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SOME FEATURES OF THE BLACK SEA SEASONAL THERMOHALINE VARIABILITY: MODERN VIEW

ABSTRACT

Results of statistical processing and physical analyses of the historical and recent hydrographic data set are presented. A seasonal thermohaline (hydrographic) variabilities of the Black Sea main baroclinic layer (0–200 m) are considered. In the upper 50-m layer, seasonal thermohaline variability is generated mainly by the heat and freshwater fluxes across the sea surface. In the main pycnocline between depths of 50 and 200 m it is caused by the flux of the wind-stress relative vorticity. Thermohaline effects of these processes are described.

KEY WORDS: The Black Sea, temperature, salinity, seasonal variability

INTRODUCTION

The Black Sea attracts considerable attention due to its natural originality, resource abundance, great historical value and vital importance to human societies of the vast region. Specifically, there has been modern increasing environmental concern over hydrocarbons transportation through the Black Sea by pipelines and ships.

The first large generalization of the earlier studies of the Black Sea physical oceanography performed in the 1890–1930s under the guidance of I.B. Shpindler, Yu.M. Shokalskii, and N.M. Knipovich was made in monographs [Knipovich, 1932], which describes the major part of the hydrographic (thermohaline) features of these seas that are known at present. Later, finer features of the thermohaline structure and related physical processes were discovered. In the middle of the 20th century we should note the monographs [Leonov, 1960, Filippov, 1968] devoted to the geographical and physical descriptions of the hydrographic regime of the Black Sea waters. The monograph [Blatov et al., 1984] presented a systematic quantitative description of the processes of the climatic, seasonal, inter-annual, synoptic, and short-period variabilities of the temperature and salinity of the Black Sea waters. Further refinements of the thermohaline regime of the Black Sea were generalized in [Simonov & Altman, 1991].

In this paper, we present the modern generalized view on the some large-scale features of the Black Sea seasonal thermohaline (temperature and salinity) variability. To a great degree, it define the condition and functioning of other components of the Black Sea ecosystem, in particular, the general circulation and chemical properties of the waters, marine flora and fauna. This study differs from the above mentioned monographs by a significantly (1,5–2-fold) greater amount of the measurement data used, an updated technology for their processing, and modern approach to interpretation of results.

DATA AND METHODS

The description is mainly based on the results of modern statistical processing and physical analysis of historical data set of the ship and coastal measurements of the water temperature and salinity vertical profiles, following the procedures and recommendations given in [Boyer & Levitus, 1994, Locarnini et al., 2006]. We processed and analyzed the data for a 50-year-long interval (1956–2005) with the highest measurement density. The total number of pairs of vertical temperature and salinity profiles in this period exceeded 90 000. Geographically, they are mostly concentrated in the near-shore areas and along standard sections. Meanwhile, it should be noted that the coverage of the entire area of the Black Sea is relatively good.

RESULTS AND DISCUSSION

The features of the thermohaline structure of the Black Sea waters in most are related to the very restricted water exchange of the Black Sea with the adjacent parts of the World Ocean (the Sea of Marmara and the Sea of Azov), because of which its external water budget is generally small [Simonov & Altman, 1991].

The fresh waters supplied to the Black Sea with the riverine runoff and precipitation are distributed by currents and turbulence over the upper mixed layer (UML) of the sea with a thickness of 5–10 m in the spring and summer and up to 40–60 m at the end of the winter. Usually, the water salinity in this layer is within the range 17,5–18,5 practical salinity units (psu). The saline (35–36 psu) waters of the Sea of Marmara flow in the southwestern part of the Black Sea through the Bosporus Strait at a level of 60 m and sink to the deeper layers. Thus, in the multi-annual mean (climatic) regime, the depth of 60 m represents the boundary of the direct influence of the surface fresh waters and the saline waters of the Sea of Marmara. They may be referred to as primary water masses [Mamayev et al., 1994], supplied to the Black Sea from outside, which have no direct contact in the Black Sea.

The Black Sea UML in the warm period of the year is underlain by the layer of the seasonal pycnocline (thermocline). This layer is also thin (10–20 m) but features high vertical gradients of temperature (0,2–0,3 °C m^{-1}) and, correspondingly, of water density (0,10–0,15 kg • m^{-4}). By the end of the winter, owing to the thermal convection, the thickness of the UML over the greater part of the area increases up to 30–60 m. At this time, the UML is limited from beneath by the layer of the main (constant) pycnocline (halocline) the depth range from 30–60 to 150–200 m of the Black Sea with vertical density gradients up to 0,03–0,04 kg • m^{-4}. In the near-mouth areas of the Black Sea, due to the high vertical gradients of the water salinity, the winter thickness of the UML comprises less than 10 m.

The absolute minimum of the water temperature in the Black Sea is usually encountered in the upper part of the main pycnocline (at a depth of 50–75 m) and has values of 6,5–7,5 °C. Only in severe winters is it located in the UML. The layer with a temperature lower than 8 °C is referred to as the cold intermediate layer (CIL). In the warm period of the year, it is "sandwiched" between the seasonal and main pycnoclines. Over the greater part of the area, at the end of the winter, the upper boundary of the CIL (the upper 8 °C isotherm) is exposed at the sea surface. At this time, the major part of the CIL is located inside the UML and only its lower part is related to the main pycnocline.

So, In the upper layer of the Black Sea approximately 40–60 m thick the principal thermal processes are represented by the winter renewal of CIL and by the spring formation and autumn destruction of the seasonal thermocline.

The seasonal signal of the Black Sea UML salinity is manifested by maximal values in February–March (from 18,4–18,7 psu in central area to 17,7–18,2 psu in coastal area) and minimal values in late spring – early summer (from 18,0–18,2 psu in central area to 17,0–17,7 psu in coastal area). Winter

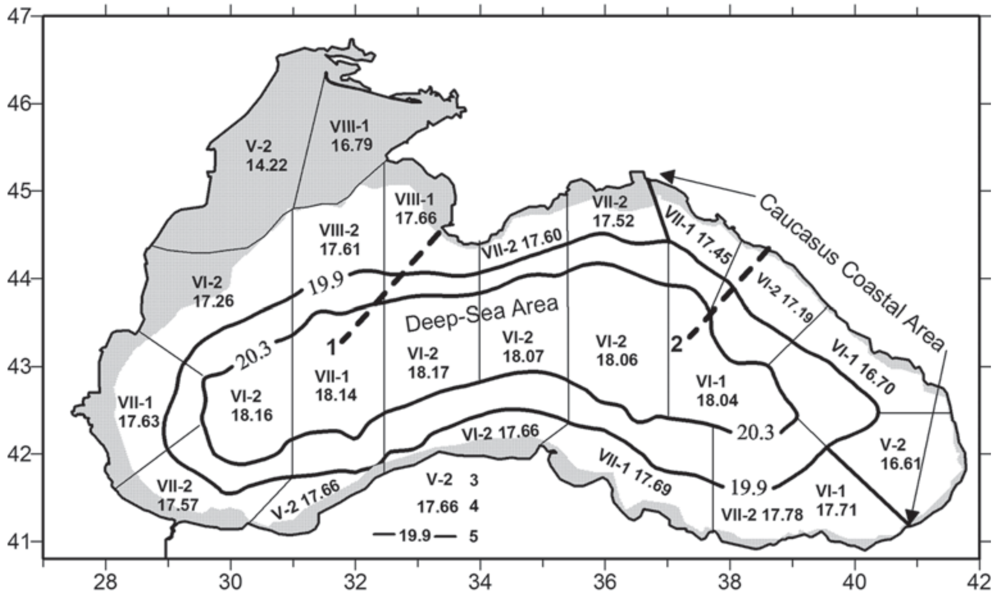

Fig. 1. Scheme of the Black Sea regions with homogeneous hydrographic conditions and distribution of annual salinity minimum value and phase: 1 and 2 – standard hydrographic sections southwestward from Sebastopol (1) and Tuapse (2), 3 – annual salinity minimum phase (half month) and 4 – value (psu), 5 – climatic annual mean isohalines at a depth of 100 m, delineated coastal (19,9 psu) and central (deep-sea, 20,3 psu) areas, and the main frontal zone between them. Shaded area with bottom depth less then 100 m

maximum exist despite the fact that the resulting winter freshwater runoff to the Black Sea (up to 40 км^3 per month, according to [Goryachkin & Ivanov, 2006]) is close to (only 25 % smaller than) the maximal spring runoff. The reason for this inconsistency lies in the intensive convective entrainment in the winter UML of the more saline underlying layers. Results of our calculations of climatic half-month sea surface salinity in 38 regions of the Black Sea show that spatial distribution of annual salinity minimum phases and values (Fig. 1) are more variable then ones of the salinity maximum.

Absolute salinity minimums (much less than 17 psu) take place in near-river-mouth north-western and south-eastern areas in 2-nd half of May. From them, tongues of freshened waters extend along the shores in the general cyclonic (anticlockwise) direction with progressive time delay and rising of salinity minimum value. In regions of the Black Sea central (deep-sea) area the annual salinity minimum value and phase are much more homogeneous (about 18,1 psu and 2-nd half of June, respectively, see Fig. 1). The reason for this is positive difference P-E (precipitation minus evaporation), lasting here from late autumn to June. The coastal water, diluted by river freshwater, diffuses into central area only after June, but its effect is compensated by high summer and early autumn evaporation.

The amplitudes of the Black Sea surface annual heating/cooling and freshening/salting rapidly decrease with depth down to a level of 30 m. Below 30 m, the principal seasonal process is the winter increase and the summer decrease of the dome height of the Black Sea main pycnocline. The first interpretation of this feature was suggested in [Blatov et al., 1984] from the point of view of the response of the large-scale potential vorticity of the Black Sea waters to the seasonal variations in the influx of the relative vorticity from the wind field over the sea surface, which has a cyclonic character in the winter and anticyclonic character in the summer.

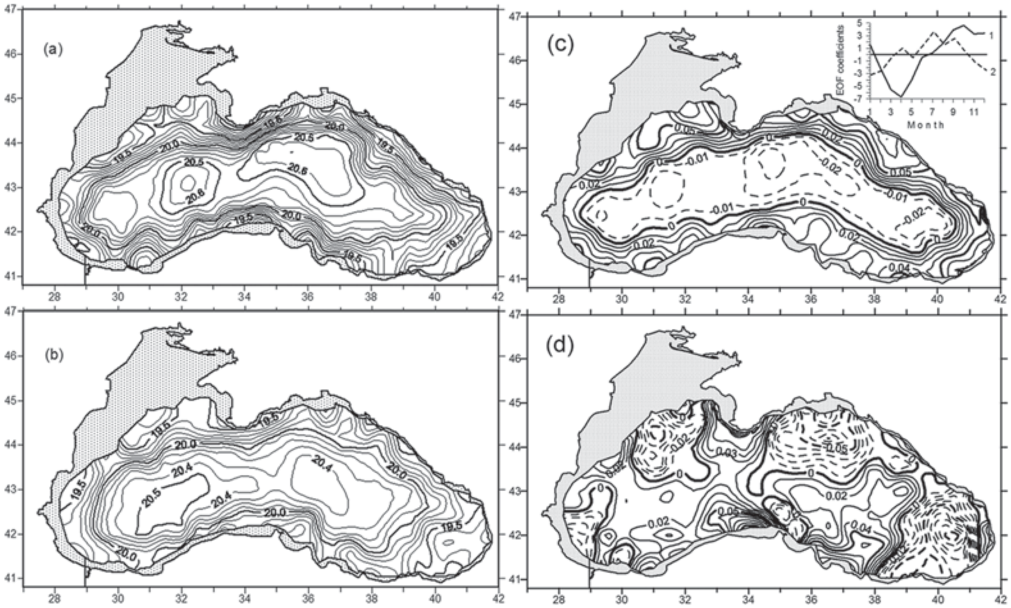

Fig. 2. Climatic monthly fields of the water salinity (psu) of the Black Sea at a depth of 100 m in February (a) and in August (b), and empirical orthogonal functions (EOF) of climatic salinity annual cycle at a depth of 100 m: the 1-st EOF (c) and the 2-nd EOF (d), and annual variations of its coefficients (inset in Fig. 2c)

In the course of this process, the seasonal changes in the temperature and salinity in the main pycnocline layer in the central and coastal areas of the Black Sea proceed in a opposite phases. The amplitudes of the corresponding oscillations reach their maximum at a depth of 100 m. The seasonal (from winter to summer) variability of the horizontal structure of the main pycnocline is especially clear manifested in the salinity field at the 100-m level (Fig. 2a, b). In all the seasons of the year, three types of structural elements are well recognized: the alongshore, the central area of the maximal salinity, the coastal area of the minimal salinity, and the Main frontal zone (MFZ) of high cross-shore salinity gradients. MFZ is closely related to the main element of the general water circulation in the upper 500-m layer of the Black Sea – the Main Black Sea Current [Blatov et al., 1984] or the Rim Current [Ozsoy & Unluata, 1997].

At the end of the winter – the beginning of the spring (from February to May), the MFZ is most intensive. The maximal cross-frontal salinity gradients are located closer to the inshore edge of the MFZ (Table 1). At the end of the summer – the beginning of the autumn (from August to October), these values decrease twofold over the entire Black

Table 1.

Section *N*	**X_{max}, km**	**$(dS/dx)_{max}$, psu km^{-1}**	**X_{off}, km**	**X_{in}, km**
February				
1	65 ± 35	0.0165 ± 0.0039	128 ± 36	11 ± 39
2	35 ± 16	0.0169 ± 0.0064	83 ± 21	10 ± 5
August				
1	72 ± 53	0.0079 ± 0.0059	94 ± 44	31 ± 37
2	41 ± 23	0.0085 ± 0.0045	73 ± 24	18 ± 16

Sea area (see Fig. 2b and Table 1), while location of the maximal cross-frontal salinity gradients shifts toward the offshore edge of the MFZ, whose width decreases. This is caused by the winter–spring strengthening and the summer–autumn weakening in the Black Sea general circulation owing to the enhanced cyclonic activity in the autumn and winter and to the anticyclonic weather conditions in the spring and summer [Simonov, Altman, 1991]. The MFZ strengthens with a delay of approximately three months with respect to the maximum of the wind forcing, which is about one-fourth of the annual cycle; this kind of delay is characteristic of the processes in "forcing–response" systems.

For a more detailed study of the annual variability of the horizontal structure of the Black Sea main pycnocline, we decomposed climatic monthly salinity fields at a depth of 100 m over empirical orthogonal functions (EOF). The results showed that 80 % of the total dispersion of the annual variability in the salinity fields are described by five EOF; two of them are presented in Fig. 2c, d.

The 1st EOF (Fig. 2c), that is responsible for 46,1 % of the total dispersion, represents the most large-scale mode of the Black Sea main pycnocline response to external forcing. The annual variability of the corresponding coefficient (curve 1 in inset of Fig. 2c) shows that the maximal positive (negative) salinity anomalies in the central (coastal) areas of the Black Sea described by this mode are observed in April, when the main pycnocline dome is especially high. An opposite situation is observed a half-year later, in October, when the dome is most low.

The 2nd EOF (Fig. 2d) that describes 14,2 % of the total dispersion represents an alongshore quasi-periodical structure with a wavelength of 300–400 km and coastal trapping of amplitudes, which decreases with the distance from the coast. The annual cycle of the variability of the 2nd EOF coefficient (curve 2 in inset of Fig. 2c) is shifted by a quarter of the period with respect to the 1st EOF. This mode of the main pycnocline variability should be most clearly manifested in the summer in the salinity fields at a depth of 100 m.

The 3rd–5th EOF (not shown), each of which covers from 5,9 to 6,8 % of the total dispersion, also feature a wave structure trapped by the coast. One may suggest that they represent overtones of the 2nd EOF.

The combined effect of the 2nd and higher modes of the annual variability of the main pycnocline was obtained by extracting the contribution of the annual mean salinity field and 1st EOF from the monthly salinity fields at a depth of 100 m. The results for the first six months of the year are shown in Fig. 3.

The areas of the salinity anomalies of different signs shown in Fig. 3 have sub-basin sizes and a complicated spatial and temporal evolution. This is manifested in the cyclonic (anticlockwise) rotation of the pairs of anomalies of opposite signs (dipoles) with respect to their common centers and in the changes of their shapes, sizes, and intensities. While approaching to the coast, the anomalies fast spread about it. In the 2nd half of the year, the evolution of the anomalies is identical to that shown in Fig. 3, but with an opposite sign.

Hence, we can suggest that, at certain stages of their joint cyclonic rotation, salinity anomalies are trapped by the coast, fast spread along it, and then are issued to the open sea. The rapid increases and decreases in the sizes and intensities of the anomalies point to their wave origin. The wavelength along the trajectory of the centers of the anomalies that form a dipole pair comprises about 300–350 km, a mean phase speed of the cyclonic motion – 1,0–1,5 km day^{-1}. Within the alongshore segments of the trajectories, the phase speed of the anomalies is greater, while at the center of the sea it is slower.

The first evidence of sub-basin termohaline undulations with annual period in the Black Sea were received in [Eremeev et al., 1994] from harmonic analysis of climatic salinity

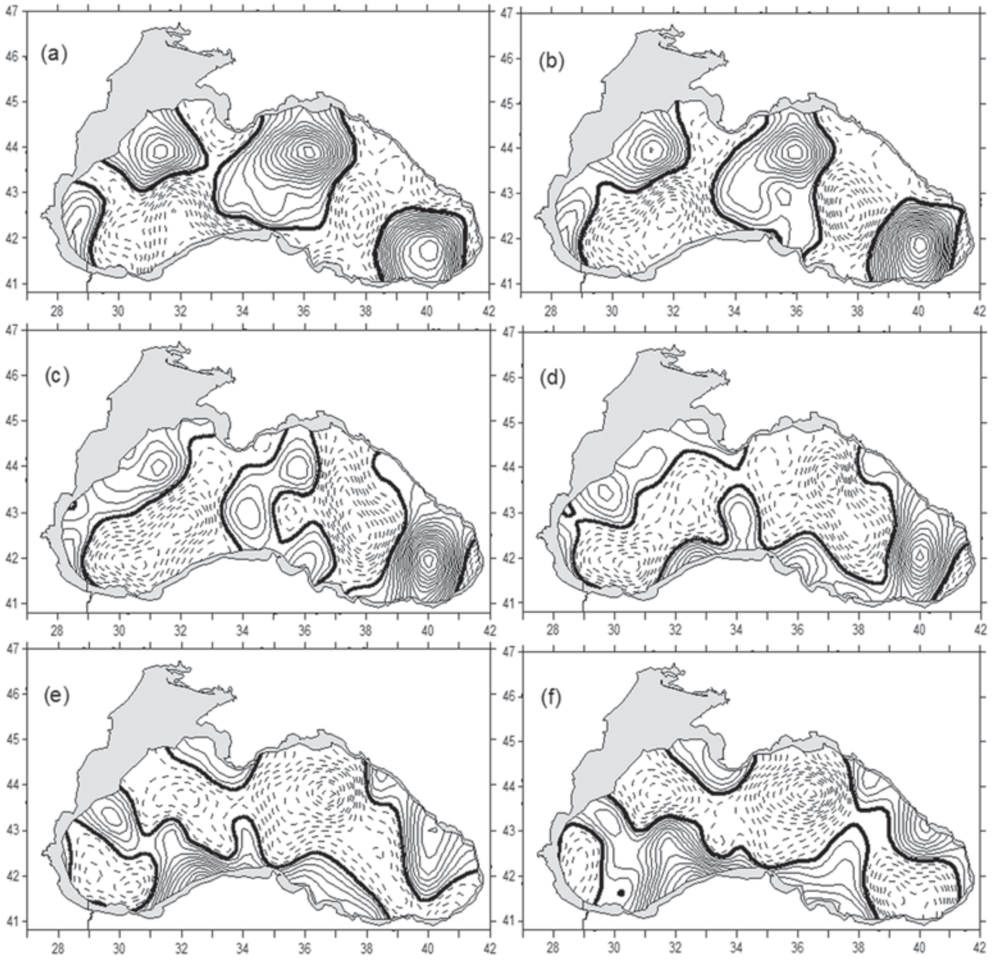

Fig. 3. Climatic fields of the Black Sea water salinity anomaly at a depth of 100 m received by subtraction the annual mean and 1-st EOF fields from climatic monthly salinity field in: (a) January, (b) February, (c) March, (d) April, (e) May, (f) June. Contour interval – 0,05 psu. Dashed lines – negative anomaly

fields. Some years later were received independent confirmations of this in space (ERS-1/2 and TOPEX/Poseidon) altimeter data [Stanev et al., 2000, Korotaev et al., 2001].

Model studies of the mesoscale water dynamics of the Black Sea waters [Rachev & Stanev, 1997, Stanev & Rachev, 1999] showed the possibility of the existence here of Rossby waves with a period about 0,5–1,0 year, a wavelength of 250–350 km, and a phase velocity of 1–2 km day^{-1}. The model Rossby waves were generated by the wind forcing in the southeastern part of the sea. While crossing the narrowest part of the Black Sea south of the Crimea, their phase speed, sizes, and intensities significantly decreased and their final dissipation occurred off the western continental slope. The topographic effects only slightly modified their evolution. Meanwhile, in [Rachev & Stanev, 1997, Stanev & Rachev, 1999] the authors reported manifestations of coastal trapped waves and discussed their possible interaction with the Rossby waves. This interaction resulting in the formation of hybrid Rossby–coastal trapped waves was obtained with the model of mesoscale water dynamics in a circular basin [Bokhove & Johnson, 1999]. The proportions of the properties of the coastal trapped waves and the Rossby waves in this model changed at different evolution stages of hybrid waves.

In our case, we may suggest that the response of the Black Sea main pycnocline to the external (wind) forcing of an annual periodicity is manifested in superposition of an annual basin-scale standing oscillation and sub-basin hybrid Rossby–coastal trapped waves, which form quasi-geostrophic cyclonic amphidromic systems (some analogous to tidal amphidromic systems).

Below the main pycnocline, where seasonal (and inter-annual) variability is indistinguishable, one finds the layer that is named sometimes generally as the deep layer. In the depth range from 200 to 1700 m, one observes a layer with a slow increase in the temperature (with the exception of an isothermal layer between 500 and 700 m) and salinity with depth sometimes broken by T, S-inversions with vertical scales about 10 m, which is typical of the fine T, S-structure of the waters [Murray et al., 1991]. The deep-water observations with conductivity-temperature-depth profilers performed in the Black Sea during the past two decades allowed one to distinguish the near-bottom mixed layer (NBML). A distinct upper boundary of the NBML is traced at depths from 1750 to 1800 m. Above it, up to a depth of 1700 m, one finds a layer with increased vertical gradients of water temperature, salinity, and density with a thickness about 100 m. It separates NBML from the deep stratified layer. In [Eremeev et al., 1997], it was shown that the observed parameters of the NBML in the Black Sea are defined by the buoyancy fluxes balance between the destabilizing geothermal heat flux and stabilizing salt flux supplied with the waters of the Sea of Marmara penetrating to great depths.

CONCLUSIONS

The generalization of the results of the studies of the Black Sea seasonal thermohaline variability presented in this paper allows us to make the following conclusions:

- the thermohaline structure of the Black Sea waters consists of a few characteristic layers with different thicknesses: the upper mixed layer (UML), the seasonal pycnocline (thermocline); the cold intermediate layer (CIL), the main pycnocline (halocline), the isothermal intermediate layer, the thickest deep layer with a slow temperature and salinity increase with depth, and the near-bottom mixed layer;
- the principal features of this structure are related to the very weak vertical turbulent exchange of the thermohaline properties between the freshened surface and the much more saline deep water mass;
- the seasonal variability of the UML, the seasonal pycnocline, and the CIL are caused by the corresponding variations in the heat and freshwater fluxes through the sea surface and in the riverine runoff;
- the seasonal variability of the main pycnocline are caused by the changes in the flux of the wind relative vorticity;
- the response of the Black Sea main pycnocline to the annual forcing by momentum and vorticity fluxes from the wind is manifested in the superposition of two principal modes – a basin-scale standing oscillation and sub-basin hybrid Rossby–coastal trapped waves, which form quasi-geostrophic cyclonic amphidromic systems.

Some of these conclusions are hypothetical in the meanwhile. The degree of their validity should be found out from further studies. ■

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