MODELING THE BLACK SEA PELAGIC ECOSYSTEM AND BIOGEOCHEMICAL STRUCTURE: A SYNTHESIS OF RECENT ACTIVITIES

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Abstract: Recent modeling studies on the structure and functioning of the plankton productivity and various other features of the vertical biogeochemical structure of the Black Sea are reviewed in this study. Major findings from the available pelagic ecosystem models, catagorized as the mixed layer based physically simplified models and the vertically resolved coupled physical-biochemical models, are described first. Capability of present models in describing nutrient cycling, oxygen dynamics and suboxic-anoxic layer interactions is then assessed.

1. Introduction

The structure and functioning of plankton community in the Black Sea have been modelled using two different approaches. One of them was to employ biologically-based, physically simplified mixed layer averaged models, as given by Lebedeva and Shushkina (1994), Cokasar and Ozsoy (1998) and Eeckhout and Lancelot (1997). They considered evaluation of the mixed layer averaged properties of the ecosystem by specifying yearly cycles of the mixed layer depth

and temperature diagnostically from available climatological data, without invoking a mixed layer dynamics and a parameterization scheme for the interfacial transports. The second approach was to utilize z-dependent models which represent the vertical biological processes in a more detailed way and involve upper layer physical dynamics. In this type of models, the internal structure of the physical-biological system is evolved solely in response to external forcings applied as the boundary conditions at the free surface and bottom of the model ocean. A principal advantage of z-dependent models is their ability to include plankton productivity and nutrient recycling processes below the mixed layer. This is particularly important during summer when most of the production takes place below the seasonal thermocline. Its applications were given by Oguz et al. (1996, 1998a,b) and Staneva et al. (1998).

In addition to simulation of plankton productivity, Oguz et al. (1998b) incorporated various other features of the upper layer biogeochemical structure. It thereby allowed a dynamical coupling between the euphotic zone, the oxycline/nitracline, and the suboxic layers. Redox processes of the anoxic interface zone were studied to some extent by Yakushev and Neretin (1997) and Lyubartseva and Lyubartsev (1997). These models were, however, based on the "coexistence layer" assumption, thus the dissolved oxygen was accepted as a main oxidizing agent for the hydrogen sulphide. But, in the presence of an oxygen and sulphide depleted zone between the anoxic pool and the oxygenated surface layer, validity of this approach is questionable. Recently, several alternative hypotheses were proposed to explain the origin of the suboxic layer (Murray et al., 1998).

A succint review of the basic findings from these models is provided in this paper. First, those concerning with the annual plankton productivity cycle are presented in Section 2 in two groups as the "mixed layer based biological models" and "vertically-resolved coupled physical-biochemical models". Section 3 deals with the models describing the general biogeochemical characteristics of the Black Sea. A discusssion of the model results are provided in Section 4.

2. Modeling Annual Plankton Productivity Cycle

2.1. MIXED-LAYER BASED BIOLOGICAL MODELS

2.1.1. Lebedeva and Shuskina Model

Lebedeva and Shushkina (1994) explored the central Black Sea ecosystem characteristics before and after the introduction of the Mnemiopsis using a relatively simple pelagic lower trophic food web structure. The plankton community involves phytoplankton, bacteria, protozoa, mesozooplankton, medusae and mnemiopsis. They are complemented by the particulate and dissolved organic matter and nutrient compartments. Phosphate was used as the limiting nutrient whereas most of the other models were based on the nitrogen limitation which seems to be more appropriate for the central Black Sea.

In the absence of Mnemiopsis, the model simulates a major phytoplankton biomass increase up to 7 gC/m^2 in late February-early March, and a fairly uniform phytoplankton biomass level of about 1 gC/m2 throughout the summer and autumn periods (Fig. 1a). A small increase signifying the autumn bloom occurs during early-October. Mesozooplankton generally follows the evolution of phytoplankton with two maxima of 2.3 gC/m^2 in late March and 1.2 gC/m^2 in October. The medusae biomass reveals peak concentrations of 3.7 gC/m2 and 2.5 gC/m^2 in April and early-November, respectively. The reason for simulation of medusae biomass higher than those of mesozooplankton is the presence of a local source representing the advective transport of juveniles from the coastal regions at certain times of the year. Bacteria and protozoa, on the other hand, have much lower biomass values throughout the year. Bacteria exhibits spring and autumn maxima of 1.0 gC/m^2 and 0.5 gC/m^2, respectively, and a rather uniform summer concentrations of 0.2 gC/m^2. Protozoa biomass attain even smaller concentrations of about 0.1 gC/m^2 except a maximum of 0.5 gC/m^2 during late March.

Once the influence of mnemiopsis is included explicitly into the model, it predicts a five-fold reduction in the mesozooplankton biomass due to an extra grazing pressure introduced by mnemiopsis (Fig. 1b). Accordingly, the medusae concentration in the upper mixed layer is decreased twice whereas phytoplankton biomass increases gradually during the late autumn and winter months since, under these conditions, mesozooplankton experience less graz-
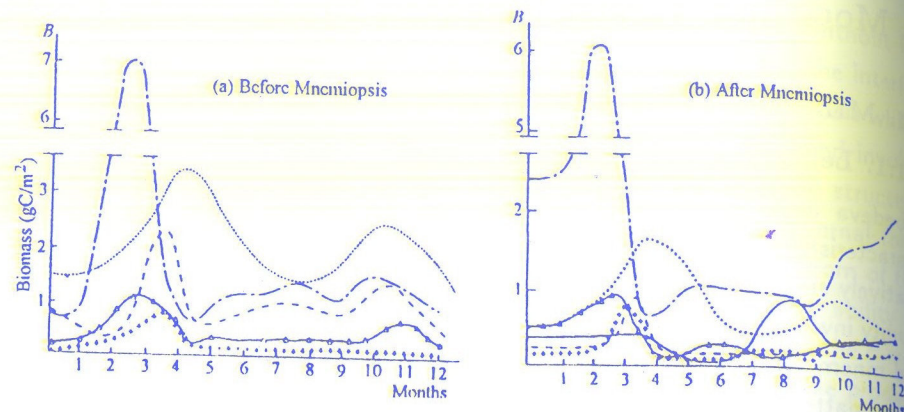
Figure 1. *Annual distributions of the plankton community elements for two simulations; (a) before mnemiopsis case, (b) after mnemiopsis case computed by Lebedeva and Shushkina (1994).*

ing pressure on phytoplankton. Such high winter phytoplankton biomass is followed by the early spring bloom in late February. It was noted that simulation of the high winter phytoplankton biomass agree with the observed winter bloom of 1991 within the interior part of the Black Sea. Mnemiopsis biomass stays typically at about 0.4 gC/m² during the autumn and winter months, followed by a slight decrease in spring. But, a two-fold increase occurs towards the end of summer.

2.1.2. Cokasar and Ozsoy Model

Cokasar and Ozsoy (1998) presented a series of simulations of the mixed layer planktonic structure using different variants of the Fasham model, ranging from a four compartment PZND model to a 9 compartment size-fractionated model for ten dynamically different regions of the Black Sea. These regions, identified according to their circulation and water mass characteristics, were the interior part of the basin, a narrow slope zone confined between the deep interior and

shelf, and eight coastal regions dominated typically by anticyclonic circulation. One of these regions was chosen at the mouth of the river Danube, to observe the effects of the river supplied nutrients.

The modeling was guided by the analyses of the observed seasonal changes of mixed layer depth, nutrients and chlorophyll-a in the model regions. Nutrients content remain at a uniform level for the whole year in the regions directly influenced by river inputs. Mixed layer nutrients generally tend to increase in the other regions during the winter season. Large uncertainties however exist in estimating nutrient concentrations supplied to the coastal waters and their effects in sustaining primary production. Despite the scarcity of data, it appears that the maximum chlorophyll-a concentration occurs in February-March in the central Black Sea, and in April-May in the peripheral regions, where the level is also an order of magnitude higher, as a result of riverine and coastal sources.

The model successfully reproduced basic features of seasonal plankton and nutrient changes. The simple four compartment model was shown to provide realistic simulations of the seasonal production cycle. The PZND model had the advantage of simplicity but better results were obtained when more complexity was invoked. For example, better representation of the seasonal cycles including spring and autumn blooms were obtained with a nine compartment size fractionated model.

The model was also used to interpret the factors responsible for the observed regional differences in productivity. The computed seasonal cycle of the chlorophyll-a compared well with the chlorophyll measurements in the central Black Sea. On the other hand, advection of nutrients was found to be important along the western and southern Black Sea coastal areas downstream of the river sources. Near the Bosphorus, reasonable agreement of model results and observations could only be ensured when the seasonal pattern of advection of river nutrients were taken into account.

In the interior Black Sea, upwelling divergence resisting mixed layer deepening (greater nutricline gradient at higher density) in the cyclonic region seems to lead to a delayed bloom that is also depleted earlier as compared to the other regions, when the effects of riverine advection (whose seasonal supply has a delaying effect in coastal areas) is not included.

Simulations of the model with mnemiopsis included was, however, not satisfac-

tory. Contrary to observed summer time increase in the mnemiopsis biomass within the interior of the basin, the model provided a late spring - early summer increase in response to the increasing zooplankton biomass, and a delayed phytoplankton bloom.

2.1.3. Eeckhout and Lancelot Model

Eeckhout and Lancelot (1997) studied the role of nutrient enrichment on destabilization of the northwestern shelf ecosystem within the last three decades. The simulation for the reference, non-perturbed coastal ecosystem of 1960's takes into account carbon, nitrogen, phosphorous and silicate cycles together with diatoms, nanophytoflagellates, bacteria, microzooplankton, copepods, as well as dissolved and particulate organic matters. This standard model structure was then extended to study the response of increased antropogenic nutrient load by including additional role of autotrophic opportunistic species on the primary production, and of gelatinous organisms called Noctiluca, Aurelia aurita and Mnemiopsis leidyi. The model also includes a benthic module.

When the model is initialized by the 1960's nutrient concentrations, it predicts an early spring diatom bloom with a maximum concentration of about 1 gC/m^2, followed by the development of a nanophytoflagellates bloom of the same size at the end of May. The zooplankton is composed of copepods and to a lesser extent of micro zooplankton. The biomass has a maximum of 0.6 gC/m^2 in April, which shows a gradual decrease in summer. When the experiment is repeated using the initial field of late 1970's nutrient concentrations, but in the absence of Mnemiopsis leidyi, the model predicts biomass increases at all trophic levels in response to this nutrient enrichment of the ecosystem. In particular, approximately 6-fold and 3-fold increases occur in the early spring diatom population and late spring nanophytoflagellates populations, respectively. The algal biomass explosion has a major impact on the copepod population which reveals a major peak of about 4 gC/m^2 at the end of March. The medusae population also shows an abrupt increase to a value of 1.2 gC/m^2 at the begining of April. This biomass concentration decreases only to about 0.8 gC/m^2 level during at the of autumn, followed by a more pronounced decrease in winter months.

Introducing Mnemiopsis leidyi into the model under the same nutrient conditions simulates the "after Mnemiopsis" scenario of the ecosystem. In this case,

the model describes how Mnemiopsis takes over the control of the ecosystem as Aurelia population decreases to very low concentrations whereas Mnemiopsis exhibits similar but somewhat stronger biomass distribution over the year. The introduction of mnemiopsis, however, does not seem to introduce changes in the phytoplankton population.

2.2. VERTICALLY-RESOLVED COUPLED PHYSICAL-BIOCHEMICAL MODELS

2.2.1. Oguz et al. 1st generation Model

It was biologically simplest version involving only single phytoplankton and zooplankton groups, detritus, dissolved inorganic nitrate and ammonium (Oguz et al. 1996). It was applied to a 150 m thick upper layer water column in the central Black Sea, resolved using approximately a 3 m grid spacing. The vertical mixing is parameterized by the order 2.5 Mellor-Yamada turbulence closure parameterization. Given a knowledge of physical forcing, the model simulated main observed seasonal and vertical characteristic features; in particular, yearly evolution of the upper layer stratification, the annual cycle of production with the fall and the spring blooms, the subsurface phytoplankton maximum layer in summer, as well as realistic patterns of particulate organic nitrogen. It is found that initiation of the spring bloom depends crucially on the local mixing conditions and follows weakening of the convective overturning mechanism. As soon as the surface layer of the water column gains a slight stability, the bloom commences before the formation of the seasonal thermocline. This suggests timing of the bloom is governed by the year-to-year and/or local variabilities in the physical processes, in addition to the biological processes. The spring bloom may thus take place at an earlier period, say in February, during mild winters as pointed out by observations (Vinogradov, 1992).

Following the spring bloom, the model predicts a weaker and shorter phytoplankton growth event within April as the water column begins to stratify and the seasonal thermocline begins to form in the near-surface levels. The formation of this bloom is caused by the ammonium, generated as a by-product of the spring bloom, and trapped in the mixed layer. A period of very low primary productivity prevails throughout the summer as a consequence of severe nitrogen limitation in the surface mixed layer. However, some phytoplank-

ton production goes on beneath the seasonal thermocline as long as this zone has sufficient light to support the phytoplankton growth. Towards the end of autumn, rapid destratification of the water column and subsequent intensification of the vertical mixing enhances the nutrient flux to the surface waters, and causes a phytoplankton bloom development of two-three weeks during the October-November-December period, depending on the local conditions.

The numerical experiments implicate the presence of a delicate balance between the growth and grazing processes in the phytoplankton dynamics. In order to get a phytoplankton distribution with two distinct blooms during the late autumn and the early spring, the grazing rate should be a certain fraction of the growth rate. If the grazing pressure is exerted too early and too strong, there will not be sufficient time for the development of sufficiently strong phytoplankton blooms. On the contrary, if it is too weak to be able to control the phytoplankton growth, one long-term bloom event occurs during the December-March period. Once the late autumn bloom is initiated, it persists whole winter since sufficient nutrient is always entrained into the surface layer to maintain the production during this period. Hence, the autumn bloom does not appear to be a robust feature of this model, contrary to the March bloom and summer subsurface chlorophyll-a maximum layer. Such modifications on the standard case of the two-bloom phytoplankton structure may also be traced in the data as a part of the year-to-year variabilities of the biological system.

2.2.2. Staneva et al. Model

Staneva et al. (1998) implemented the Oguz et al. (1996) five compartment model to different locations in cyclonic, anticyclonic and slope regions using the daily atmospheric forcing data for the period of 1980-1987. Significance of daily-to-interannual variabilities in the mixed layer thickness, the temperature and biological structures is noted in this study. The model simulates different phytoplankton structures for the cyclonic and anticyclonic regions depending on the local conditions. The anticyclones were shown to exhibit a standard two-bloom structure similar to the one presented above in Oguz et al. (1996), whereas the cyclones attain a one-bloom structure during the whole winter period. The strength of these blooms were almost half of the phytoplankton concentrations suggested by observations, implying that the model does not

support a realistic nutrient cycling.

2.2.3. Oguz et al. 2nd generation Model

One drawback of the simplified five compartment ecosystem model given in Oguz et al. (1996) was underestimation of the summer production. The limited capability of such simple models in predicting summer chlorophyll values has in fact been noted by other studies (Sarmiento et al., 1993). It was also pointed out that multiple prey-multiple predator models can alleviate the limitations imposed by such simplified approaches and may generate increased chlorophyll concentrations comparable with observations (Armstrong, 1994). Oguz (1998a) therefore extended their previous "1st generation model" by introducing two phytoplankton species groups, typifying diatoms and flagellates, and two zooplankton groups (micro- and mesozooplankton). Microzooplankton (nominally $< 200~\mu m$) consist of heterotrophic flagellates, ciliates and juvenile copepods, whereas mesozooplankton (0.2-2 mm) are formed essentially by copepods. Both of them feed on two types of prey with different prey capture efficiencies. Microzooplankton are considered to be more efficient at capturing flagellates, whereas diatoms are consumed predominantly by mesozooplankton.

Such a simple fractionation of the biogenic community structure was shown to yield increased primary production and development of more pronounced subsurface chlorophyll maximum layer during the summer period. Diatom-based early spring (March) bloom is followed by summer and autumn blooms of flagellates. They were either absent or had only a weak signature in the previous model of Oguz et al. (1996). The reason for the presence of stronger summer phytoplankton growth in the multi-species/multi-group pelagic food web model may be explained as follows. In the case of single phytoplankton and zooplankton groups, the enhanced grazing pressure exerted on phytoplankton following the March bloom prohibits noticeable phytoplankton development near the base of the euphotic zone during spring and summer months. In the presence of two phytoplankton and two zooplankton groups, the situation is somewhat different. Diatoms are responsible from March bloom, and support increased mesozooplankton activity later in spring and summer months. As a result of predator control by mesozooplankton on their grazers, flagellates do not experience any grazing pressure from the microzooplankton group, and may

therefore provide a stronger subsurface production during the summer. This result implies that the choice of five compartment model may not be entirely adequate for representation of all bloom events within a year.

The second major feature of the model was its ability to reproduce a fairly realistic nutrient recycling mechanism. Dead cells and fecal matter sinking from the euphotic zone are continually remineralized to ammonium which is subsequently oxidized to nitrate. These conversion processes are accompanied at the same time with upward transport of both nitrate and ammonium to supply them back to the surface waters. The model simulations indicate that a major part of this recycling process takes place within the upper 50 m of the water column. Nearly 90 % of the primary production is recycled there. The annual nitrogen budget for the euphotic zone shows that 60% of the primary production is supported by the ammonium resources recycled within the euphotic zone. About 15% of the nitrate-based production constitutes new production whereas the rest originates from recycled nitrate within the euphotic layer as a result of the remineralization-ammonification-nitrification pathway. The remaining remineralization-nitrification occurs within the oxycline-nutricline zone confined between the euphotic zone and the suboxic layer (50-75 m). This gives rise to gradually increasing nitrate concentrations from the near-surface to about 75 m depth where the nitrate maximum occurs with concentrations of about 7.0 mmol N m^{-3}.

One interesting finding from the Oguz et al. (1998a) is the possibility of having oscillatory solutions for the linear food chain in which flagellates are consumed by microzooplankton whereas mesozooplankton are fed on diatoms and microzooplankton. In this case, all plankton community exhibit oscillatory character following the March bloom. The system is however stabilized by including some consumption of flagellates by mesozooplankton and diatoms by microzooplankton. The stability of the system was not found to depend on the type (i.e. linear, parabolic, hyperbolic, etc.) of mortality function.

Using the model, feasibility of using two different types of food preferences formulation was also explored. Assigning constant values for the coefficients of food capturing efficiencies turned out to be more practical for obtaining realistic model simulations in the vertically resolved models. On the other hand, since the weighted preferences formulation introduces depth and time dependences on these coefficients they generate an additional complexity on

the model simulations.

2.2.4. Oguz et al. 3rd generation Model

The vertically resolved model of Oguz et al. (1998a) was further modified by adding carnivorous macrozooplankton, bacterioplankton and dissolved organic nitrogen compartments (Oguz et al. 1998b). The macrozooplankton compartment represents the medusae "Aurelia aurita" group dominated the Black Sea ecosystem before the invasion of the ctenophore "Mnemiopsis leidyi" (Shushkina and Musayeva, 1990; Vinogradov and Shushkina, 1992). The model simulations indicate that peaks of phytoplankton (diatoms and flagellates) and zooplankton (mesozoo and macrozoo) biomasses march sequentially one after the other as a result of their prey-predator interactions (Fig's. 2,3). Three diatom blooms occur during March (with maximum biomass of ~5 gC/m^2), late May-early June and December (~1.5 gC/m^2), whereas flagellates dominate the system during most of the summer and the entire autumn (~1-2 gC/m^2) starting from the end of June to the begining of November (Fig. 2a). This phytoplankton structure possesses more pronounced bloom characteristics during summer months as compared with the previous model described in Oguz et al. (1998a), and may point out the role of gelatinous carnivores started dominating the ecosystem during 1980's. This is due to a new "top-down" control mechanism in the food web structure in which increasing the gelatinous carnivore population puts a stronger control on the mesozooplankton community which subsequently weakens their grazing pressure on the phytoplankton structure. The most pronounced signature of this effect is observed towards the end of May and September which coincide with the periods of major increase in the Medusae population (Fig. 3a).

It may be inferred from the vertical structure of the total phytoplankton distribution (Fig. 2b) that the March and December blooms are surface-intensified events. They extend to the depth of 40-50 m coinciding approximately with the depths of winter convective overturning and the 1 % light level. Their formation is the result of entrainment of subsurface nitrates by the convective overturning and therefore is related to the new production. The late spring diatom bloom, on the other hand, is a subsurface event between the seasonal thermocline and the base of the euphotic zone and is essentially originated by the regenerated production.

(a) Euphotic Zone Integrated Biomass

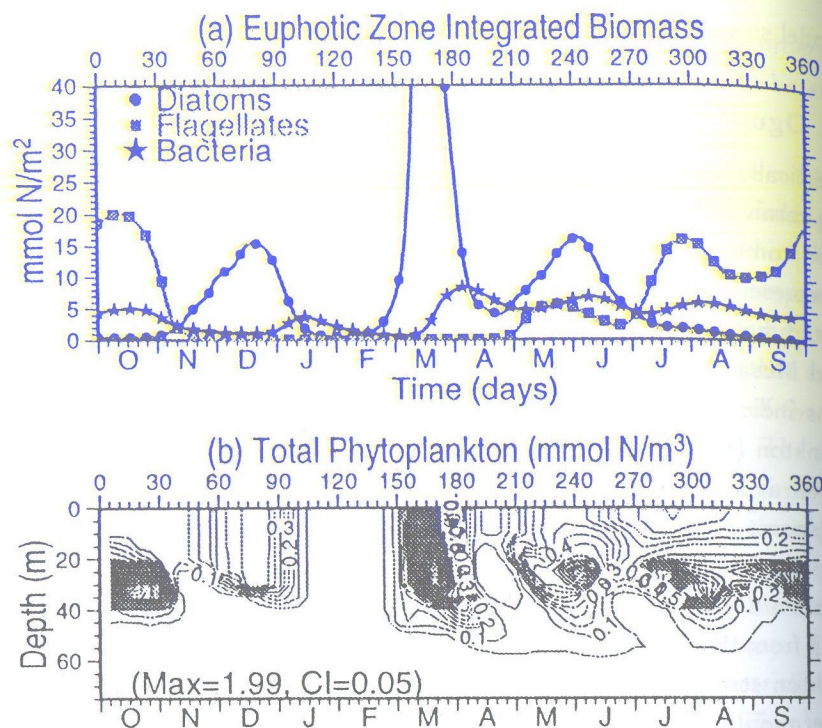## (b) Total Phytoplankton (mmol N/m³)

Figure 2. Annual distributions of the (a) euphotic zone integrated diatom, flagellate and bacterioplankton biomasses, (b) vertical structure of the total phytoplankton biomass within the upper layer water column computed by Oguz et al. (1998b)

(a) Euphotic Zone Integrated Biomass

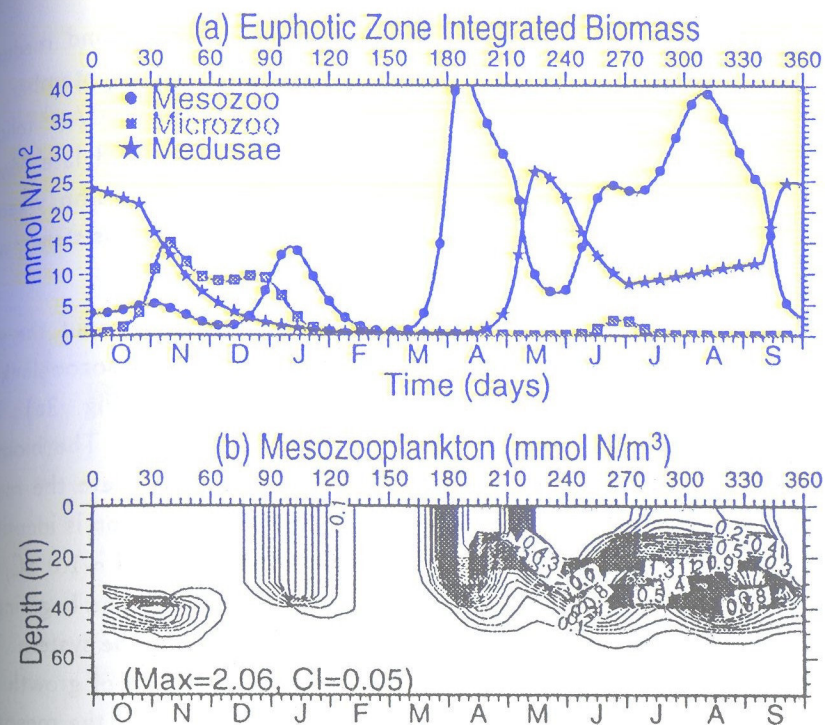## (b) Mesozooplankton (mmol N/m³)

Figure 3. Annual distributions of the (a) euphotic zone integrated zooplankton biomasses, (b) vertical structure of the mesozooplankton biomass within the upper layer water column computed by Oguz et al. (1998b)

As compared to diatoms and flagellates, bacterioplankton biomass exhibits a somewhat weaker distribution within the euphotic zone (Fig. 2a). The stock is typically less than 0.5 gC/m² in the late autumn and winter months. It almost doubles itself after the March diatom bloom till the end of summer. The summer bacterioplankton population is located mainly below the seasonal thermocline at the same levels with the flagellates. The simulated annual bacterioplankton distribution seems to be consistent with the data which indicate slightly higher biomasses after the Mnemiopsis invasion. This is, however, expected since increasing the biomass of gelatinous species should ultimately cause an increase on the particulate and dissolved organic matter contents.

This in turn should lead to some increase in the bacterioplankton population in the system.

As soon as the March diatom bloom degrades, the mesozooplankton biomass starts increasing as they assimilate the diatoms (Fig. 3a). As the grazing pressure introduced by the mesozooplankton decreases the diatom population towards the end of March, mesozooplankton biomass keeps increasing in the euphotic zone. Their biomass tends to decline during May, which coincides with the period of Medusae growth. The summer mesozooplankton growth is principally caused by the reduction in medusae population, with additional contributions by the degradation of the phytoplankton blooms towards the

end of June. A similar interaction between mesozooplankton and medusae taking place earlier in May repeats itself once again during September. A secondary increase on the mesozooplankton stock up to ~1.5 gC/m² follows the December diatom bloom event. The winter (January) and late March mesozooplankton growths take place in the upper 40 m water column, whereas the summer growth is confined below the seasonal thermocline consistently with the annual phytoplankton production sequence (Fig. 3b).

The microzooplankton biomass remains negligibly small throughout the year (Fig. 3a), because of its almost complete predation by the mesozooplankton community. The Medusae biomass exhibits two major peaks (Fig. 3a). The first one follows the mesozooplankton development in spring. The biomass reaches a maximum value of ~2.8 gC/m² in May as they deplete the mesozooplankton stock available for their growth. The summer season is identified by a general decrease in their population to a minimum level of ~1.0 gC/m². The second increase in the medusae population takes place at the begining of October following the abundance of mesozooplankton stock in the system. The population decays during the winter months, until a new cycle of growth and reproduction begins in April. Following the vertical structure of the mesozooplankton community, the first medusae growth event is distributed uniformly within the upper 40 m, whereas the second event is confined below the seasonal thermocline. The form of the annual medusae distribution predicted by the model thus agrees reasonably well with the data.

3. Modeling the Upper Layer Biochemical Structure

3.1. YAKUSHEV MODEL

Modeling the nitrogen and sulfur cycles across the oxic-anoxic interface region was described by Yakushev and Neretin (1997). The model considers the water column between 50 m and 200 m depths. It is forced by a constant dissolved organic matter concentration from the upper boundary, and by a fixed sulphide concentration from the lower boundary. Organic matter is decomposed to the form of ammonium under aerobic, subaerobic and unaerobic conditions at the expense of oxygen, nitrate and sulfate, respectively. Nitrification (ammonium to nitrate conversion) and denitrification (nitrate loss to the form of nitrogen gas) are two other processes of the nitrogen cycle. The main feature of the
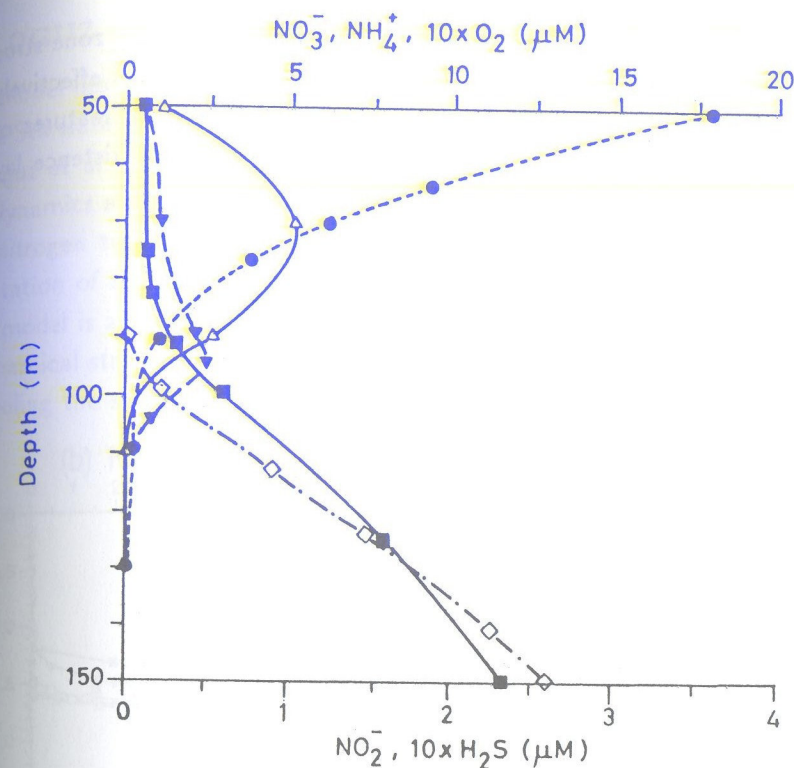
Figure 4. Vertical Profiles of hydrogen sulphide, oxygen, nitrate, ammonium and nitrite simulated by Yakushev and Neretin (1997)

sulfur cycle is the oxidation of H_2S primarily by the oxygen available at the anoxic interface zone. Thiodenitrification involving H_2S oxidation by nitrate is considered as a complementary process. The oxygen is the main oxidizer in the upper part of this layer, whereas the nitrate is in the lower part. The amount of oxygen necessary to maintain the H_2S oxidation and the rest of the sulfur cycle seems to be supplied there by specifying a rather high downward diffusive oxygen flux. The vertical diffusion coefficient taken as 0.1 cm²/s is approximately an order of magnitude higher than its typical values estimated from the Gargett (1984) formula for the pycnocline region of the Black Sea. This is also apparent from the presence of 50 μM oxygen concentrations in the vicinity of nitrate maximum (Fig. 4), contrary to about 10 μM values suggested by observations. A similar model given by Lyubartseva and Lyubartsev

(1997) in fact points to the sensitivity of the hydrogen sulphide zone structure to the values of vertical diffusion coefficient since this controls effectively the amount of oxygen supplied from the aerobic zone. The main features of the Yakushev model (1997) are shown in Fig. 4, where the co-existence layer is indicated between 90 m and 110 m depths.
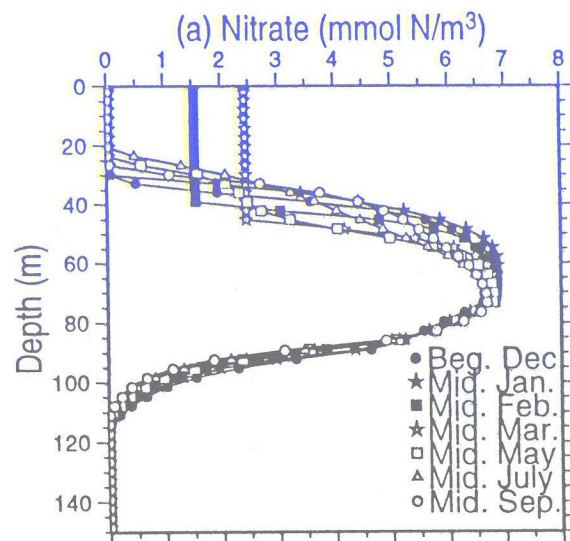

Figure 5. (a) Nitrate profiles versus depth at selected times of the year simulated by Oguz et al. (1998b)

One extension of this model includes the manganese cycling near the anoxic interface zone (Yakushev, 1997). However, oxygen is also considered to be the principal oxidizing agent in the manganese oxidation-reduction reactions. In this repect, the manganese cycling is nothing more than an intermediate step of the H_2S oxidation by the oxygen. On the other hand, as proposed by Murray et al. (1998) the manganese cycle plays a different role, and is used to explain the sulphide oxidation in oxygen depleted environment where the dissolved manganese is oxidized by the nitrate, the particulate manganese formed by this reaction is then utilized in the oxidation of hydrogen sulphide. For that reason, it is quite reasonable to obtain similar vertical structures of H_2S and oxygen in two different version of the models, as reported by Yakushev (1997). This was however interpreted as a negligible contribution of the manganese cycling to the sulphide oxidation process.

3.2. OGUZ ET AL. MODEL

The model describing the upper layer biogeochemical structure for the central Black Sea waters constitutes an extention of the pelagic ecosystem model given by Oguz et al. (1998b). The food web model was modified to include oxygen dynamics and its role in the processes of particulate matter decomposition and nitrogen transformations, as well as denitrification and a simplified representation of the hydrogen sulphide oxidation processes in the suboxic zone. This model is able to simulate many observed features of the upper layer biogeochemical structure, and to provide some understanding on the mechanisms controling the suboxic zone dynamics.
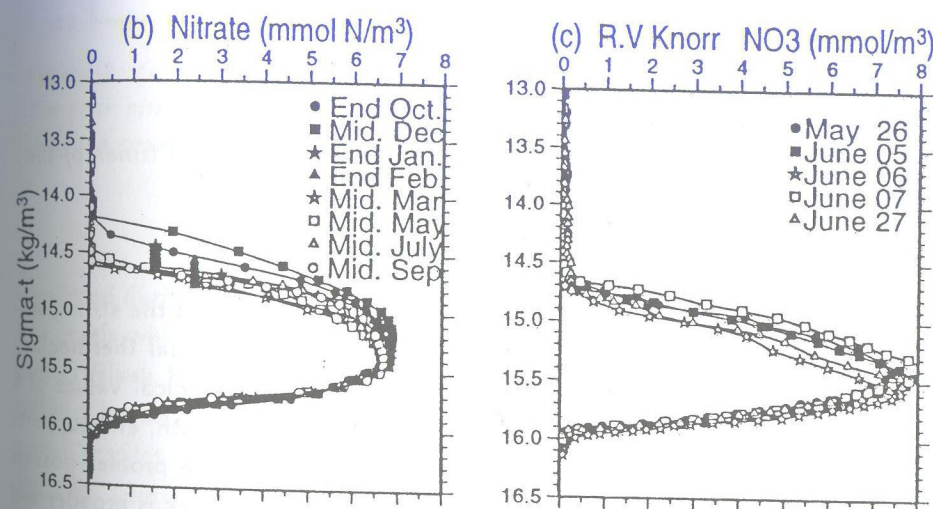

Figure 5. (b) Nitrate profiles versus density at selected times of the year simulated by Oguz et al. (1998b), (c) observed nitrate profiles versus density obtained by the R.V. Knorr surveys in the Black Sea during summer 1988

The nitrogen cycling, which supports the plankton productivity within the interior Black Sea, seems to occur over the uppermost 75 m of the water column. During the winter months, prior to the March diatom bloom event, intense vertical convective mixing gives rise to enhanced nitrate concentrations more than 2 $mmol/m^3$ within the upper 50 m (Fig. 5a). The summer mixed layer, on the other hand, is characterized by depleted nitrate and ammonium stocks, because
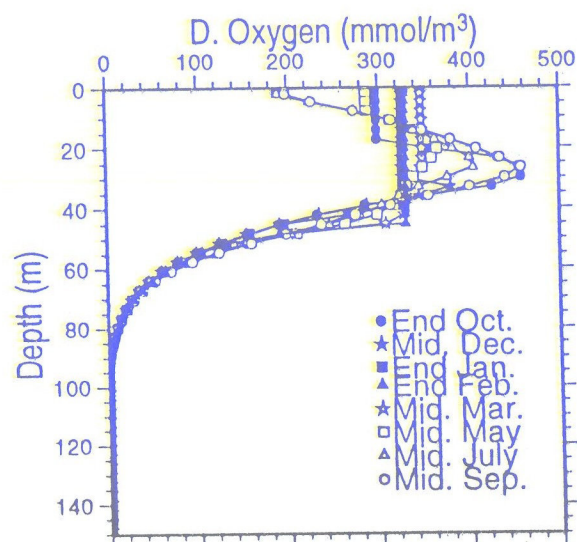
Figure 6. *Dissolved oxygen profiles versus depth at selected times of the year simulated by Oguz et al. (1998b)*

Figure 7. *(a) Dissolved oxygen profiles versus density at selected times of the year simulated by Oguz et al. (1998b), (b) observed dissolved oxygen profiles versus density obtained by the R.V. Knorr surveys in the Black Sea during summer 1988*

of the lack of sufficient supply from the subsurface levels across the strong seasonal thermocline/pycnocline. In the region below the seasonal thermocline, nitrate and ammonium concentrations increase linearly to typical values of 6 mmol/m^3 and 0.2-0.4 mmol/m^3, respectively, around 50 m depth, and supports the summer subsurface production. Further below, the nitrate profiles possess a distinct maximum of about 7 mmol/m^3 near 70 m. The peak is broader and stronger during the autumn and winter corresponding to a more active nitrogen recycling phase after the spring and summer phytoplankton productions. Its position coincides approximately with the 15.4 sigma-t level (Fig. 5b), as suggested by the available observations (Fig. 5c) (Tugrul et al., 1992; Basturk et al., 1994; Murray et al., 1995; and others). During the less productive and poorly-recycled winter months, the ammonium subsurface peaks are eroded to a large extent as it is oxidized to the nitrate form. The nitrate concentrations do not possess any seasonal variability below the peak. They tend to decrease uniformly to their trace level values around 16.0 sigma-t level, which is located roughly 40 m below the position of the nitrate maximum.

The oxygen, generated photosythetically within the euphotic zone and modulated by the ocean-atmosphere interactions at the near-surface levels, are
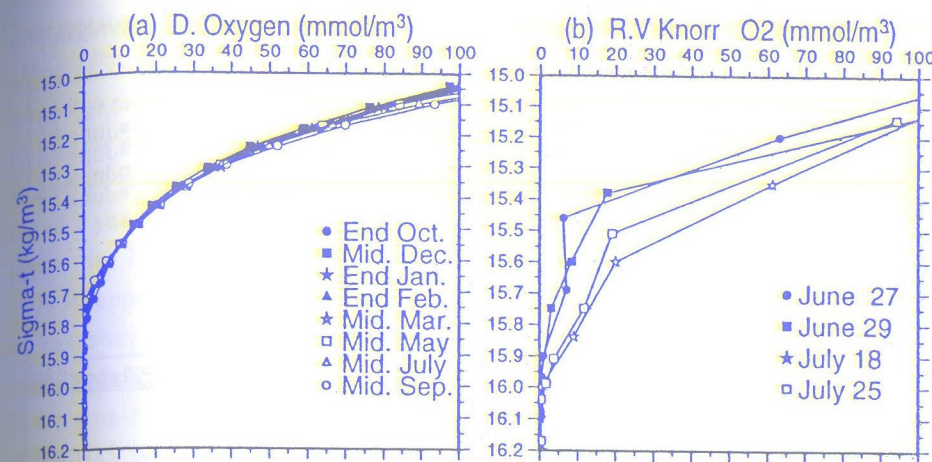
consumed during the organic matter decomposition and nitrification at subsurface levels which normally reveal very restricted ventilation below 50 m in the central Black Sea. The euphotic layer oxygen concentrations vary seasonally within a broad range of extremum values from 200 to 450 μM (Fig. 6a). The winter profiles exhibit vertically uniform mixed layer concentrations of about 350 μM, ventilating at most the upper 50 m part of the water column as a result of the winter convective overturning process. After March, once the cooling season comes to an end, oxygen is lost to the atmosphere, and the surface concentrations can reduce up to 200 μM in the summer. Depending on the strength of summer phytoplankton productivity, the sub-thermocline concentrations vary from 350 μM in mid-May to 450 μM during July and October at the times of flagellate blooms. Both the form of the euphotic layer oxygen structures and the range of variability of the oxygen concentrations agree well with the observations.

Below the euphotic zone, the vertical oxygen structure undergoes very steep variations with almost two order of magnitude changes in their concentrations
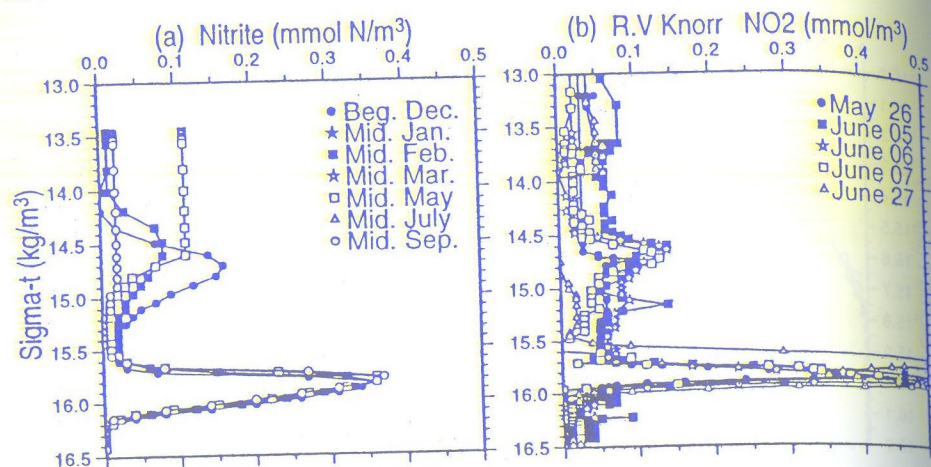
Figure 8. (a) Nitrite profiles versus density at selected times of the year simulated by Oguz et al. (1998b), (b) observed nitrite profiles versus density obtained by the R.V. Knorr surveys in the Black Sea during summer 1988

within about 25 m interval (oxycline) (Fig. 6). Typically, the $\sim 10 \, \mu M$ oxygen level, corresponding roughly to the 15.6 sigma-t level, identifies the position of vanishing aerobic mineralization and nitrification processes in the water column (Fig. 7a). The oxycline thus coincides with strong nitrate variations (upper nitracline) in which the nitrate concentrations increases from their trace level values in the mixed layer up to the maximum values of 6-8 μM across this zone. These model predictions on the position and slope of the oxycline zone, as well as its structure within the suboxic layer agree reasonably well with the available observations (Fig. 7b).

In the oxygen deficient part of the water column (i.e. $O_2 < 10 \mu M$), the organic matter decomposition occurs via the denitrification process. This causes excessive nitrate consumption within a narrow layer adjacent to the oxycline and associated strong reduction in the nitrate concentrations. A distinguishing signature of the denitrification in the model is the formation of a narrow nitrite peak located at about 15.8-15.9 sigma-t levels (Fig. 8).

Oguz et al. (1998b) model also considers interaction of hydrogen sulphide

with oxygen and nitrate near the anoxic interface in a more simplified form of the sulfur cycle than given by Yakushev and Neretin (1997). As oxygen maintains the vertical structure shown in Fig. 6 in the absence of its oxidation by oxygen and nitrate, hydrogen sulphide evolves the form shown in Fig. 9a as a result of the diffusive transport from the prescribed bottom source at the end of 4 years of time integration of the model. It is noted that the subsurface (below the 75 m depth) value of the vertical diffusion coefficient of 2.0×10^{-6} m^2/s is approximately an order of magnitude smaller than the one utilized by Yakushev and Neretin (1997) and is computed from the Gargett (1984) formula. It is shown that, under such conditions, H_2S can penetrate up to the 15.4 sigma-t level and co-exists with oxygen (Fig. 9a). Once the oxidation of the H_2S with the dissolved oxygen and NO_3 is allowed in the model, the oxygen and hydrogen sulphide overlapping layer is eroded and the oxygen and H_2S profiles are separated gradually within the subsequent year (Fig. 9b). During the following year of time integration, an anoxic-nonsulfidic layer is finally established between 15.65 and 16.10 sigma-t levels (Fig. 9c), which resembles the suboxic layer structure inferred from the observations. Clearly, choices of higher a thiodenitrification rate would lead to more rapid depletion of sulphide and generate the suboxic zone much earlier.

In the case of slightly higher choices of the vertical diffusion coeeficient (e.g. 5.0×10^{-6} m^2/s in the experiment described herein), the model was shown to exhibit a much deeper penetration of oxygen, in the absence of its utilization in the H2S oxidation (Fig. 10). The two July 1988 profiles shown in Fig. 7b provides an observational support for this type of oxygen structure. In this case, it is characterized by 30 μM concentrations at 15.6 sigma-t level and 10 μM around 16.0 sigma-t level. H_2S attains the values of about 5 μM near the anoxic interface and decays exponentially towards 15.6 sigma-t level (Fig. 10). Once the oxidation of H_2S by O_2 and NO_3 is allowed in the model, for the case of realistic oxidation rates about 0.05-to-0.1 day^{-1}, the entire H_2S present in the oxygenated part of the water column is oxidized rapidly within a few weeks (Fig. 11a, b). H_2S remains to exist only below $\sigma_t \sim 16.05$ level where the oxygen and nitrate are no longer available due to their consumption up to this level. These numerical experiments therefore suggest that H_2S and O_2 cannot exist together since the fast reaction rate of the oxidation process will quickly deplete the H_2S. At most, H_2S can penetrate up to a level of vanishing oxygen
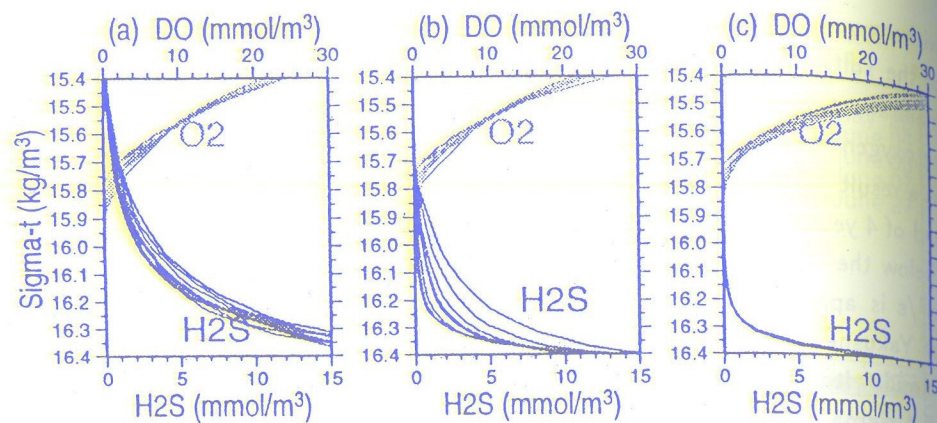
Figure 9. Dissolved oxygen and hydrogen sulphide profiles versus density near the anoxic interface zone simulated by Oguz et al. (1998b). These profiles show the evolution of the oxygen-H₂S structure shown in Figure 6 (a) within the fourth years of integration in the absence of oxygen-sulphide interactions, (b) within the subsequent year of integration after the sulphide oxidation by oxygen and nitrate is allowed, (c) during the following year of integration
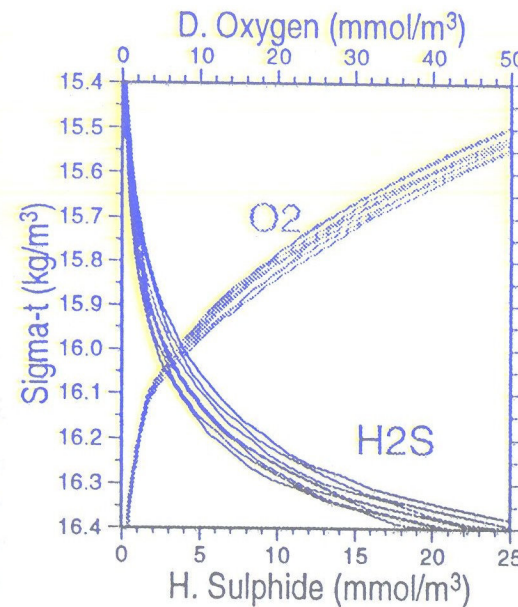

Figure 10. Evolution of the dissolved oxygen and hydrogen sulphide profiles versus density near the anoxic interface zone during the fourth years of integration (after Oguz et al., 1998b).

concentrations. These results, contradicting with the findings of Yakushev and Neretin (1997), suggest that even this simple model of H²S oxidation is sufficient to provide a quantitative confirmation for the existence of the oxygen-sulphide free suboxic zone and for the absence of the coexistence layer in the Black Sea. The manganese and iron cycles might further refine this structure by contributing to the oxidation of H²S near the anoxic interface.

4. Summary and Discussion

The present paper describes an overview of the existing numerical modeling studies on the structure and functioning the ecosystem as well as the biogeochemical structure of the upper layer water column in the Black Sea. Some of the pelagic ecosystem models consider only the mixed layer integrated properties of the system (Lebedeva and Shushkina, 1994; Eeckhout and Lancelot, 1997; Cokasar and Ozsoy, 1998). Even if their simplicity of implementation and experimentation, they have deficiency of neglecting the plankton produc-

tion below the seasonal thermocline when the mixed layer is shallower than the euphotic zone during late spring, summer and early autumn periods. The success of these models crucially depends on the specification of the daily mixed layer depth and temperature as well as the subsurface nutrient structure which controls the nutrient flux across the thermocline. These models therefore rely on the quality of external input coming from the observations. Despite these drawbacks, this type of biological models were useful for understanding the ecosystem changes during the last several decades. Lebedeva and Shushkina (1994) model suggested that recent increase in the gelatinous carnivore population in the interior Black Sea results in approximately five-fold decrease in mesozooplankton biomass and subsequently considerable increase in the winter phytoplankton biomass. It was however not supported by the findings of Cokasar and Ozsoy (1998) and Eeckhout and Lancelot (1997) which seem to be less successful in simulating the observed features of the annual plankton cycle.

The mixed layer based biological models were complemented by the vertically-resolved models (Oguz et al., 1996, 1998a,b; Staneva et al., 1998). They
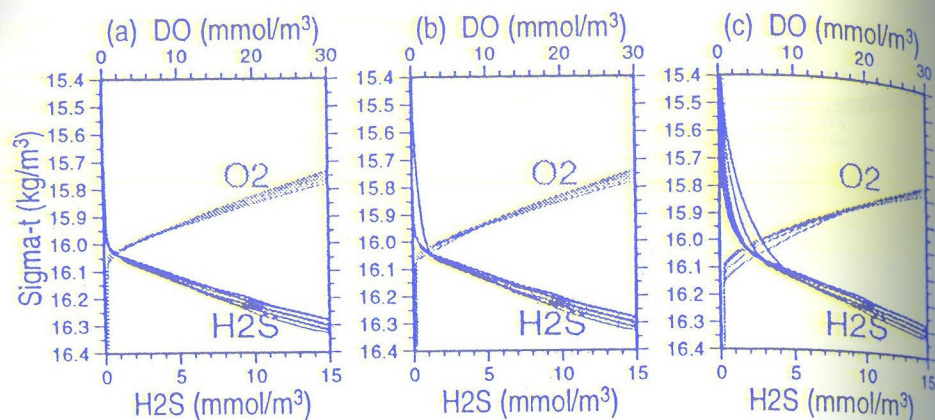
Figure 11. Evolution of the oxygen-H_2S structure shown in Figure 10 within the subsequent year of integration after the sulphide oxidation by oxygen and nitrate is allowed using three different oxidation rates of (a) 0.1 day^{-1}, (b) 0.05 day^{-1}, (c) 0.01 day^{-1}

consider biogeochemistry of the entire upper layer water column with varying degree of complexity, depending on the specific purposes of these models. The most simplified, five compartment, version (Oguz et al., 1996; Staneva et al., 1998) explored the most robust biological features of the ecosystem and the role of upper layer physics on the evolution of the euphotic zone biological processes. For example, Oguz et al (1996) described quite interestingly how the early spring bloom was triggered immediately after the weakening of the convective mixing in the water column well before the formation of the seasonal thermocline which is traditionally accepted as a prerequisite for the spring bloom formation. The other models (Oguz et al., 1998a and 1998b) introduced some biological complexities to the five compartment model and explored how these biologically structured models were more capable of simulating intensified subsurface summer production, and more dynamic plankton structure arising after the increasing role of the gelatinous carnivores in the ecosystem during 1980's. The sensitivity studies carried out with these models were instrumental in exploring the possible causes of regional as well as year-to-year variabilities of the system, and how the internal structure of the biological pump is in action under different scenarios.

The vertically-resolved model (1998b) reveals fairly sophisticated nitrogen cycling in the water column characterized by remineralization, ammonification, nitrification and denitrification processes with the water column. These processes are complemented by the oxygen dynamics in the oxygenated part of the water column and a simplified sulfur cycle near the anoxic interface zone. The model, which was principally similar to the one given by Yakushev and Neretin (1997) but employed different parameter setting, provided a quantitative evidence for the presence of the oxygen and sulphide depleted suboxic layer between the anoxic pool and the oxycline. The model suggested that, under given realistic oxidation and vertical diffusion rates, the oxygen and hydrogen sulphide can not exist together because of the fast reaction rate of the oxidation mechanism. While the lower boundary of the suboxic zone has a fairly stable character, the upper boundary (i.e. the slope of the oxycline) might change up and down depending on the local, internal mixing characteristics. The oxygen dynamics, on the other hand, suggest that the subsurface levels are very poorly ventilated by the surface layer processes. This is the key element for the permanency of the suboxic layer in the Black Sea.

Acknowledgements

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