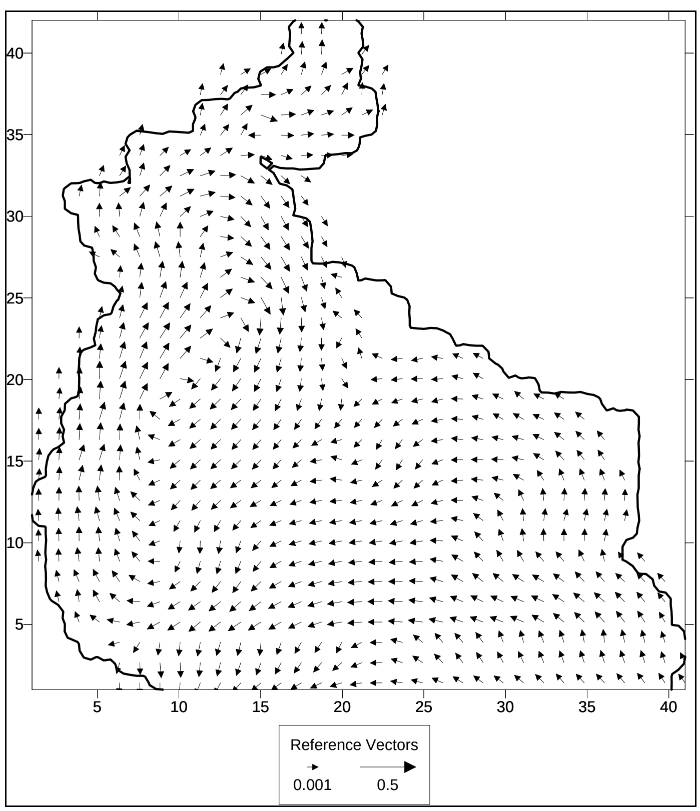

Figure 3.6 Velocity field of the lower layer under the influence of NW wind (velocities in m/s)

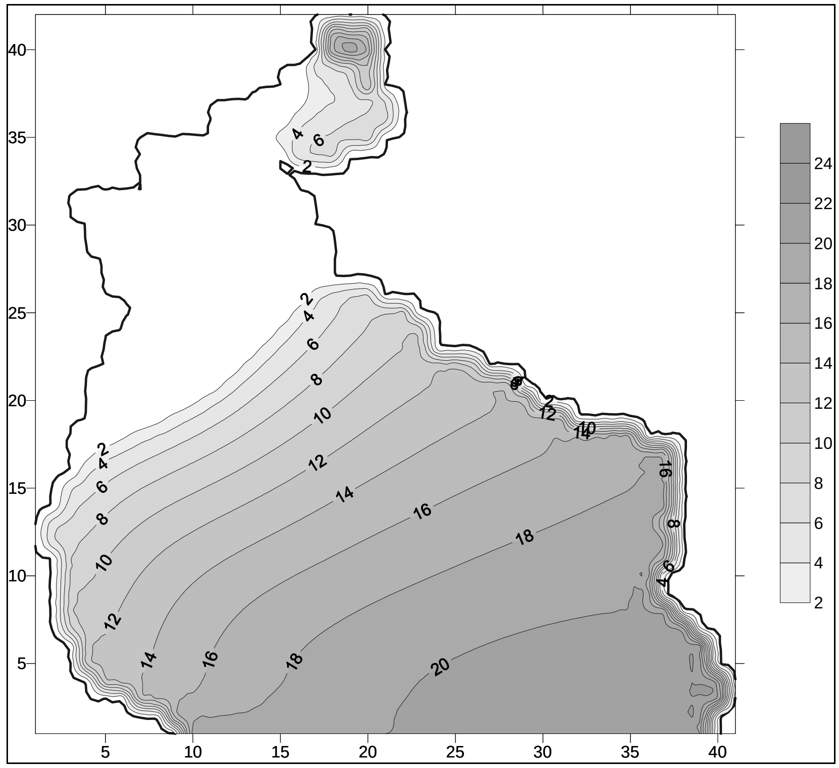

Figure 3.7 Depth contours (thickness in meters) of the upper layer under the influence of NW wind

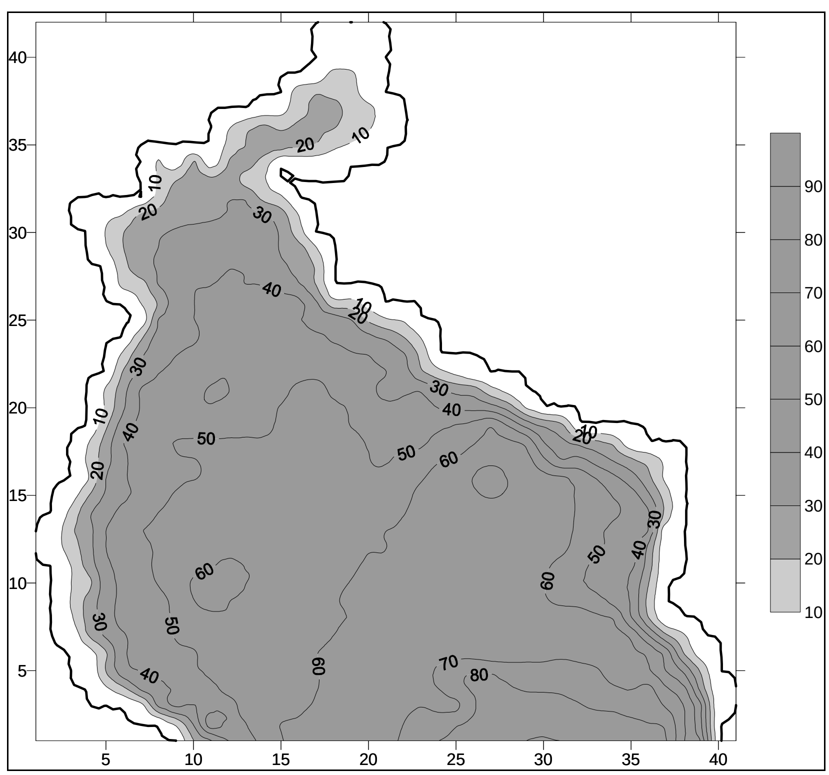

Figure 3.8 Depth contours (thickness in meters) of the lower layer under the influence of NW wind

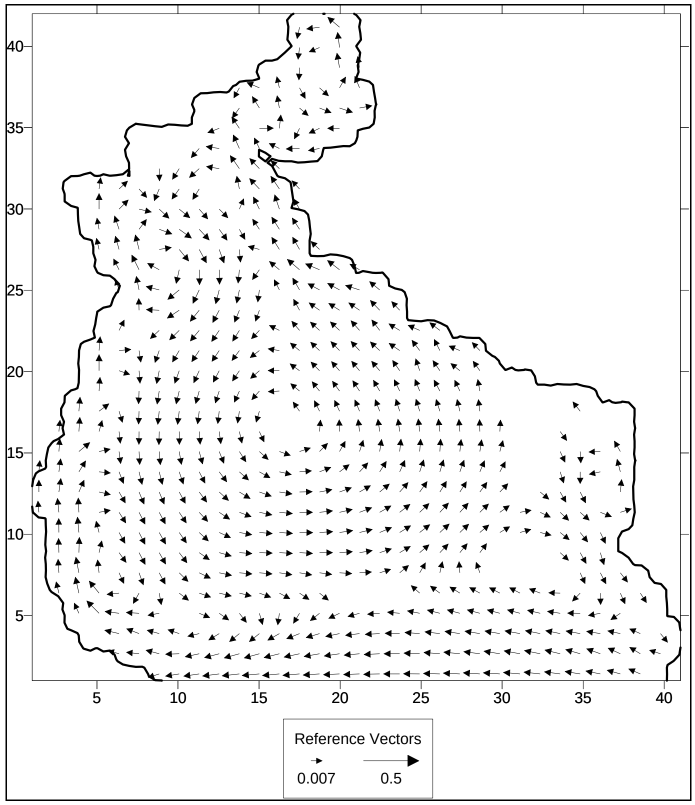

Figure 3.9 Velocity field of the upper layer under the influence of SE wind (velocities in m/s)

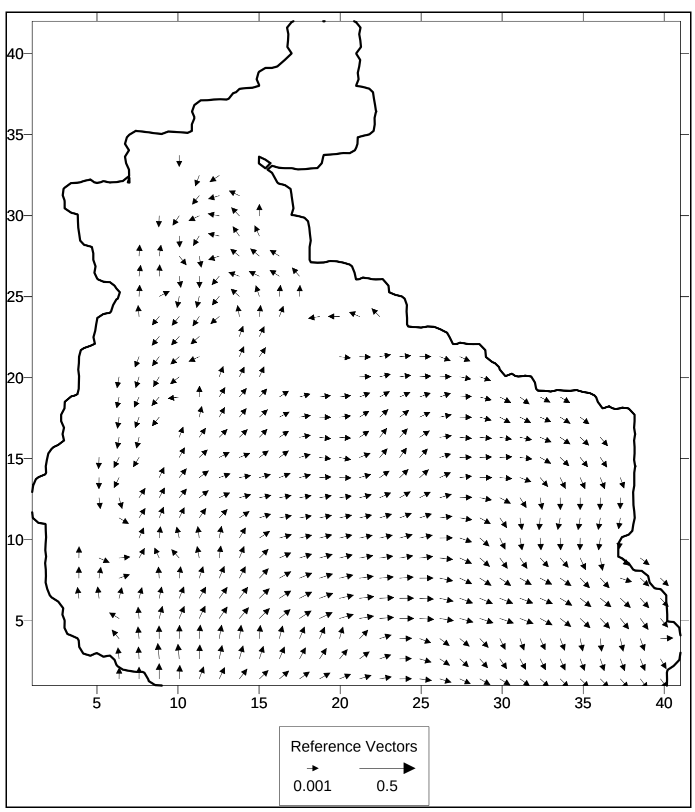

Figure 3.10 Velocity field of the lower layer under the influence of SE wind (velocities in m/s)

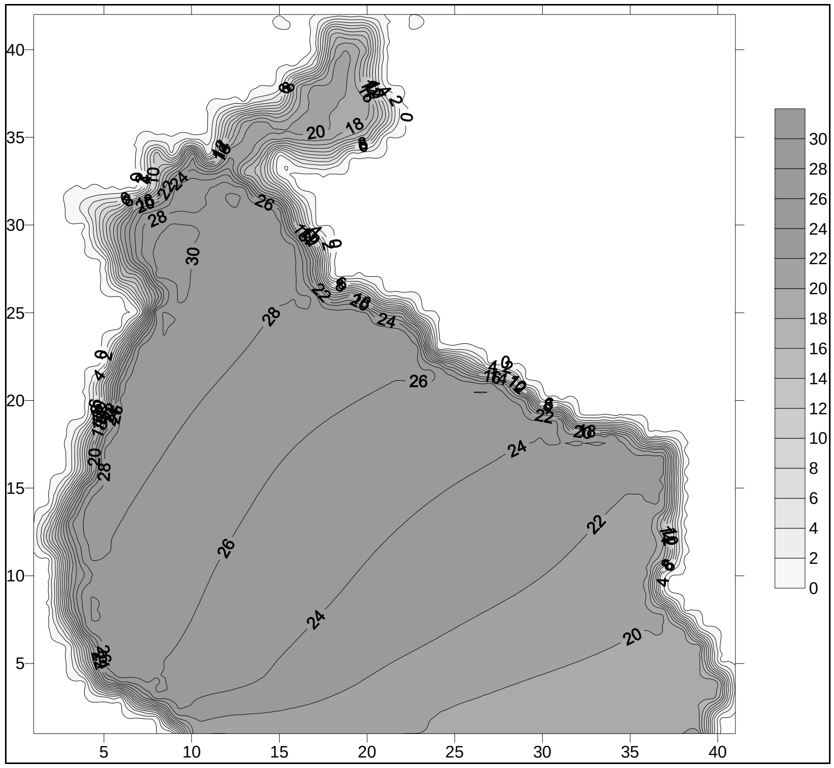

Figure 3.11 Depth contours (thickness in meters) of the upper layer under the influence of SE wind

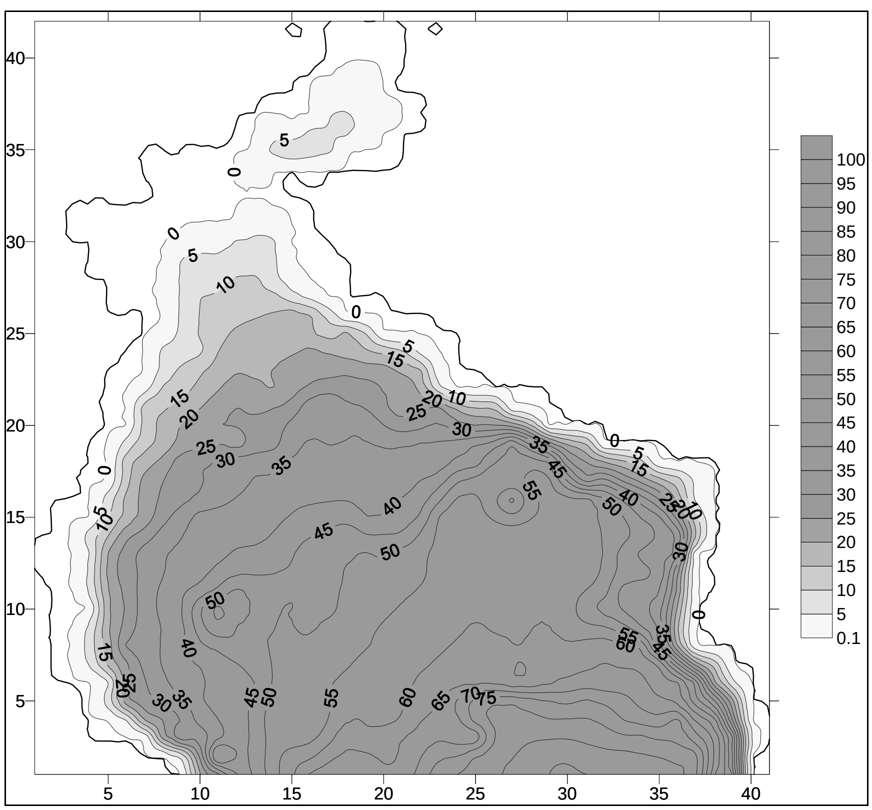

Figure 3.12 Depth contours (thickness in meters) of the lower layer under the influence of SE wind

4. Discussion

Model application in the real topography of the Thermaikos Gulf raised several interesting points:

1) Upwelling process takes place in several sub-regions of Thermaikos Gulf coastal domain depending on the prevailing wind conditions, as well as on the density gradients. In the case of the most frequent NW wind, a characteristic inflow of seawater masses is observed in the lower layer, eastern of the south open sea boundary, part of which enters the Gulf of Thessaloniki. Theses masses form an anticyclone and come up to the sea-surface, refreshing surface waters, with cold, deep waters, enriched with nutrients. In that way, the results of mathematical simulation concerning the hydrodynamic circulation in the Gulf are in line with the general pattern of circulation according to Lykousis et al. (1981). Furthermore, the highest amounts of surface nutrients in the northern and western parts of the Thermaikos Gulf, during the period June – July 2000, reported by Pavlidou (2001), in combination with the prevailing NW winds measured by the Institute of Forest Research (Sani's station), during June – July 2000, may be considered as a first positive indication for the reliability of the model's results.

2) The sub-region, where upwelling occurs (at the northern and western parts of the gulf), is expected, given that the prevailing NW wind, blowing offshore the northern and western coastal zones is characterized by an important component normal to the coastline of these zones. According to the theory, the most favorable wind concerning upwelling events in the case of shallow waters is an offshore wind normal to the coastline. More analytically, the three following zones on the continental shelf, with different upwelling dynamics, are distinguished:

- Upwelling in the shallow, nearshore, coastal region occurs when the wind blows offshore (normal to the coastline).
- Upwelling in the middle continental shelf develops under the influence of winds parallel to the coastline, with the coastline on the left at the north hemisphere or on the right at the south hemisphere.
- Furthermore, upwelling events may be observed on the external zone of the continental shelf, due either to fluctuations of the ocean current or tidal pumping.

3) Respectively, in the case of an onshore wind blowing normal to the coastline, the inverse phenomenon of upwelling is expected, i.e. downwelling, which is described by the sinking of waters and their intrusion from the upper layer to the lower. The above expectation is confirmed by the diagrams that resulted from the application of the model for SE wind (Figures 3.9-3.12).

4) Summarizing, the importance of the model can be focused on the fact that it constitutes a useful tool to pass from a general rule to more accurate results. More specifically, the generalized rule of relating the dominant winds in a coastal region with the occurrence of upwelling events is considered a well-known valid theory; these upwelling events imply increased biological productivity. Furthermore, the mathematical simulation, described above, contributes to an exact tracing process of specific upwelling areas, taking into account the influence of the coastline complexity and the bathymetry to the development of the upwelling process.

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