OCEANOLOGY, English Translation, VOL. 35, NO. 6, JUNE 1996
Russian Edition: NOVEMBER – DECEMBER 1995

Steric oscillations of the Black Sea level

V. S. Arkhipkin and V. Yu. Berezhnoi

M. V. Lomonosov Moscow State University

Abstract. Steric oscillations of the Black Sea level are studied using two methods. First, features of spatial oscillations are considered; the sea level with respect to a reference "average station" is calculated, and a reference steric level, being an analog of the dynamical surface topography of the Black Sea, is obtained. Second, temporal steric oscillations of sea level are studied; oscillations in spatial averaging trapezoids are centered (i.e., they are brought to a zero mean value) with respect to average annual values of the level in these trapezoids. The contribution of individual components of steric sea level oscillations, both thermal and haline are evaluated. The annual and semiannual harmonics of steric oscillations of the sea level and their phases are calculated. It is shown that the amplitude of the steric oscillation reaches 20 cm and comprises about 80% of the total sea level oscillations in some areas of the Black Sea. Physical processes responsible for the nature of oscillations of the steric level, and of the haline and thermal components are discussed.

1. Introduction

Until now, sea level variations in the Black Sea have been studied mainly on the basis of observations at coastal hydrometeorological stations. Distinct seasonal sea level variations associated with river discharge were revealed [*Gidrometeoizdat*, 1991]. Spatial and temporal oscillations of sea level in the open Black Sea have not yet been studied. The role of variability of the density field in these oscillations is not clear. However, as discussed previously [*Galerkin*, 1961], the contribution of density oscillations to the total sea level variations can be considerable. Steric oscillations in closed basins were investigated only in the Caspian, White, and Baltic Seas, and then only the temporal variability in several areas of a basin was analyzed [*Pobedonostsev*, 1977]. The present study is aimed at investigation of the contribution of steric (density) oscillations to the formation and variability of total sea level over the entire Black Sea area.

2. Data and Methods

In the present study, use is made of a hydrological array compiled from domestic data archived in the National Information Center (Obninsk), and also from archives of the Marine Hydrophysical Institute of the National Academy of Sciences of Ukraine [*Mamayev et al.*, 1994]. We used data only from those stations which had simultaneous measurements of temperature and salinity. The total number of such stations exceeded 6500.

0001–4370/96/3506–0002$18.00/1

Calculations of the steric level and of its thermal and haline components were made on the basis of actual measurements at 11 horizons (0, 10, 20, 30, 50, 75, 100, 150, 200, 250 and 300 dbar) for the 0 to 300 dbar layer. Averaging was done over 1° by 1° latitude-longitude trapezoids; only data within a 90% confidence interval for each horizon were used in the calculations. The lower layer boundary is chosen from the following lines of reasoning: first, the depth of penetration of seasonal temperature and salinity oscillations; second, an abrupt reduction of the number of observations below the level 300 dbar; third, rigid requirements on accuracy (as the layer thickness increases, the error of calculations carried out by (1), (2), and (3) greatly increases at the expense of a numerical approximation of the integral and of a lesser accuracy of instrumental measurements of oceanological characteristics).

The steric level can be determined by the formula given by *Arkhipkin and Baulin*, [1994]

$$\Delta z_L = \frac{1}{g} \int\limits_{300}^{0} [L(S,T,p) - L^*(S,T,p)]\, dp \qquad (1)$$

where $L(S,T,p)$ and $L^*(S,T,p)$ are the actual and corresponding mean values of specific volume (the choice of this mean is considered below) and g is the acceleration of gravity. The specific volume is calculated by the international equation of state (EOS-80). The contributions of temperature and salinity are evaluated on the basis of the expansion of the quantity $\Delta L_{STp} = L(S,T,p) - L^*(S,T,p)$ into a Taylor series with an accuracy to terms of the first order of smallness by the equations

$$\Delta z_T = \frac{1}{g} \int_{300}^{0} \left(\frac{\partial L}{\partial T} \right)_{STp} \Delta T \, dp \qquad (2)$$

and

$$\Delta z_S = \frac{1}{g} \int_{300}^{0} \left(\frac{\partial L}{\partial S} \right)_{STp} \Delta S \, dp \qquad (3)$$

where $\Delta S = S - S^*$ and $\Delta T = T - T^*$; T^* and S^* are the mean values of the temperature and salinity, respectively. Expressions (1), (2), and (3) are integrated by the trapezoidal method. On average, steric level errors calculated by procedures put forward in *Lebedev* [1977] do not exceed 0.5 cm, except some areas with insufficient data where the errors approximate 1 cm.

Values of steric level in empty trapezoids were obtained using the method of objective analysis, more precisely by the minimum curvature method [*Arkhipkin and Baulin*, 1994].

To recognize the structure of steric oscillations in the Black Sea, calculations by (1), (2), and (3) were done in two ways. First, to reveal features of spatial oscillations, the level was calculated with respect to a reference "average station" obtained through averaging of data of hydrologic stations over the entire sea and over all months. As a result, a reference steric level, being an analog of the dynamical surface topography of the Black Sea, is obtained. The second line methods of investigation focused on temporal steric oscillations of sea level. Level oscillations within the averaging trapezoids were centered (i.e., they were brought to a zero mean value) with respect to average annual values of the level within these trapezoids. The obtained values were then subjected to harmonic analysis, to obtain the coefficients a_k and b_k of the Fourier series [*Vysshaya Shkola*, 1976]

$$y(t) = \frac{a_0}{2} + \sum_{k=1}^{\infty} (a_k \cos 2\pi k \frac{t}{T} + b_k \sin 2\pi k \frac{t}{T}) \qquad (4)$$

where k is the number of a harmonic, T is the maximum period of the function $y(t)$, and t is the mesh width with respect to time. From the derived coefficients a_k and b_k the amplitude $A_k = \sqrt{a_k + b_k}$ and phase $\varphi_k = -\arctan(b_k/a_k)$ of oscillations (cosine curves) of the annual and semiannual harmonics of steric level are calculated. The phase of oscillations is expressed in terms of a degree, numerically approximating a day. Coefficients of the Fourier series are obtained by formulas of numerical integration for the method of rectangles.

3. Characteristics of the Spatial Structure of the Steric Level

To analyze spatial oscillations of the level, average annual and average monthly maps of the reference steric level are constructed. Figure 1a displays the average annual steric level of the Black Sea. The sea level is lowest in central areas of the sea, particularly in its western part (down to 6 cm below the reference level). The level is elevated toward the coasts and reaches 6–7 cm above the reference level in the southeastern part of the sea. A comparison of steric level maps prepared for all months yielded that March and September possess the most characteristic features typical of winter and summer periods, respectively, therefore, we used these months for further analysis (Figures 1b and 1c). We note that the position of sea level during the chosen months in some areas of the sea does not reach extreme values; however, it most completely represents the qualitative structure of sea level over the entire sea. The March steric level surface is characterized by a pronounced depression (down to 17 cm below the reference value) occupying the major part of the sea (Figure 1b). Such a structure of the level surface is explained by the fact that the level is lowered in winter by about 6–10 cm almost throughout the entire sea with the exception of the southeastern part, where it shows a minor rise of 1–5 cm. The lowering is particularly significant in the central part of the sea between the Crimea and Turkish coast. The summer steric level (Figure 1c) is almost everywhere elevated with respect to the average annual value, and the pattern of this elevation is not uniform over the space. To see this, a maximum level elevation (up to 6 cm) is noted between the Crimea and Turkish coast and in the southeastern area, and minimum variations in the position of the level surface are observed at the center of the eastern and western areas of the sea. As a result, two separate lowered sea level areas are seen in summer; in the west (down to 4 cm below reference level) and in the east (down to 6 cm).

We mention that the above spatial distribution of the steric level coincides with the level surface distribution obtained previously with the help of hydrodynamical models, for example, by *Trukhchev and Demin* [1992].

The spatial structure of the average annual Black Sea level with respect to the "average station" is determined by salinity. Its average annual contribution comprises more than 70% in the major part of central sea areas and amounts to 90% at the center of the eastern part; only in the southwestern most part does its contribution fall to 50%. This confirms the conclusion by *Bulgakov and Korotaev* [1989] on the prevailing role of salinity in the formation of the general circulation of the Black Sea waters.

The greatest annual amplitude of steric level oscillations in the Black Sea is noted in the central (to 20 cm) and southeastern (to 16 cm) areas, and its lowest values are observed at the center of the eastern part (Fig-

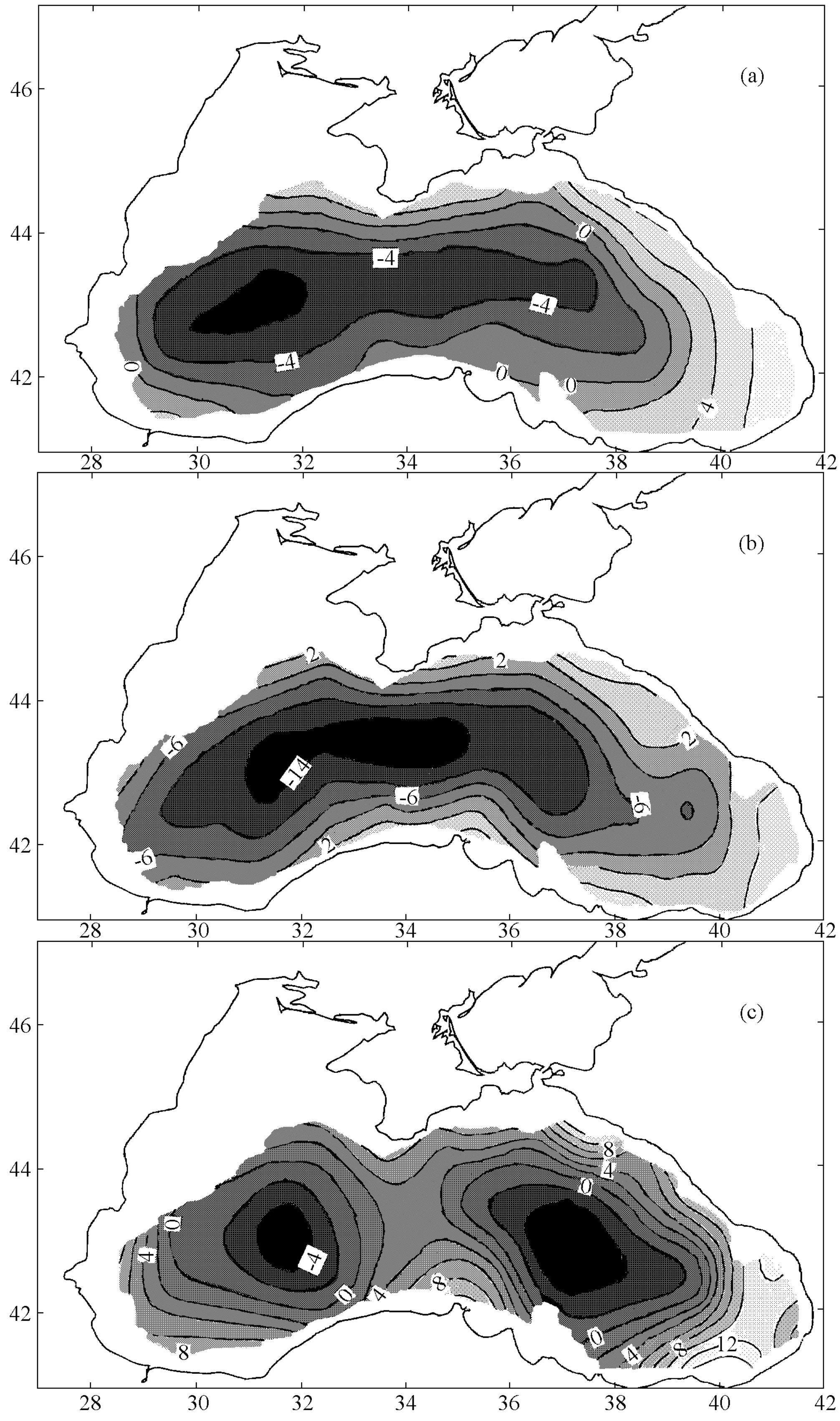

Figure 1. Black Sea steric sea level averaged over many years (in cm): (a) average annual level, (b) March, and (c) September.

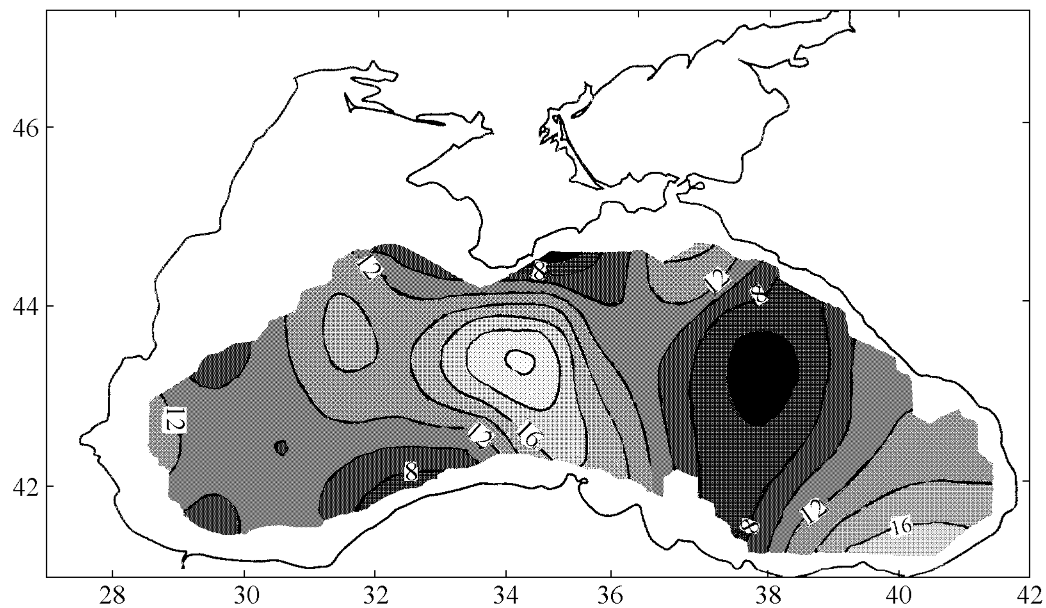

Figure 2. Amplitude of steric level oscillations (in cm).

ure 2). The cause of such a distribution of oscillations is explained below, where the seasonal contributions of the thermal and haline components of the level are discussed.

4. Seasonal Oscillations

Now, we consider an analysis of seasonal deviations of the steric level from the average annual positions in trapezoids or, what is similar, from the average annual reference level surface (Figure 1a). Some aspects of this matter are considered in section 3. Here, we consider problems of the relationship between the salinity and temperature contributions to these oscillations as well as the results of a harmonic analysis.

Maps of the March and September distributions of the parameter ΔH are constructed; this parameter involves the temperature contribution to the total oscillations of the steric level and may be calculated from

$$\Delta H = |\Delta H_T| / (|\Delta H_T| + |\Delta H_S|) \qquad (5)$$

where ΔH_T and ΔH_S are the deviations of the steric level due to temperature and salinity, respectively.

Along with a pronounced minimum contribution of the temperature component in central areas of the sea, an increase in the temperature contribution to deviations of the steric level of up to 90% is observed in coastal areas. Regions with a prevailing contribution of the temperature component are characterized by a wavelike structure framing the central part of the sea. Parameters of this structure do not qualitatively change with season. The wave length approximates 350 km.

To elucidate physical processes responsible for the spatial and temporal structure of steric oscillations, we used a harmonic analysis. Figure 3a displays the amplitude distribution of the annual harmonic of the total steric level. This distribution almost completely coincides with the field of amplitudes of steric oscillations (Figure 2), with the exception of some differences in absolute values. Hence it follows that the calculated amplitude of oscillations is determined mainly by oscillations with the annual period, except for some areas where the semiannual harmonic is important. The largest values of the annual amplitude are noted in the central part of the Black Sea between the Crimea and Turkish coast as well as in the southeastern most part of the sea.

It is of interest to investigate the individual contributions of temperature and salinity to the amplitude of annual oscillations. The amplitude of the annual harmonic of steric level due to the thermal component is equal to 3–4 cm, except for the central area of the eastern part of the sea, where it forms a closed area with values below 2 cm (Figure 3b). The spatial amplitude distribution of the annual harmonic of the haline component has a more complex structure (Figure 3c). It is characterized by alternating zones of increased and decreased amplitudes (from 0 to 5 cm).

The sum of the annual amplitudes of the haline and thermal components should be equal to the total amplitude. Such a statement is true only for some areas, for example, the central part of the sea. In other areas, such as in the southeastern part, the sum of the amplitudes of the components considerably exceeds the total annual harmonic. This fact may be explained by considering the phases of the annual harmonics of the total level and its components (Figures 4a–4c).

A maximum of the thermal component of annual steric level harmonic is attained approximately at the

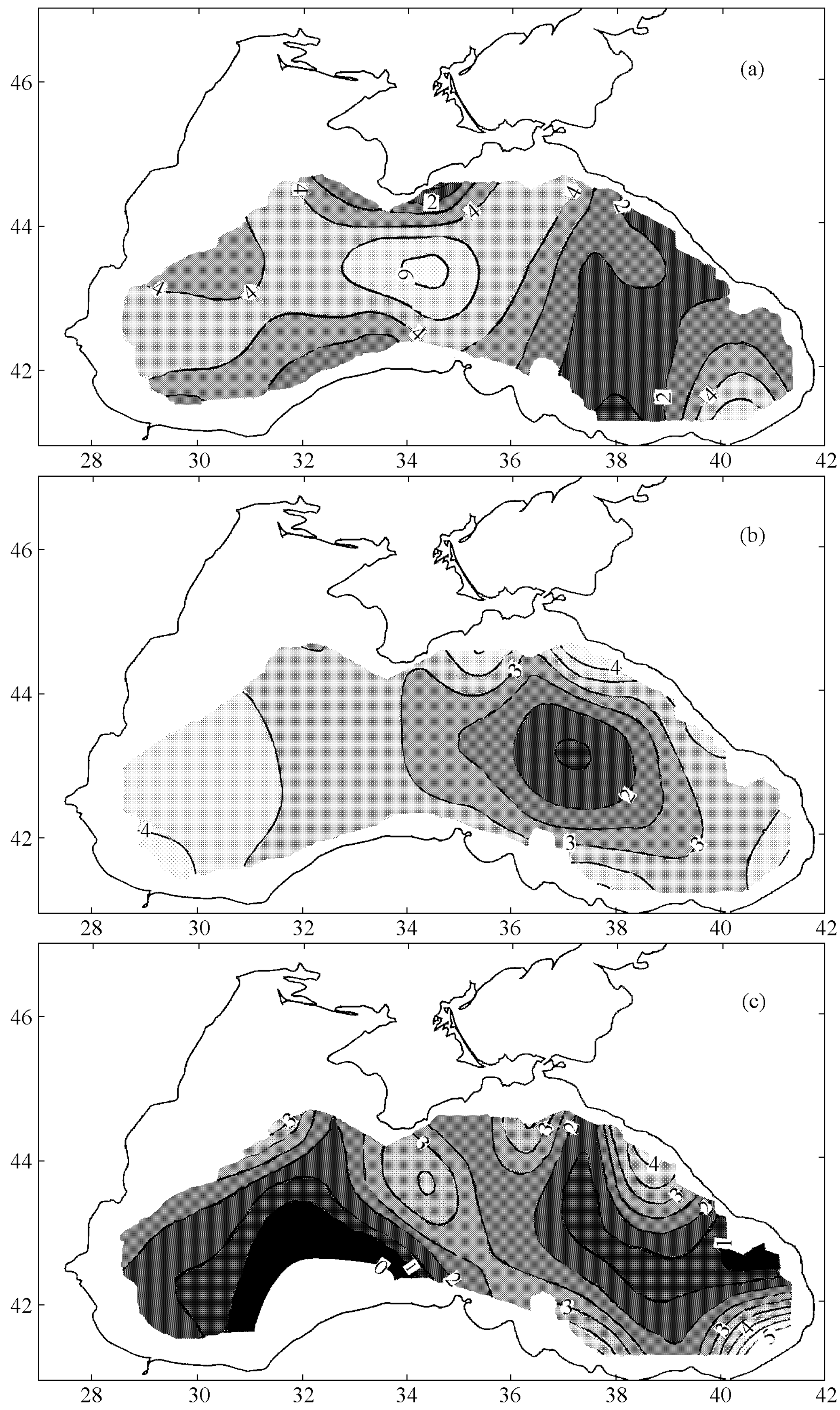

Figure 3. Amplitude distribution of the annual harmonic of steric level oscillations (in cm): (a) total amplitude, (b) thermal component, and (c) haline component.

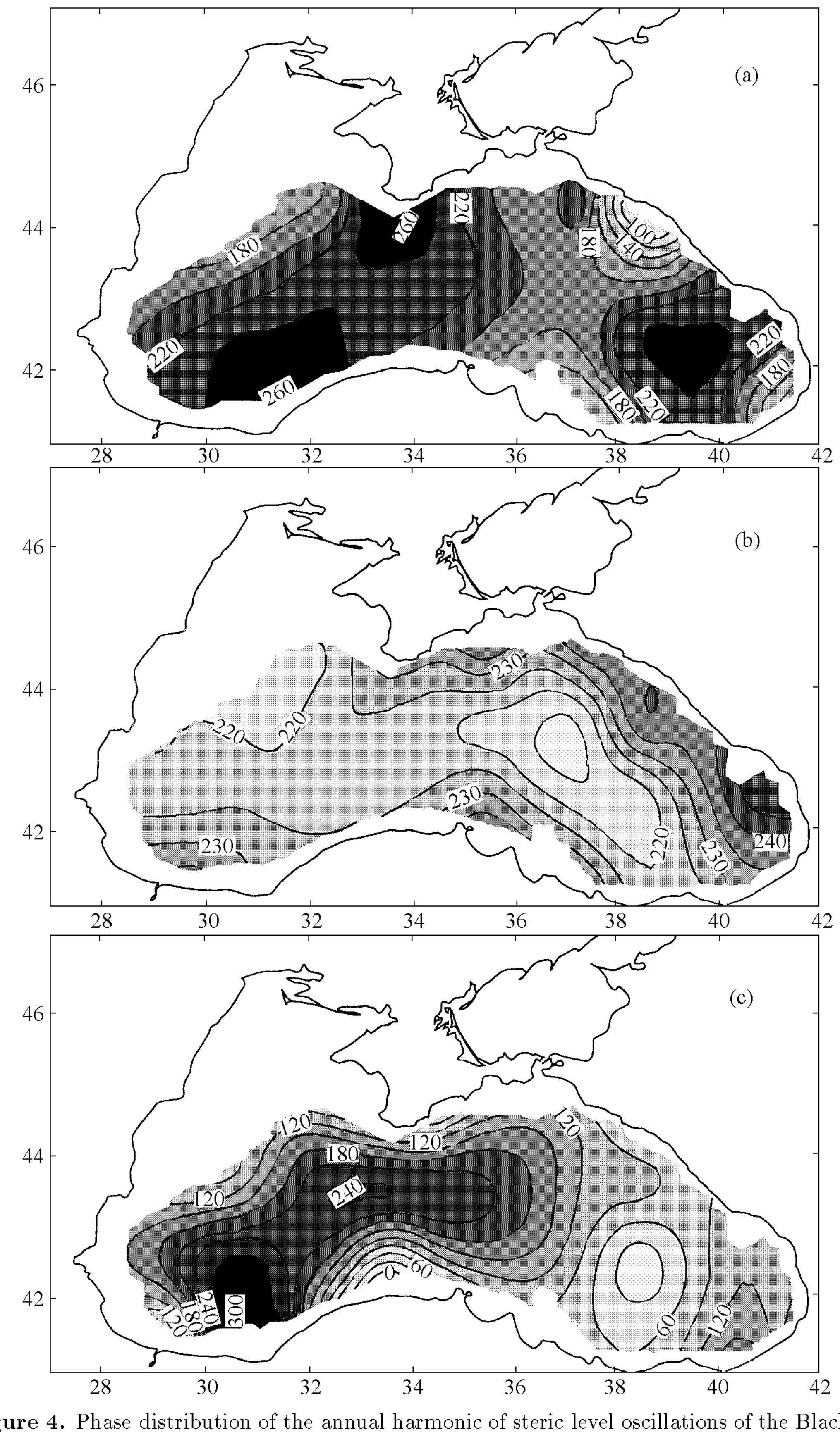

Figure 4. Phase distribution of the annual harmonic of steric level oscillations of the Black Sea (in degrees): (a) total phase, (b) thermal component, and (c) haline component.

same time throughout the sea (August), because of the location of the Black Sea in the same climatic zone (Figure 4b). However, the difference of phases of the attainment of a haline component maximum in different areas of the sea amounts to 7–8 months; this can be inferred from the fact that the amplitude maximum in coastal areas is observed in spring, which is associated with the river runoff, and that in central areas is attained in August, being a period of a lesser cyclonic circulation intensity. The summarized amplitude equals the total amplitude in areas where the phases of the components coincide (the central region), and the summarized and total amplitudes do not coincide because of different phases (for example, in the southwestern area). Figure 4a shows the sum of the cosine curves of the haline and thermal components of level oscillations.

The amplitude of the semiannual harmonic of the steric level is considerably smaller than the annual harmonic almost all over the Black Sea, except for central regions of the eastern part. Its greatest values (up to 2.5–3 cm) are observed at the Turkish coast, off the Crimea, in the southeastern part of the sea, and at the Russian coast in the vicinity of the city of Novorossiisk. Values of the amplitude of the semiannual harmonic approximate those of the annual harmonic only in the central part of the eastern one half of the Black Sea. The phase distribution of the semiannual harmonic is characterized by the fact that there is an alternation of closed zones in which phase values amount to 240°–260° and 60°–80° along the east-west direction, respectively, and this alternation begins with a zone with phases of 240°–260°. The distance between the centers of adjacent zones with equal phases is close to 350 km.

5. Conclusions

The analysis of steric sea level oscillations in the Black Sea allows several conclusions. First, the prevailing role of salinity in the formation of the spatial structure of the average annual reference steric level is revealed. Second, the contributions of the haline and thermal components to seasonal deviations from this level are determined, and areas with the predominance of these components are differentiated. Third, harmonic analysis has allowed us to reveal physical processes responsible for the structure of seasonal sea level oscillations. Fourth, the conclusion on an important role of density oscillations in the formation of the general sea level of the Black Sea is drawn. This is exemplified by Figure 5, which shows a comparison of the calculated steric level with the level observed at coastal hydrometeorological stations.

Acknowledgments. The authors are grateful to S. A. Dobrolyubov, V. L. Lebedev, and A. N. Pantyulin for valuable advice. This work is dedicated to the memory of professor O. I. Mamayev, who initiated and supported this study. The work was supported by the Russian Foundation for Basic Research (project 94–05–17159).

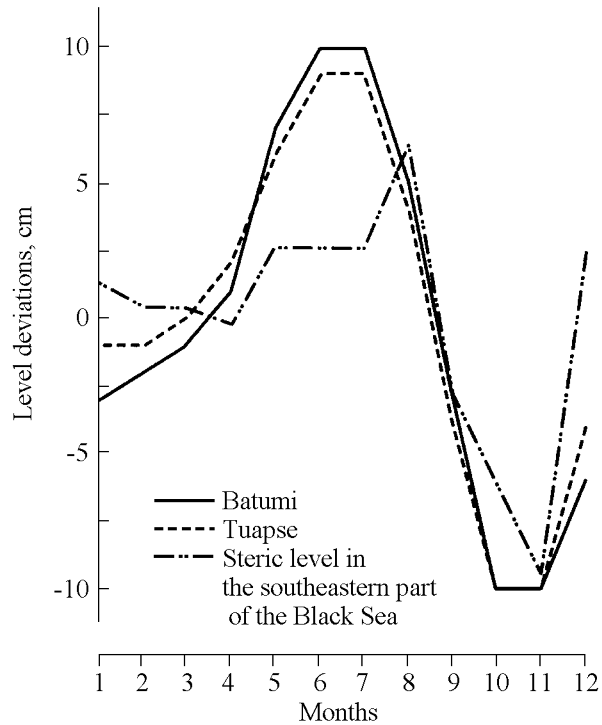

Figure 5. Comparison of the calculated steric level with observations over the level at coastal hydrometeorological stations (in cm). The data are given in terms of deviations from the average level position.

References

Arkhipkin, V. S., and A. V. Baulin, On the interpolation of oceanological fields, *Vestnik Mosk. Gos. Univ. Geogr., 3*, 64–70, 1994.

Bulgakov, S. N., and G. K. Korotaev, The role of haline factors in the formation of circulation of the Black Sea waters, in *Simulation of Hydrophysical Processes and Fields in Closed Basins and Seas*, pp. 71–78, Nauka, Moscow, 1989.

Galerkin, L. I., Problems related to the study of seasonal oscillations of the World ocean level, *Oceanology, Engl. Transl., 1*, No. 6, 1108–1115, 1961.

Hydrometeorology and Hydrochemistry of the USSR, vol. 4: The Black Sea, 429 pp., Gidrometeoizdat, Leningrad, 1991.

Lebedev, V. L., On the accuracy of calculations of relative isobaric topography and of the relative velocity of geostrophic sea flows, *Meteorologiya Gidrologiya, 12*, 51–56, 1977.

Mamayev, O. I., V. S. Arkhipkin, and V. S. Tuzhilkin, A T,S-analysis of the Black Sea waters, *Oceanology, Engl. Transl., 34*, No. 2, 178–192, 1994.

Numerical Methods, 346 pp., Vysshaya Shkola, Moscow, 1976.

Pobedonostsev, S. V., The influence of sea water density on sea level, examplified by the White Sea, *Proc. State Oceanogr. Inst., 138*, 76–81, 1977.

Trukhchev, D. I., and Y. L. Demin, The Black Sea general circulation and climatic temperature and salinity fields, *Tech. Rep. 92–34*, 132 pp., WHOI, 1992.

(Received February 22, 1995.)