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Experimental and Field Research

Seasonal and spatial variability of the content of suspended organic substances in the active layer of the Black Sea*

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Abstract — On the basis of the generalized data of multiannual observations (1985–1994), we analyze the seasonal variability of the vertical and spatial distributions and composition (C_{SOS}, N_{SOS}, $C_{SOS}/\text{ch}\,a$, and C/N) of suspended organic substances (SOS) in the shelf zone and in the upper active layer of the abyssal part of the Black Sea. The results of our analysis enable us to conclude that only a narrow coastal band of the shelf in the northwest and west parts of the sea suffers to an extremely pronounced anthropogenic impact, which manifests itself in a significant increase in the mass of suspended organic substances. The formation of new organic substances and, hence, the mass of suspended organic substances in these regions attain the level of eutrophic waters in the late-spring and summer periods. In the open-sea region, the anthropogenic impact is less pronounced and the spatial distribution of suspended organic substances is determined by the general dynamics of waters and the intensity of phytoplankton production.

In order to estimate the productivity of marine ecosystems and their stability under various impacts, it is necessary to study the qualitative and quantitative compositions of suspended organic substances as well as their time and spatial variability.

Despite significant attention given in the last decade to the investigation of suspended organic substances in the Black-Sea water, the data on regional and seasonal variability of their contents are quite poor.

Separate measurements of the concentration of suspended organic carbon (C_{SOS}) carried out in May–October 1962 and 1978 did not reveal any significant changes in the open part of the sea [1, 2]. At the centers of the western and eastern halistases, the mean content of the suspended organic substance in the 0–100-m layer was as high as 260 mgC m^{-3}. Regional variations of the concentration C_{SOS} were detected in the course of the investigations of the coastal zone of the sea carried out from the Danube to the Bosporus in May 1982 [3], along the section from Batumi to Burgas in May 1984 [4], and in March–April 1988 [5].

Thus, the investigations of suspended organic substances were mainly carried out during the warm period of the year. Moreover, they were separated in space and time and, therefore, it was impossible to study the seasonal and interannual variability of the analyzed parameter even for some local regions of the sea. Regular investigations of the distribution of suspended organic substances were originated in 1985 jointly by the Institute of Biology of Southern Seas and Marine Hydrophysical Institute of the Ukrainian Academy of Sciences. As a result of these studies, a significant

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amount of data was accumulated and it became possible to analyze the distribution and chemical composition of suspended substances in the warm and cold periods of 1985 and 1987 in the northeast part of the sea [6], the qualitative and quantitative variations of suspended organic substances within the winter-spring period in the abyssal and shallow-water parts of the sea [7], and the regularities of the vertical distribution of organic substances and biochemical processes in the zone of interaction of aerobic and anaerobic Black-Sea waters [8, 9]. At present, the authors accumulated a vast amount of data on the contents of suspended organic substances in the Black Sea for different seasons within the period 1985–1994 (the data of about 460 stations 231 of which are located along the vertical) (Fig. 1).

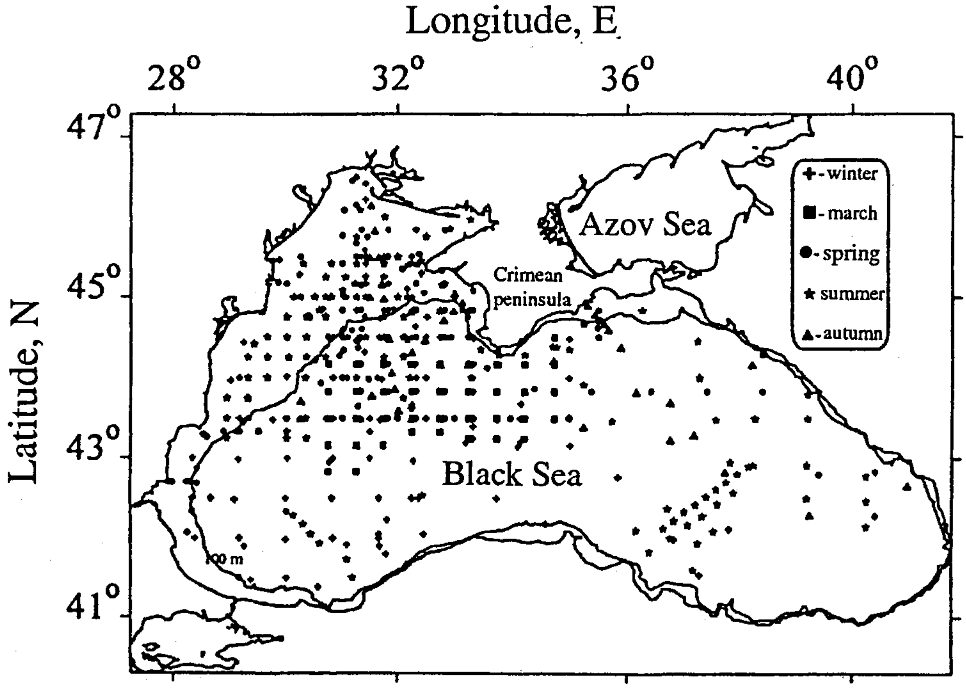


Figure 1. Positions of the stations aimed at measuring the contents of suspended organic substances in the Black Sea.

The aim of the present work is to generalize the data of multiannual investigations of the processes determining the vertical, spatial, and seasonal variability of suspended organic substances in the active layer of the sea.

METHODS OF INVESTIGATIONS

Samples of water used to determine the contents of suspended organic substances were collected with bathometer cartridges after measuring temperature and salinity with an ISTOK probe. In the warm period, the suspended organic substances were separated by filtration of 0.3–2.5 liters of water through *GF/F* glass-fiber filters 22 mm in diameter calcinated at 400°C for 12 h. In the cold period, these substances were separated by filtration of 1.0–2.5 liters of water through *GF/C* glass-fiber filters. We compared the retentivity of *GF/C* and *GF/F* glass-fiber filters and showed that 11% of mass of suspended organic substances was lost, on the average, in *GF/C* filters in the open part of the sea in winter.

The concentrations C_{SOS} and N_{SOS} were measured with a CHN-analyzer made in Czechoslovakia. Prior to the analyses, the filters were treated with a 0.01 M solution of hydrochloric acid to remove carbonates. In our work, we used both the results of our own measurements of concentrations of chlorophyll *a* and the database of the Department of Ecological Physiology of Algae of the Institute of Biology of Southern Seas. The concentration of chlorophyll *a* was measured by the fluorimetric method [10].

The data on the content of suspended organic substances obtained for the same seasons but different years were used to construct the plots of their vertical distribution and the maps of spatial distribution of the components in the surface layer and in the zone of photosynthesis in the Black Sea.

Since the hydrological conditions in the northwest part of the shelf zone are quite complicated, in order to analyze the distinctive features of the distribution of suspended organic substances, we performed averaging over layers 5–10 m in thickness for stations located in different regions of the northwest part of the sea.

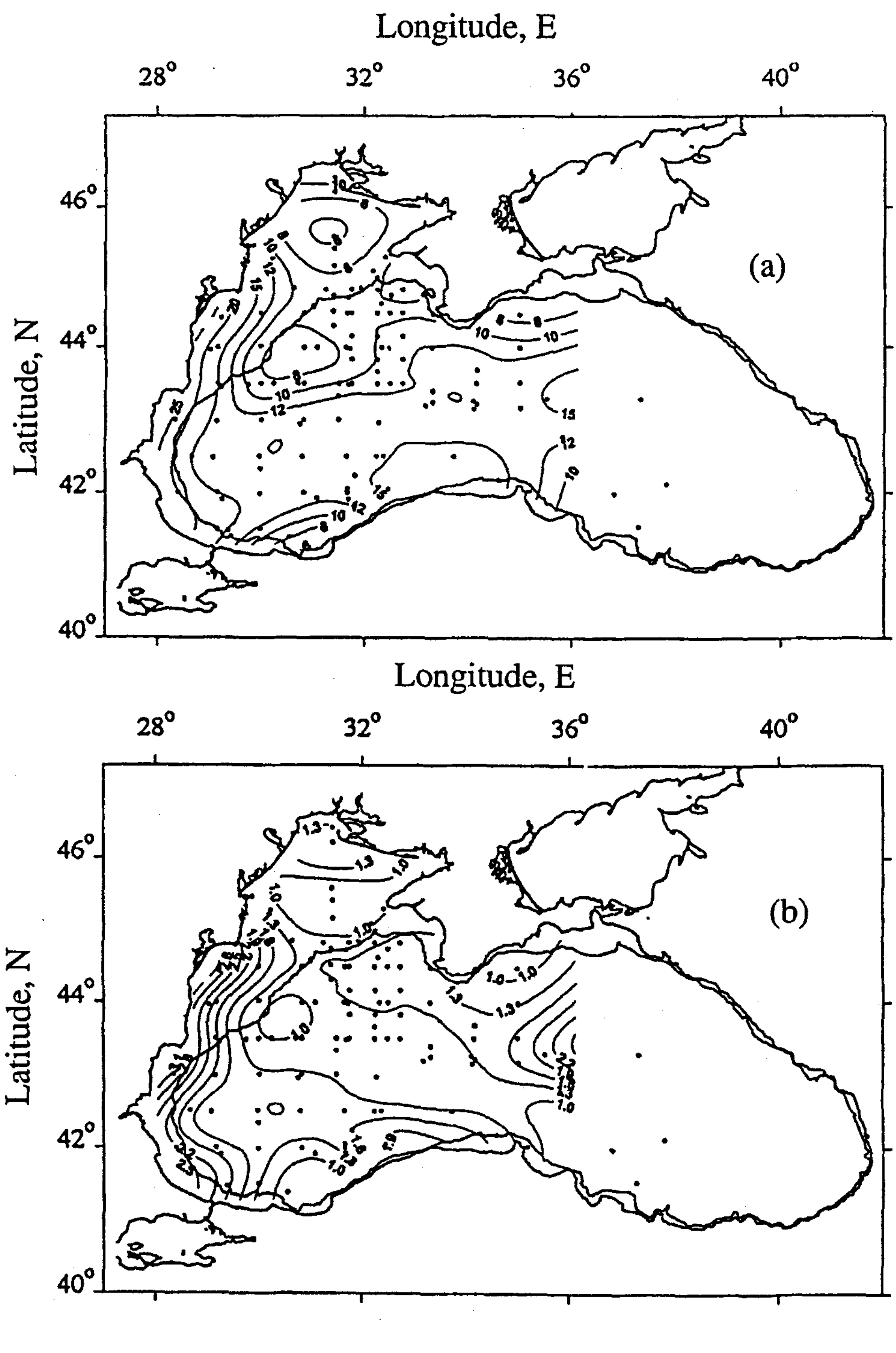
RESULTS

The Black Sea can be split into two regions with absolutely different oceanographic conditions, namely, the shelf zone and the abyssal part of the sea. The shelf occupies about 25% of the total area of the sea. Its specific features are explained by the fact that the annual discharge of rivers together with precipitations constitute about one-third of the total volume of water in this region. Here, the time dependence of hydrological conditions is more pronounced due to the low inertia of water masses and their high sensitivity to external impacts [11]. In the abyssal regions, in all hydrological seasons, we observe large cyclonic circulations with variable locations and sizes [12, 13]. Their boundaries are determined by the location of the Main Black-Sea Current to the right of which we see a system of quasistationary anticyclonic vortices. The presence of two regions with quite different characteristics explains the necessity of separate analysis of the shelf zones and the abyssal part of the Black Sea in describing the distributions of suspended organic substances over the sea area for different seasons.

SPATIAL DISTRIBUTIONS OF SUSPENDED ORGANIC SUBSTANCES

WINTER

Shelf. The concentrations C_{SOS} and N_{SOS} in the surface layer of the northwest part of the sea and in the west shelf zone in winter vary within the ranges 6–25 and 0.6–3.0 mg-atom·m^{-3}, respectively (Figs 2a, b).



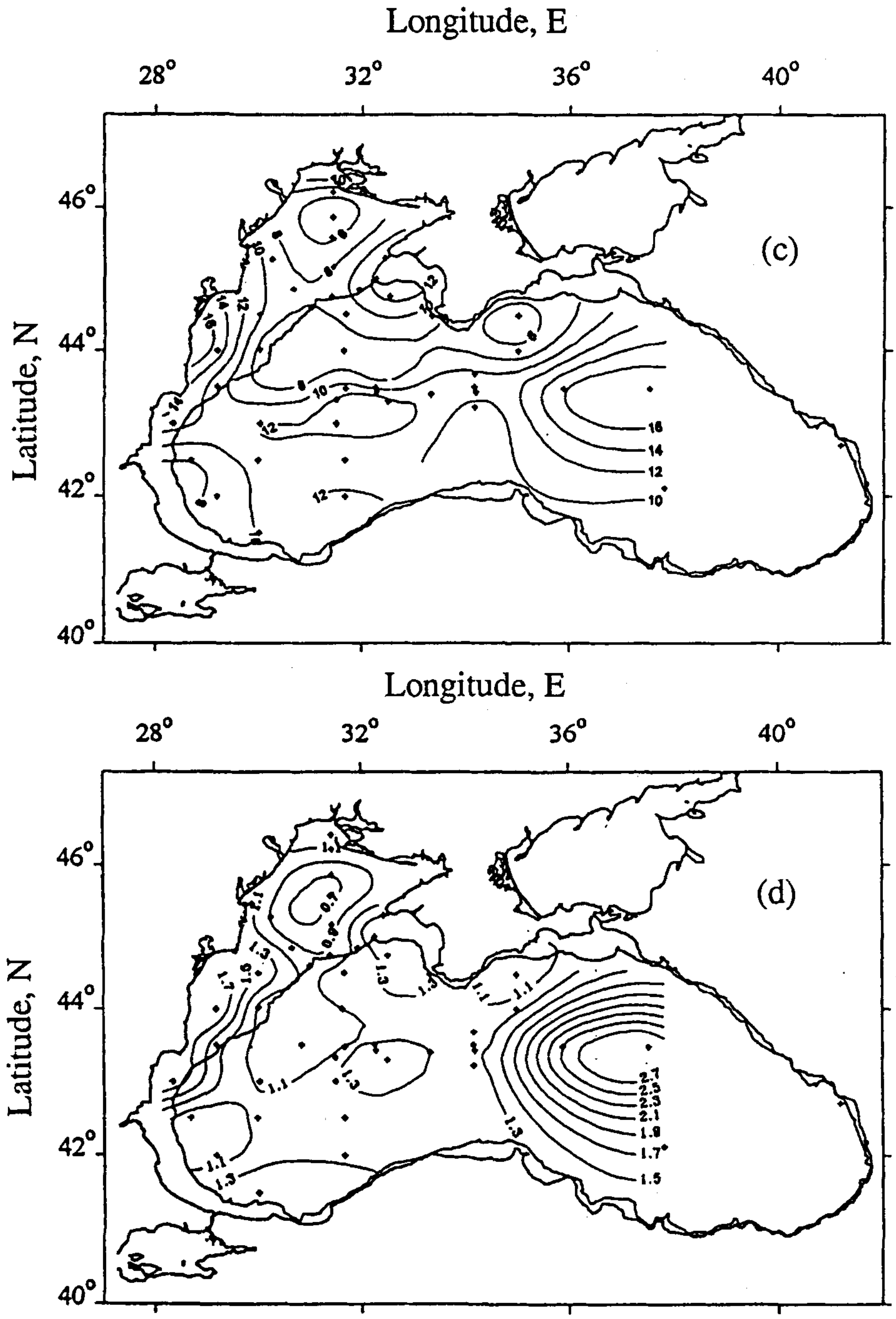


Figure 2. Distributions of suspended organic carbon and nitrogen (mg-atom·m^{-3}) in the surface layer [(a) C_{SOS}, (b) N_{SOS}] and their weighted-mean concentrations in the zone of photosynthesis [(c) C_{SOS}, (d) N_{SOS}] in the winter period.

The maximum concentrations C_{SOS} and N_{SOS} in the surface layer (12–25 mg-atomC$\cdot$m^{-3} and 1.8–3.0 mg-atomN$\cdot$m^{-3}, respectively) were observed in the west shelf zone (from the estuary of the Danube to the Bosporus). However, according to the hydrological data, the influence of the Danube was detected only to Cape Kaliakra. This region coincides with the region of freshened water bounded by an isohaline of 17‰. To the south of Cape Kaliakra, high concentrations of suspended carbon and nitrogen are most likely explained by the influence of coastal waste waters of industrial towns in Bulgaria.

Elevated concentrations of the organic suspension are observed in the near-estuary part of the River Dnieper (10–12 mg-atomC$\cdot$m^{-3} and 1.6–1.8 mg-atomN$\cdot$m^{-3}) and in the Kalamit Bay (10–12 mg-atomC$\cdot$m^{-3}). One more zone of elevated concentrations C_{SOS} (14–17 mg-atom$\cdot$m^{-3}) and N_{SOS} (1.6–1.9 mg-atom$\cdot$m^{-3}) is located in the region of divergence of the Main Black-Sea Current near the Anatolia Coast bounded between 32 and 34°E [12].

The minimum concentrations of C_{SOS} (6–8 mg-atom$\cdot$m^{-3}) and N_{SOS} (0.6–1.0 mg-atom$\cdot$m^{-3}) are recorded at shallow-water stations located at the center of the northwest shelf.

The distributions of C_{SOS} and N_{SOS} in the zone of photosynthesis are presented in Figs 2c, d. Their weighted-mean concentrations in the zone of photosynthesis and in the upper layer in the northwest part of the sea in the winter period are practically equal with the exception of the region subjected to the influence of Danubian waters. In the near-Danube region, the weighted-mean concentrations of both components of the organic suspension in the zone of photosynthesis are 1.5 times lower than in the surface layer. This can be explained both by the specific features of the distribution of phytoplankton in winter and the delivery of suspended organic substances by the Danubian waters, which spread over the sea surface in the form of a thin layer. The influence of river waters manifests itself by elevated concentrations of suspended organic substances and is observed in a narrow coastal zone (~ 30 miles). This is most likely explained by the low discharge of rivers in winter and the predominant influence of northeast winds.

Abyssal part of the sea. In the abyssal part of the sea, the concentrations of suspended carbon and nitrogen in the surface layer (Figs 2a, b) are close or coincide with the weighted-mean concentrations in the zone of photosynthesis (Figs 2c, d). The maximum values of concentrations (12–15 mg-atomC$\cdot$m^{-3} and 1.3–2.8 mg-atomN$\cdot$m^{-3}) are clearly located at the centers of cyclonic circulations. Thus, the concentrations of weighed organic hydrogen and nitrogen in the west and east cyclonic circulations are, respectively, twice and four times as high as at the center of the northwest part of the sea. In the same period, relatively high rates of primary production (600 mgC$\cdot$m^{-2} day^{-1}) were recorded in the west part of the abyssal zone of the see [14]. Outside the zone of cyclonic circulations, the rate of production of organic substances dropped to 200 mg-atomC$\cdot$m^{-2} day^{-1}. This was accompanied by a decrease in the content of suspended organic substances (8–10 mg-atomC$\cdot$m^{-3} and 0.9–1.1 mg-atomN$\cdot$m^{-3}).

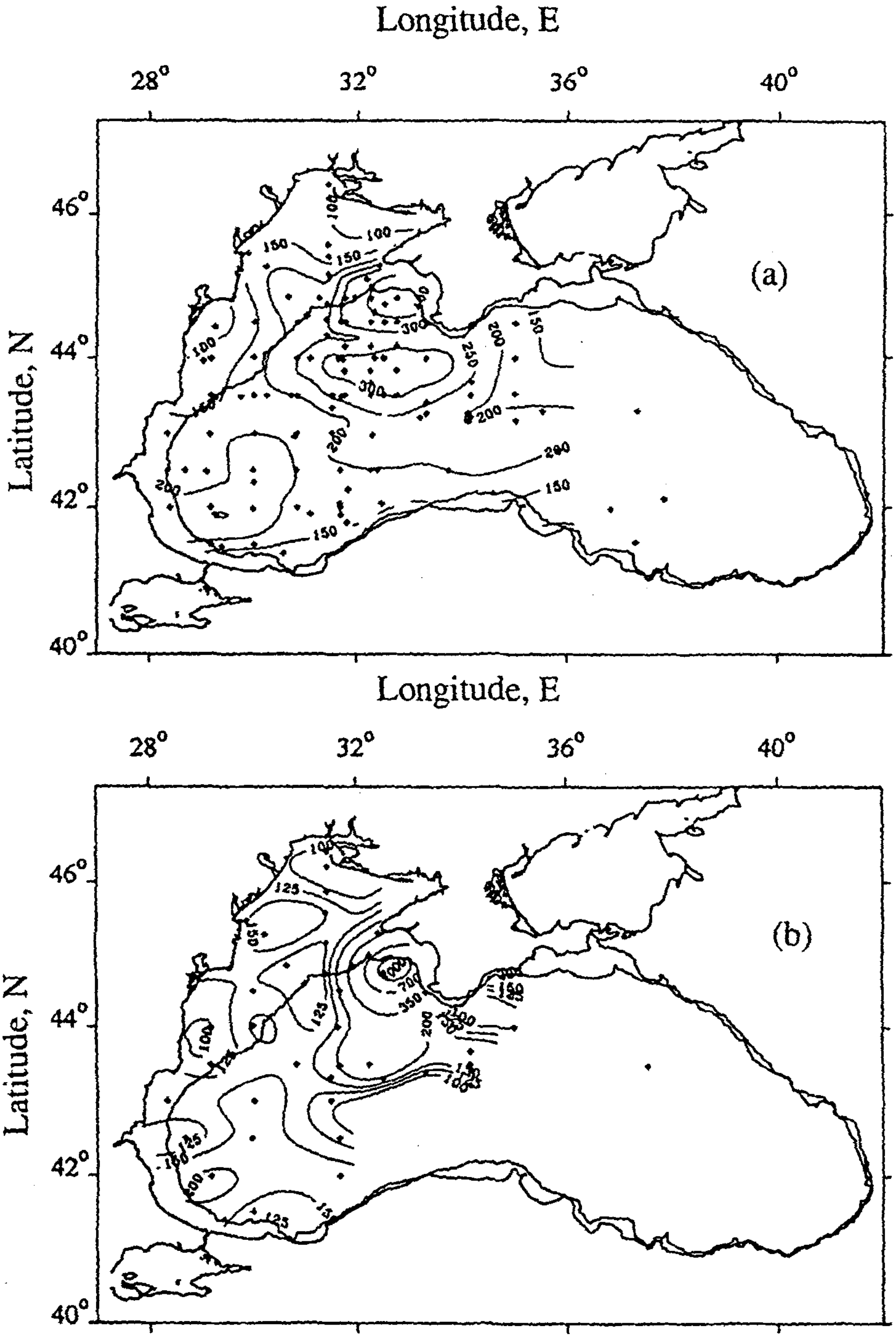


Figure 3. Distributions of the ratio $C_{SOS}/\mathrm{ch}\,a$ in winter: (a) in the surface layer, (b) in the zone of photosynthesis.

It is also of interest to analyze the data on the ratio of the concentration of active chlorophyll a to C_{SOS} characterizing the ratio of the planktonic and detrital fractions ans used to describe the production cycle [15, 16]. The values of $C_{SOS}/\mathrm{ch}\,a$ in the surface layer and in the zone of photosynthesis on the northwest shelf in winter vary from less than 100 to 200, with the exception of the Kalamit Bay where the values of this quantity can be as high as 300–600. The last fact can probably be explained by large amounts of detritus coming from the mussel plantations located in the bay (Figs 3a, b). In the winter period, the ratio $C_{SOS}/\mathrm{ch}\,a$ in the abyssal part of the sea varies within the ranges 200–350 in the surface layer (Fig. 3a) and 100–300 in the zone of photosynthesis (Fig. 3b). The maximum values of $C_{SOS}/\mathrm{ch}\,a$ for this period were observed in an anticyclone located to the south-west of the Crimea. They were equal for the surface layer and the zone of photosynthesis.

By using the concentration of chlorophyll a and the biomass of phytoplankton computed according to the number of cells in the samples of water characterized by visually observed "blooming" of *Rhizosolenia calcar-avis* and *Nitzschia delicatissima* diatoms, we determined the transition coefficient for these parameters equal, on the average, to 50 mgC. The biomass of phytoplankton in the zone of photosynthesis computed according to the data on the concentration of chlorophyll a was equal, on the average, to 55 $\mathrm{mgC \cdot m^{-3}}$ in the central part of the west cyclonic circulation and to 39 $\mathrm{mgC \cdot m^{-3}}$ in the peripheral parts of this zone. The fraction of phytoplankton in C_{SOS} was equal to 39 and 36%, respectively. If we assume that the overall relative amount of carbon of microzoo- and bacterioplankton in the suspended organic carbon is about 6% [5], then we can conclude that, in the winter period, the fraction of detritus in the suspended organic substance is approximately equal to 55–58%.

MARCH

It should be emphasized that, in the present work, the term "March" corresponds to a relatively short transient period between the winter and spring geological seasons characterized by

(i) the beginning of formation of the vertical stability of water,

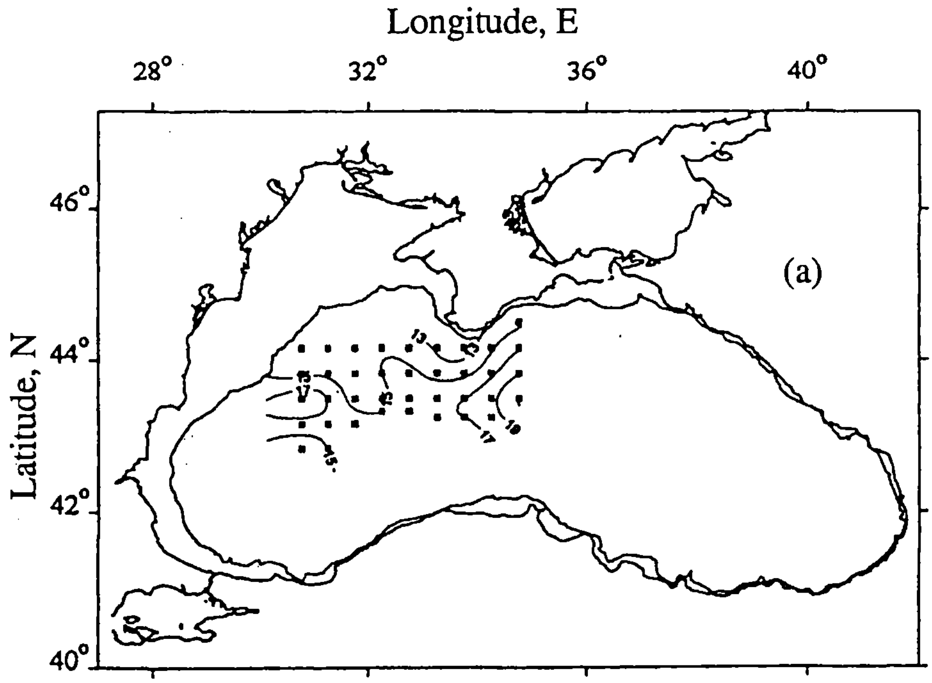
(ii) elevated amounts of biogenic elements coming from the upper layers of the main pycnocline in the process of winter convective mixing, and

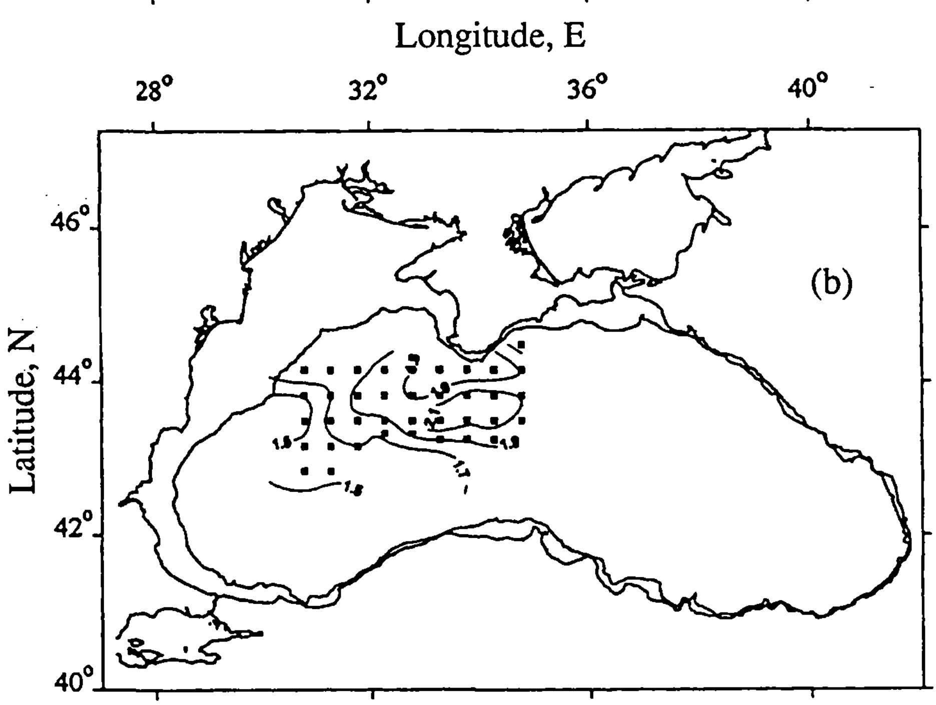
(iii) a significant increase in illumination as compared with the winter season.

This period, as a rule, coincides with the calendar March but may differ from it depending on the actual weather conditions.

It is characterized by the presence of a thick layer (from the surface down to a depth of 40 m) of high concentrations C_{SOS} (15–20mg-atom$\cdot \mathrm{m^{-3}}$) and N_{SOS} (1.9–

2.7 mg-atom·m^{-3}) in the central part of cyclonic circulations (Figs 4a, b, c, d), which completely corresponds to the layer occupied by "blooming" phytoplankton [17].





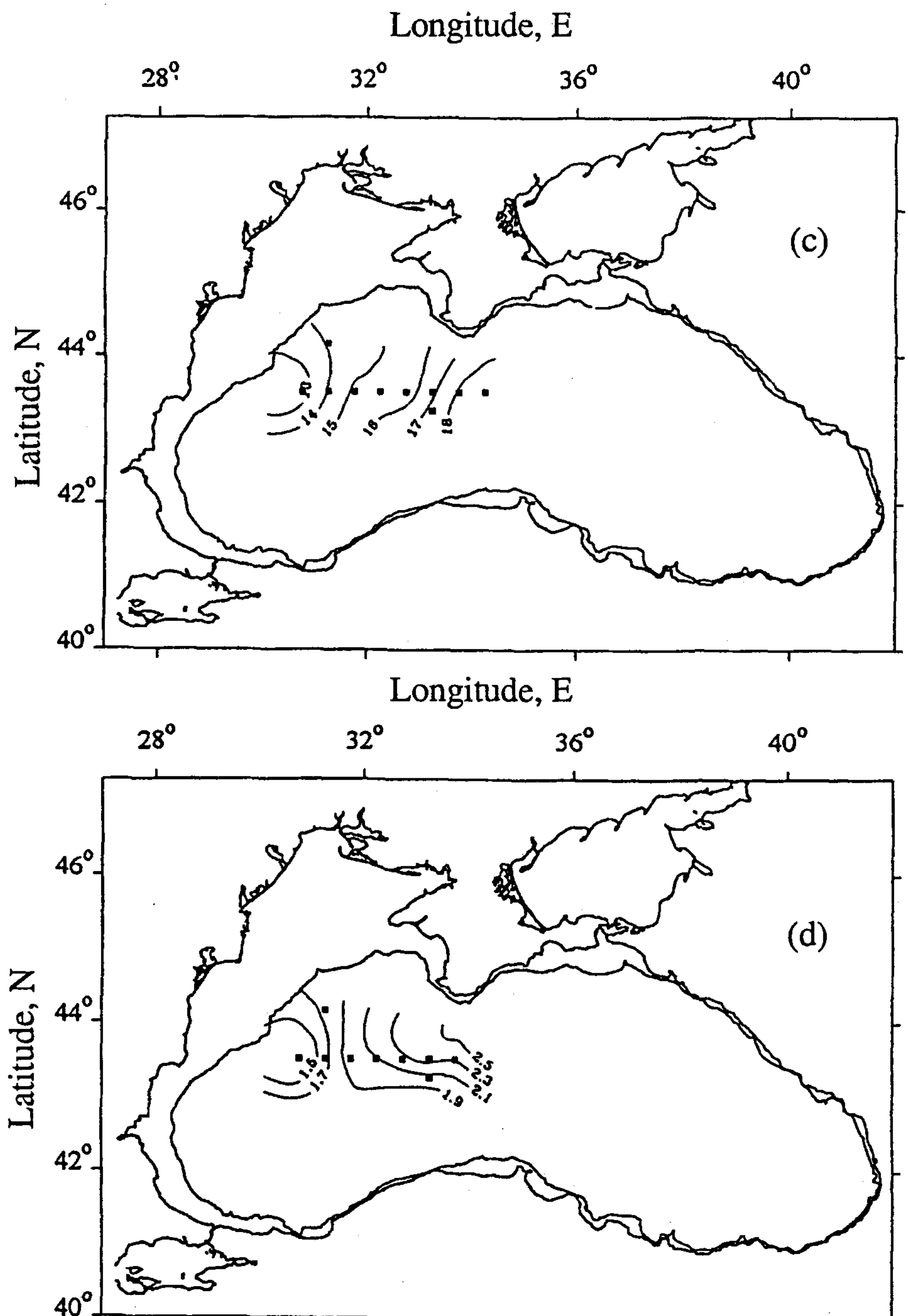


Figure 4. Distributions of the concentrations of suspended organic substances (mg-atom·m^{-3}) in the surface layer [(a) C_{SOS}, (b) N_{SOS}) and their weighted-mean values in the zone of photosynthesis [(c) C_{SOS}, (d) N_{SOS}] in March.

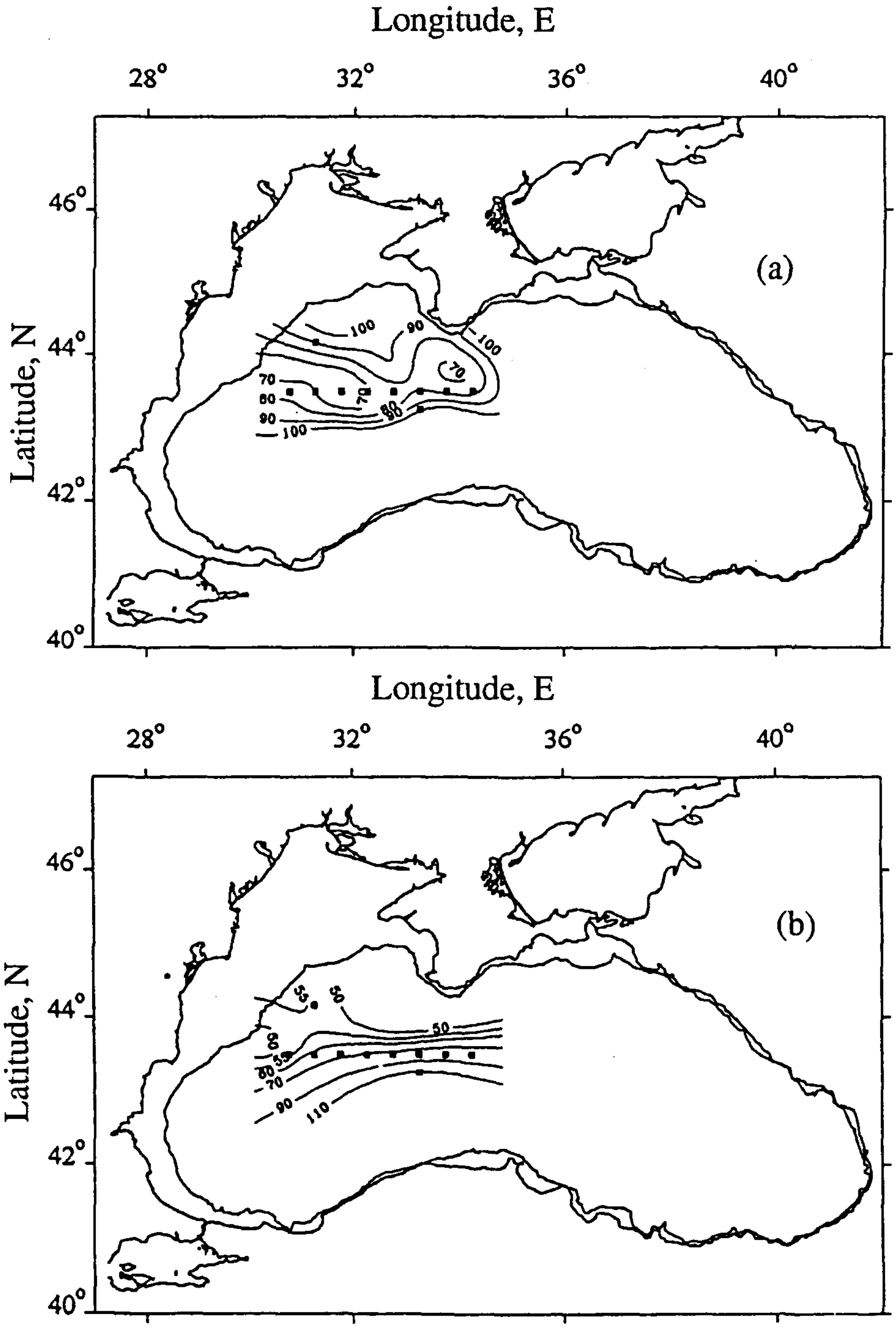


Figure 5. Distributions of the ratio $C_{SOS}/ch\,a$ in March: (a) surface layer, (b) zone of photosynthesis.

Note that, in March 1988, the weighted-mean concentrations C_{SOS} and N_{SOS} in the zone of photosynthesis were 1.5 times higher than in January. By comparing these facts with the literature data [5], we conclude that the values of C_{SOS} obtained in the present work are typical of the region under consideration in the early spring period.

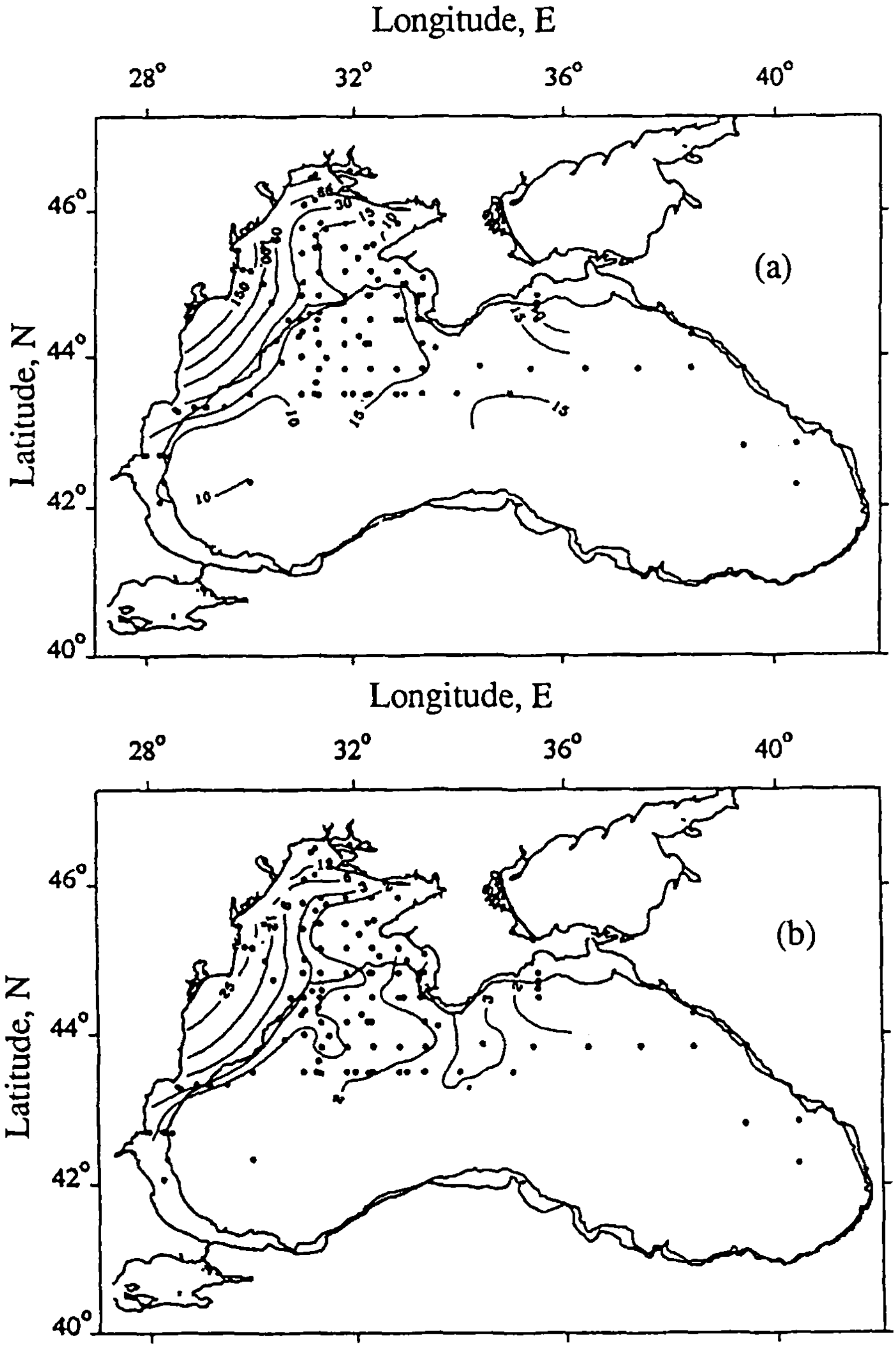
The ratios $C_{SOS}/\mathrm{ch}\,a$ in the surface layer and in the zone of photosynthesis are practically equal because the zone of photosynthesis coincides with the upper mixed layer and the indicated ratios vary within the range 50–110 (see Figs 5a, b). Low values of $C_{SOS}/\mathrm{ch}\,a$ (50–80) mean that the suspended organic substance is, in this case, formed by a physiologically active phytoplankton community. According to the data obtained by Sukhanova, the process of "blooming" of phytoplankton was explained by the intense development of *Nitzschia delicatissima* and *Rhizosolenia calcar-avis* and the qualitative structure of phytocenosis was stable for a period of three weeks [17]. The biomass of phytoplankton computed according to the data on the concentration of chlorophyll a ($\mathrm{chl}\,a \times 50$) and averaged over the investigated water area was 133.4 mgC m^{-3} and its fraction in C_{SOS} was 67%. According to [5], the total fraction of carbon of microzoo- and bacterioplankton in C_{SOS} in March was equal to 7%. Thus, 74% of suspended organic substances were concentrated in the form of plankton and the predominant role in its formation was played by phytoplankton. This relationship between living and dead substances is typical of highly productive regions of the World Ocean [15].

SPRING

Shelf. In the spring period, we observe an increase in the concentrations C_{SOS} and N_{SOS} in the surface layer as compared with winter in the entire shelf zone in the northwest and west parts of the sea up to Cape Kaliakra (Figs 6a, b). The maximum concentrations of both components of the suspension (100–180 mg-atomC·m^{-3} and 15–25 mg-atomN·m^{-3}) were observed in the near-estuary regions and their absolute values are higher than in the winter period almost by an order of magnitude. The central, northeast, and south parts of the shelf (with the exception of the coastal zone near the west part of the Crimea) are less productive (< 15 mg-atomC·m^{-3} and < 2.0 mg-atomN·m^{-3}). However, in these regions, the concentrations C_{SOS} and N_{SOS} are also 1.5–2 times higher than in the winter period.

In the west half of the northwest shelf subjected to the influence of rivers, the concentration C_{SOS} in the zone of photosynthesis (Figs 6c, d) increases to 40–120 mg-atom·m^{-3} and N_{SOS} increases to 5–15 mg-atom·m^{-3}. The east half of the northwest shelf is characterized by lower C_{SOS} and N_{SOS} (10–12 mg-atomC·m^{-3} and < 1.6 mg-atomN·m^{-3}).

In the surface layer, the values of $C_{SOS}/\mathrm{ch}\,a$ vary within the ranges 100–400 and 400–600 for the west and east halves of the shelf, respectively. For the zone of photosynthesis in the west half of the shelf, the ratio $C_{SOS}/\mathrm{ch}\,a$ does not exceed 300. In the east half, it varies from 200 to 400. The indicated difference between the values of $C_{SOS}/\mathrm{ch}\,a$ in the northwest shelf zone is explained by specific features of the development of phytoplankton determined, for the most part, by the inhomogeneity of heating of water and different degrees of availability of biogenic elements.



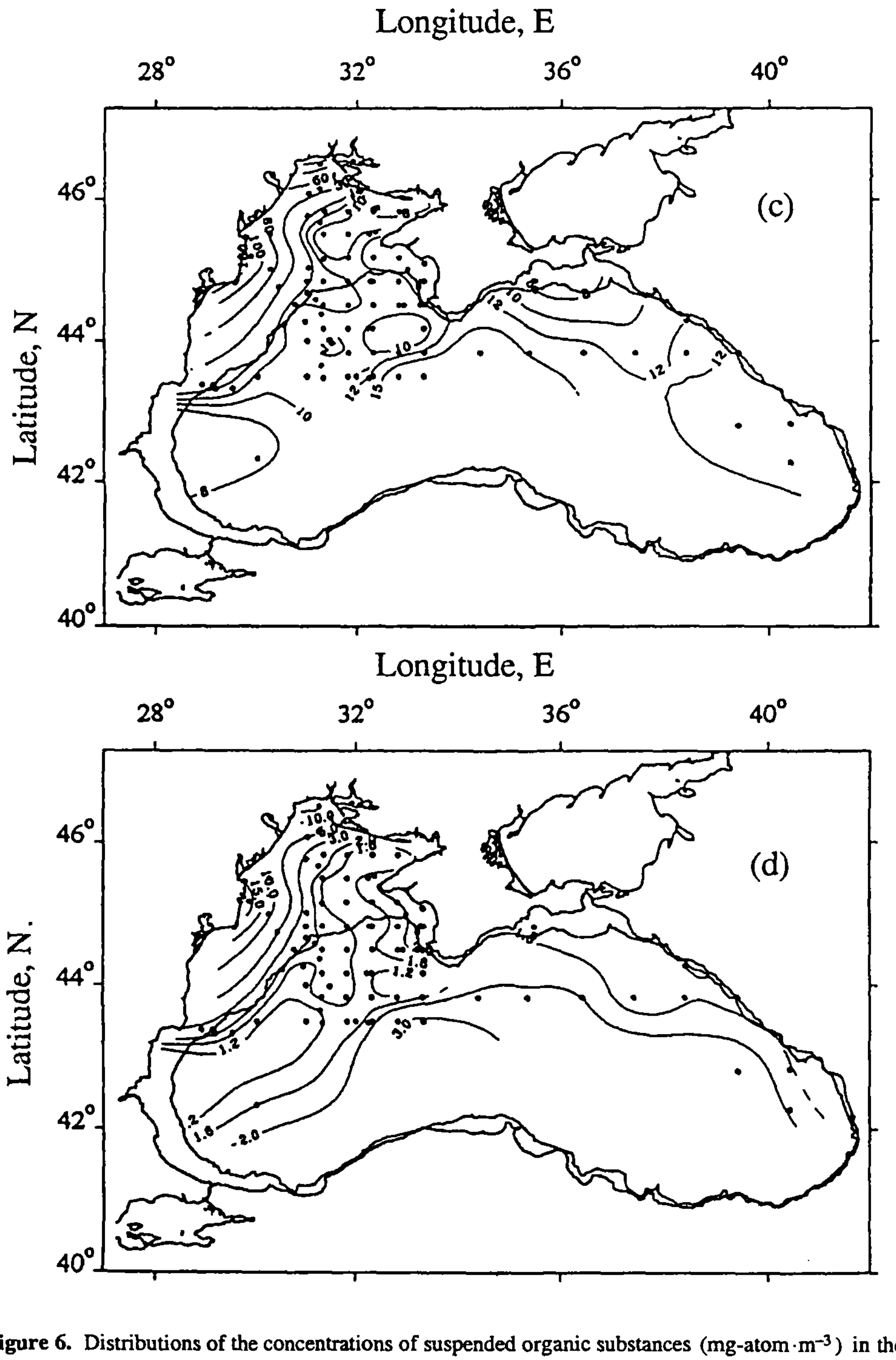


Figure 6. Distributions of the concentrations of suspended organic substances (mg-atom·m^{-3}) in the surface layer [(a) C_{SOS}, (b) N_{SOS}) and their weighted-mean values in the zone of photosynthesis [(c) C_{SOS}, (d) N_{SOS}] in the spring period.

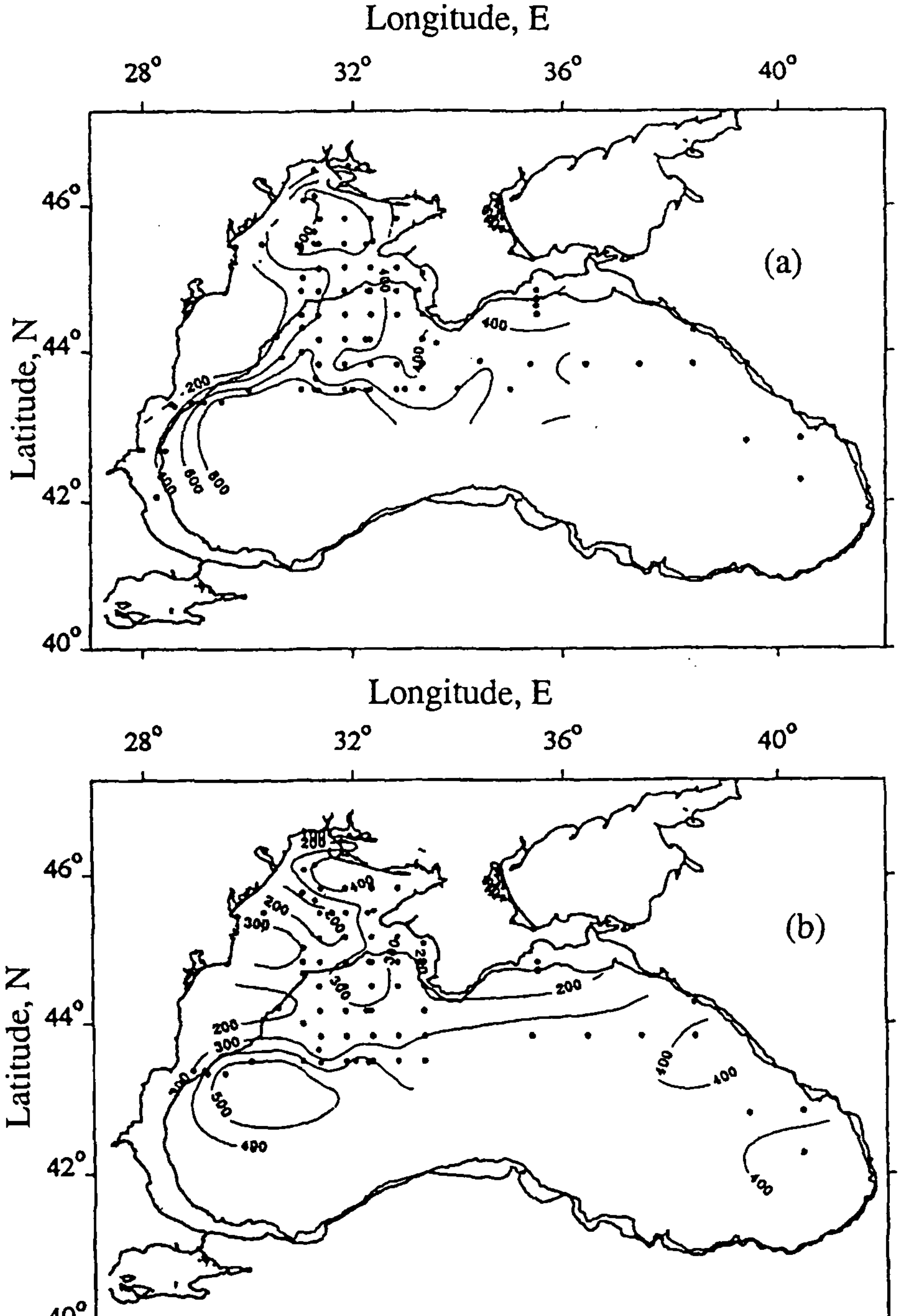


Figure 7. Distributions of the ratio Csos/ch*a* in the spring period: (a) surface layer, (b) zone of photosynthesis.

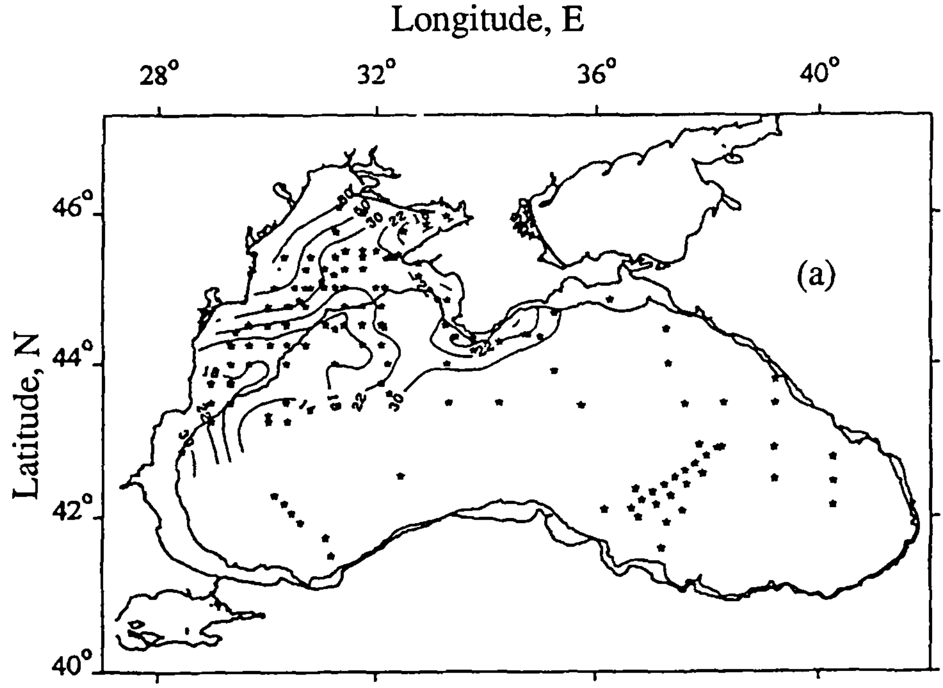
The weighted-mean concentration of chlorophyll a in the zone of photosynthesis playing the role of the most general characteristic of the biomass of phytoplankton varies from 0.7 $mg \cdot m^{-3}$ in the central part of the west half of the northwest region of the sea to 35.0 $mg \cdot m^{-3}$ in the near-estuary regions. In the northwest part of the sea not subjected to the influence of the discharge of rivers, the concentration of chlorophyll a varies within the range 0.27–0.70 $mg \cdot m^{-3}$. For very high concentrations of suspended organic substances in the near-estuary regions, the relative content of chlorophyll a varies within the range 1.2–1.6% and the biomass of phytoplankton computed according to the content of chlorophyll a is responsible for the 46% of the weighted-mean concentration of organic carbon. As the distance from the estuaries of rivers increases, the concentration of chlorophyll a and its relative content in the suspended organic substance abruptly decrease. Thus, the relative contents of ch a in C_{SOS} are equal to 0.42 and 0.2% for the west and east halves of the northwest part of the sea, respectively.

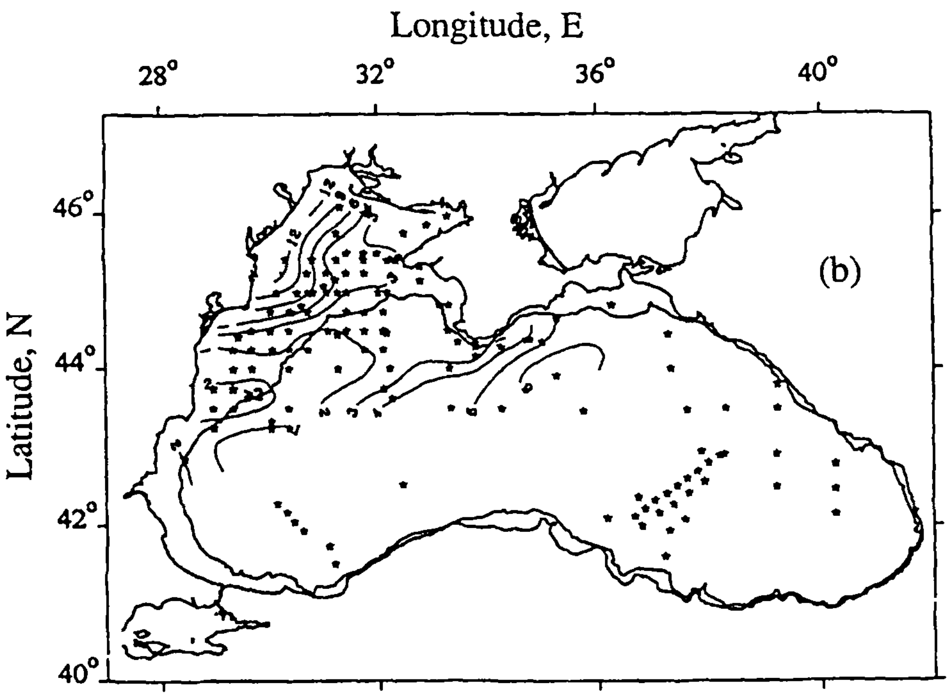
Abyssal part of the sea. In the abyssal part of the sea, in spring (April–May), the concentrations of suspended organic substances in the surface layer and their weighted-mean concentrations in the zone of photosynthesis remain practically the same as in the early spring period of "blooming" phytoplankton (Figs 6a, b, c, d). However, in this case, we observe an abrupt (more than fivefold) decrease in the weighted-mean concentration of chlorophyll a. As a result, the ratio $C_{SOS}/\text{ch}\,a$ significantly increases in April–May, especially in the surface layer (Figs 7a, b). The biomass of phytoplankton computed according to the data on the concentration of chlorophyll a (ch $a \times 40$ [18]) and averaged over the investigated abyssal part of the sea is equal to 21.2 mg-atom $C \cdot m^{-3}$ for the zone of photosynthesis, i.e., 14% of the average concentration of C_{SOS}. This means that the living fraction of suspended organic substances formed in the course of early spring "blooming" rapidly transforms in this period into detritus and the formation of density stratification does not allow the suspension to leave the zone of photosynthesis. Note that this period is also characterized by a decrease in the biomass as a result of dying of diatomic plankton accompanied by an increase in the amount of phytoplankton caused by the growth of picoplankton and of small flagellates, i.e., we observe the transition to the summer form of succession with significant amounts of heterotrophic forms [19].

SUMMER

Shelf. The general picture of the distribution of suspended organic substances in the surface layer for the northwest part of the sea in the summer period does not undergo serious changes as compared with spring (Figs 8a, b). One must only mention some details characterizing the changes in the spatial distributions of C_{SOS} and N_{SOS} in summer as compared with spring. Thus, these concentrations are high in the entire northwest part of the sea because west winds predominant in the summer period promote the distribution of freshened surface waters over large areas in the northwest shelf zone (including its central part). As in spring, the zones of maximum values of

C_{SOS} and N_{SOS} are regularly located in the near-estuary regions but these values become about half as large (40–80 mg-atom C · m^{-3} and 8–10 mg-atom N · m^{-3}).





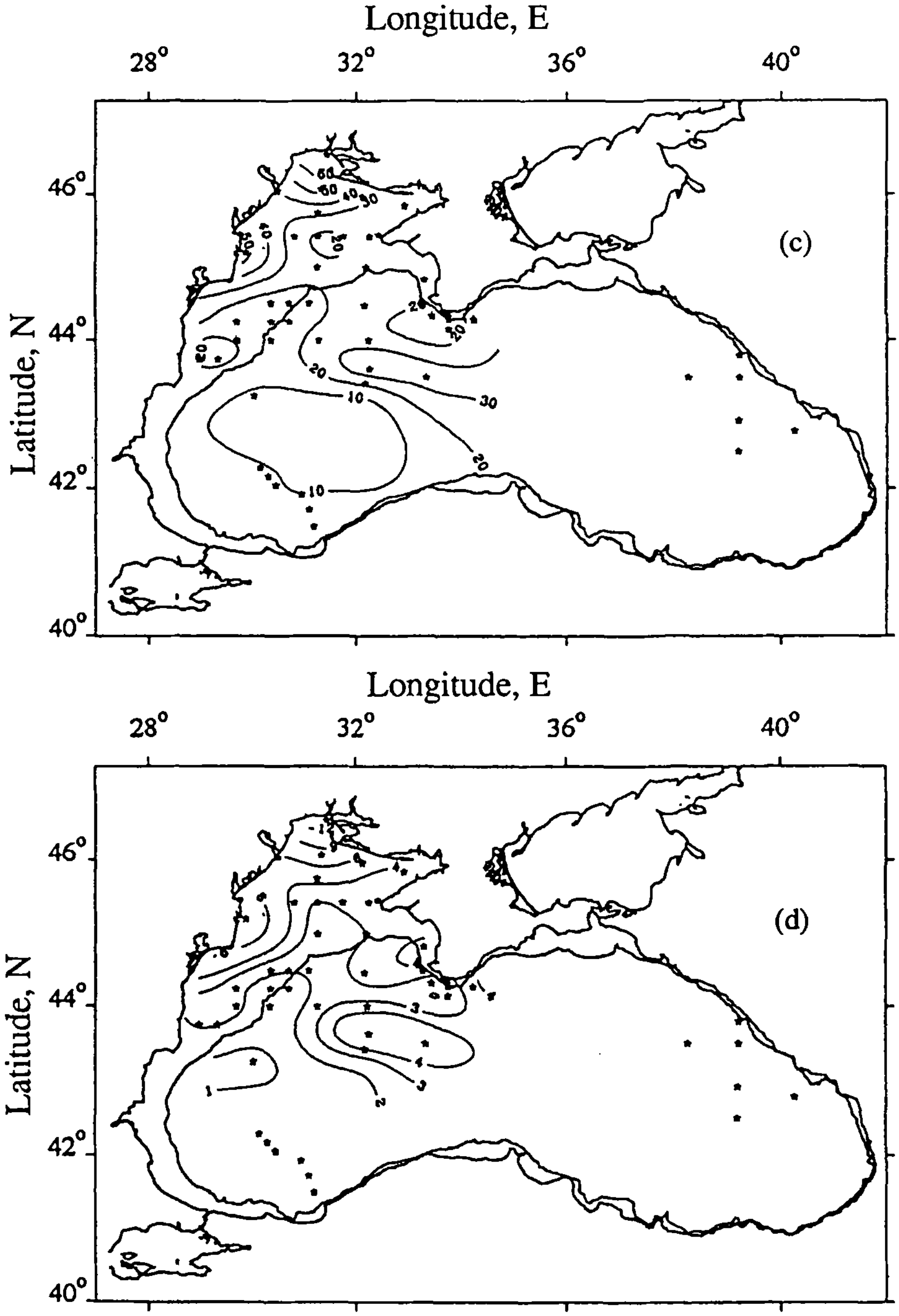


Figure 8. Distributions of the concentrations of suspended organic substances (mg-atom·m^{-3}) in the surface layer [(a) C_{SOS}, (b) N_{SOS}) and their weighted-mean values in the zone of photosynthesis [(c) C_{SOS}, (d) N_{SOS}] in the summer period.

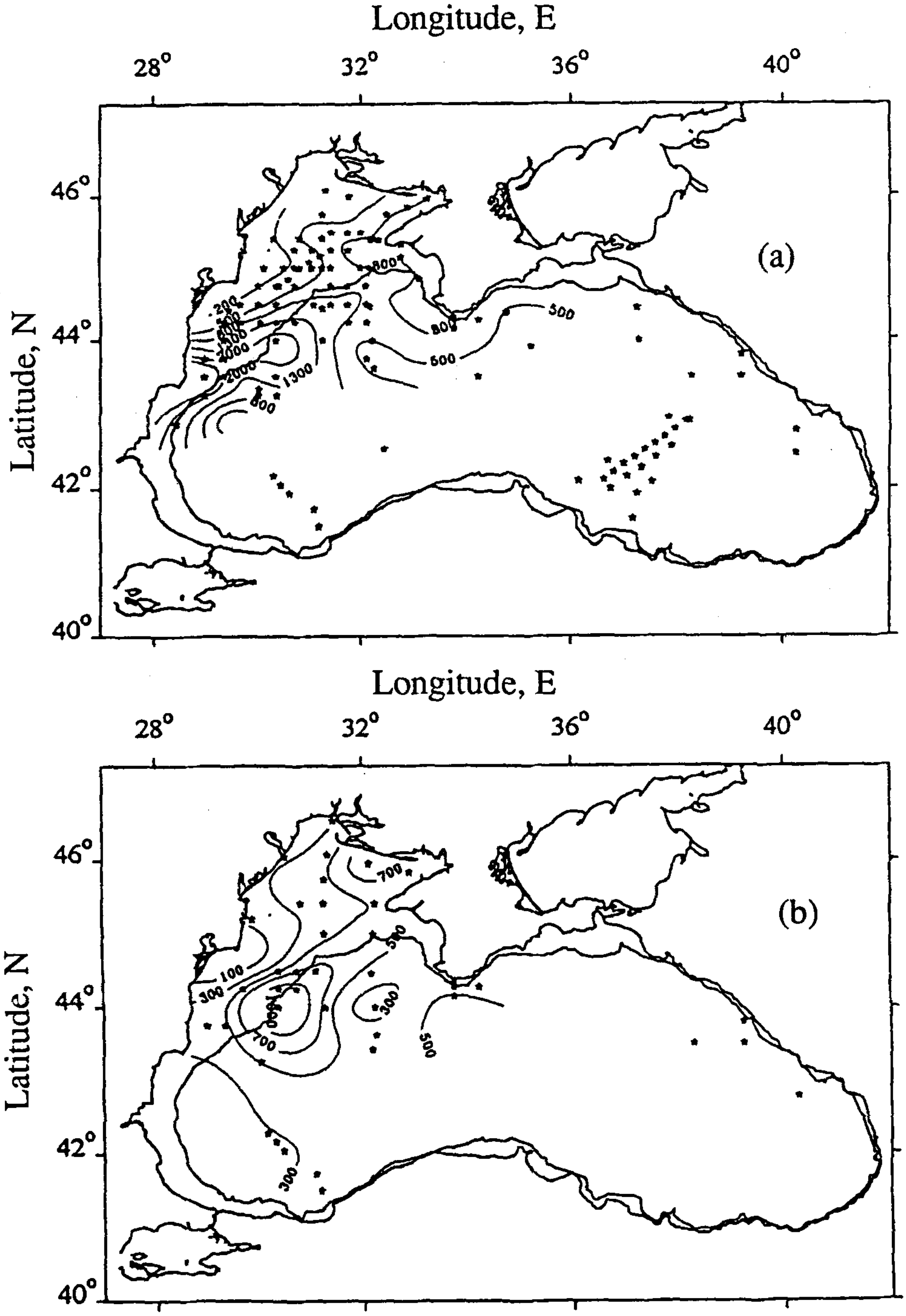


Figure 9. Distributions of the ratio Csos/ch *a* in the summer period: (a) surface layer, (b) zone of photosynthesis.

The impact of the discharge of the Danube on the distribution of suspended organic substances in 1985–1994 was bounded by 44°N. To the south of this latitude, in the west shelf zone and in the region of continental slope, we observed much lower concentrations C_{SOS} and N_{SOS} (< 18 mg-atom$\,C \cdot m^{-3}$ and < 2mg-atom$\,N \cdot m^{-3}$). The local increase in C_{SOS} observed in the west shelf zone near Cape Kaliakra is most probably explained by the transportation of biogenic elements from the coast of Bulgaria.

The amount and distribution of suspended organic substances in the zone of photosynthesis in the summer period (Figs 8c, d) are characterized (on the average) by a threefold decrease in the concentrations C_{SOS} and N_{SOS} in the near-estuary regions and their twofold increase in the central part and near the west coast of the Crimea. In this case, the maximum values of the investigated parameters are always detected in the shelf zones where the impacts of the Dnieper and Danube are especially pronounced. However, the zone of this influence in summer is 2–3 times smaller than in spring. In this case, as in the spring period, the ratios $C_{SOS}/\mathrm{ch}\,a$ do not exceed 300 both in the surface layer and in zone of photosynthesis (Figs 9a, b). In the remaining part of the northwest region of the sea, we observe a significant increase in the ratio $C_{SOS}/\mathrm{ch}\,a$ (400–800). Its maximum values are attained near the west coast of the Crimea and in the Karkinit Bay. This is explained by the fact that the detrital fraction of suspended organic substances increases and their planktonic fraction decreases. The relative amount of chlorophyll a in C_{SOS} in the near-estuary regions is 0.4%, whereas the mean value of this parameter for the west half of the northwest part of the sea is 0.31%. For the east half of the northwest region of the sea, the relative amount of chlorophyll a in suspended organic carbon varies from 0.12–0.17% near the west coast of the Crimea to 0.23% in its central part.

In agreement with the oscillations of the amount of chlorophyll a, the calculated values of the biomass of phytoplankton ($\mathrm{ch}\,a \times 50$ [20]) for the zone of photosynthesis varied from 168.0 to 44.5 mg$\,C \cdot m^{-3}$ in the region subjected to the influence of rivers. This is equal to 22% of the mean value of C_{SOS} in the near-estuary regions and decreases to 14.5% as we move to the center of the northwest part of the sea. In the east half of the northwest part of the sea, the biomass of phytoplankton varied from 14.5 to 27.4 mg$\,C \cdot m^{-3}$ with the average value equal to 20.5 mg$\,C \cdot m^{-3}$, which constitutes 9% of the average amount of suspended carbon. Since phytoplankton, as a rule, makes the major contribution to the mass of the planktonic fraction of suspended carbon, we can conclude that, in summer, detritus forms about 65–70% of suspended organic substances in the region affected by rivers and about 85–90% of their amount in the east half of the investigated zone.

Abyssal part of the sea. In the abyssal part of the sea, the concentration of suspended organic substances in the surface layer in summer increases as compared with the spring period. High values of C_{SOS} (20 mg-atom$\,C \cdot m^{-3}$) and N_{SOS} (more than 10 mg-atom$\,N \cdot m^{-3}$) are observed near the continental slope of the southeast coast of the Crimea (Figs 8a, b). In the zone of photosynthesis (Figs 8c, d), the range of the concentrations C_{SOS} and N_{SOS} in the west half of the sea is preserved but, in the central part of the sea, these parameters of the organic suspension are somewhat elevated. The appearance of regions of elevated concentrations of suspended organic substances near the Caucasian coast is, most likely, not systematic and can be explained by the influence of the discharge of coastal waters.

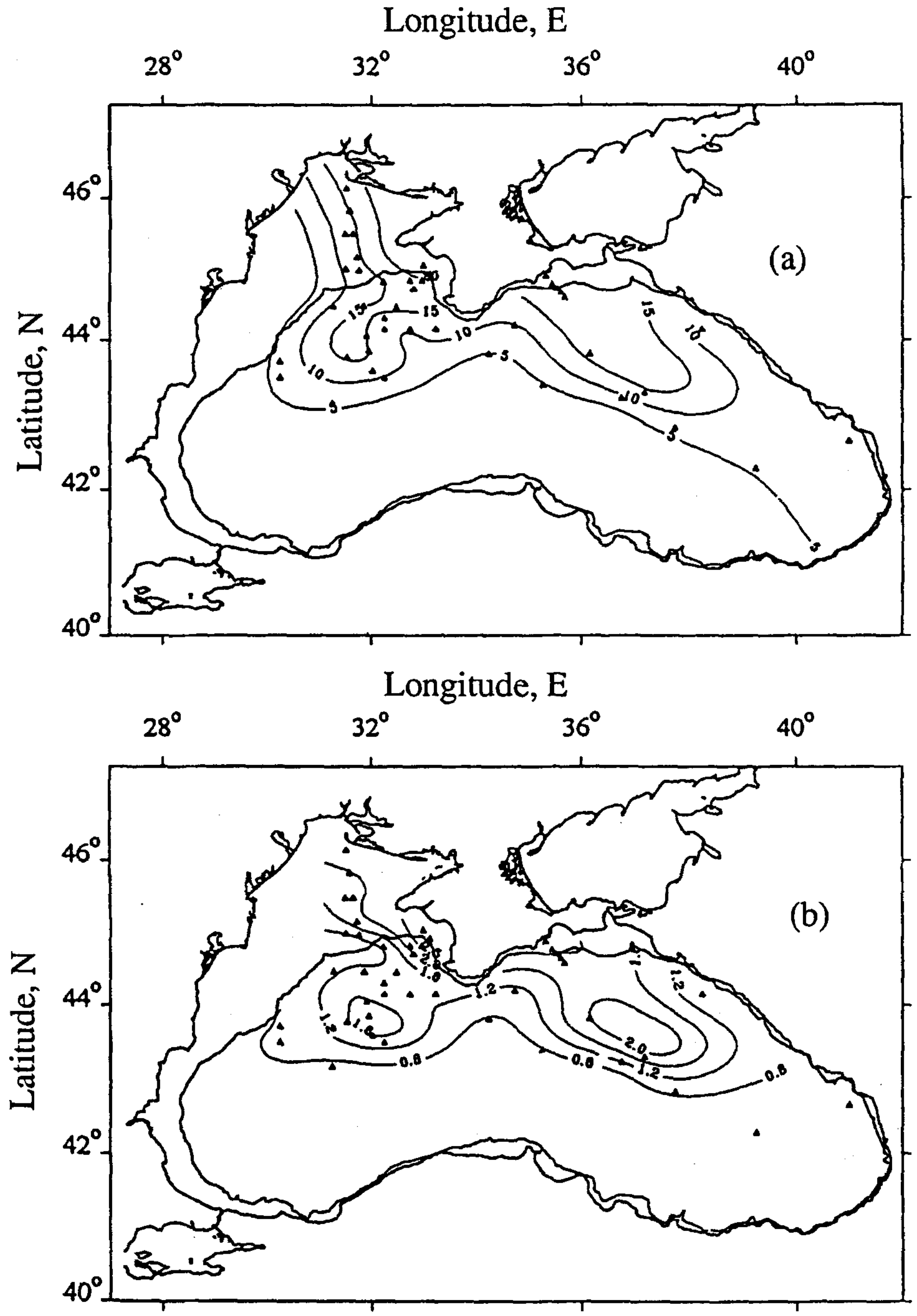
The values of the ratio $C_{SOS}/\mathrm{ch}\,a$ (Figs 9a, b) vary from 400 to 2000 in the surface layer and from 300 to 1000 in the zone of photosynthesis. The minimum values of this ratio in the summer period (300–500) were detected in the entire west part of the sea. The maximum values were observed in the anticyclonic vortex located in the west part of the northwest continental slope. Very high values of the ratio $C_{SOS}/\mathrm{ch}\,a$, the fact that the fraction of chlorophyll a in the suspended organic carbon is quite small (0.18%) and, hence, small amounts of the biomass of phytoplankton ($8\,\mathrm{mgC \cdot m^{-3}}$, i.e., only 9% of the average amount of C_{SOS}) indicate that, in the region of drop of depths, the suspended organic substance is represented by detritus.

The relative content of chlorophyll a in C_{SOS} in the western halistase varies insignificantly and is equal, on the average, to 0.33%. The calculated biomass of phytoplankton is equal to $37\,\mathrm{mgC \cdot m^{-3}}$, i.e., 33% of the mean amount of suspended carbon. Since the total amount of heterotrophic plankton in the euphotic zone in the summer period is approximately equal to 10% of C_{SOS} [5], we conclude that detritus constitutes about 60% of suspended organic substances in the investigated zone of the abyssal part of the sea. The rigid seasonal pycnocline forms a kind of "liquid" bottom guaranteeing the accumulation of suspended organic substances in the euphotic zone. The same pycnocline blocks the delivery of inorganic forms of biogenic elements from the lower layers of water. The formation of salts of nitrogen and phosphorus in the zone of photosynthesis occurs mainly in the processes of their regeneration inside the community. For the zone of photosynthesis, the fraction of newly-formed substances in this period constitutes, on the average, 30–35% [21].

AUTUMN

For the autumn period, the data on the amount and distribution of suspended organic substances are poor. It is customary to believe that, in autumn, the main physical factor determining the amount and distribution of organic substances is a decrease in vertical stability of waters.

Shelf. In the shelf zone, both in the surface layer and in zone of photosynthesis, we observe a decrease in the amount of suspended organic substance as compared to the summer period (Fig. 10). The values of C_{SOS} and N_{SOS} in autumn are 1.5–2 times lower than in summer in the central zone of the northwest part of the sea and more than three times lower than in summer in the zone of influence of the Dnieper. The concentrations of suspended organic substances varied from 10.0 to 25.0 mg-atom$\mathrm{C \cdot m^{-3}}$ and from 1.2 to 2.4 mg-atom$\mathrm{N \cdot m^{-3}}$ in the surface layer and within the ranges 12–20 mg-atom$\mathrm{C \cdot m^{-3}}$ and 1.3–2.5 mg-atom$\mathrm{N\,m^{-3}}$ in the zone of photosynthesis. In the surface layer, the ratio $C_{SOS}/\mathrm{ch}\,a$ (Figs 11a, b) in the section drawn from the Dnieper to the drop of depths is 3–4 times smaller than in summer. The values of the ratio $C_{SOS}/\mathrm{ch}\,a$ averaged over the zone of photosynthesis did not exceed 350 (see Fig. 11b). The concentration of chlorophyll *a* in this section varied from 0.74 to 0.40 mg·m^{-3}.



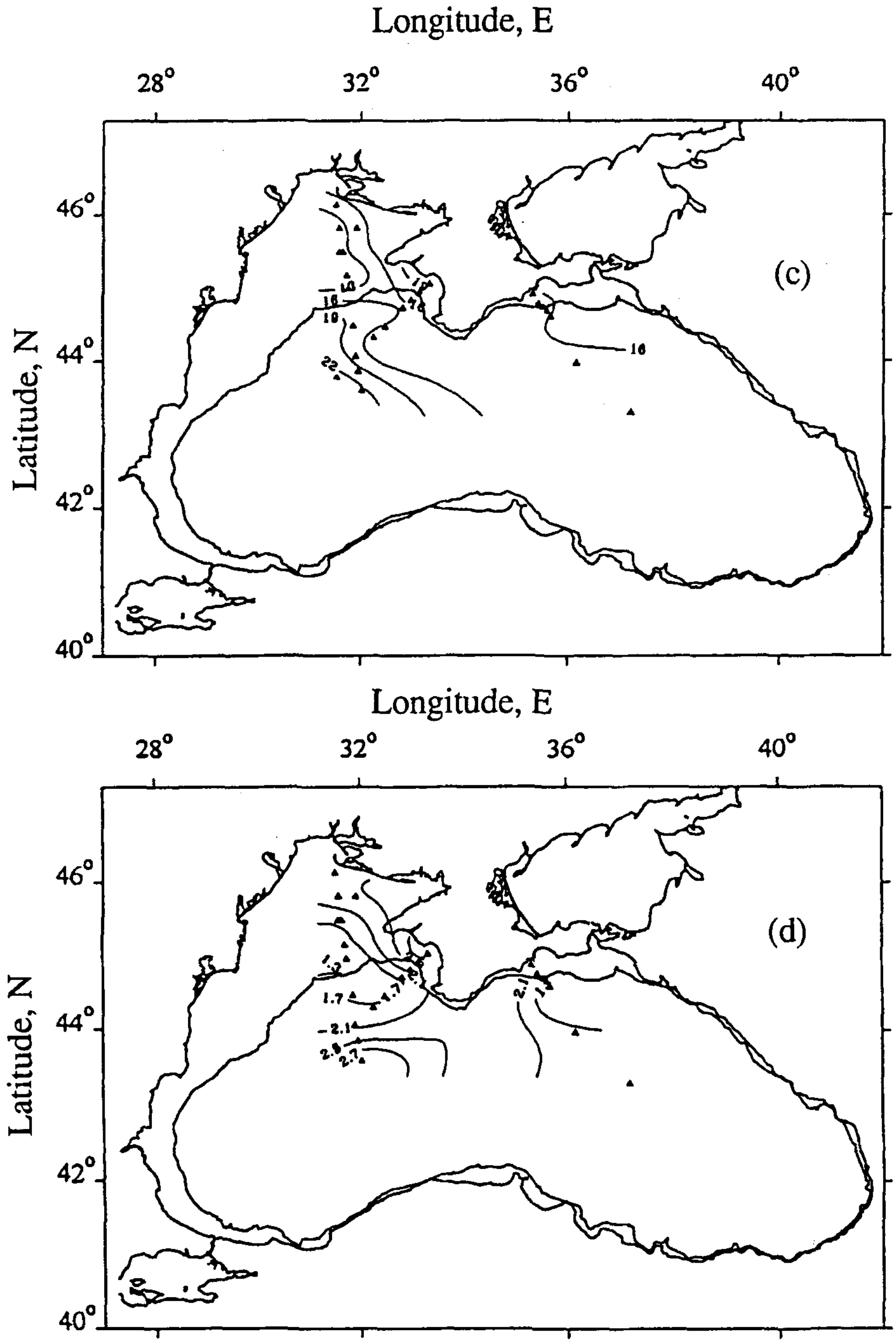


Figure 10. Distributions of the concentrations of suspended organic substances (mg-atom·m^{-3}) in the surface layer [(a) C_{SOS}, (b) N_{SOS}) and their weighted-mean values in the zone of photosynthesis [(c) C_{SOS}, (d) N_{SOS}] in the autumn period.

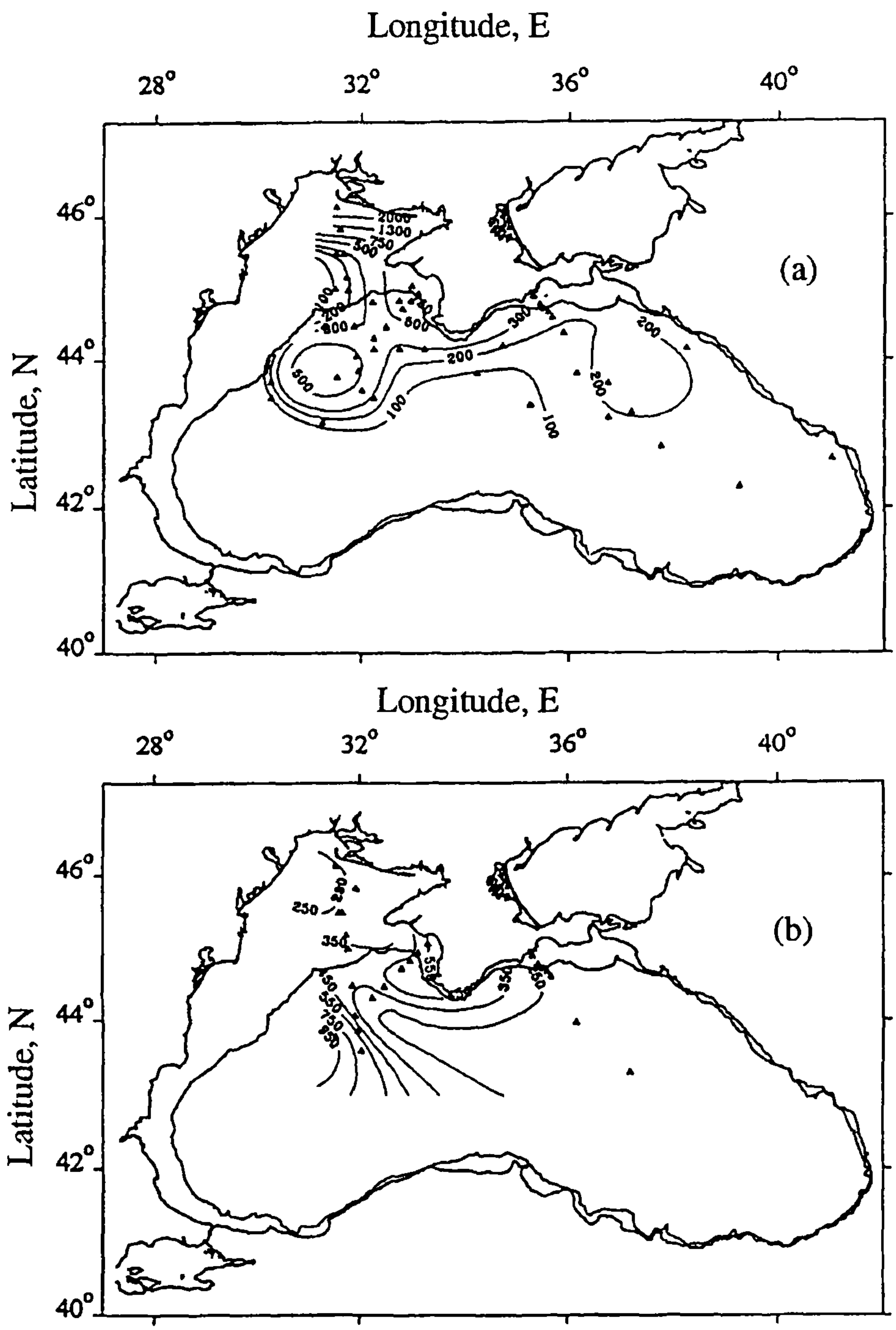


Figure 11. Distributions of the ratio Csos/ch*a* in the autumn period: (a) surface layer, (b) zone of photosynthesis.

In the same region, the concentrations of chlorophyll *a* of the same order were observed in November 1983 [22]. The values of the biomass of phytoplankton calculated according to the oscillations of the concentration of chlorophyll *a* varied from 37.0 to 20.0 $mgC \cdot m^{-3}$ with the mean value equal to 29.0 $mgC \cdot m^{-3}$, i.e., 17.5% of the average amount of suspended carbon. Thus, from summer to autumn, the fraction of phytoplankton in suspended organic substances is almost doubled, which can be caused both by the seasonal succession of the phytoplankton community—pyrophyte species are again followed by diatoms—and the intensification of the delivery of inorganic forms of biogenic elements caused by the intensification of exchange processes in the course of destruction of the seasonal pycnocline.

<u>Abyssal part of the sea.</u> In the surface layer of the abyssal part of the sea, the concentrations C_{SOS} and N_{SOS} are noticeably lower than in summer. The values of C_{SOS} and N_{SOS} vary within the ranges 5.0–15.0 mg-atom$\cdot m^{-3}$ and 0.8–2.0 mg-atom$\cdot m^{-3}$, respectively. The weighted-mean concentration of organic substances decreases also in the zone of photosynthesis (Figs 10c, d). It is worth noting that the concentrations C_{SOS} measured by the authors in the west part of the abyssal region of the sea coincide with the data obtained in this region in October 1965 and October 1978 [1, 2].

The ratio $C_{SOS}/\mathrm{ch}\,a$ in the abyssal part of the sea in autumn decreases as compared with summer. In the surface layer, this ratio varied from 100 to 300 in the major part of the water area and higher values were, as a rule, observed in the anticyclonic vortex located on the traverse of Cape Kaliakra (500–750) (Fig. 11a). For the zone of photosynthesis, the values of this ratio were somewhat higher and varied from 250 to 750. In the region of the anticyclonic vortex formation, this ratio may be as large as 950 (Fig. 11b).

The weighted-mean concentrations of chlorophyll *a* in the zone of photosynthesis varied from 0.40 to 0.80 $mg \cdot m^{-3}$ and, in the anticyclonic vortex, from 0.19 to 0.24 $mg \cdot m^{-3}$. The mean concentration of chlorophyll *a* in this region was as large as 0.5 $mg \cdot m^{-3}$. The biomass of phytoplankton computed for this mean concentration is equal to 29.5 $mgC \cdot m^{-3}$, i.e, 14.5% of the mean value of C_{SOS}. Thus, the relative content of detritus in the total mass of suspended organic substances decreases from about 90% in summer to about 80% in autumn.

VERTICAL DISTRIBUTIONS OF SUSPENDED ORGANIC SUBSTANCES

Vertical distributions of suspended organic substances in the abyssal part of the Black Sea were described in [2, 5, 23, and 24]. However, the results used in these works were not systematic. We performed regular investigations of the distributions of suspended organic substances in the active layer of the sea for the last seven years. This enables us to give a more accurate quantitative picture of the vertical distributions of suspended organic substances in the shelf zone and in the abyssal part of the sea taking into account the influence of various biotic and abiotic factors.

Table 1.
Weighted-mean concentrations of suspended organic substances in the northwest shelf zone

Region	Season (region)	Layer (m)	Mean concentration in the layer (mg-atom·m^{-3}) C_{SOS}	N_{SOS}	C_{SOS} max. (mg-atom ·m^{-3})	N_{SOS} max. (mg-atom ·m^{-3})	C_{SOS}/ch*a* max.	Depth of the maximum (m)
Near-estuary regions	Winter	20	9.90	1.03	10.6	1.00	116	0–10
	Spring	20	50.7	7.80	146.8	21.74	104	0
	Summer	35	34.4	4.50	63.32	8.90	240	5
	Autumn	20	14.7	1.80	15.7	2.34	290	0–10
North-west part of the sea not affected by rivers	Winter	40	8.54	0.70	—	—	160	—
	Spring (north)	30	8.75	1.37	—	—	270	0
	Spring (center)	50	8.06	1.16	9.79	1.45	152	0–35
	Spring (south)	50	9.46	0.99	22.49	3.03	817	0
					15.86	1.76	390	20
	Spring (Kalamit Bay)	50	8.52	1.75	14.90	2.46	226	0
	Summer	50	18.2	2.46	17.5	2.48	724	0
					29.9	3.55	340	20
	Autumn	50	9.60	1.28	16.45	2.44	340	0

NORTHWEST SHELF

As one of the principal specific features of the hydrodynamics of waters in the northwest part of the sea, one can mention the influence of significant river discharges. Thus, there are regions in which the delivery of fresh river waters determines the formation of vertical inhomogeneities in the field of density for the whole year. The averaged data on the concentrations C_{SOS} and N_{SOS} for a water column with the indication of the depths of maximum concentrations are presented in Table 1.

In the regions subjected to the direct influence of rivers, in all seasons, we observe a single surface maximum of all components of the organic suspension connected with the jump of density. The quantitative characteristics of this maximum (depth, half width, and maximum concentrations) depend on the level of development of phytoplankton and the amount of allochthonous detritus delivered by river waters. As a rule, the maximum of suspended organic substances coincides with the maximum of chlorophyll *a*. A decrease in the concentration of suspended organic substances with depth occurs against the background of variations of the ratio of the fractions of plankton and detritus.

In winter, in the near-estuary regions, the distribution of organic suspension is practically uniform down to the pycnocline with an insignificant maximum in the 0–10-m layer. In the investigated 20-m-thick layer, the ratio $C_{SOS}/\mathrm{ch}\,a$ does not exceed 130.

In spring, in this region of the shelf zone, stratification becomes more pronounced as a result of heating of waters. This significantly inhibits the process of mixing of surface waters (freshened and enriched with biogenic elements) with bottom waters. As a result, the vertical distribution of suspended organic substances is characterized by the presence of a sharp maximum on the surface. In this case, the values of C_{SOS} and N_{SOS} at a depth of 10 m are five times lower than the maximum value and, at a depth of 20 m, they are lower by an order of magnitude. The ratio $C_{SOS}/\mathrm{ch}\,a$ in the upper 5-m layer does not exceed 150. At a depth of 10 m, it is higher than 300 and, at a depth of 20 m, higher than 2000.

In summer, in the near-estuary regions, as the discharge of rivers decreases and the intensity of insolation increases, the absolute concentrations C_{SOS} and N_{SOS} decrease and their maxima shift to a depth of 5 m. As in spring, the main mass of suspended organic substances is concentrated in the upper freshened layer over the thermocline. Below the thermocline, the values of C_{SOS} and N_{SOS} abruptly decrease (and become three and two times lower, respectively). The ratio $C_{SOS}/\mathrm{ch}\,a$ varies from 240 at the maximum to 1300 at a depth of 30 m.

In the autumn period, under the conditions of more intense mixing of waters, we observe the equalization of concentrations of suspended organic substances from the surface to the bottom. In this case, the maximum of chlorophyll *a* is observed, as a rule, on the surface. On the surface, the ratio $C_{SOS}/\mathrm{ch}\,a$ is equal to 180 and increases to 400 at a depth of 10 m.

In the northwest part of the sea not subjected to the influence of the discharge of rivers, the vertical distribution of suspended organic substances is more complicated.

In winter, when wind mixing covers the entire depth of waters, the distribution of suspended organic substances is monotonic down to the bottom. The mean value of the ratio $C_{SOS}/\mathrm{ch}\,a$ in the water column is equal to 160.

In the spring period, we observe the following three types of vertical distributions of suspended organic substances:

1. In the north shallow-water part of the sea (with depths that do not exceed 30 m) where, as a rule, the distributions of temperature and density are monotonic down to the bottom, the distribution of suspended organic substances is uniform from the surface to the bottom. A relatively high value of the ratio $C_{SOS}/\mathrm{ch}\,a$ (270) means that a significant part of suspended organic substances in the entire water column is represented by dead organic substances. In spring, this part of the shelf is characterized by low levels of the biomass of phytoplankton and primary production [25].

2. In the central part of the shelf (with depths that do not exceed 65 m), the temperature of water is higher and close to the optimal temperature for the development of diatoms [26]. Within the zone of photosynthesis (30 m), the distribution of suspended organic substances is uniform. Below the zone of photosynthesis, we observe an abrupt (2–2.5-fold) decrease in the concentrations of C_{SOS} and N_{SOS}. Relatively low ratios C_{SOS}/ch a (150) and a large fraction of chlorophyll a in the suspended organic substances (0.8% C_{SOS}) indicate that the fraction of organic suspension represented by phytoplankton at the center of the northwest part of the sea increases.

3. In the south part of the shelf characterized by a quite intense exchange of waters with the abyssal part of the sea, the distributions of suspended organic substances have, as a rule, two maxima. The first maximum is located in the surface layer and the second maximum can be found near the upper boundary of the thermocline and coincides with the maximum of chlorophyll a. The absolute concentrations of suspended organic substances in the first maximum are 1.5 times higher than in the second maximum. The ratio C_{SOS}/ch a takes high values for both maxima. This may serve as an indication of both the low level of development of phytoplankton and the presence of large amounts of destroyed suspended organic substances delivered by waters from the abyssal part of the sea into the layer of the lower maximum or by waters of the central part of the shelf into the layer of the surface maximum.

In summer, when the waters of the shelf are stratified, we have, as a rule, two maxima in the vertical distributions of suspended organic substances. The first maximum is located on the surface and the second (with higher values of C_{SOS} and N_{SOS}) in the layer of the thermocline. Below the thermocline, the concentrations of suspended organic substances decrease although their absolute values near the bottom remain high.

In autumn, in the period of cooling of surface waters, the summer thermocline is destroyed, the maximum of concentrations of suspended organic substances connected with this thermocline disappears, and we observe the process of gradual equalization of the concentrations C_{SOS} and N_{SOS}.

ABYSSAL PART OF THE SEA

The vertical distributions of suspended organic substances in the abyssal part of the sea are, to a large extent, determined by the thermohaline structure of waters characterized by the uplifting of isosurfaces of all characteristics at the centers of cyclonic circulations.

WINTER

In the winter period, in the central part of cyclonic circulations, we have, as a rule, uniform distributions of C_{SOS} and N_{SOS} in the upper mixed layer with insignificant maxima near its lower boundary (Fig. 12a). In deeper layers, the concentrations of the components of the suspension abruptly decrease and, at depths of 50–60 m, reach the background values (1.83–2.40 mg-atom C $\cdot$ m^{-3} and 0.25–0.36 mg-atom N $\cdot$ m^{-3}).

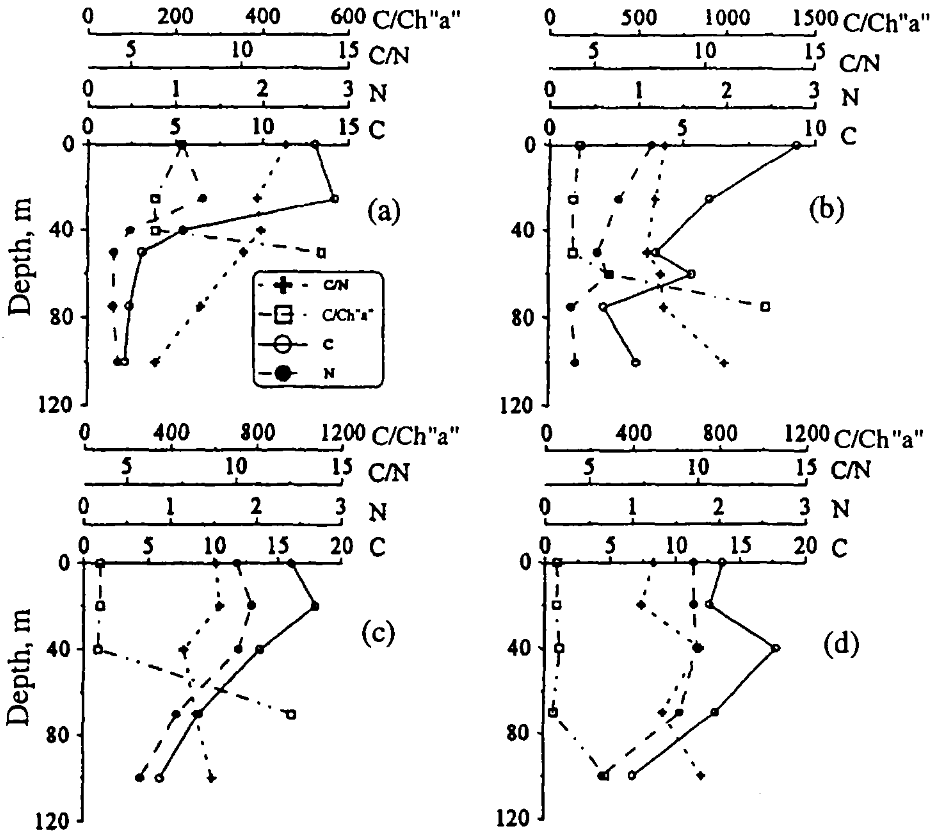


Figure 12. Typical profiles of the vertical distributions of C_{SOS}, N_{SOS}, C/N, and C_{SOS}/ch*a* in winter [(a) cyclone, (b) anticyclone] and early spring (March) [(c) cyclone, (d) anticyclone].

In the peripheral parts of cyclonic circulations, we see the appearance of the second insignificant maximum of C_{SOS} and N_{SOS} over the upper boundary of the H_2S-zone at depths of 75–100 m.

In the anticyclonic vortex formations, the vertical distributions of suspended organic substances have three maxima. The first (highest) maximum is located on the surface, the second maximum is on the lower boundary of the upper mixed layer (50–60 m), and the third maximum is detected directly on the upper boundary of the hydrogen-sulfide zone or above it (Fig. 12b).

MARCH

In March, at the center of the cyclonic formation, high values of C_{SOS} and N_{SOS} are observed from the surface to a depth of 40 m. At the same time, the ratio C_{SOS}/ch*a* varies within the range 50–80 for the whole layer (Fig. 12c). In some cases, within the limits of this layer, we have two maxima: on the surface and at a depth of 20 m. For some stations, the maximum concentrations insignificantly vary and are equal to 17.2–18.0 mg-atom$C \cdot m^{-3}$ and 1.94–2.90 mg-atom$N \cdot m^{-3}$. Below 40 m, the concentrations of both components of the suspension gradually decrease with depth. At a depth of 100 m, the concentrations attain their background values for the indicated period (3.4–5.9 mg-atom$C \cdot m^{-3}$ and 0.40–0.66 mg-atom$N \cdot m^{-3}$).

In the periphery of domes, high concentrations (18.0–19.6 mg-atom$C \cdot m^{-3}$ and 2.10–3.20 mg-atom$N \cdot m^{-3}$) are practically uniformly distributed from the surface to a depth of 40 m. Below this layer (at a depth of about 70 m), the concentrations of both components of the suspension abruptly decrease (by a factor of 6–7). On the boundary of the hydrogen-sulfide zone (~100 m), we detect the formation of a new maximum characterized by an increase (on the average, twofold) in the values of C_{SOS} and N_{SOS} as compared with a depth of 70 m.

In the anticyclonic formation (Fig. 12d), high concentrations of the components of the organic suspension (17.7–22.0 mg-atom$C \cdot m^{-3}$ and 1.8–2.3 mg-atom$N \cdot m^{-3}$) are observed in the 0–70-m layer and the maximum of C_{SOS} is detected at a depth of 40 m. Low values of the ratio $C_{SOS}/\mathrm{ch}\,a$ may serve as an indication of the fact that the major part of the mass of suspended organic substances is formed by phytoplankton whose accumulation occurs as a result of its passive drift from the region of massive "blooming" of algae [14]. Below a depth of 70 m, we observe a gradual decrease in the concentrations C_{SOS} and N_{SOS} down to a depth of 100 m.

SPRING

The vertical distribution of suspended organic substances in spring in the upper 100-m layer in the central parts of cyclonic circulations is characterized by the presence of three maxima of C_{SOS} and N_{SOS} (Fig. 13a). The first maximum is located in the upper mixed layer above the thermocline, the second is detected in the lower part of the upper mixed layer above the pycnocline and coincides with the maximum of chlorophyll *a*, and the third is above the upper boundary of the hydrogen-sulfide zone. The climatic conditions of the preceding winter periods do not affect the qualitative characteristics of the vertical distributions of suspended organic substances in this region of the sea. However, the absolute values of concentrations of suspended organic substances after "cold" winters were 1.2–2 times higher than the values typical of the spring periods after "warm" winters.

The concentrations C_{SOS} and N_{SOS} in the surface maximum can be as high as 11.13–14.51 mg-atom$C \cdot m^{-3}$ and 2.27–2.60 mg-atom$N \cdot m^{-3}$ (Fig. 13a). The ratio $C_{SOS}/\mathrm{ch}\,a$ corresponding to this maximum varies within the range 900–1300 and the ratio C/N within the range 10–20. In view of the fact that, in living substances, the ratio C/N varies, as a rule, from 2.7 to 7.0 [15], it becomes clear that the major part of organic substances in this maximum is represented by detritus.

The sufficient amount of light penetrating to the depth of the second maximum and the delivery of biogenic elements in the course of turbulent exchange with deeper layers of water create favorable conditions for the development of phytoplankton.

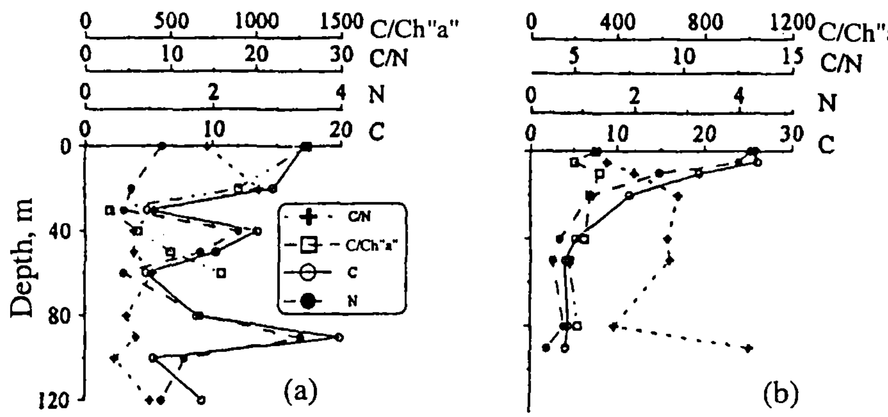


Figure 13. Typical profiles of the vertical distributions of C_{SOS}, N_{SOS}, C/N, and C_{SOS}/ch*a* in spring [(a) cyclone, (b) anticyclone].

Low levels of C/N in the second maximum of concentration also show that the role of phytoplankton in the formation of suspended organic substances above the pycnocline is relatively important. At the same time, the appearance of detritus sinking from the surface layer leads to an increase in the ratio C_{SOS}/ch*a* in the samples of suspended organic substances taken from this layer.

The appearance of the deep maximum of suspended organic substances on or above the boundary of the hydrogen-sulfide zone can be explained both by the accumulation of sinking substances in the layer of the main pycnocline additionally intensified by the adsorption of suspended organic substances on suspended hydroxides of metals and the production of organic substances as a result of the living activity of bacteria.

In the anticyclonic formations (Fig. 13b), the concentrations of suspended organic substances gradually decrease and attain the background values (2.16–4.27 mg-atomC$\cdot$m^{-3} and 0.27–0.36 mg-atomN$\cdot$m^{-3}) at a depth of 50 m.

SUMMER

In the summer period, the distribution of suspended organic substances is determined by the thermal stratification of waters. In the vertical distributions of suspended organic substances, we detect one or two maxima of the components of the organic suspension, namely, the surface maximum (0–10 m) and the maximum located at the depth of the seasonal thermocline. Most often, these maxima have practically the same amplitudes and often merge into a single maximum from the surface to the seasonal pycnocline (Fig. 14a).

In the surface maximum, the major part of suspended organic substances is formed by dead organic substances (the ratio C_{SOS}/ch*a* is, as a rule, larger than 500).

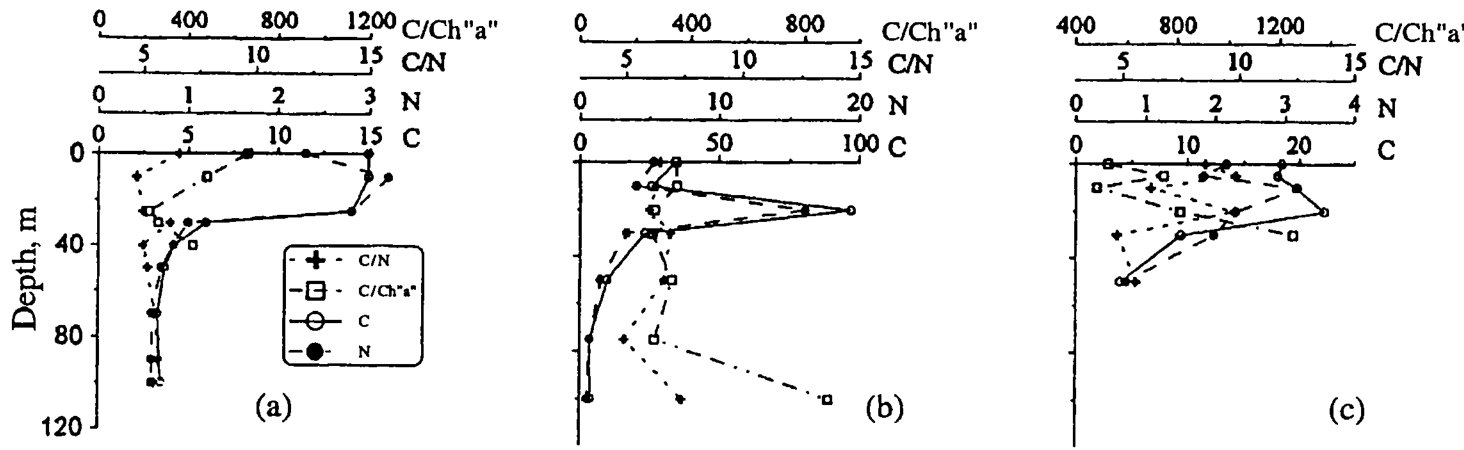


Figure 14. Typical profiles of the vertical distribution of C_{SOS}, N_{SOS}, C/N, and C_{SOS}/Ch "a" in summer [(a) no "blooming," (b) intense "blooming" of phytoplankton] and in autumn (c).

In the lower part of the seasonal thermocline, where the conditions are favorable for the development of phytoplankton, the values of the ratio $C_{SOS}/\mathrm{ch}\,a$ rapidly decrease and vary in different regions of the sea within the range 50–237. Note that the fraction of "new" production in the maximum can be as high as 80% vs. 30% in the upper layers of the water column in summer [21].

The summer periods of some years are characterized by the appearance of local spots of "blooming" phytoplankton in the open part of the sea. In these cases, the mass of phytoplankton differ in the neighboring areas by several orders of magnitude [25, 27]. An example of the vertical profile of distributions of C_{SOS}, N_{SOS}, C/N, and $C_{SOS}/\mathrm{ch}\,a$ in the zone of "blooming" phytoplankton in the cyclonic formation is presented in Fig. 14b (for July 1992). The values of C_{SOS} and N_{SOS} in the region of maximum were as high as 97.0 mg-atom C $\cdot$ m^{-3} and 16.1 mg-atom N $\cdot$ m^{-3}, respectively, whereas outside the zone of "blooming" phytoplankton, the concentrations of the components of suspension in the maximum were 21.0–28.0 mg-atom C $\cdot$ m^{-3} and 3.3–4.2 mg-atom N $\cdot$ m^{-3}. The concentration of chlorophyll *a* in this maximum was quite high (4.3 mg $\cdot$ m^{-3}) and the ratio $C_{SOS}/\mathrm{ch}\,a$ was close to 200, i.e., very low for the summer period.

AUTUMN

Autumn can be regarded as a transient period and the character of the vertical distribution of suspended organic substances gradually approaches its winter type (see Fig. 14c). The maximum concentration of suspended organic substances is observed in the upper mixed layer and the thermoclinic maximum disappears. Due to the low intensity of solar irradiation (3–20 cal $\cdot$ cm^{-2} day^{-1}), the entire biomass of phytoplankton is concentrated in the upper mixed layer. In the analyzed period, this layer, as a rule, coincides with the euphotic zone (~ 20 m). The ratio $C_{SOS}/\mathrm{ch}\,a$ in the upper mixed layer varies from 500 to 750 and increases to 1200 at a depth of 30 m, which means that the role of phytoplankton in the formation of suspended organic substances is negligible.

DISCUSSION

The data of multiannual (1985–1994) observations presented above enable us to characterize the principal specific features of the seasonal variability of suspended organic substances and their chemical composition both in the shelf zone and in the abyssal part of the sea. The structure and distribution of suspended organic substances in the northwest part of the sea depend on the discharge of rivers, temperature of water, illumination, transparency, and predominant directions of wind determining the dynamics of waters. The analysis of the dynamics and composition of suspended organic substances in the northwest part of the sea clearly reveals the difference between the regions located in the zone of influence of the estuaries of rivers and outside this zone. In near-estuary regions, the biogenic elements delivered by the rivers guarantee the possibility of intense production of organic substances within the entire period from spring till autumn.

The general dynamics of waters, intensity of vertical mixing, illumination, and temperature are the principal factors determining the seasonal and spatial variability and structure of suspended organic substances in the abyssal part of the sea. In all seasons, in the active layer of the sea, the highest concentrations C_{SOS} and N_{SOS} are observed in the surface layers 30–40 m in thickness in the central part of the sea and 60–80 m in thickness in the peripheral regions and anticyclonic formations. For almost all seasons, except winter and March, we have one or two maxima of suspended organic substances in this layer explained either by the presence of the seasonal jump of density or by the active development of phytoplankton. Under the surface layer, the concentrations of suspended organic substances abruptly decrease to their background values. However, just in this case, against the background of a general decrease in the concentration C_{SOS} on or above the upper boundary of the H_2S-zone (75–100 m), we detect thin layers of water with elevated C_{SOS} caused, most likely, by the living activity of zooplankton.

The winter period of the annual cycle is characterized by the lowest concentrations of suspended organic substances. Under the conditions of low illumination, practically all primary production is formed in the upper 5-m layer.

Elevated amounts of biogenic elements in the zone of photosynthesis in March, together with a 3–4-fold increase in illumination as compared with winter, result in the massive "blooming" of phytoplankton in the central part of the sea.

In spring, the dynamic stability of waters becomes more pronounced and the formation of the seasonal thermocline is originated. An increase in the discharge of rivers and the formation of new predominant direction of winds (northwest in spring instead of northeast in winter) increase the area subjected to the influence of freshened surface waters. As compared with winter, we observe an increase in the values of C_{SOS} and N_{SOS} in the entire shelf zone of the northwest and west parts of the sea. The maximum concentrations of both components of the suspension (100–180 mg-atom$\,C \cdot m^{-3}$ and 15–25 mg-atom$\,N \cdot m^{-3}$) are observed in the near-estuary areas and their absolute values are higher than in the winter period almost by an order of magnitude. Spring is the most productive season for the west half of the northwest part of the sea subjected to the influence of rivers. The east half of the northwest part of the sea is less productive. Lower temperatures of water and lower amounts of biogenic elements decrease the intensity of production of new organic substances in this region.

The principal hydrophysical factor determining the distribution and dynamics of suspended organic substances in summer in the Black Sea is the presence of the seasonal thermocline whose formation is usually terminated in June. In the northwest part of the sea, the discharge of rivers is still an important factor affecting the distributions of organic suspensions. However, in this period, it is much less intense.

Autumn is a typical transient period in which the characters of spatial and vertical distributions of suspended organic substances gradually approach the winter type.

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