UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL ATOMIC ENERGY AGENCY
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

SMR/989 - 25

"Course on Shallow Water and Shelf Sea Dynamics"
7 - 25 April 1997

"Investigation of the Coastal Upwelling in the Black Sea & its Influence on Oxygen & Hydrogen Sulphide Distributions"

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INVESTIGATION OF THE COASTAL UPWELLING IN THE BLACK SEA AND ITS INFLUENCE ON OXYGEN AND HYDROGEN SULPHIDE DISTRIBUTIONS

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INTRODUCTION

The Black Sea, as all the inland seas, has very specific hydrological and hydrochemical structure of waters. Having comparatevely small area, it contains a considerable volume of water owing to rather deep-sea trench located in the central part. The vast shallow-water area, which determines the hydrological conditions in the subsurface layers of the entire sea is located in its north-west region. The inflows of fresh water to the surface layer and the salt Marmara Sea waters to the intermediate and deep layers of the sea, being low as to their transports but acting constantly during millenniums, have formed the extremely intense and comparatively thin layer of sharply increasing density-pycnocline, which in the upper layer of the sea is closely connected with increasing salinity from surface to bottom (Fig.1). The thinner and more intense density jump layer - thermocline - is located above it in summer. A cold intermediate layer (CIL) is formed between these jump layers.

Moreover, the presence of oxic and anoxic zones in the Black Sea designate the fact, that investigation of space-temporal characteristics of oxygen and hydrogen sulphide distributions, their dynamics and interaction is the one of the central question. The oxygen penetration depth don't exceed 80-100 m in central areas and 180-200 m in offshore ones. So only 0.1 part of the Black Sea water is suitable for biological forms and communities living. Namely this fact defines the topicality of investigation of anoxic zone dynamics and processes, determining oxic interface position and its stability.

The generalized curves of the oxygen and hydrogen sulphide distributions for the Black Sea are shown in Fig.1. The oxygen concentration is near saturation (90-110%) at the surface layer ($0-h_1$). The thickness of this layer is different in various points of the sea. It has the minimum value in the central part and the maximum value in the shelf areas. When the depth being increased from h_1 to h_2, oxygen concentration is decreased tenfold.

According to previous hydrochemical investigations the oxygen concentration has been supposed to reduce gradually from h_2 to h_5 (dashed line in Fig.1), where it attained zero value. Herewith h_5 was always greater then h_4 (the upper interface of anoxic water). This layer (h_4-h_5) was called H_2S and O_2 co-existence zone. The hydrogen sulphide concentration has been assumed to change due to oxidization by the oxygen dissolved in this layer. The process of oxidization has multistep character, including a series of intermediate reactions. It was described by summary equation (Scopintsev, 1975):

$$\alpha O_2 + \beta H_2S \; ----> \; H_2SO_4, \qquad (1)$$

and the rate of interaction was represented by formal equation:

$$V = K \times [O_2]^n \times [H_2S]^m \; . \qquad (2)$$

Here the ratio α/β shows in what relation gases interact with each other; V- the rate of reaction; K - constant of reaction; n - the oxygen order of reaction; m - the hydrogen sulphide order of reaction; m+n - total order of reaction.

The connection between vertical water exchange and oxygen/hydrogen sulphide distribution was described by Ayzatullin and Skopintsev (1974), Belyaev (1974). The values of vertical velocities in the deeper part of the sea, the rate of oxidization of hydrogen sulphide and "turnover time" of H_2S were estimated from the chemical data. The influence of hydrophysical processes on co-existance zone position was investigated by Stanev (1986, 1987) in the framework of one-dimentional models. The horizontal gradient of oxygen/hydrogen sulphide concentration was supposed smaller than vertical one in these elaborations.

Later investigations (1988 joint US - Turkey cruise on R/V "KNORR") have shown that co-existance zone in the central part of the Black Sea wasn't present at all. The conception of "sub-oxygen zone" (h_2-h_4) was proposed instead of "co-existance zone" (h_4-h_5).

Anyway, theoretical modeling based on experimental chemical data have been carried out for the central part of the Black Sea. Now the question is how oxygen/hydrogen sulphide distribution changes near the shelf-slope areas, where the most powerful dynamical processes take place. Unfortunately chemical measurements almost did not conduct in these areas. Partly it deals with complicated technology of determination of gases concentration near the shore.

The Black Sea is a basin with a low tidal activity. So the main dynamical processes are generated by means of the wind forcing. Seiches are one of the probable movement in semi-enclosed basin. According to Arhipkin et al.(1989), the frequency band of the Black Sea seiches corresponds to periods varying from 3.8 till 9.7 hours. Barotropic seiches can generate internal waves over the shelf break. Internal waves affect on fluid mixing and hydrochemical fields evolution. Such investigation had been carried out in (Vlasenko et al., 1993) early. It was shown the seiches influence on the oxygen/hydrogen sulphide distribution near the continental slope is negligible.

Another types of motions affected on nearshore dynamics and connected with wind forcing, are upwelling-downwelling processes and inertial oscillations. Phenomenon of upwelling in the Black Sea is differed from the ocean one, because of short time of wind forcing (approximatelly one day). But even small time of wind forcing is enough to upwell of cold water to the free surface, because of the upper interface of the Black Sea CIL (8° C isotherm) is situated at the depth of 30 m. The thickness of CIL is nearly $50 \div 80$ m (Fig.1). The upper hydrogen sulphide interface isn't deeply located and a probability of strong lifting of this water by upwelling is essential. Accidents of hydrogen sulphide entrance on the surface are known in some places of the ocean.

Upwellings are often registered in summer season at the shelf of the Crimean Peninsula. The north-west part of the Black

Sea is shallow one, and concentration of the hydrogen sulphide is hardly determined here. So, our interest will be limited by central part of the shelf-slope zone of the peninsula where continental slope is steep (Fig.2).

The main goal of this paper is investigation of water dynamics caused by wind forcing in the coastal zone of the Black Sea and its influence on the oxygen/hydrogen sulphide distributions.

MODEL FORMULATION

Introduce the right-hand side coordinate system, with z-axis directed vertically upwards, so that z=0 represents a free surface (Fig.3). The x-axis is perpendicular to the isobaths and y-axis is oriented along the shore. We assumed relief and thermohaline structure uniform along y-axis. The depth is varied from 20m on the shelf to 2000m in the deep part at distance 40km. The model domain is a vertical plane ranging from the sea surface to the bottom and from the coast to 200km offshore.

Coastal upwelling regions are typical areas where both advection and mixing play important role in the water movement and transformation. Therefore, linear inviscid coastal models generally have little applicability for upwelling simulation. Hence, we will employ a complete system of Reynolds hydrodynamic equations including nonlinear members, as well as the turbulent exchange terms:

$$u_t+uu_x+vu_y+wu_z - fv = -P_x\rho_a^{-1} + au_{xx} + av_{yy} + Au_{zz},$$

$$v_t+uv_x+vv_y+wv_z + fu = -P_y\rho_a^{-1} + av_{xx} + av_{yy} + Av_{zz},$$

$$w_t+uw_x+vw_y+ww_z = -P_z\rho_a^{-1} - g\rho\rho_a^{-1} + aw_{xx} + aw_{yy} + Aw_{zz},$$

$$u_x+v_y+w_z=0, \qquad (3)$$

$$S_t+uS_x+vS_y+wS_z = mS_{xx}+mS_{yy}+MS_{zz},$$

$$T_t+uT_x+vT_y+wT_z = mT_{xx}+mT_{yy}+MT_{zz}.$$

Here u, v, w are the components of the velocity vector; P and ρ - pressure and density respectively, ρ_a - the mean value of density; f- Coriolis parameter; g - gravity acceleration ; S - salinity; T - temperature; a, m, A and M - coefficients of horizontal and vertical eddy viscosity and turbulent diffusion, used as constants values in (3). Choice of turbulent submodel adequately reflected subgrid processes taking place in the considered area is a serious problem. Allen et al. (1995) have fulfilled numerical experiments with vertical turbulent viscosity and diffusivity parameterized as constants or as functions of local Richardson number for Oregon upwelling. These experiments have shown substantial dependence of the response flow field on the choice of turbulence submodel in case of long (two decades) oceanic upwelling. For the Black Sea case when upwelling developes during one day utilization of constant coefficients of turbulent viscosity and diffusivity is acceptable.

These follow from a sensitivity study on the parametrization of turbulent exchange for the Black Sea conditions in diagnostic and semidiagnostic models carried out by Stanev et al. (1988). The comparison between the results obtained with constant and variable (assumed as function of scale and shift of velocity) coefficients indicated that for the Black Sea conditions the optimum ones can be determined as $a = 30\ m^2 \cdot s^{-1}$, $A = 10^{-4}\ m^2 \cdot s^{-1}$. Values of vertical and horizontal coefficients of turbulent diffusivity were $m = 30\ m^2 \cdot s^{-1}$, $M = 10^{-5} m^2 \cdot s^{-1}$ according to experimental works of Kolesnikov and Boguslavskii (1978) and Konovalova (1972). Density ρ was calculated from T and S following to Fofonoff (1962).

The model is originally three-dimensional, but in the present study it is reduced to two-dimensional one for two reasons. Firstly, in situ data indicate that the mass and heat balances on the shelf are basically two-dimensional during the active upwelling when averaged over some alongshore distance (Lentz, 1986; Mooers et al., 1976). Secondly, our primary interest is to investigate the peculiarities of cross-shore water thermohaline structure, characteristics of dynamical and chemical fields during coastal upwelling. As it was shown by Kraus (1979) two-dimentional model of coastal upwelling would be true when time scale of the process is less than 5-10 days - the time scale of shelf waves.

So, all derivatives along y were supposed as equal to zero ($\partial/\partial y \equiv 0$). After eliminating of the pressure and defining of stream-function and eddy as follows

$$u = \psi_z, \qquad w = -\psi_x, \qquad \omega = \psi_{zz} + \psi_{xx},$$

the system of equations (3) is reduced to the form:

$$\begin{aligned} &\omega_t + J(\omega,\psi) - fv_z = g\rho_a^{-1}(\rho)_x + a\omega_{xx} + A\omega_{zz}, \\ &\omega = \psi_{zz} + \psi_{xx}, \\ &v_t + J(v,\psi) + f\psi_z = av_{xx} + Av_{zz}, \\ &S_t + J(S,\psi) = mS_{xx} + MS_{zz}, \\ &T_t + J(T,\psi) = mT_{xx} + MT_{zz}, \end{aligned} \qquad (4)$$

where J is Jacobian.

It is likely the hydrogen sulphide may penetrate to the oxygen layers during the uprising of deep water. The presence of a mixture of two compounds will proceed to reaction between them. This leads to reinstate the former results about "co-existance zone". As it was shown by Stanev (1987) the minimum time of oxygen and hydrogen sulphide interaction is nearly 6 hours in the co-existance zone. So it is necessary to consider the reaction between these two gases.

Two following equations describe the processes of mixing and advection of $[H_2S]$ and $[O_2]$ and reaction between them:

$$\begin{aligned} &[H_2S]_t + J([H_2S],\psi) = b[H_2S]_{xx} + B[H_2S]_{zz} - K_s[H_2S][O_2], \\ &[O_2]_t + J([O_2],\psi) = b[O_2]_{xx} + B[O_2]_{zz} - K_o[O_2][H_2S]. \end{aligned} \qquad (5)$$

Here $b = 30\ m^2 \cdot s^{-1}$ and $B = 10^{-5} m^2 \cdot s^{-1}$ - coefficients of horizontal and vertical turbulent diffusion. These values are corresponded to mean ones, obtained in the Black Sea in experiments on radioactive isotopes spreading (Ozmidov, 1986). K_o and K_s - constants of reaction for oxygen and hydrogen sulphide. Numerical experiments concerning the choice of chemical constants and values of horizontal and vertical diffusivity will be considered below.

Boundary conditions were as follows. On the sea surface z=0, the "rigid-lid" condition and velocity shear, induced by the tangential wind stress, were assumed:

$$\psi = 0, \qquad Au_z = -\tau_x\rho_a^{-1}, \qquad Av_z = -\tau_y\rho_a^{-1}.$$

The wind stress was calculated by the formula:

$$\tau_x = \tau\cos\alpha, \qquad \tau_y = \tau\sin\alpha, \qquad \tau = \rho_b C V_o^2.$$

Here, V_0 is the wind speed, ρ_b is air density, C is empirical factor ($C=1,6\cdot10^{-3}$ at $V_0<7\ m\cdot s^{-1}$, $C=2,5\cdot10^{-3}$ at $V_0\geqslant7\ m\cdot s^{-1}$) and α is wind direction.

For thermohaline and the hydrochemical fields at the sea surface z=0

$$T_z=0,\quad S_z=0\ ,\quad [O_2]=5.3\ ml\cdot l^{-1}\ ,\quad [H_2S]=0.$$

At the bottom z=-H(x) the kinematic non-flow and no-slip conditions are imposed:

$$\psi_z = \psi_x = v = 0,\quad T_n = 0,\ S_n = 0,\quad [H_2S]=f_1(x),\ [O_2]=f_2(x),$$

$$[H_2S] = 6.5\ ml\cdot l^{-1},\ \text{at the depth } z=2000\ m.$$

Reproduction of hydrogen sulphide in the Black Sea is realized due to putrefaction of sulfur-containing organic compositions and restore of sulphate by bacteria. The greatest productivity of bacteria and their concentration take place at the sea bottom. This circumstance and recent ideas about distributions of chemical elements near bottom (Bezborodov, 1988) were took as a principle for definition of functions $f_1(x)$ and $f_2(x)$.

At the coast x=0 the following boundary conditions were used:

$$\psi_x=0, v=0, T_x=0, S_x=0,\quad [H_2S]_x=0,\quad [O_2]_x=0.$$

At the open "liquid" boundary x=200 km were considered:

$$\psi_x=0,\ v_x=0,\ T_x=0,\ S_x=0,\ [H_2S]_x=0,\ [O_2]_x=0.$$

Before constructing a numerical analogue of system (4)-(5) the latter was transformed into the form suitable for development of a computational algorithm using substitution of variable:

$$z_1 = \int_0^{z} N(s)ds \ \Big/ \int_0^{-H(x)} N(s)ds \qquad (6)$$

Function N(s) - is Vaisala-Brunt frequency. This substitution allowed one to reduce the spacing of the computation grid in the upper layers with large vertical gradients of the quantities. Moreover the replacement of (6) renders the irregular computation area into the rectangular one. The transformed system of equations is derived in the Appendix.

The problem was solved numerically. For the finite difference approximation of equations an implicit difference scheme was applied whose general structure is discussed in Paskonov et al. (1984). The method of variable directions on a rectangular grid with the second order approximation was used.

Initial distributions of water temperature and salinity were assumed uniform in the horizontal direction, while their vertical profiles was typical for summer season in the Black Sea (Fig.1). We used hydrochemical in situ data as the raw information for $[H_2S]$ and $[O_2]$ distribution. Sinking of these isolines near shelf-slope zone was also taken into consideration (Fig.3).

The question is in what relations hydrogen sulphide and oxygen step into reaction in area where their concentrations are small. Following to the rule of active masses the rate eq. (2) of hydrogen sulphide oxidization may be satisfactory presented as a reaction of the second order (n=1; m=1; n+m=2). If the relation of reagents in reaction defers from 1:1, the rates and rate constants will be different for oxygen and hydrogen sulphide. Most scientists (Stanev,1987; Ayzatullin and Skopintsev, 1974; Belyaev, 1974 et al.) prefer to use relation $\alpha:\beta=3:1$ according to Cline and Richards (1969). In this case constants of reaction will be $K_o = 1.5\times10^{-3}$ $l\cdot mkg\text{-}at^{-1}\cdot h^{-1}$ and $K_s = 0.5\times10^{-3}$ $l\cdot mkg\text{-}at^{-1}\cdot h^{-1}$. From Besborodov's (1988) point of view the constants of reaction are equal to $K_s = K_o = 3.2\times10^{-3}$ $l\cdot mkg\text{-}at^{-1}\cdot h^{-1}$. In this case reagents will step into reaction in relation 1:1.

We had realized investigation of stable state to obtained clarity in choice of constants of reaction. Evolution of initial thermohaline and hydrochemical fields without any external influence were considered. The adaptation of fields to the boundary conditions, constants of reactions and numerical scheme was achieved during definite time. At first experiment we used constants according to Cline and Richards (1969). The distributions of hydrogen sulphide and oxygen were stabled after 450 hours (~20days). The resulting vertical displacements of H_2S and O_2 boundaries from their initial positions didn't exceed 10m. The second experiment with $K_s = K_o = 3.2\times10^{-3}$ $l\cdot mkg\text{-}at^{-1}\cdot h^{-1}$ (Besborodov, 1988) was failure. Stabilization of fields were not attained after 450 hours as in first one, besides oxygen field, for example, dropped to additional 100 m. To sum up, we used in the following callculations the stable thermohaline and hydrochemical fields obtained with following constants of reaction $K_o = 1.5\times10^{-3}$ $l\cdot mkg\text{-}at^{-1}\cdot h^{-1}$ and $K_s = 0.5\times10^{-3}$ $l\cdot mkg\text{-}at^{-1}\cdot h^{-1}$.

The motion originates from the state of rest when the fluid is not moving and thermohaline and hydrochemical fields have come to the steady state after the adaptation process. Wind forcing putting to the sea surface leads to development and formation of nearcoastal circulation. According to the long-term wind measurements conducted from 1971-1980 (Altman and Matushevskiy, 1987) the duration of wind, blowing in some base direction, as a rule, don't exceed one day. Moreover the direction of wind are different from season to season. The winds are general from west-northwest in winter, but they often blow from east-southeast in summer. This is the summer wind as a rule cause a lifting of a cold water near the Crimean coast. The greatest day-averaged magnitude of wind velosity from east is approximately equal to 15 m/s. The winds with greater magnitude are registrated only in winter and their duration don't exceed 15 hours.

RESULTS

a. Upwelling event

Before the consideration of oxygen and hydrogen sulphide dynamics in the coastal zone of Crimea during the upwelling it is necessary to investigate the characteristics of currents which promote the evolution of these hydrochemical fields.

A series of calculations with different magnitudes of wind velocity (from 7 till 15 m/s) was carried out. The period of wind action was equal to 10, 16 and 24 hours. After the finishing of initial wind impulse the quiet weather is established. First of all we shall consider the results of the basic numerical experiment (basic case - BC) fulfilled for the wind velocity 15 m/s and one day forcing. The influence of wind velocity and value of wind action period will be discussed in the end of this part.

Figure 4 shows the model predicted fields of along-shore and cross-shore currents, vertical velocity and temperature right after the finishing of wind action (t=T). Such kind of structure of water circulation during nearcoastal upwelling was found and discussed earlier (for ex. Mooers et al., 1976, Chen and Wang, 1990, Allen et al., 1995). Therefore, we shall describe concisely these resulting hydrodynamical fields and focus our attention on the later stages of their free evolution (relaxation process) in more detail. The value T=24 hours here and in all Figures is used as a temporal scale.

During the first stage of upwelling the alongshore Stocks's drift is developed by influence of wind stresses. The maximum value of this current (75cm/s) is situated at the sea surface on the shelf. Half day after the beginning of fields evolution the alongshore countercurrent is generated on horizons 20-70m over the continental slope and in the open part of the sea. It's core is situated at the depth about 25-35m and has velocity approximately 15cm/s (Fig.4a).

Excitation of the alongshore currents leads to development of cross-shelf circullation. In the offshore direction the geostrophic current is generateded in the upper 10-30m surface layer due to the Coriolis force. The seaward velocity attains 65 cm/s at the sea surface. A deficit of water near the shore is compensated by the nearbottom countercurrent. The greatest value of the onshore velocity equals to 22cm/s and is located near bottom between isobaths 50÷100m (Fig.4b).

Existence of cross-shelf circulation (nearbottom shoreward and in the surface layers seashore) leads to the formation of vertical circulation cell on the shelf. The maximum value of upward velocities in the region of shelf break attains 0.82cm/s. (Fig.4c). The similar lifting of water takes place near the shore, and cold water upwells to the sea surface. Several vertical circulation cells can be excited on the shelf depending on the value of Rossby deformation radius, width of the shelf and structure of bottom relief. So, a local zones of sinking water can appear in various points of the shelf (see Fig.4c). As a rule they are connected with the boundaries of the cells.

The structure of nearcoastal currents has influence on the peculiarities of evolution of water temperature field. By the end of one day wind action the primarily horizontal thermocline (at horizons 10-15m) has lifted to the sea surface (Fig.4d) due to the vertical advection in cell. However, one day duration of wind forcing is not sufficient for the exit of cold water to the sea surface. The warm water (20^{0}C) still remains on the shelf.

After cessation of wind forcing the thermochaline fields continue their evolution without any external influence. Two different types of movements are formed on the shelf and in the open part of the sea. In shelf zone the quasistable advective cell is established. Its structure at t=1.5T is shown in Fig.5. Horizontal dimension of cell (~10 km) coincides with the first baroclinic Rossby radius of deformation. The maximum value of vertical velocity in upward fluxes is equal to 0.13cm/s while descending of water with maximum velocities 0.26cm/s (Fig.5d) takes place in the shelf-break area. Isotherms (isopicnals) on the shelf are inclined toward the coast and along-shore geostrophic jet supports this density front. Maximum value of alonshore speed is equal to about ≈10 cm/s.

The shelf advective cell exists a few days without wind forcing and relaxes in time due to the dissipation. It continues to supply nearbottom cold water to the upper layers and lifts thermocline. During two days of the quiet weather the value of shoreward velocity near the bottom reduces from 25cm/s (t=T) to 5cm/s (t=3T). This weakening of vertical circulation on shelf proceeds on the background of attenuated subinertial oscillations. We shall discuss this type of motions below.

Another type of movement is established at the seaward side of the shelf break. The evolution of cross-shelf velocity, vertical velocity and temperature during two days after the atmospheric impact is represented in Fig.6. The analysis of vertical profiles of cross-shore velocity shows that in the open part of the sea they have basically two-layer character. Horizontal current change its direction on horizons 40-140m. For example, the cross-shore current in the surface layer is derected seaward and in opposite direction at the depth deeper then 100m at time moment t=1.8T. It is interesting to note that such kind of peculiarity of currents profiles take place at any moment of time (see Fig.6).

The second interesting finding of cross-shore dynamics is the temporal periodicity of currents. The conclusion about oscillation character of horizontal currents is followed from the comparison analysis of u-fields pairs in Fig.6 (t=1.4T and t=2.4T; t=1.6T and t=2.6T; t=1.8T and t=2.8T). The likelihood of these pictures sugests the temporal periodicity of evolution. Really, the dispositions of positive and negative velocity zones and shapes of zero izoline qualitatevly coincide at these moments.

The above-mentioned periodicity of movement is presented in Fig.7 more obviously. Here the time series of stream functions ψ and alongshore velocities v at 10m depth on the shelf, over the shelf-break and at the seaward side of shelf edge are shown. During the wind forcing the fluid in coastal zone is receiving the initial impulse. When the wind is ceased, the system continues its evolution due to three factors: gravity force, Coriolis force and dissipation. Under such conditions an inertial oscillations can arise in the nearcoastal zone. The generation of nearinertial oscillations by wind impulse have been discussed earlier by D'Asaro (1985), Kunze and Sanford (1984), Wang (1991). It was shown that they are horizontal, located in the upper layer and slowly penetrate in the depth with vertical grope velocity 10÷20 m/day (Wang, 1991). Frequency of these oscillations depends on the effective local inertial frequency f_{eff} (Mooers, 1975):

$$(f_{eff})^2 = (f + v_x) \cdot f.$$

Here v_x is horizontal vorticity. Thus, f_{eff} can be both greater and less than inertial frequency depending in sign of vorticity. According to Mooers (1975), free internal-inertial waves can exist at anomalous low frequencies

$$\sigma_1 < \sigma < f_{eff}, \qquad \sigma_1^2 = f_{eff}^2 - S^2N^2,$$

where $S = - M^2/N^2$ - isopicnal slope, M^2 and N^2 - horizontal and vertical density gradients.

The period of obtained oscillations in our case also don't equal to inertial one at 44°30' N (the local inertial period is 17.08 h). As it is seen from Fig.7 its value is different in shelf zone, over the shelf break and offshore. This discrepancy in magnitude may be explained by different hydrological conditions (local vorticity of alongshore current and value of horizontal density gradient). It is equal to local inertial value near the bottom in the open part of the sea, where horizontal gradient is small and attains ~ 21-22h in areas with large horizontal gradients over the shelf break. Besides, as it is seen from Fig.7 oscillation period can change its value during upwelling relaxation. Attenuation decrement also is not the same on the shelf and offshore. The greater distance from the shelf the weaker is dissipative effects. In the open part of the sea oscillations have retained during five days.

Consider now the spatial characteristics of nearinertial oscillations in the shelf-slope area. Inertial waves in the open sea, as was described by Wang (1991), had been generated in the upper mixed layer and penetrated slowly into the depth. The presence of steep shelf-slope in our investigations totally changes situation. Horizontal inertial currents u, propagating onshore in the upper layer (Fig.6, t=1.4T; t=1.6T) run upon the wall (shelf-slope). According to water discontinuity the powerful fluxes of descended water must arise over the slope. After the half of period surface currents are directed offshore (Fig.6 t=1,8T; 2.0T) and descending of water over slope is changed to uprising. So, the periodical subinertial vertical oscillations are established over the slope. The existance of such kind of periodical vertical water fluxes (zones of convergence and divergence in Fig.6) is shown more distinctly from the patterns of w-velocity. The period of these oscillations is near-inertial, it is clearly seen from analysis of velocity fields when t=1.2T÷2.8T, Fig.6.

The other interesting peculiarity of upwelling relaxation is the excitement of internal waves. They are generated over continental slope and moving onshore from the open part of the sea. An evolution of pycnocline after the cessation of wind forcing is the main reason of internal waves generation. At first stage during wind forcing a pycnocline is deviated from its stationary position by vertical and horizontal currents inherent to upwelling. Then, in relaxation time, the inclined pycnocline begins to return to its initial position. Herewith internal waves are generated at the frontal side of overturning density front. This process is shown in Fig.6. The shift of the position A at t=1.2T-1.8T indicates the propagation of frontal zone onshore, the shift of position B and C represents movements of internal waves phase. The latter readily can be traced from w-fields by comparison of patterns at t=2.4T-2.8T. So, the phase velocity of moving onshore internal waves is equal to 0.35 m/s.

We propose the following scheme of coastal upwelling relaxation occurring in the Black Sea (Fig.8):

-dissipating vertical circulation cell on shelf;

-horizontal reversive subinertial oscillations in the open part of the sea (current and countercurrent in upper and deep layers);

-vertical subinertial oscillations over the continental slope;

-propagating shoreward internal waves, generated on the frontal side of moving density front;

-reflected from continental slope progressive internal waves moving seaward.

The possibility of excitement of vertical subinertial oscillations during relaxation of nearcoastal upwelling is confirmed by in situ data, collected in coastal zone of the Black Sea. Figure 8 represents the vertical displacements of thermocline measured at point A (see Fig.2) over the shelf break (izobath ~100m). Measurements of thermocline dynamics was conducted by distributed sensor of temperature. This device allows one to calculate vertical pycnocline displacement using temperature difference between ends of sensors and mean temperature water value (method was described by Konyaev and Sabinin, 1973). Experiment was conducted during upwelling event in summer, 1993. It is clearly seen from Fig.9, that at first stage of upwelling (13.06-14.06) thermocline was lifted by the wind forcing at and then oscillated with descending during relaxation. Period of these oscillations (T~17.9 h) was shifted to the red part of spectrum in comparison with local inertial one (T_{in}~17.0 h). These results confirm the existence of model predicted vertical subinertial oscillations in transition zone (see Fig.8) during process of upwelling relaxation at first and show red frequency shift at second.

b) Evolution of oxygen and hydrogen sulphide fields.

Now let us consider the evolution of oxygen and hydrogen sulphide fields during the upwelling event. Before the discussion of the obtained results, it is important to put attention on two circumstances. Firstly, because of the dissolved gases O_2 and H_2S are used in equations (5) as a passive admixture, their evolution is defined by the dynamic processes. On the other hand the reaction will be occurred between them, if they proved to be together in some area, and their concentration may be altered nondynamicaly.

As it was shown in the previous section, two different types of motion take place at the coastal zone of Crimea during the upwelling event: the formation of quasistable advective cell on the shelf and generation of subinertial oscillations offshore. The evolution of hydrochemical fields will be considered further according to these two different types of movement.

The evolution of hydrogen sulphide and oxygen fields corresponding to the basic case is firstly considered. The comparison analysis of modification of hydrochemical fields caused by modifications of wind velocity and time of its action will be considered further.

The distribution of initial undisturbed concentrations of H_2S and O_2 are shown in Fig.3. Isolines of oxygen and hydrogen sulphide are horizontal in the open part of the sea and descended shoreward. Figure 9 shows the time depth contours of hydrochemical fields evolution during the coastal upwelling for the BC (basic case).

At first let us consider the processes occurring near the shore. The upward fluxes of cold bottom water along continental slope to the surface are accompined by elevation of H_2S and O_2 isolines onshore. The hydrogen sulphide interface displaced up on 100m during the first stage of upwelling and attained the depth of 40m (Fig.10, t=1.4T). The horizontal shift of interface is equal to 8 km in onshore direction. It is interesting to note the upward displacement of hydrogen sulphide layer wasn't stopping in spite of wind cessation, it has continued during additional 0.5T. Two days later hydrogen sulphide interface has returned to the initial position, where it had been located at the beginning of the upwelling event (Fig.10, t=2.8T). It is ought to consider this process of relaxation in more detail.

As it is seen from Fig.3 isolines of $[O_2]$ and $[H_2S]$ in the initial field don't cross each other. During the upwelling this situation violates. The extensive co-existance zone of H_2S and O_2 arises over the shelf break at place of upward water fluxes. The vertical scale of the co-existance zone don't exceed 5÷10 m, but in horizontal direction the mutual penetration distance is about some kilometers (Fig.10 t≥1.6T). This strange result can be explained from the point of view of dynamics of passive admixture. At first, one should be taken into account that the horizontal coefficient of turbulent diffusion at some order greater than vertical one. During upwelling event the dome of hydrogen sulphide, extended along the slope onshore, begins to spread quickly in horizontal directions due to the large values of horizontal diffusion. The hydrogen sulphide begins to penetrate into the layers enriched by oxygen. The process of oxygen penetration to the hydrogen sulphide dome takes place simultaneously. As a result a huge co-existance zone has formed by moment t=2T. Due to the chemical reaction between these two gases the co-existance zone has vanished by time t=2.8T. Thus the return of hydrogen sulphide isolines to their initial position is a result of chemical reaction between O_2 and H_2S, but isn't as a consequence of dynamic processes on the shelf.

One ought to pay the attention to some interesting problem, followed from the mathematical modeling. If the hydrogen sulpide isolines had returned to their initial position three days after the beginning of upwelling processes, the oxygen isolines didn't restore their initial view. The area with small oxygen concentration has remained over the shelf break (Fig.10, t=2.8T). The presence of such area is a result of reaction between O_2 and H_2S in the places of upwelling of cold nearbottom water. One important practical conclusion can be formulated from this result. The above-mentioned extended area of low oxygen concentration may be considered as a "trace" of upwelling event. This trace can exist a few days, until water will be enriched by incoming flux of oxygen. During this time the upwelling trace may be measured by usual chemical methodic.

The evolution of hydrochemical fields out of the shelf proceeds on the background of the nearinertial oscillations generated here during the upwelling event. Because of the inertial movement is basically two-dimensional here, and its vertical velocity is small, so the vertical oscillations of $[H_2S]$ a $[O_2]$ isolines are small too. As it is seen from Fig.10 the displacement of isolines out of the shelf don't exceed the value of 10 m, and periods of oscillations are closely connected with periods of internal-inertial waves existed here. The co-existance zone of hydrogen sulphide and oxygen don't appear out of the shelf during all time of upwelling.

Essential periodical vertical displacements of the upper boundary of H_2S and lower one of O_2 (20÷30 m) take place in the transition zone (see Fig.8) over the shelf break where intensive vertical subinertial oscillations are generated (compare Fig.10 at t = 1.4T÷2.8T).

Now we dwell on the comparison analysis of the BC results with ones calculated for the case when the magnitude of wind velocity and winds duration were smaller then in the BC. The model response to the different wind forcing are shown in Fig. 11. The upper three pairs of pictures in Fig.11 were obtained for one day wind forcing with wind velocities V_0: 7m/s, 10m/s, 15m/s (BC), the lower two pairs for the wind speed of 15m/s, but wind duration was 16 and 10 hours. The left column in Fig.11 represents the moment of time when hydrogen sulphide lines are the most essentially displaced to the sea surface. The moment of time when anoxic zone has returned to its initial position is shown in right column.

From the analysis of oxic and anoxic zone dynamics shown in

Fig. 11 the following withdrawals can be done. The greater value of wind velocity and time of its duration the higher is the hydrogen sulphide lifting. Extended area of low oxygen concentration isn't arised at the conditions V_0<10 m/s, duration < 12h. This event take place only for winds with velocity 15m/s and time duration 16 hours and more. But it is clear, the greater wind duration the more extensive will be dome of small oxygen concentration.

All above presented calculations were carried out with coefficients of vertical and horizontal diffusivity brought from experiments on spreading of radioactive isotopes according to Ozmidov (1986). The question arises how sensitive the model patterns of oxygen and hydrogen sulphide to the choice of coefficients values. A series of simulations have been realized to answer this question. The BC was chosen for comparison. It was found that if horizontal coefficient ten times smaller than in basic case or vertical coefficients ten times greater than in BC had been used, the hydrogen sulphide would have been at the surface during upwelling event. But these results contradict to observations, because the smell of hydrogen sulphide didn't note at all.

For the coefficients of horizontal diffusivity ten times greater than in BC we couldn't find the initial steady state of H_2S and O_2 fields, qualitatevly corresponding to experimental conceptual picture presented in Fig. 3. The characteristic peculiarity of hydrochemical fields obtained experimentaly is sinking of isolines shoreward. Adaptational calculations have shown that large horizontal diffusivity washes out the horizontal gradients H_2S and O_2 fields over the continental slope very quickly. During 20 days of adaptation the primary inclined shoreward hydrogen sulphide and oxygen izolines become more and more gently sloping and by the end of adaptation they become horizontal over the shelf and continental slope. This result is contradicted to experimental data.

DISCUSSION

Although the anoxic zones in the World Ocean are rarely occurred, their investigation is very important. The most of stable and periodically formed anoxic zones are situated in the northen hemisphere. The Black Sea is one of example of basin with oxic and anoxic zones. Huge areas of fish starve can also be connected with periodical formation of anoxic zones, mainly in upwelling areas. In the Peru upwelling area during El-Nino phenomenon (approximately once a 7 years), extensive anoxic zone is arised and results in mass of fish starve according to Monin (1979). It is possible that anoxic zones appear and exist during short time in some regions of fish starve at the western ocean coast. They are not registrated yet because of hydrochemical investigation are rarely held.

The Black Sea acts as an unique basin due to its hydrological structure (existence of cold intermediate layer, oxic and anoxic zones). In some extent it can be considered as ocean model. The advantage of experimental investigations in the Black Sea in comparison with oceanic is in smaller space-temporal scales most of processes taking place here. Time scale of oceanic coastal upwelling is equal to weeks. For the Black Sea one day wind forcing is sufficiently for development of upwelling due to the shallow thermocline and steep bottom topography. This experimental fact was often observed and confirmed. The lifting of the nearbottom cold water is accompined by uprising of passive admixture together with dissolved gases. What is happen in upwelling areas it is important question of today ecology. But expensive applications may also need to be proceed by resarch in modeling.

The one of conceptual model of upwelling was formulated by Mooers et al. (1976). Hickey and Hamilton (1980) applied a two-dimentional numerical model, in which Munk and Anderson's (1948) model is used for vertical mixing to a 5-week simulation on the Oregon-Washington continental shelf. Chen and Wang (1990) simulated a coastal upwelling season on the northern California shelf and slope using a two-dimentional mixing-advection coupled model. They employed a simple numerical scheme with decreasing step from deep layer to ocean surface. Allen et al. (1995) and Federiuk and Allen (1995) realized all-round investigations of upwelling modeling by varying of different parameters on base of the Blumberg-Mellor (1987) model. They used potential density as variable and this was simplified numerical scheme.

The presented model has both advantages and shortcomings in comparison with described above. Two kinds of variables substitutios were realized in it. The first deals with transformation of irregular calculation domain to regular one, the second exaggerates the numerical grid in areas with great gradients. These manipulations result in high quality of calculations. The equations of diffusivity of hydrogen sulphide and oxygen with chemical reaction between them were also added for investigation of influence of upwelling event on distributions of O_2 and H_2S in the Crimean coastal zone of the Black Sea. Typical for the Black Sea short time of wind forcing (nearly day) and following relaxation process of hydrophysical and hydrochemical fields were considered.

The shortcoming of presented model is in constant values of vertical turbulent kinematic viscosity and diffusivity. Really, long time experiments to compare the effects of some different parametrizations for the vertical turbulent kinematic viscosity and diffusity by Allen et al.(1995) show that with constant coefficients values the amount of dense water upwelled are strongly depended on the magnitude of the coefficients. However, the considered short-term process allows us to use constant coefficients, and our obtained results had qualitative coincidence with observed data and results of previous authors.

Scenario of water circulation during nearcoastal upwelling was described in detail for various shelf zones of Atlantic and Pasific Oceans. All of them have both the common features and the specific peculiarities for each region depending on local bottom relief, fluid stratification and meteorological factors. As was mentioned above the main difference of the Black Sea upwellings from oceanic ones consist in short time interval of their development due to specific conditions of the Black Sea fluid stratification. Really, remote sensing measurements show that one day wind forcing (with velocity approximately 15m/s) is enough for exit of thermocline onto the sea surface. After this, as a rule, a quite weather is established and hydrophysical fields is developed without external influence. This process of upwelling relaxation in the Black Sea was not considered earlier.

Following our investigations of the Black Sea upwelling, it has all features inherent to oceanic ones at the first stage: development of the alongshore Stocks drift in the upper layer because of the wind stresses, excitement of cross-shore circulation due to Coriolis force and formation of vertical advective cell on the shore and thermohaline front, moving seaward.

One interesting finding from this study is consideration of upwelling relaxation. After the cessation of wind forcing an evolution of the thermochaline fields continues without any external influence and two types of movements are formed on the shelf and in the open part of the sea. The diagram of cross-shelf circulation during the upwelling relaxation was represented in Fig.8. A quasistable dissipating vertical advective cell is formed on the shelf (its dimension coincides with the first baroclinic deformation Rossby radius). Cold water remains during a few days near the shore. Out of the shelf-slope region several types of motions take place during relaxation:

- horizontal reversive subinertial oscillations with current and countercurrent in upper and deeper layers;
- the movement of thermohaline front shoreward (position A in Fig.6);
- progressive internal waves, generated on the frontal side of onshore moving density front (in the transition zone these internal waves are devided on reflected waves and passed ones on the shelf);
- vertical subinertial oscillations over the continental slope in the transition zone.

The period of subinertial oscillations changes from the inertial one (T_{1n}~17h) near the bottom out of the shelf till 22 hours at the free surface in the shelf break area due to various local vorticity of along shore currents and values of horizontal density gradient.

The evolution of oxygen and hydrogen sulphide during the upwelling event is defined, first of all, by the velocity fields and their evolution because of the dissolved gases O_2 and H_2S are used in the system of hydrodynamic equations as a passive admixture. Two additional factors aid in altering the concentrations of O_2 and H_2S : diffusion due to vertical and horizontal turbulent exchange and the chemical reaction of oxidization of hydrogen sulphide.

Second interesting finding from this study is in influence of upwelling event on the evolution of hydrochemical fields. The upward fluxes of cold nearbottom water along continental slope to the surface are accompined by vertical displacement of H_2S and O_2 isolines over the shelf break and continued during additional half a day after the cessation of wind forcing. So, the extended dome of H_2S arises over shelf break. Hydrogen sulphide begins to penetrate into the layers enriched by oxygen. The process of oxygen penetration into the hydrogen sulphide dome takes place simultaneously. As a result the extensive co-existance zone of H_2S and O_2 arises over the shelf break at place of upwelled water. After chemical reaction between H_2S and O_2 the co-existance zone vanished and by time t=3T hydrogen sulphide isolines returned to their initial positions. The oxygen isolines don't restore their initial view, and the area with small oxigen concentration remains over the shelf break in the places of upwelled cold water. This extended area with low oxygen concentration may be considered as a "trace" of upwelling event. The dimensions of this area are depend on the value and time of wind duration.

Unfortunely, their is no possibility to compare modeling results with chemical data in situ now. Firstly it is deal with rarely carrying chemical measurements in the shelf area. Secondly, these measurements could not be followed even if they had been held. Because of chemists will throw off results with unexpected concentrations of oxygen and hydrogen sulphide, thinking that probe is failure.

APPENDIX

With new variables (6) involved, the system of equations (4)-(5) assumes the form

$$\omega_t + c(x,z_1)J(\omega,\psi) - c(x,z_1)fv_{z1} = gR_1(\rho)/\rho_0 + aR_2(\omega) + AR_3(\omega),$$

$$\omega = R_2(\psi) + R_3(\psi),$$

$$v_t + c(x,z_1)J(v,\psi) + c(x,z_1)f\psi_{z1} = aR_2(v) + AR_3(v),$$

$$S_t + c(x,z_1)J(S,\psi) = mR_2(S) + MR_3(S), \tag{A1}$$

$$T_t + c(x,z_1)J(T,\psi) = mR_2(T) + MR_3(T),$$

$$[H_2S]_t + c(x,z_1)J([H_2S],\psi) = bR_2([H_2S]) + BR_3([H_2S]) - K_s[H_2S][O_2],$$

$$[O_2]_t + c(x,z_1)J([O_2],\psi) = bR_2([O_2]) + BR_3([O_2]) - K_o[O_2][H_2S],$$

where

$$c(x,z_1)=N(z_1)r(x), \quad r(x)=1/h(x), \quad h(x)=\int_0^{-H(x)} N(s)ds,$$

$$R_1 = \frac{\partial}{\partial x} - z_1p(x)\frac{\partial}{\partial z}, \quad R_3 = r(x)\frac{dN}{dz}\frac{\partial}{\partial z_1} + r^2(x)N(z_1)\frac{\partial^2}{\partial z_1^2},$$

$$R_2 = \frac{\partial^2}{\partial x^2} - 2z_1p(x)\frac{\partial^2}{\partial x\partial z_1} + z_1^2p^2(x)\frac{\partial^2}{\partial z_1^2} + z_1(2p^2(x)-q(x))\frac{\partial}{\partial z_1},$$

$$p(x)=r(x)dh/dx, \quad q(x) = r(x)d^2h/dx^2$$

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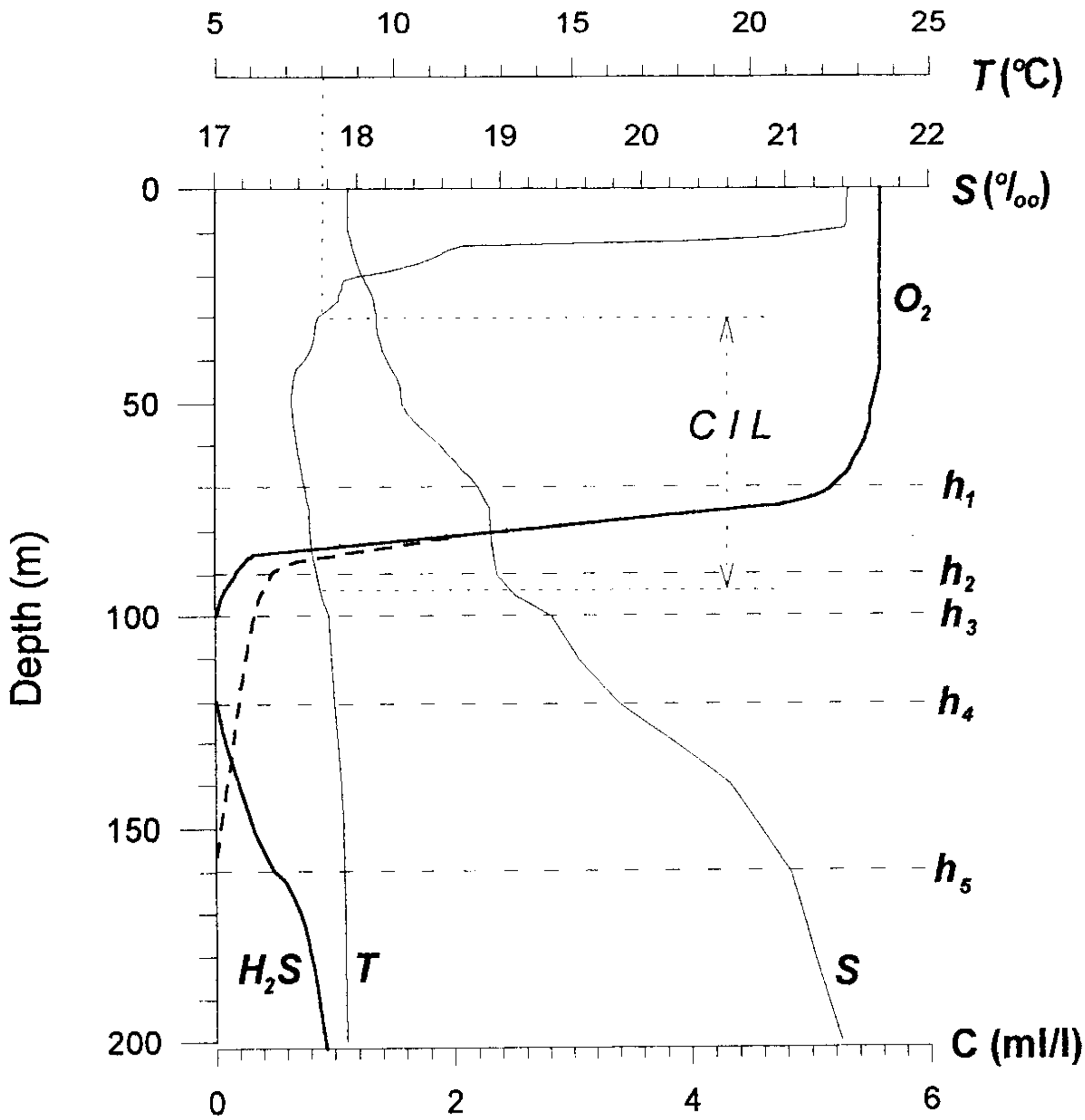

Fig.1. The typical profiles of the temperature (*T*), salinity (*S*), oxygen (O_2) and hydrogen sulphide (H_2S) for the Black Sea. CIL - is a cold intermediate layer with temperature less then 8°C.

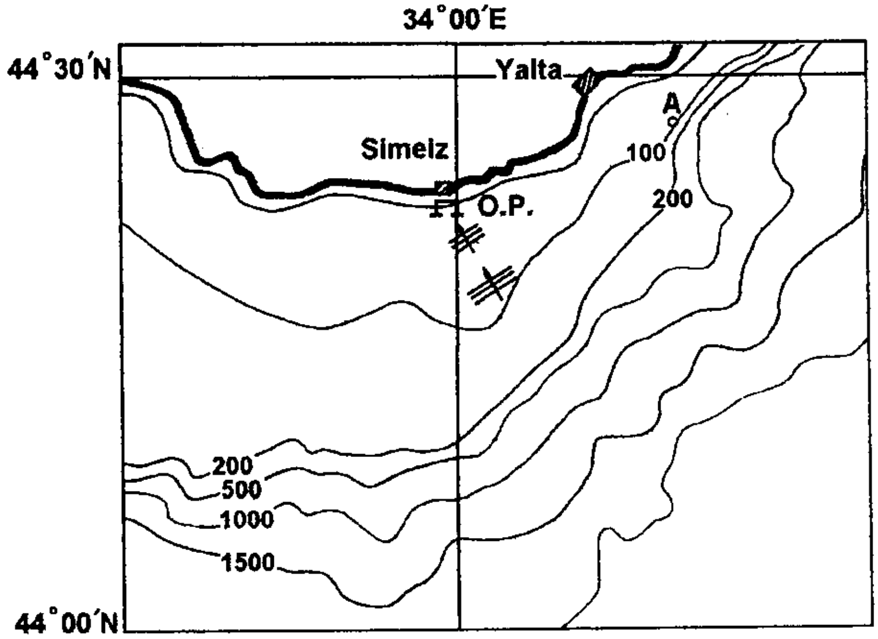

Fig. 2. Bathymetry of the Southern Coast of Crimean Peninsula.
OP - oceanographic platform, A - mooring.

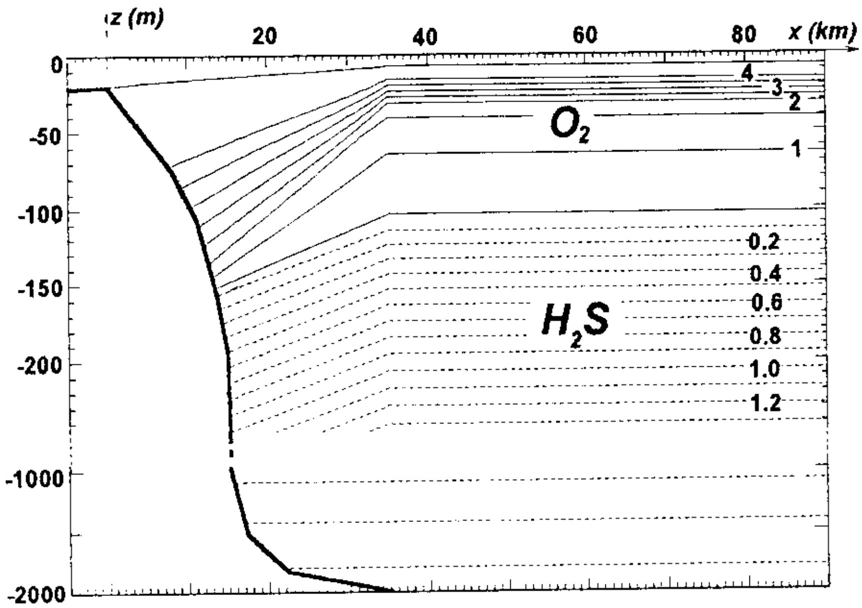

Fig. 3. Model geometry and initial cross sections of oxygen and hydrogen sulphide (ml/l).

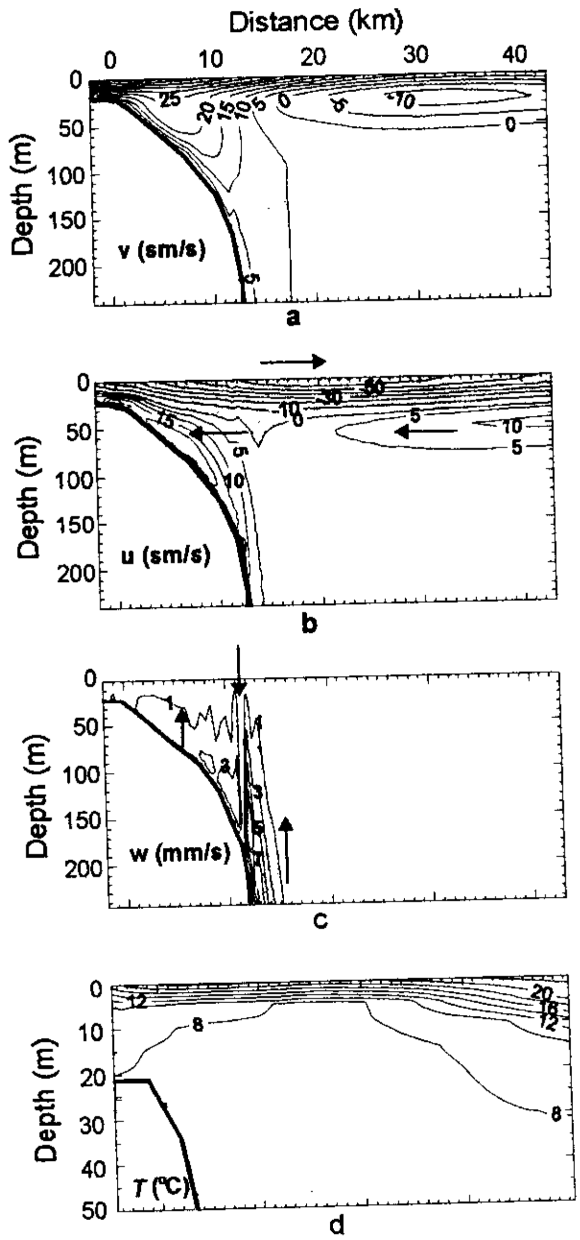

Fig. 4. Fields of alongshore (v), cross-shore (u), vertical (w) velocities and temperature (*T*) at the end of wind forcing (t = T, T=24 hours)

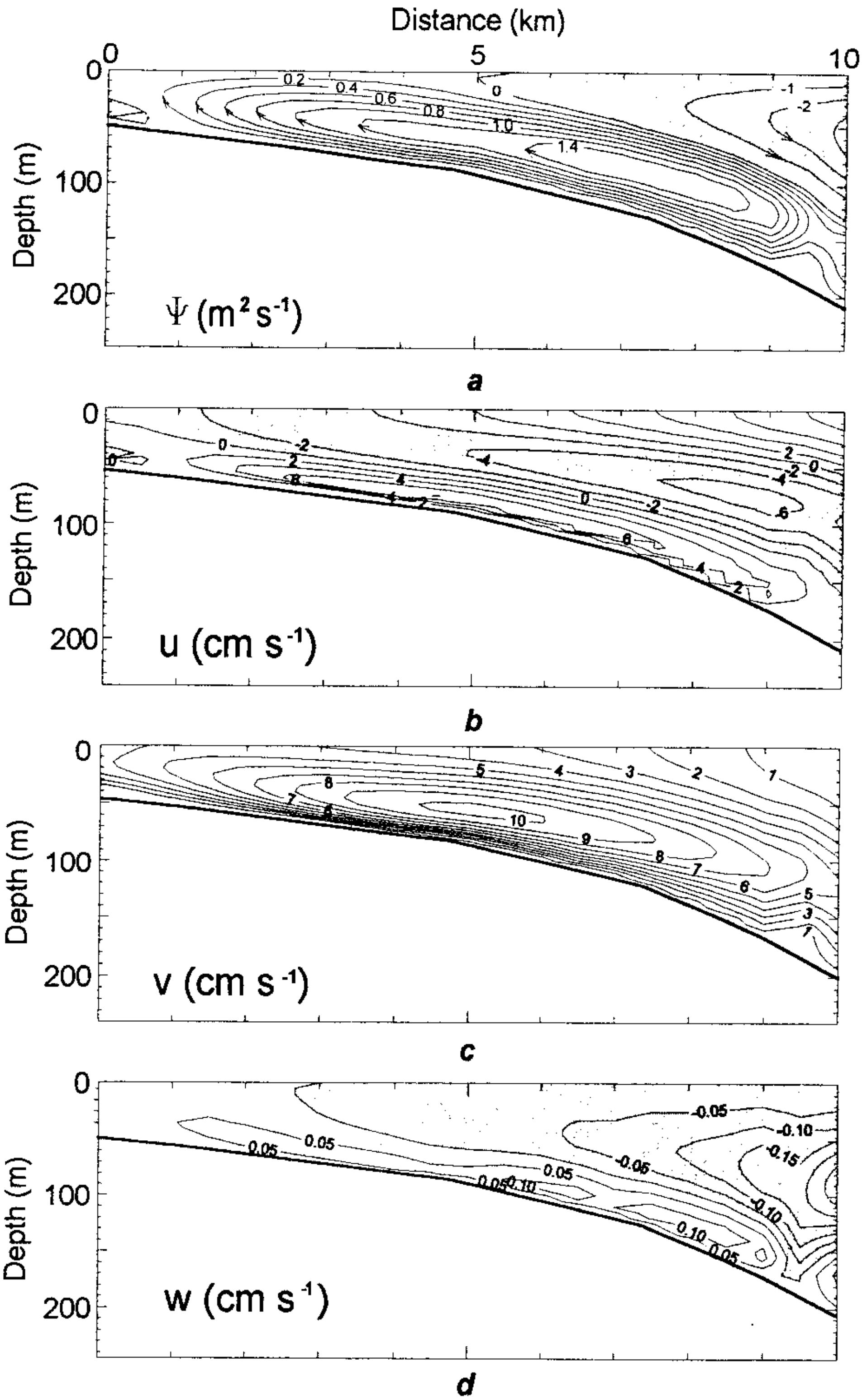

Fig. 5. The cross-shelf structures of stream function Ψ, cross-shelf velosity u, alongshore velocity v and vertical velocity w in the vertical circulation cell on the shelf.

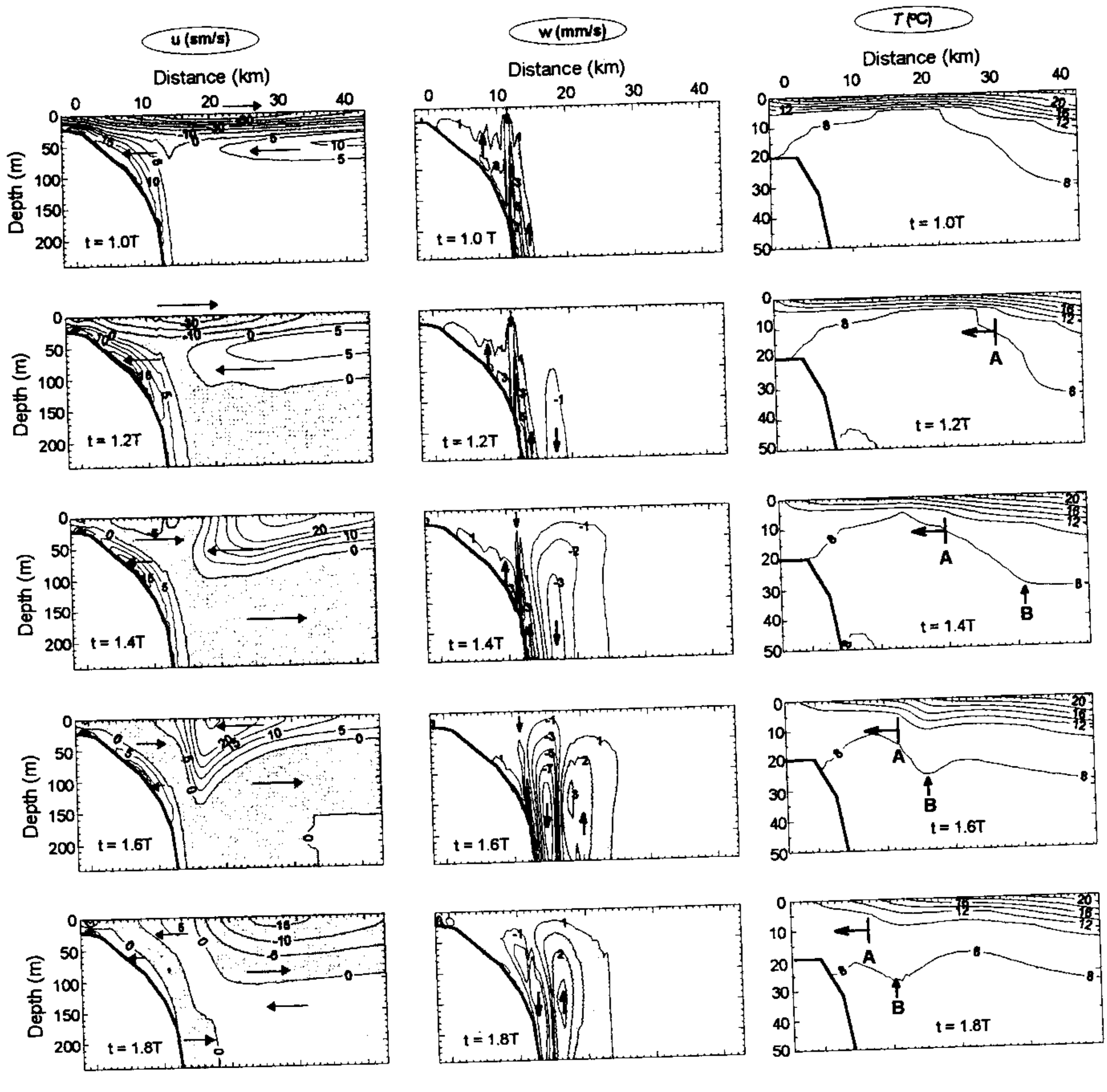

Fig. 6. Evolution of cross-shelf current u, vertical velocity w and temperature T after the cessation of find forcing. Arrows on u,w cross-sections indicate currents directions. Positions A, B, C, E show onshore propagation of temperature front and internal waves.

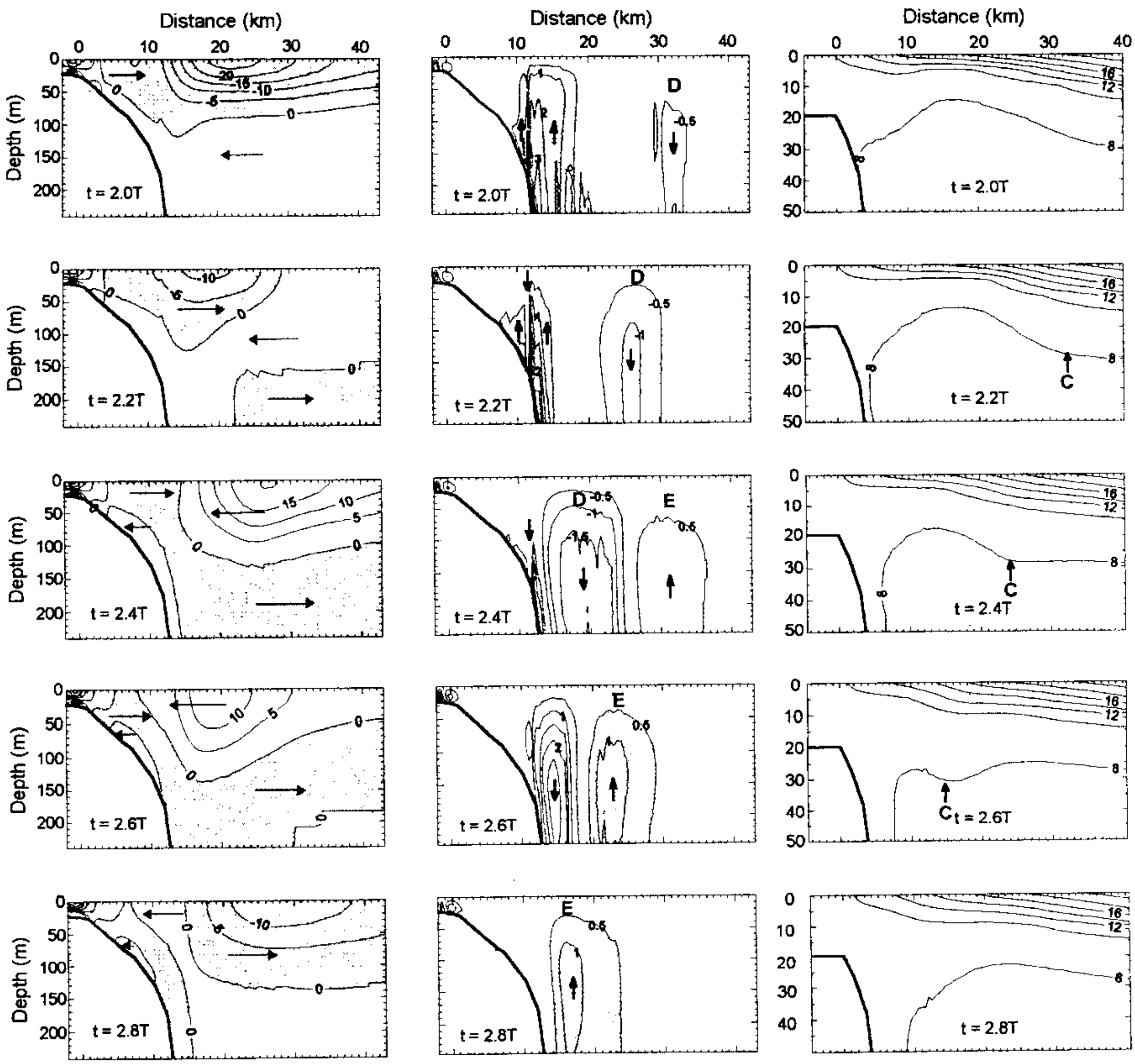

Fig. 6. (Continued)

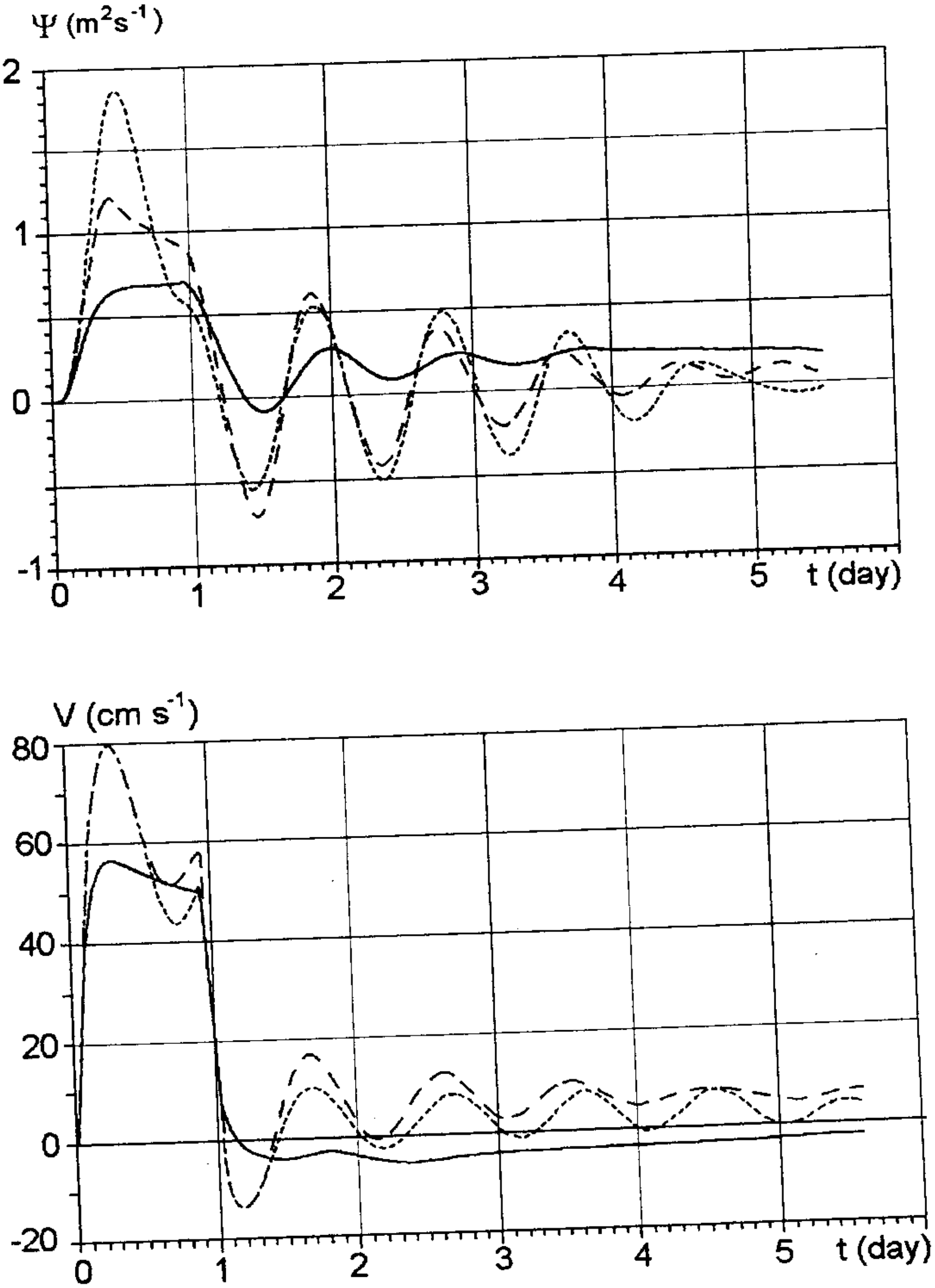

Fig. 7. Time series of the stream function Ψ and alongshore current V in various points of nearcoastal zone: on the shelf (solid line ——); over the shelf break (dashed line — — —); in the open part of the sea (dotted line - - - -);

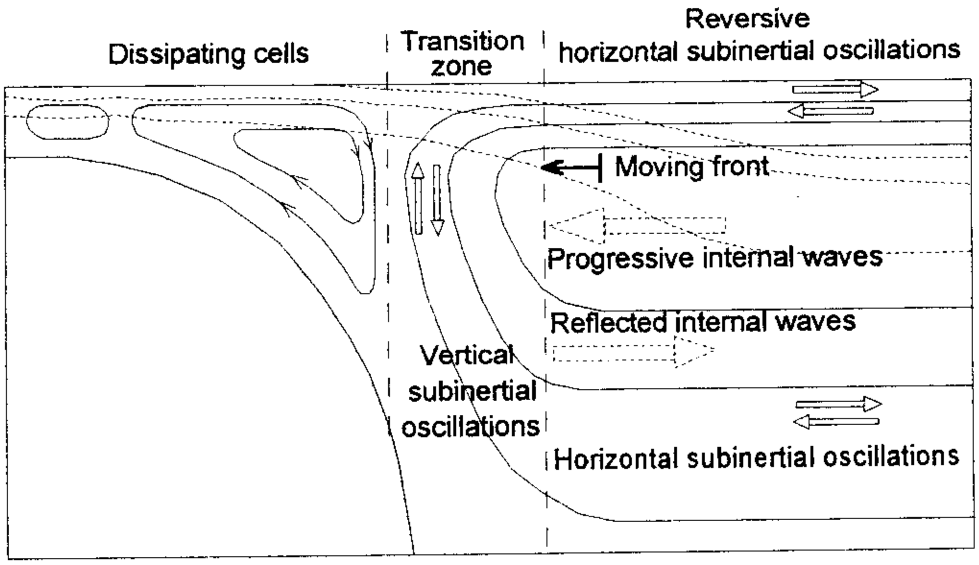

Fig. 8. Schematic diagram of across-shelf motions during the upwelling relaxation. Dashed lines are izopicnals.

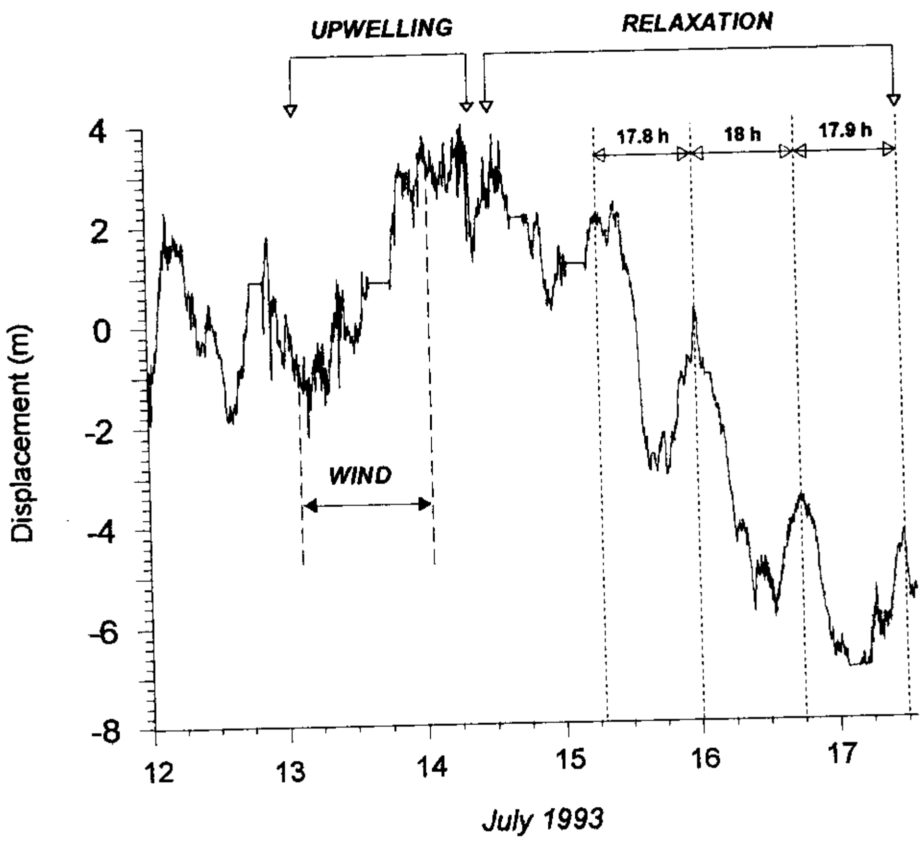

Fig. 9. Time series of observed displacement of thermocline at mooting A (Fig. 2).

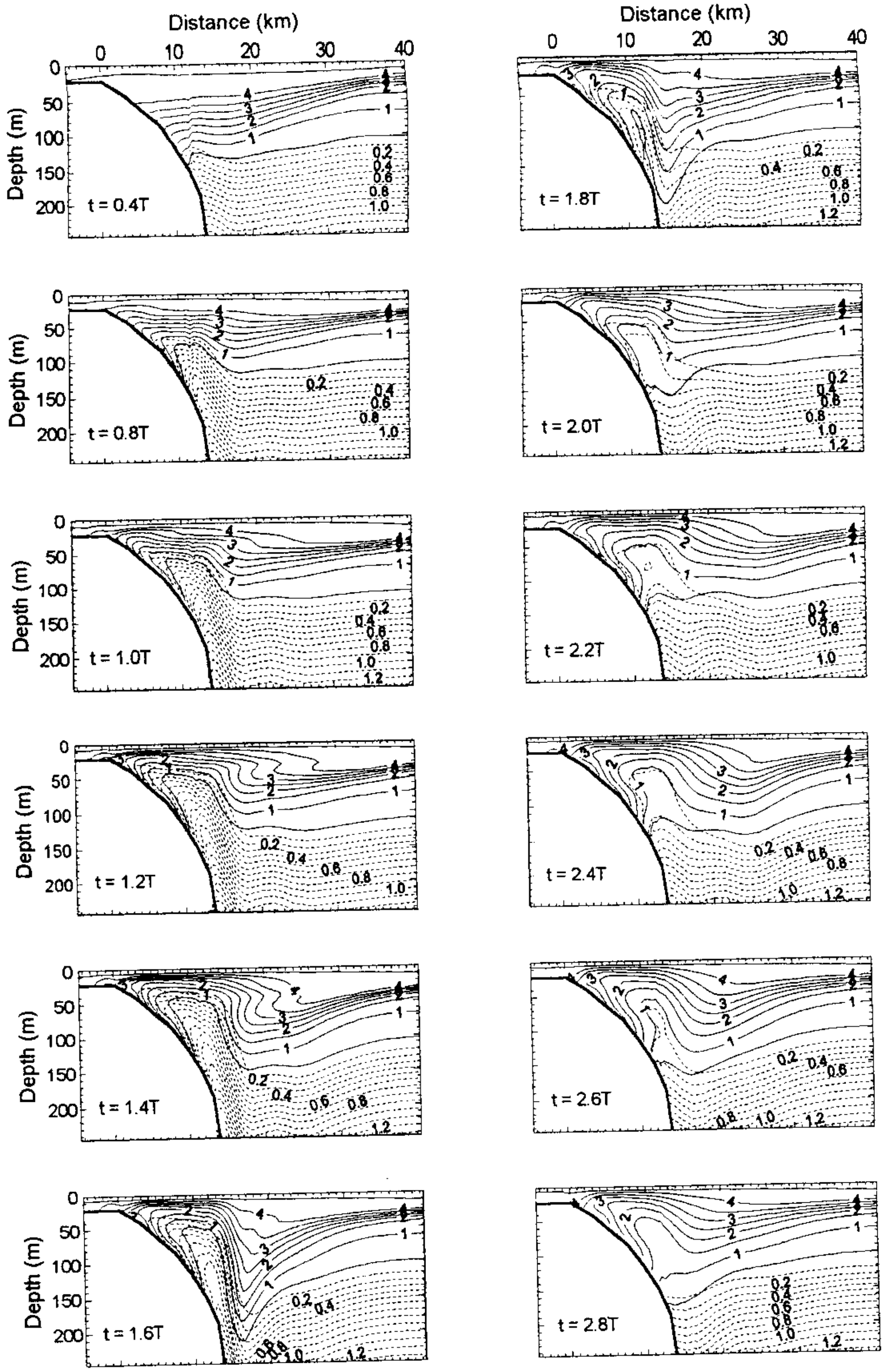

Fig.10. Model - predicted evolution of cross - shelf structure of oxygen (solid lines) and hydrogen sulphide (dashed lines) during 3 days of coastal upwelling. Concentration is given by in ml/l. Intersections of dashed and solid lines indicate on the co-existance zone of oxygen and hydrogen sulphide.

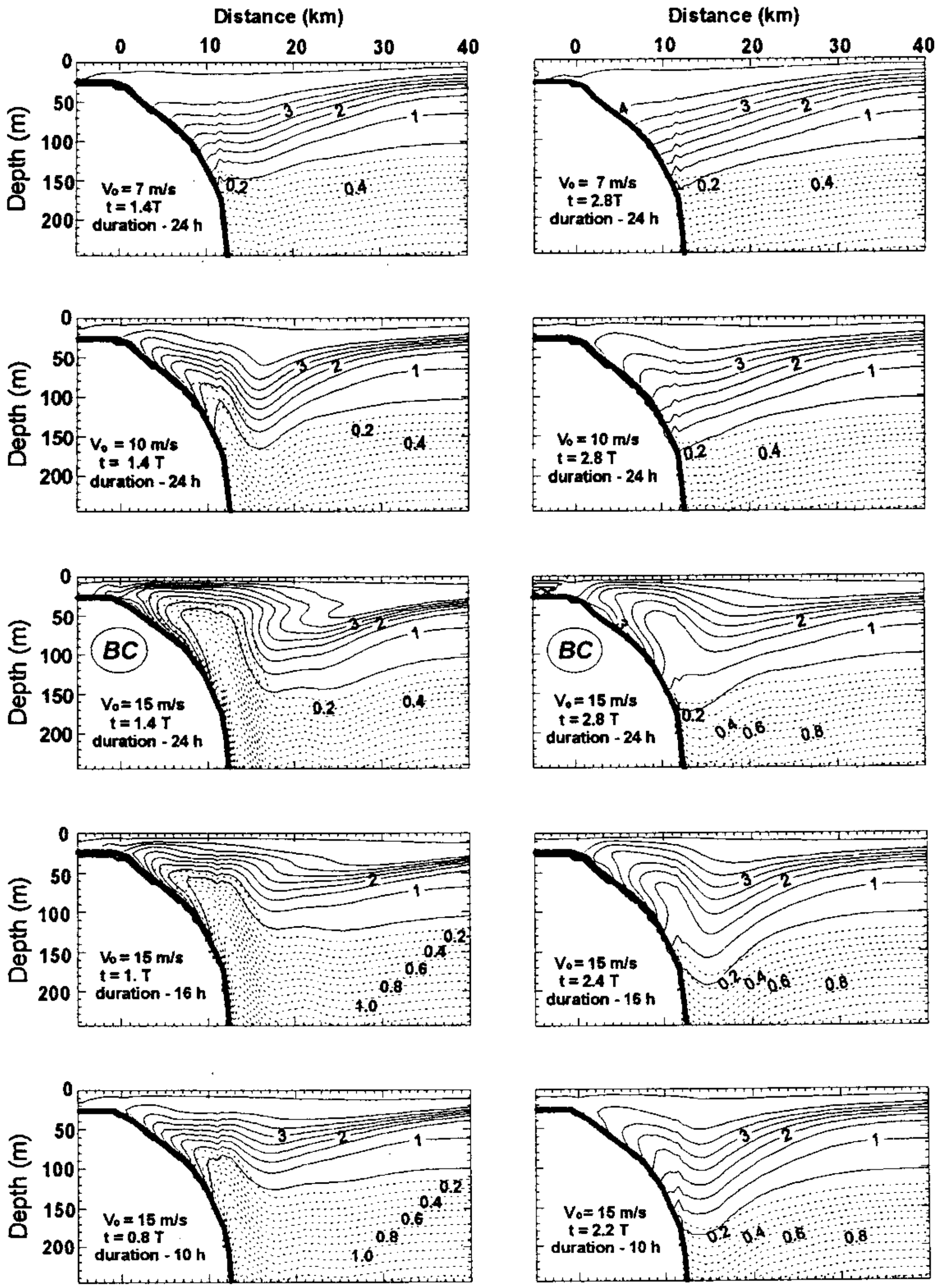

Fig. 11. Model-predicted cross-shelf patterns of oxygen (solid lines) and hydrogen sulphide (dashed lines) for different values of wind velocities and time forcing.