COASTAL UPWELLING

Coastal upwelling is the dynamic system formed in coastal areas of oceans and the seas under influence atmospheric or internal marine forcings. It is characterized by intensive upward water motions in a zone between coast and the front zone which is being on distance from the coast of the order baroclinic Rossby radius R_d (in the Black sea coastal zone - 3-5 km). If the width of a shelf is more then $2R_d$, then above midshelf and also above shelf-break at favorable conditions can be formed, accordingly, midshelf and shelf-break upwellings (Blatov and Ivanov, 1992).

Coastal upwelling subdivided into two genetic types. Upwelling of the first type is generated as a result of action of the wind having alongcoastal component, concerning which coast remains at the left (in the Northern hemisphere). If to look from coast that such wind has component, directed from right to left. Wind-driven upwelling can be dynamically local and three-dimensional. Localiness means, that the basic processes operate in a vertical plane, normal to coast (x, z). Alongshore variations in a wind, bottom topography and a coastal line break two-dimensionality of coastal upwelling because of occurrence and alongshore distributions of coastal trapped waves and eddies.

Upwelling of the second type is generated by internal marine processes, mainly owing to synoptic variability (meandering) of alongshore large-scale currents. Upward movements of waters arise, when large-scale current in a surface layer has off-shore component. In the Black Sea this type of upwelling is of great significance, because of predominant nearshore position of the Black Sea Rim current (e.g. the Southern Coast of the Crimea, the Anatolian Coast near Synop, the Caucasus Coast near Novorossiysk et al.), but until now it is poorly investigated.

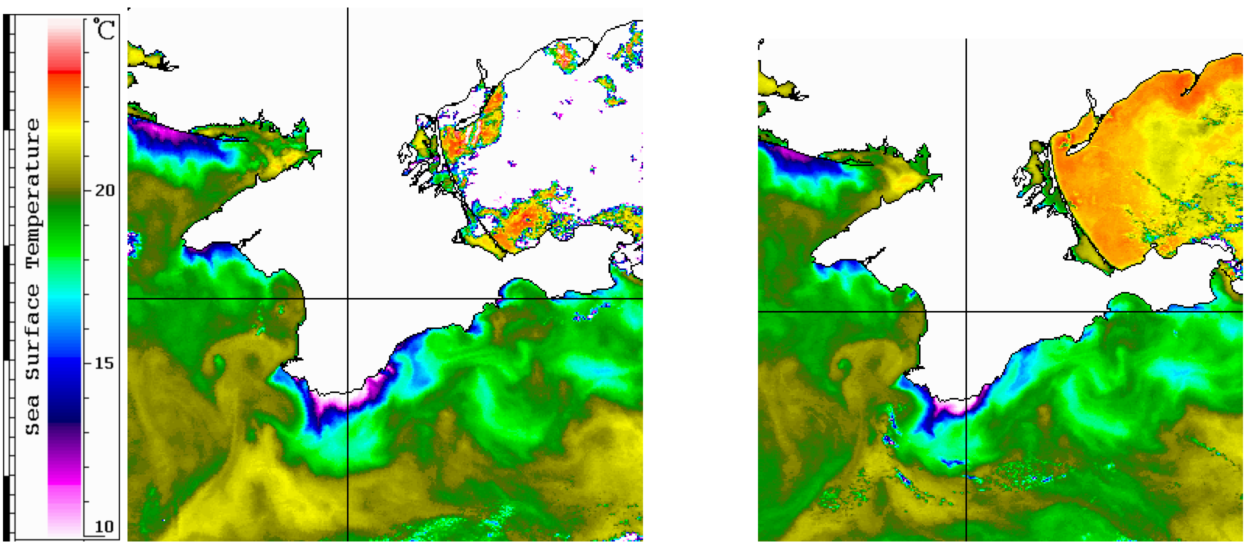
Significance of coastal upwelling is extremely great. Owing to inflow of the deep waters, riched by nutrients, to surface in a narrow coastal zone is created very high bioproductivity of sea water. Formation at the warm period of year cold anomaly in a zone of upwelling influences on a climate of adjoining territory of a land and breeze circulation of a wind.

On a vertical direction in area of upwelling divide into three layers: surface, intermediate and near bottom. The surface layer thickness of 10-30 m is characterized by significant vertical uniformity of waters and component of the speed of current directed from coast with speeds up to 0.10-0.20 m/s. Below, in intermediate and near bottom layers are observed currents to coast with speeds of the order 0.02-0.10 m/s. Surface layer carry of water from coast in two-three times is more then undersurface, directed to coast. With increase in a wind stress this disproportion decreases. In cross-section to coast usually is formed the following structure.

In a 10-30 km coastal strip, has a zone of the most intensive rise of deep waters. Here the vertical component of current speed achieves 10^{-4} m/s. Characteristic feature of coastal upwelling is surface downwind jet, with speeds up to 0.30-0.50 m/s, coincides with a front zone of sharp density gradients in 15-30 km from coast. The width of a jet achieves 10-15 km, and penetration depth - 25-50 m below settles upwind undercurrent. In an initial stage of development of upwelling the front zone representing seasonal pycnocline outcrop, it is displaced to offshore. Then, at slowing upwelling favorable wind, it moves shoreward. Speed of cross-section displacement of upwelling front achieves 0.05-0.15 m/s. In an upwelling relaxation phase and displacement of upwelling front to coast it is narrowing and strenthening. In same time most develop alongshore unhomogeneities of upwelling: local centers and filaments. The local centers represent the spots of the coldest waters, owing to heterogeneity of bottom topography (in particular, to underwater canyons) and a coastal line (capes, gulfs). Filaments are narrow strips of the coldest waters extending far beyond a shelf. Both are usually localized in the top 50-m layer.

In the Black sea upwelling is most brightly shown in the spring and in the summer in a sea surface temperature – SST, in particular on satellite infra-red images (fig 1). The greatest repeatability, intensity and level of scrutiny upwelling has at Southern Coast of the Crimea (SCC) and at coast of the Caucasus from Novorossiysk up to Sochi (Blatov and Ivanov, 1992).

a) b)



c) d)

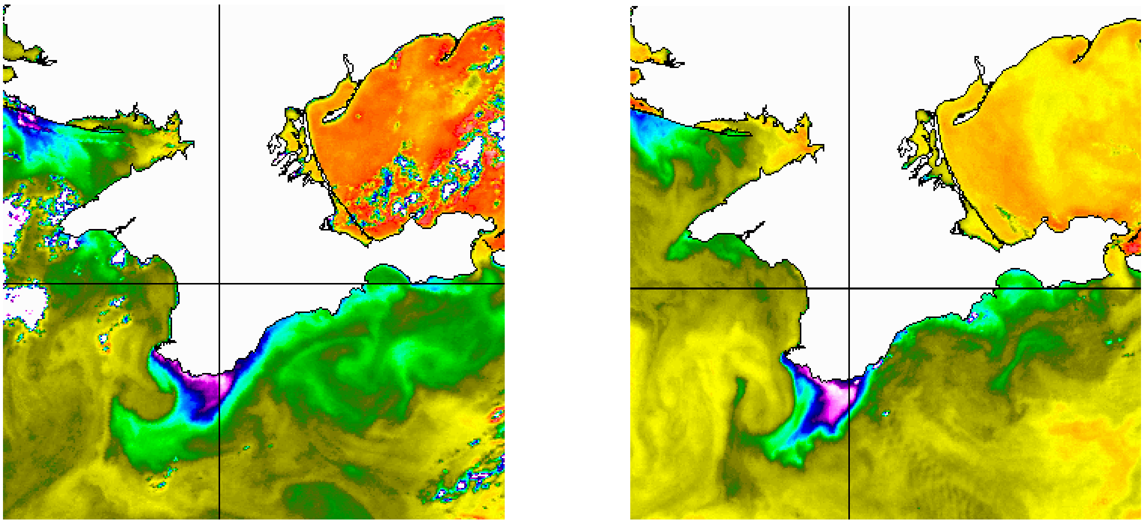


Fig. 1 – Satellite infrared SST images (AVHRR NOAA-17) of synoptic evolution of coastal upwelling area at SCC: (a) 12 June 2005, (b) 13 June 2005, (c) 15 Jine 2005, (d) 17 June 2005. Take note of the offshore and westward shifts of cold water area with time (day after day). From Internet data of Remote Sensing Dept. MHI NASU: http://dvs.net.ua/data/index.shtml

At southern coast of the Crimea (SCC) long-term researches of upwelling are spent with use of autonomous measurements on sea stationary platforms and on moored buoys, and also ship survey of coastal zone in the area adjoining settlement Katsiveli where the Experimental Branch of Marine Hydrophysical Institute of the National Academy of Sciences of Ukraine (MHI NASU) is located.

Especially favorable conditions for formation wind-driven upwelling near SCC fall to June-July on the southernmost zone of coast and on the east of it, between settlement Katsiveli and Alushta Town. At this time here are formed nearby 5 upwellings, in other areas - less than 3. Total duration of upwelling at settlement Katsiveli makes 11 % of all researched period of time (17 day), at a Yalta - 8 %, in other areas less than 5 % (Blatov and Ivanov, 1992).

Speed of change of temperature of water at an initial stage of development of wind-driven upwelling near SCC makes 0.2-0.8°C/h, but can sometimes achieve 1.5°C/h. Duration of an initial stage of wind-driven upwelling varies from 2 hours up to 1.5 days, duration of all phenomenon - from 1 up to 10 days. Total downturn of superficial temperature of water can achieve 16°C (from 24°C up to 8°C).

At outcrop of the sea seasonal termocline, here is formed the front zone of upwelling in which horizontal gradients of temperature, salinity and density have high values (usually 1-3°C/km, 0.1-0.2 ‰/km and 0.3-0.5 kg/m^3 km. According to the data of autonomous measuring instruments located and sea platform МГИ НАНУ in settlement Katsiveli, 12 July, 1984 the horizontal gradient of superficial temperature of water achieved 13.3°C/km at an upwelling relaxation phase. The distance of upwelling frontal zone from the coast, approximately equal to local (coastal) baroclinic Rossby radius (3-5 km).

In July, 1981 water in upwelling zone rose on a surface from depth of 15-20 m. The axis alongshore jet current in top 15-m layer had speed of 0.25 m/s and was in 4 km from coast. The total width of a jet was about 7 km. The axis of current coincided with a front zone of upwelling. Below, in 15-m near-bottom layer settled down undercurrent, which also had the form of a jet in width about 7 km. The maximum speed of undercurrent (0.20 km/s) was observed between 30 and 50 m. Estimations of speed of ascending movements on the bottom Ekman layer during of upwelling have given value of 2.6 10^{-4} m/s that is close to the maximal values of similar speeds in areas of the most intensive upwellings of the World ocean (Blatov and Ivanov, 1992).

The detailed picture of time variability of vertical displacement of termocline at stages of development and a relaxation of upwelling (fig. 2) has been received in July, 1993 in shelf zone near SCC at a Yalta in area of shelf-break on depth of 100 m. Measurements were spent during of 6 day. At a stage of development of upwelling (13-14th of June) termocline rose upwards due to wind forcing. Then, after slowness of a wind there were fluctuations with the prevailing period (17.9h) close by the local inertial period (17.0h). Besides quasi-inertial fluctuations observed also and more high-frequency internal waves.

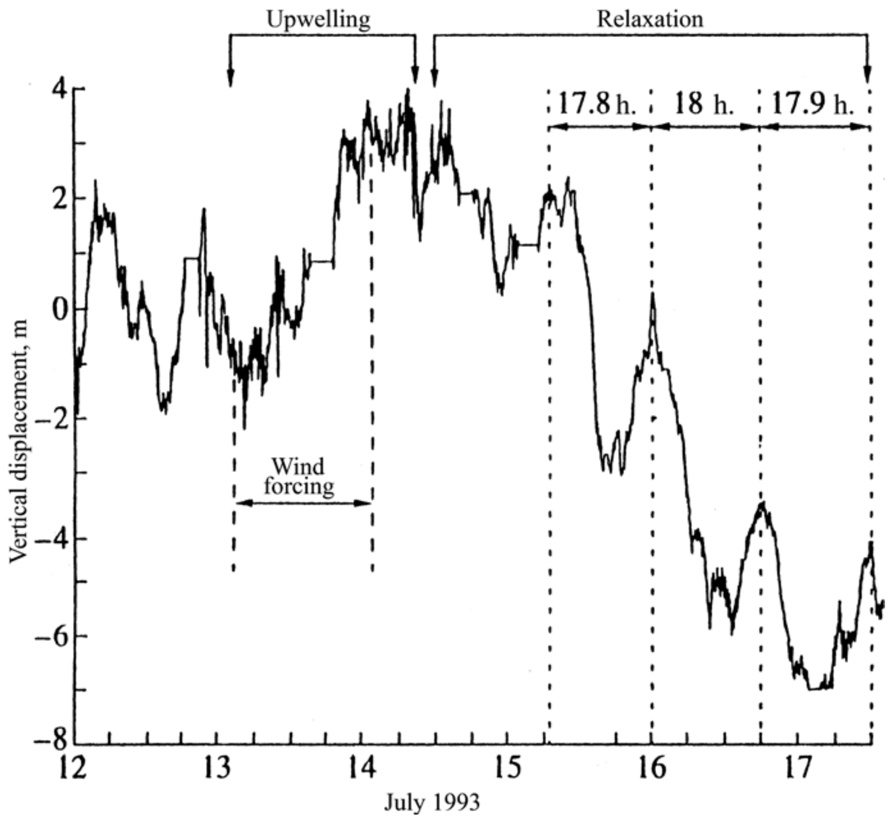


Fig. 2 - Vertical displacement of termocline in July, 1993 in shelf-break zone near SCC at a Yalta. After Stashchuk and Vlasenko (1998)

Coastal upwelling in the Black sea is actively researched by means of numerical hydrodynamical modelling. On fig. 3 are presented some results of the modelling of the dissolved oxygen and hydrogen sulphide evolution in cross-shelf sections in area near SCC at influence of a upwelling-favorable wind with a speed of 15 m/s (Stashchuk and Vlasenko, 1998). Time scale (T) on fig. 3 equal to 1 day, that is the step on time makes 4.8h.

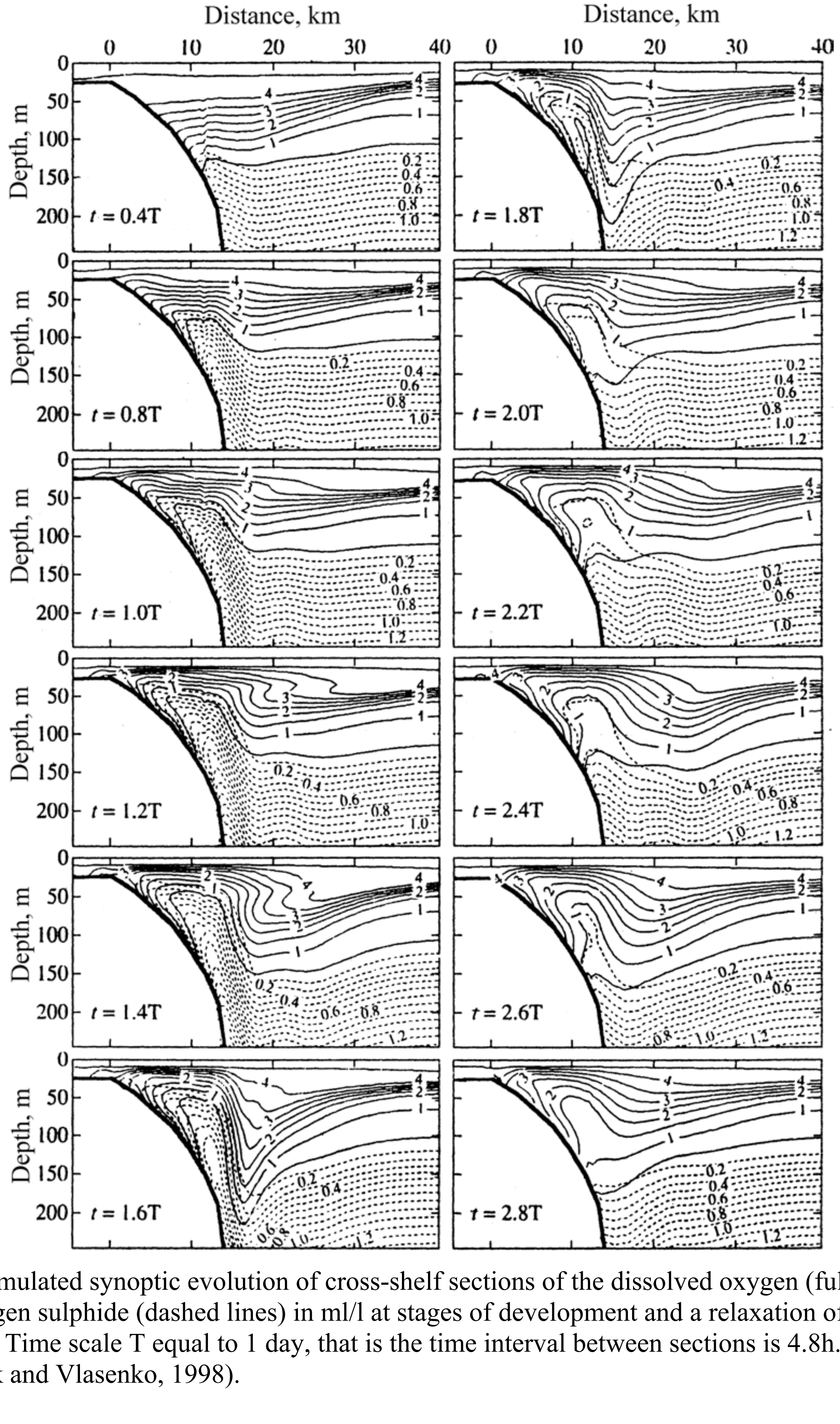


Fig. 3 – Simulated synoptic evolution of cross-shelf sections of the dissolved oxygen (full lines) and hydrogen sulphide (dashed lines) in ml/l at stages of development and a relaxation of upwelling. Time scale T equal to 1 day, that is the time interval between sections is 4.8h. After (Stashchuk and Vlasenko, 1998).

Rise of benthic cold water along a continental slope to a surface at coast is accompanied by a deviation of izolines of oxygen and hydrogen sulphide. The top border of a hydrosulphuric layer is displaced on 100 m within the first day and achieves depth of 40 m (the moment of time t = 1.4T).

Horizontal shift of this border makes 8 km aside from coast. Let's note, that displacement izoline of hydrogen sulphide upwards proceeds half of day after cancellation of a wind. After two days of relaxation, under action of chemical reaction between oxygen and hydrogen sulphide, the top border of a hydrosulphuric layer appears in the same position, as up to upwelling (the moment of time t = 2.8T). But position of izoline of oxygen is not restored. The area with the low contents of oxygen remains above shelf-break still long enough time (to look fig. the moment of time t = 2.8T). This fact is result of chemical reaction between two gases in places where was a rise of cold waters. Thus the extensive area with the low content of oxygen can be considered as certain "trace" of upwelling, which some time can exist, yet it will not be enriched with oxygen.

Calculations at various speeds of a wind (Stashchuk and Vlasenko, 1998) have shown, that with increase in speed of a wind and its duration rise of izoline is increases. The extensive zone of the lowered concentration of oxygen does not arise, if speed of a wind is less then 10 m/s, and its duration is less than 12 hours. It is obvious, that than duration of a wind more, the area with the lowered concentration of oxygen will be especially extensive.

Outside of shelf and slope areas time changes of hydrochemical fields are shown in the form of quasi-inertial fluctuations with insignificant amplitude.

The presented results of modelling have been compared to ship survey of hydrophysical and hydrochemical fields in October, 1997 in coastal zone near SCC at Simeiz Town (in 2 km to the east of settlement Katsiveli). In total it has been carried out more than 100 CTD vertical profiles (ship stations). In the field of shelf-break the distance between stations has made 1 mile, and in sea parts of area of survey up to depths of 1000 m - 2 miles (Vlasenko et al., 1999).

2nd and 3th of October here prevailed western and northwest winds with a speed of 10-15 m/s with impulses up to 23 m/s. It has led to development of coastal upwelling. Supervision by means of a CTD-probe on 3-rd of October at coastal stations have shown exit on a surface of the sea of cold waters from depths of 20-25 m with temperature from 7.5 up to 8°C.

On fig. 4 are presented results of measurements of concentration of the dissolved oxygen on 12-mile cut on a normal to coast. The Fig. 4a corresponds to an initial stage of upwelling (2nd of October), fig. 4b - its development, fig. 4c - its relaxation. At stages of development of upwelling (2-4 of October, fig. 4a,b) occured essential rise of oxycline. His core was displaced to a surface of the sea on 20-25 m and extended in area of shelf-break. At a stage of a relaxation the bottom border of oxycline has actually returned to a starting position up to horizons of 110-120 m. But top border of oxycline even after a week after upwelling has not restored the initial form. In area of shelf-break on fig. 4c is clearly visible the residual dome of oxycline. As a whole, direct measurements have confirmed the basic conclusions of modelling researches.

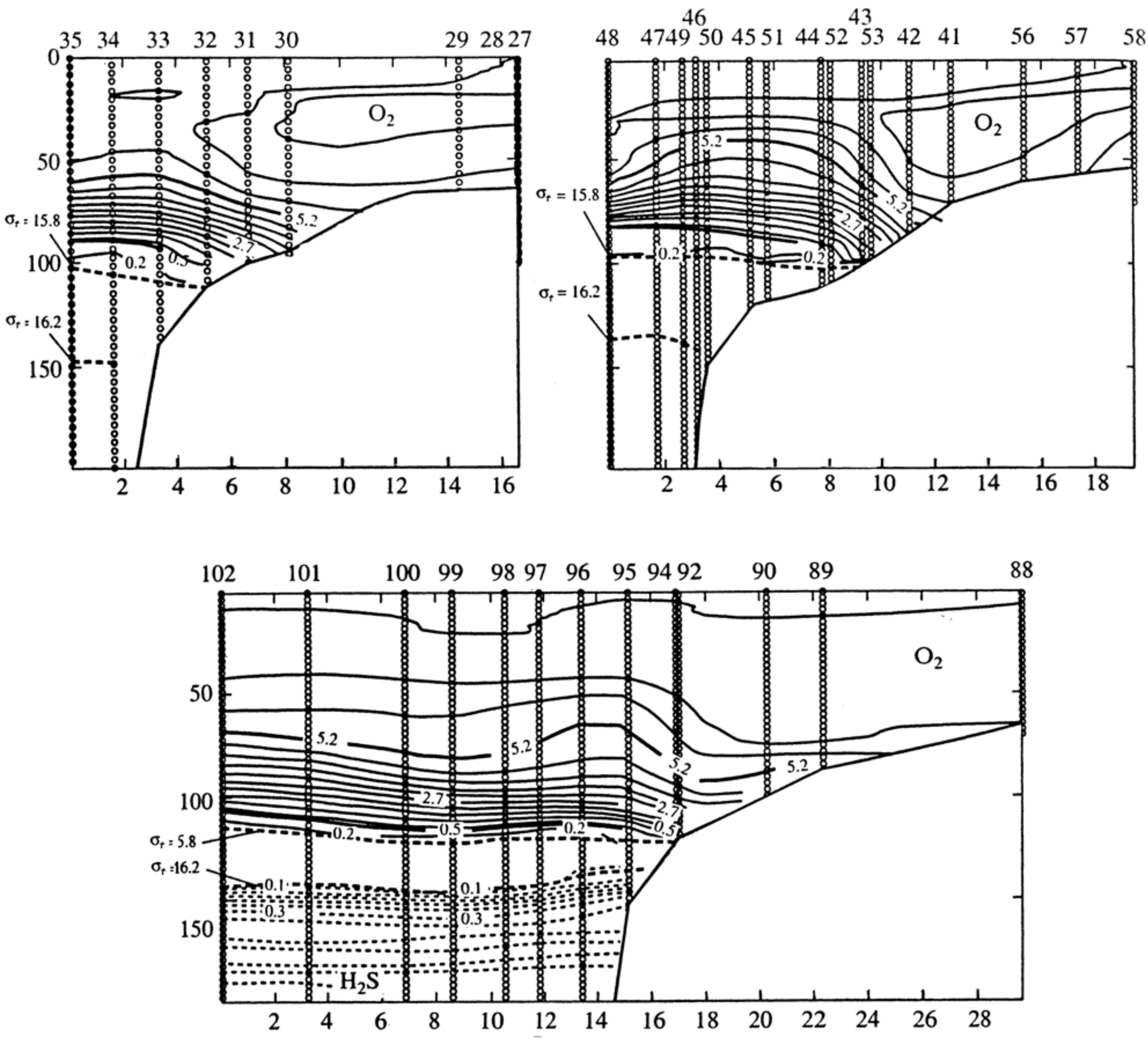


Fig. 4 - Cross-shelf sections of the dissolved oxygen (full lines) and hydrogen sulphide (dashed lines) in ml/l, in October, 1997 in coastal zone near SCC at Simeiz Town. After (Vlasenko et al., 1999).

At the Caucasian coast of the Black sea from Novorossisk up to Sochi is favorable for formation of upwelling the northeast wind with a speed of 15 m/s and more, which is observed each time when the region of the East Europe occupies an anticyclone, and above a southeast of the Black sea at this time there is a cyclone. Repeatability here averages 21 times in a year (Tkatchenko et al., 2002). Unlike southern coast of the Crimea, cold season have most of them(18) and only 3-warm season (from April up to August). Most often speed of a wind makes 11-15 m/s (61 %), speed of drift current in a surface layer achieves 0.26-0.28 m/s. In 20 % of cases the wind is observed of 16-20 m/s and current – 0.34-0.36 m/s. In 19 % of cases the wind is observed more than 21 m/s, and speeds of drift currents make up to 0.45-0.56 m/s.

Owing to shielding wind influences by mountain ridges water near at the Caucasian coast are slightly involved in wind circulation. As a result of this rise of cold deep waters takes place on some distance from coast, the order of several kilometers.

Rise of waters occurs from depths of 35-55 m. Speed of upward water movements varies within the limits of from 1.0x10-5 up to 3.0x10-4 m/s. Their duration usually makes 1-2 day. The greatest reduce of temperature in connection with upwelling at the Caucasian coast has made more then 10°C (from 26.0°C down to 15.3°C). With rise of termocline to a surface of the sea, there is a front of upwelling with a horizontal gradient of temperature of the order of 0.4-0.5°C/km, salinity - 0.03 ‰/km.

Rise of deep waters enriches a surface layer with nutrients, that leads to increase of primary production of waters. The increase in concentration of mineral phosphorus in a coastal zone makes more than in 1.5 times, nitrate nitrogen - at 5-10 time.

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