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Acoustical Scattering Layers of Two Mesozooplanktons as a Tool for Hydrographic Features of the Black Sea

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Abstract

Two dominant acoustical scatterers of fodder zooplankton (*Calanus euxinus* and *Sagitta setosa*) performed diel emigrational speeds depending highly on the profile of dissolved oxygen (DO) in the Black Sea: *C. euxinus* started accelerating upon entering the oxycline while *S. setosa* accelerated only after entering well-oxygenated subsurface water. The speed and their daytime depths suggest profile of the DO, sub-region classification and thickness of the oxic layer. Oxygen profile: layer where *Sagitta* migrate very fast is subsurface maximum oxygen and chl-a (σ_θ=14.0-14.7), layer where *Sagitta* speed down whereas *Calanus* still swim fast is oxycline (σ_θ=15.3-15.9), layer where *Sagitta* spend their daytime is a zone just above oxygen minimum zone (OMZ) (σ_θ=15.9-16.0), and layer where *Calanus* spend their daytime is OMZ (σ_θ=16.15 to 16.20). Sub-regions: If *Calanus* start the upward migration very fast, the region is downwelling. If they perform slow ascendance and then speed up (this means that they settle down in a layer with σ_θ=16.15 to 16.20 during day), the region is upwelling. Thickness of oxic layer is depth between surfaces to a depth where *Calanus* are found during the daytime; *Calanus* and *Sagitta* coexist in OMZ during the cold season. Depth preference of *Calanus* in sub-regions must be taken into account of the thickness estimates.

Key words: Acoustics, mesozooplankton, hydrography, Black Sea

INTRODUCTION

Active acoustics provides a powerful tool for revealing the spatial distribution of sound-scattering layers (SSL) in the ocean. Both strong scatterers (organisms and abiotic particles with strong density and sound velocity contrasts relative to the water) and weak scatterers (e.g. many zooplanktors, physical microstructure) can be detected, depending on sound frequency. Acoustic data alone are inherently ambiguous with regard to the identities of the scatterers. With few exceptions the taxonomic identity of scatterers must be verified by supplementary information, such as nets, pumps or optical plankton counters [1]. Direct identification of organisms, however, appears impractical with present acoustical knowledge and techniques, even though bioacoustics have functioned well in visualizing movement under water [2-8]. Integrating such techniques with previously obtained background knowledge on characteristics specific to certain organisms may, therefore, be the most fruitful strategy for species identification.

The striking hydrodynamic features of the Black Sea are the cyclonically meandering rim current together with two interior, western and eastern gyres, and several mesoscale anticylonic eddies (Figure 1) [9]. The Black Sea pelagic upper aerobic zone is separated from lower anaerobic layers containing hydrogen sulfide (H_2S) by the main pycnocline, which lies at depths of 70 to 200 m [10].

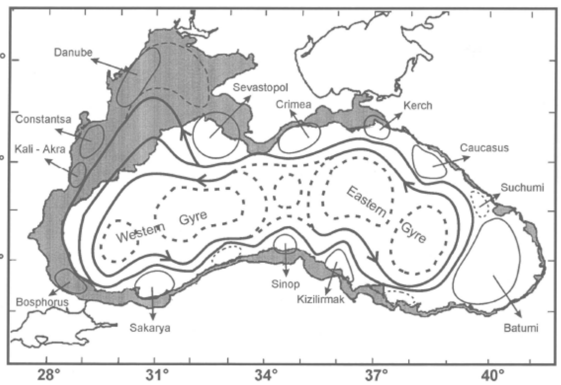

Figure 1. General circulation of surface currents in the Black Sea ([from 23]). The bold line is the rim current. The hatched area is the continental shelf (bottom depth <200 m). Dashed line is circulation seasonally occurred.

The pycnocline is accompanied by the oxycline, where oxygen concentration decreases from 7.9-9.8 mg l^{-1} at the water density interval, σ_θ=14.0-14.7 to 0.47-0.84 mg l^{-1} at σ_θ=15.3-15.9. The oxycline (OXL) generally occurs over a depth change of 50 to 93 m [11]. Below this the oxygen concentration declines slowly to <0.16 mg O_2 l^{-1} at σ_θ=15.9-16.0 (AOMZ), and can no longer be detected at σ_θ=16.15 to 16.20 (OMZ), where sulphide concentrations are 0.03 to 0.1 mg H_2S l^{-1}. This oxygen-deficient water, formed within the oxic/anoxic transition layer with oxygen concentration <0.64 mg O_2 l^{-1} and H_2S <0.03 mg H_2S l^{-1}, is called the suboxic zone [12]. In the surface mixed layer (~0 to 30 m) temperature varies from 7 to 25 °C due to seasonal fluctuations. The temperature of the deeper waters remains consistent throughout the year, with a layer of cold intermediate water (CIL), characterized by core temperatures of ~6 ^{o}C, and a deep layer at 8 ^{o}C. [12, 13].

C. euxinus were acoustically discriminated with respect to vertical migration and swimming speed, according to dissolved oxygen (DO) concentration and the timing of migrations. Species became torpid in water with DO values <0.5 mg l^{-1}. The time spent swimming under DO conditions between 2 and 5 mg l^{-1} was insignificant, and varied greatly from the 10% to 25% of total time spent swimming under normoxic conditions (5–10 mg l^{-1}). *C. euxinus* formed a concentration layer in the water of 1–3 m thickness. Upward migration was completed in about 3.5 h, starting 2.5 h before and ending 1 h after sunset (average rate: 0.95 cm s^{-1}) in summer. Species ascended discretely from the suboxic to the lower boundary of the cold intermediate layer (CIL) at 0.82 cm s^{-1}, and passed up the CIL and thermocline fast (2.3 cm s^{-1}). Downward migration took less time (2 h), starting ~1 h before and ending ~1 h after sunrise. Swimming speed within the thermocline and CIL was 2.7 cm s^{-1}; copepods subsequently returned to daylight depth at a sinking speed of 0.57 cm s^{-1}. Total time for *C. euxinus* to settle to their nocturnal depth layer was about 5 h. Taking the minimum background noise threshold and detection limit of acoustical frequencies (120, 150 and 200 kHz) into account, the concentration layer of *S. setosa* can acoustically be identified by observing their diel migrational pattern during different months in the Black Sea. *Sagitta setosa* showed different patterns in time depending on their generation time and stage composition. During the cold-water season when their population consisted mainly of adult individuals, their daytime concentration layer coexisted with that of *C. euxinus* in the OMZ whereas in the warm-water season, the concentration layer stayed in the oxycline. In July and September, detectable individuals of the new generation did not migrate during the day and stayed in subsurface water. *Calanus euxinus* started accelerating upon entering the oxycline while *S. setosa* accelerated only after entering well-oxygenated subsurface water. This feature distinguishes *S. setosa* from *C. euxinus*. *Sagitta setosa* completed its migration within 4 hrs [14, 15]

This paper is aimed at tracking lower depth of oxic and upper depth of anoxic layer in space and time in reference to vertical distribution of both zooplanktons monitored with acoustic systems in the Black Sea. Additionally, the acoustical knowledge on their migrational pattern of the zooplanktons in response to the dissolved oxygen can classify the region as downwelling and upwelling subregions (Figure 1) besides the oxygen profile in the Black Sea.

MATERIAL AND METHODS

Acoustical backscatter data (echo intensity) were examined to discriminate and identify the concentration layer of *S. setosa* in the Black Sea. Acoustical data were collected with a scientific echosounder (BioSonics Model 120) at 120 kHz (October 1999, July 2000) and 200 kHz (June 1991, January 1992, February 1994, October 1999 and July 2000) and an acoustic Doppler current profiler (ADCP, RD broadband) at 150 kHz (March 1995, April 1993, 1994, 1995, May 1994, July 1997, August 1993, September 1995, 1996, 1999, October 1995, December 1993, Fig. 2).

The echosounders were calibrated with a spherical ball of tungsten, and the transmitter of the echosounder was disabled to estimate the background noise that would be used to set the signal-to-noise threshold during post-processing of the data. During acoustical recording, Nansen rosette water samples and Conductivity Temperature Depth profiles (Sea Bird Electronics, Model 9/11) were collected. Dissolved oxygen concentrations were determined using the Winkler titration method.

Converted acoustical data were plotted as enhanced echograms (Figure 3) showing the vertical distribution of scattering layers for each sampling period. A MatLab script I wrote extracted the lower depth of vertical distribution of

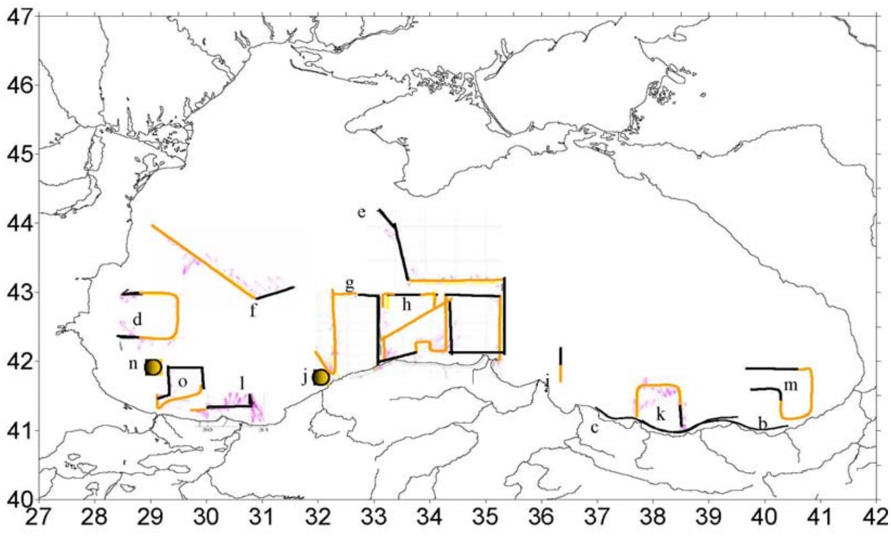

Figure 2. Locations (b; January 1992, c; February 1994, d; March 1995, e; April 1993, f; April 1994, g; May 1994, h; June 1991, I; July 2000 off Samsun, j; July 2000 off Zonguldak, k; August 1993, l; September 1999, m; October 1995, n; October 1999 and o; December 1993) of acoustic studies in the Black Sea to recognize concentration scattering layers of two zooplanktons (circle: fixed stations, Dark line on trackline is nighttime and light line is daytime) (from [15]).

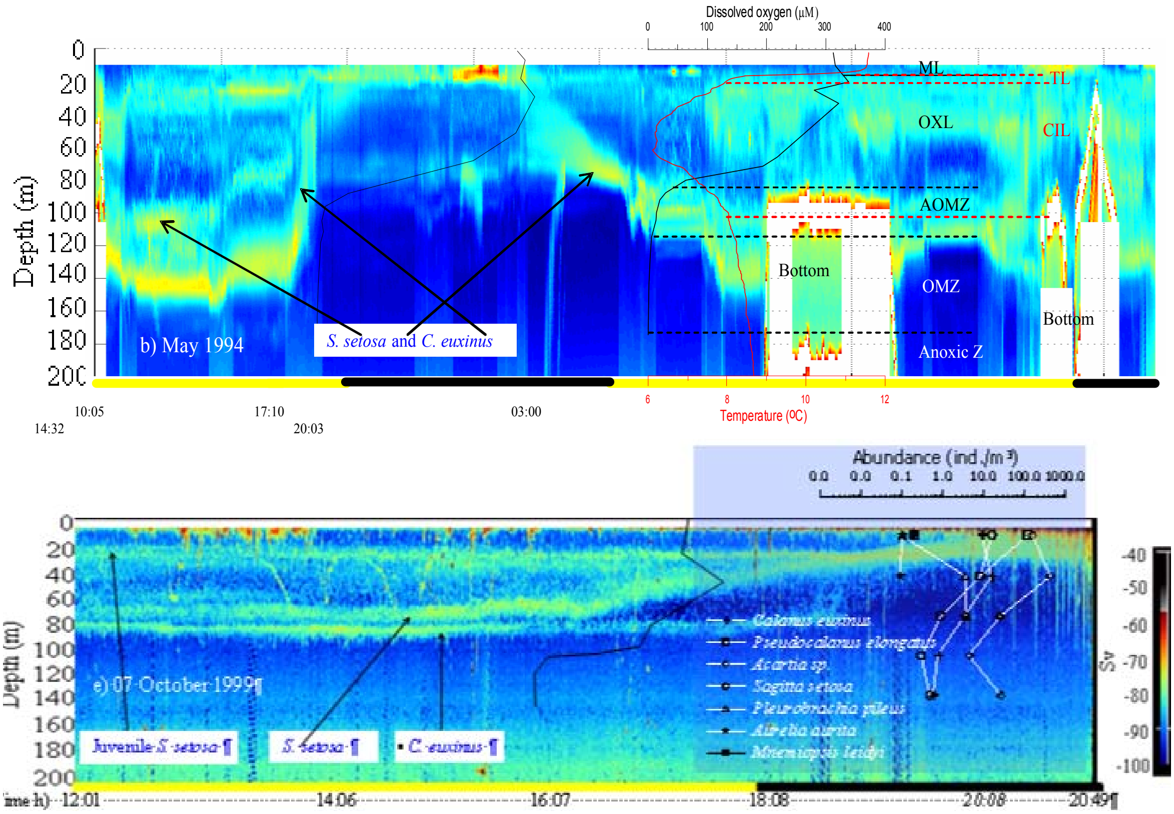

Figure 3. Diel vertical migration patterns of *Calanus euxinus* and *Sagitta setosa* in upwelling (above, acoustical data obtained from ADCP) and downwelling (below; the data from the scientific echosounder) regions of the Black Sea (see Figure 2 for the locations) (from [15]). (ML: Mixed layer; OXL: oxicline; AOMZ: Just above the OMZ; OMZ: Oxygen Minimum Zone; Anoxic Z: Anoxic Zone; TL: Thermocline; CIL: Cold Intermediate Layer).

Calanus and *Sagitta* zooplankton to determine spatio-temporal lower depths oxygenated water in the Black Sea.

RESULTS AND DISCUSSION

Acoustical pattern of DVM

Two zooplankton, *Calanus euxinus* (Copepoda) and *Sagitta setosa* (Chaetognatha) are significant acoustical scatters which are observed with acoustical system (scientific advanced echosounder and ADCP) at higher frequency >120 kHz throughout the oxygenated waters of the Black Sea. They perform diel vertical migration (DVM) in the oxygenated layer between surface and suboxic zone (Figure 3). They stayed within OMZ or AOMZ during the day and by dusk started upward migration and spent their night time near surface waters and by twilight started downward migration. In autumn (September 1995), *C. euxinus* was within the oxygen minimum zone (OMZ), while *S. setosa* stayed in a layer just above the OMZ [16]. Since abundance of *C. euxinus* in the concentration layer was high, the probability of detection of *C. euxinus* at 120 and 200 kHz frequencies could increase, as detected them at 150 kHz [17]. Although its individual response lies in Rayleigh zone for 120 and 200 kHz, *C. euxinus* could still be detected by these frequencies. [18] suggested that adult individuals feed intensively in the subsurface water at night and then return to their daytime depth to digest their prey. Migration speed of *Calanus euxinus* within OMZ was low and then they speed up to ~3 cm s^{-1} through the upper layer above OMZ [14]. Species became torpid in water with DO values <0.5 mg l^{-1}. The time spent swimming under DO conditions between 2 and 5 mg l^{-1} was insignificant, and varied greatly from the 10% to 25% of total time spent swimming under normoxic conditions (5–10 mg l^{-1}) [17]. *Sagitta setosa* accelerated their migration speed up to 3-4 cm s^{-1} only within subsurface maximum of the oxygen just above OXL [15]. *S. setosa* swam at a maximal speed of 1 cm s^{-1}, and migratory movement upward took 4 h in the Black Sea; *C. euxinus* lagged behind *S. setosa*, which ascended from deeper layers [19]. Similar migration speeds (2.8 and 0.94 cm s^{-1}) for the species were obtained by a series of vertical tows [20]. The faster swimming could be related to the higher oxygen or to feeding movements or activities as a function of metabolic rates. Chaetognaths can produce very rapid, directed movements to catch their prey and to avoid predators, and most of the pelagic species that are denser than sea water show regular brief bursts of swimming alternating with passive sinking [21]. Planktonic chaetognaths attack at very short range [22].

Overall, the species completed its upward migration in 3 h, while its downward migration lasted less time (2 h). In some cases, downward migration could last longer (5–7 h) than usual, depending on location of the suboxic zone. In some cases, where the suboxic zone was located in a layer deeper than 100 m and where its daylight concentration layer remained just above the

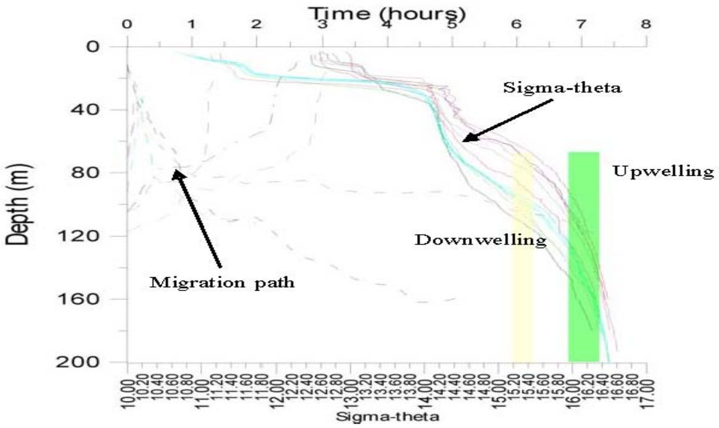

Figure 4. Daytime concentration depth and preference of water density (sigma-theta) of *Calanus euxinus* in the up (gyres) and downwelling (eddies) regions (Figure 1) of the Black Sea.

suboxic zone, the species' upward migration was completed in a very short time (~1 h), at its highest speed. [17] concluded that migration downwards takes 2.0 h and movement upwards lasts for 3.0 h.

Calanus euxinus alternated location where they stayed during the day in the Black sea: in downwelling region they preferred a layer with sigma-theta between 15.2 and 15.8 near above OMZ (Figures 3b and 4); in upwelling region they stayed within OMZ (Figures 3a and 4). *Calanus euxinus* started upward migration at their highest speed at once (Figure 3b).

Profiling dissolved oxygen

Taking all knowledge ascertained to the two zooplankton DVM patterns into account, dissolve oxygen curve in depth could be profiled in place where the DVM was observed from the enhanced echogram. The knowledge was made up of their migration timing, time spent dependent the oxygen, migration or swimming speed, and starting swimming speed of only *Calanus*' upward migration. The speed and their daytime depths suggest profile of the DO, sub-region classification and thickness of the oxic layer. Oxygen profile: layer where *Sagitta* migrate very fast is subsurface maximum oxygen and chl-a (σ_θ =14.0-14.7), layer where *Sagitta* speed down whereas *Calanus* still swim fast is oxycline (σ_θ =15.3-15.9), layer where *Sagitta* spend their daytime is a zone just above oxygen minimum zone (OMZ) (σ_θ =15.9-16.0), and layer where *Calanus* spend their daytime is OMZ (σ_θ =16.15 to 16.20). Sub-regions: If *Calanus* start the upward migration very fast (this means that they settle down in a layer with σ_θ =15.2-15.4 during day), the region is downwelling. If they perform slow ascendance and then speed up (this means that they settle down in a layer with σ_θ =16.15 to 16.20 during day), the region is upwelling. Thickness of oxic layer is depth between surfaces to a depth where *Calanus* are found during the daytime; *Calanus* and *Sagitta* coexist in OMZ during the cold season. Depth preference of *Calanus* in sub-regions must be taken into account of the thickness estimates.

Thickness of oxic layers

The permanent pycnocline maintains vertical separation of the oxic, suboxic and anoxic waters of the Black Sea. The lateral ventilation of the main pycnocline by Bosporus plume waters is responsible for consuming or removing sulfide from the anoxic zone [24]. Figures 5 and 6 show representatives of spatio-temporal depths of lower limits of OMZ in the Black Sea. In general, shallower waters than 200 m should not be taken into account to thickness of the oxygenated layer. The H_2S and O_2 ambient profiles present adequately the onset of anoxic zone. The corresponding bottom values calculated from these profiles show clearly the decoupling between surface (oxygenated) and deep (anoxic), which occurs on the steep continental slope [25]. A permanent halocline at a depth of 100–200m separates the brackish, oxygenated surface waters from the saline, sulfide-rich deep waters [26-28], acting as a natural barrier and inhibiting vertical fluxes. A suboxic zone with undetectable levels of oxygen and hydrogen sulfide (H_2S) in the center of the Black Sea [29] further inhibits the downward flux of oxygen and all other advective and diffusive processes allowing interaction between the oxic/anoxic zones. The onset of hydrogen sulfide, on average, coincides with the permanent halocline at sigma-theta=16.2 [24]. In April 1993, the cruise was conducted in the entire western part of the Black Sea. The thickness ranged from 75 to 190 m in the part (Figure 5a, b). Upper depths of the suboxic zone varied between 120 and 190 m on the bottom depth ranging from 500 and 1500 m whereas it was shallower about 75-80 m on the bottom deeper than 1500 m seaward. The upper boundary of the profiles of H_2S from the southwestern shelf region differs significantly from those in the center of the western gyre. At the center of the western gyre the onset of H_2S is shallow, sigma-theta= 16.2 and depth ~110 m, compared to the deeper onset of H_2S, sigma-theta= 16.4 and depth greater than 170 m, near the southwestern shelf [24]. The thicker oxic layers were well coincided with path of the rim current in the Black Sea. In an ADCP trackline conducted off Zonguldak (Figure 5a, b), deep sea scattering layer corresponding to lower depth limit of oxic layer was located around 110 m, as it was moved seaward, the limit was shoaled up to 75 m. The thickest oxic layer (~190 m) was observed on the bottom with depth between 1000 and 1500 m. The vertical distribution of oxygen with range was well studied in the northern part of the Black Sea [30]: The least depth (45 m) was characteristic of the cores of the cyclonic gyres, and the largest depth (197 m) coincided

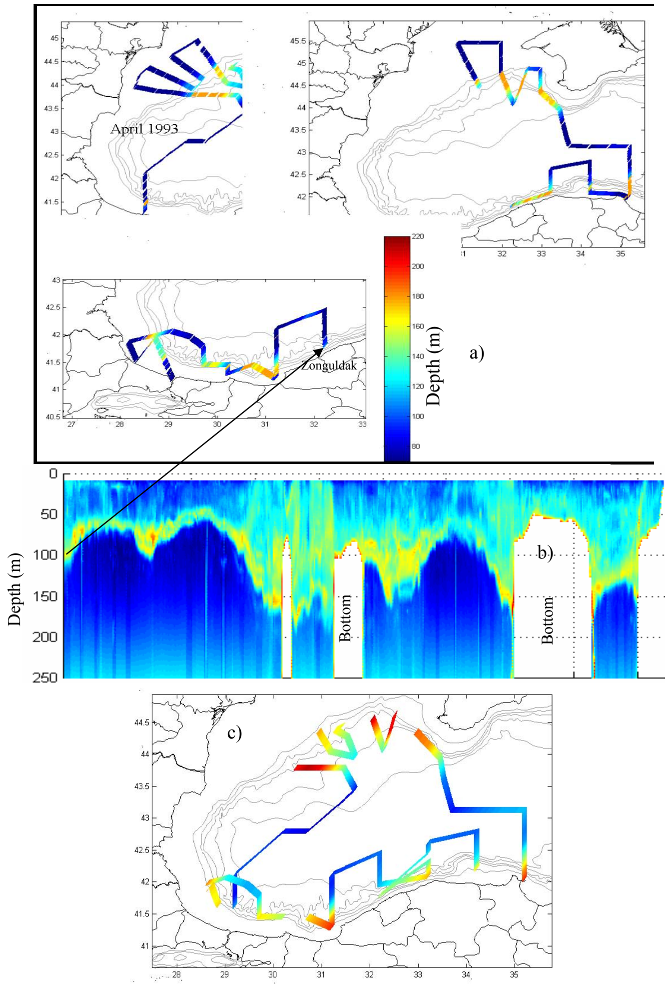

Figure 5. Spatial thickness of the oxic layer observed with ADCP (a) and enhanced echogram of acoustical scattering layer (b) and CTD (c) in the entire western part of the Black Sea in April 1993.

with the location of the major cyclonic gyres in the vicinity of the continental slope edge.

Relatively, the estimates of oxic layer thickness obtained with the CTD probe was in good concordance with those obtained from the acoustical system. In general, there was a significant difference between two methods. Average depth of the layer with sigma-theta between 16.1 and 16.2 measured with SeaBird CTD probe (Figure 5c) is definitively more reliable as compared with the depth estimated from the acoustical system (Figure 5a), and there was an about 10 m difference. These difference could be due primarily to vertical resolution of bin length (4-8 m) of ADCP (acoustical scattering layer extended to 8 m), and to preference of their (two zooplanktons) day time concentration depths in up and downwelling regions (the eddies; Figure 1) of the Black Sea in April 1993 (Figure 5a, b).

In August 1993, a cruise covering the entire southern Black Sea (Figure 6), a striking feature is that the thickness of oxic layer seemed to be shallower than comparative parts of the Black Sea in April 1993 (Figures 5c and 6a) in references to the CTD measurements. A transect entering Batumi anticyclonic eddy (Figure 1) is a good example to track the upper limit depth of the suboxic zone (Figure 6b, c). Scattering layer of two zooplanktons was located at about 100 m outside the eddy. Within eddies a diapausing scattering layer of *Calanus* during the night shows that the thickness of oxic layer ranged from 180 to 210 m (Figure 6b, c) which is in good agreement with presence of a persistent suboxic zone structure with its lower boundary located at depths of around 160–180 m within the quasi-permanent anticyclonic gyre of the eastern basin [23, 34].

Average depths of oxic layers determined with CTD probe seemed to be difference in the months or years from March to August. Due to internal waves and long-term changes in mean circulation, the actual depth of the onset of H_2S varies both spatially and temporally [27, 28, 31-33]. For instance, the Batumi eddy (Figure 1) had shallower oxic layers in March than those in August (Figures 6a and 7). It was truly same for Sakarya eddy (Figure 1) in April as compared with that in May (Figures 5c and 7). In general, the depth of the upper boundary of the anoxic layer in the Black Sea varied from 88 to 220 m [30], which is consistent with range of the values documented during the previous field studies. Naturally, the smallest values were observed in the areas where central cyclonic features occurred, the smallest were recorded within anticyclonic vortices in the vicinity of the continental slope [30].

In conclusion, the acoustic systems could be useful tools for profiling the dissolved oxygen and for monitoring thickness of oxic layers in space and time in the Black Sea, in regard

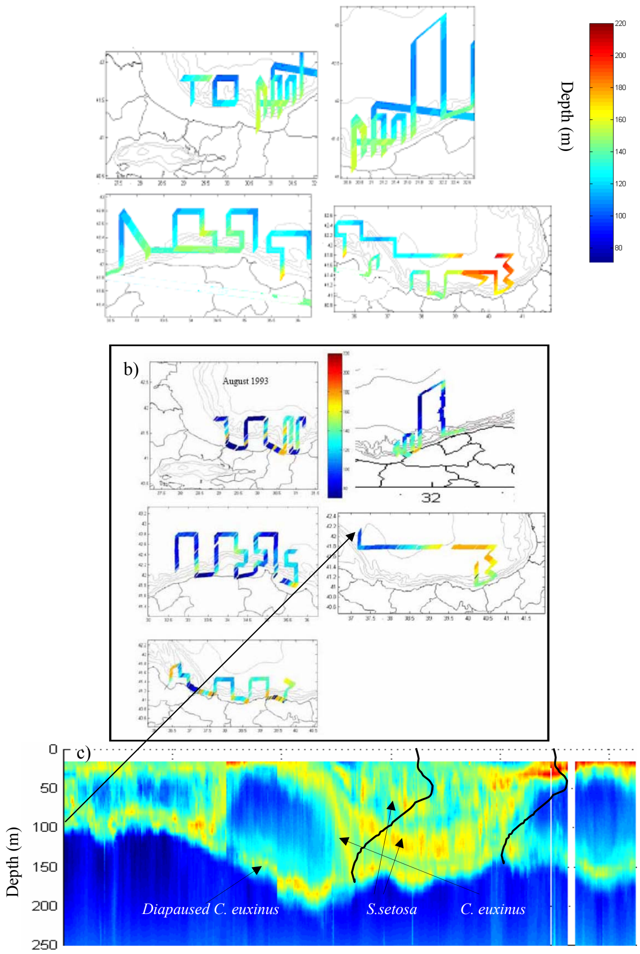

Figure 6. Spatial thickness of the oxic layer observed with CTD (a) and ADCP (b) and enhanced echogram (c) of acoustical scattering layer with the guessed oxygen profiles (bold line profile) overlapped in regard to DVM of two zooplanktons in the southern Black Sea in August 1993.

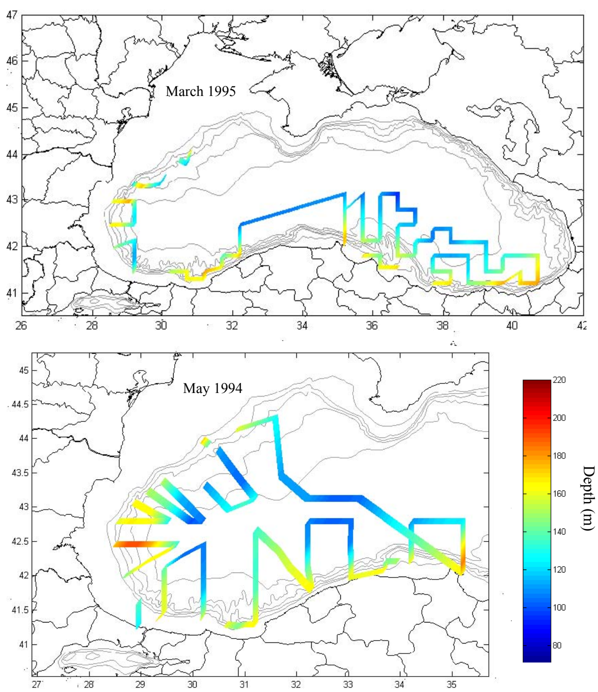

Figure 7. Average depth of a layer with sigma-theta of 16.1 to 16.2 measured with CTD probe in March 1995 and May 1994.

to DVM pattern, migration speeds and depth locations of daytime concentration layers of acoustical two significant scatterers, *Calanus euxinus* (Copepoda) and *Sagitta setosa* (Chaetognatha).

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REFERENCES

[1]. Foote KG, Stanton TK, 2000. Acoustical methods, ICES Zooplankton Methodology Manual. Chapter 6. Academic Press. 223-258.

[2]. Wiebe PH, Greene CH, Stanton TK, Burczynski J 1990. Sound scattering by live zooplankton and micronekton: empirical studies with a dual-beam acoustical system. J Acous Soc Am 88: 2346-2360.

[3]. Mutlu E 1996. Target strength of the common jellyfish (Aurelia aurita): a preliminary experimental study with a dual-beam acoustic system. ICES J Mar Sci 53(2): 309-311.

[4]. Stanton TK, Chu D, Wiebe PH 1996. Acoustic scattering characteristics of several zooplankton groups. ICES J Mar Sci 53:289-295

[5]. Monger BC, Chinna-Chandy S, Meir E, Billings S, Greene CH, Wiebe PH 1998. Sound scattering gelatinous zooplankters Aequorea victoria and Pleurobrachia bachei. Deep-Sea Res II 45:1255-1271

[6]. David PM, Guerin-Ancey O, Van Cuyck JP 1999. Acoustic discrimination of two zooplankton species (mysid) at 38 and 120 kHz. Deep-Sea Res I 46:319–333

[7]. Benoit-Bird KJ, Au WWL 2001. Target strength measurements of Hawaiian mesopelagic boundary community animals. J Acoust Soc Am 110(2):812-819

[8]. Brierley AS, Ward P, Watkins JL, Goss C (1998) Acoustic discrimination of Southern Ocean zooplankton. Deep Sea Res II 45 (7): 1155

[9]. Oguz T, Latun VS, Latif MA, Vladimirov VV, Sur HI, Markov AA, Ozsoy E, Kotovshchikov, BB, Eremeev VV, Unluata U, 1993 Circulation in the surface and intermediate layers of the Black Sea. Deep-Sea Res, 40: 1597-1612.

[10]. Vinogradov MYe, Sapozhnikov VV, Shushkina EA 1992. The Black Sea Ecosystem. Nauka, Moscow

[11]. Poyarkov SG 1989. Peculiarities of water hydrochemical structure in relation to its stratification. In: Vinogradov ME, Flint MV (eds) Structure and productional characteristics of planktonic populations in the Black Sea. Nauka, Moskow, pp 10-23 (in Russian).

[12]. Yilmaz A, Tugrul S, Polat C, Ediger D, Coban Y, Morkoc E 1998. On the production, elemental composition (C, N, P) and distribution of photosynthetic organic matter in the southern Black Sea. Hydrobiologia 363: 141-145.

[13]. Ozsoy E, Unluata U 1997. Oceanography of the Black Sea: a review of some recent results. Earth-Sci Rev 42: 231-272.

[14]. Mutlu E 2003. Acoustical identification of the concentration layer of a copepod species, Calanus euxinus. Mar Biol 142:517-523

[15]. Mutlu E, 2006. Diel vertical migration of Sagitta setosa as inferred acoustically in the Black Sea. Mar Biol. 149(3): 573-584

[16]. Besiktepe S, Unsal M 2000. Population structure, vertical distribution and diel migration of Sagitta setosa (Chaetognatha) in the south-western part of the Black Sea. J Plankton Res 22:669 -683

[17]. Svetlichny LS, Hubareva ES, Erkan F, Gucu AC 2000. Physiological and behavioral aspects of Calanus euxinus females (Copepoda: Calanoida) during vertical migration across temperature and oxygen gradients. Mar Biol 137:963–971

[18]. Pearre SJr 1979. On the adaptive significance of vertical migration. Limnol Oceanogr 24:781-782

[19]. Vinogradov MYe, Flint MV, Shushkina EA 1985. Vertical distribution of mesoplankton in the open area of the Black Sea. Mar Biol 89:95-107

[20]. Besiktepe S 2001. Diel vertical distribution, and herbivory of copepods in the south-western part of the Black Sea. J Mar Syst 28:281-301

[21]. Bone Q, Duvert M 1991. Locomotion and buoyancy. In: Bone Q, Kapp H, Pierrot-Bults AC (eds) The Biology of Chaetognaths, Oxford University Press, New York, pp. 32-44.

[22]. Feigenbaum D 1991. Food and feeding behaviour. In: Bone Q, Kapp H, Pierrot-Bults AC (eds) The Biology of Chaetognaths, Oxford University Press, New York, pp. 45-54.

[23]. Oguz, T., S. Tugrul, A.E. Kideys, V. Ediger, N. Kubilay 2005. Physical and biogeochemical characteristics of the Black Sea. The Sea, Vol. 14, Chapter 33, 1331-1369.

[24]. Hiscock, W.T., F. J. Millero, 2006. Alkalinity of the anoxic waters in the Western Black Sea. Deep-Sea Research II, 53: 1787–1801.

[25]. Stanev, E.V., J.A. Simeonov, E.L. Peneva, 2001. Ventilation of Black Sea pycnocline by the Mediterranean plume. Journal of Marine Systems 31: 77–97.

[26]. Sorokin, Y.I., 1983. The Black Sea. In: Ketchum, B.H. (Ed.), Estuaries and Enclosed Seas. Elsevier, New York, pp. 253–292.

[27]. Kempe, S., Liebezett, G., Diercks, A.R., Asper, V., 1990. Water balance in the Black-Sea. Nature 346, 419.

[28]. Lyons, T.W., Berner, R.A., Anderson, R.F., 1993. Evidence for large preindustrial perturbations of the Black-Sea Chemocline. Nature 365, 538–540.

[29]. Murray, J.W., Jannasch, H.W., Honjo, S., Anderson, R.F., Reeburgh, W.S., Top, Z., Friederich, G.E., Codispoti, L.A., Izdar, E., 1989. Unexpected changes in the oxic anoxic interface in the Black-Sea. Nature 338, 411–413.

[30]. Eremeev, V.N., Konovalov, S.K., Romanov, A.S., 1998: Analysis of observations and methods of calculating oceanic hydrophysical fields: The distribution of oxygen and hydrogen sulfide in the Black Sea waters during winter-spring period. Physical Oceanography, 9(4): 259-272.

[31]. Shaffer, G., 1986. Phosphate pumps and shuttles in the Black-Sea. Nature 321, 515–517.

[32]. Skopintsev, B.A., 1975. Formation of the contemporary chemical composition of the Black Sea waters. Leningrad: Gidrometeoizdat.

[33]. Ryabinin, A.L. and Kravets, V.N. 1989. Current state of the Black Sea hydrogen sulfide zone (1960-1986). Moscow: Gidrometeoizdat.

[34]. Basturk, O., S.Tugrul, S.Konovalov, I., Salihoglu, 1998. Effects of circulation on the saptial distributions of principle chemical properties and unexpected short- and long-term changes in the Black Sea. In: Ecosystem modeling as a management tool for the Black Sea. Ivanov, L.I. and T. Oguz (eds.), NATO ASI Series, Vol. 47, Kluwer Academic publishers, Netherlands, pp. 39–54.