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Hydrometeorological Conditions

Aleksey N. Kosarev (✉) · Viktor S. Arkhipkin · Galina V. Surkova

Geographic Department, Lomonosov Moscow State University, Vorobievy Gory, 119992 Moscow, Russia
akosarev@mail.ru

Abstract Based on long-term and seasonal data, the basic hydrometeorological features that form the natural regime of the Black Sea are under consideration, which include climate (regional atmospheric circulation, winds, atmospheric pressure, air temperature, moisture content, precipitation), wind waves, water balance, sea level (multiannual and seasonal changes, storm surges, seishes, tidal oscillations), as well as sea ice.

Keywords Black Sea · Climate · Hydrometeorological conditions · Sea ice · Sea level · Water balance · Wind waves

1 Introduction

The main distinctive property of the Black Sea is its inland location and high isolation from the World Ocean. Because of this, formation of the sea hydrological regime and water structure is governed by outer factors: the fluxes of heat, moisture, and wind stress via the sea surface, as well as the river runoff. In this connection, the sea is characterized by a high level of environmental variability. At the same time, in different parts of the Black Sea, the influence of outer factors are very unequal. Therefore these factors exert a different impact on the formation of hydrological fields and vertical thermohaline structure in the sea. All this determines the necessity of more detailed and regular observations of hydrometereological parameters of the Black Sea.

2
Climate

The climate of the Black Sea and its coastal regions is defined by three principal factors, which depend on the latitude and topography of the area—the irradiance processes, the atmosphere circulation (both large-scale and local), and the character of the underlying surface. With regard to the type of the air masses that dominate throughout the year, the northern and the southern parts of the Black Sea may be referred to as the temperate and subtropical climatic zones, respectively [1].

Solar irradiance. The southern position of the region determines the supply of a great amount of solar irradiance. The low albedo of the underlying water surface (4–5% under calm weather at a sun height of $h = 60°$) and the adjacent land areas at the absence of a permanent snow cover leads to the high values of the irradiance balance (Fig. 1); it is positive over the major part of the Black Sea throughout the year except for selected sites off its northern coasts.

Atmospheric circulation. The atmospheric circulation represents the most important process that defines the movements of the air masses over the Black Sea. Owing to its particular features, the climates in the western and eastern parts located within the same latitudinal belt differ in their thermal regimes and moisture contents, and therefore, over the eastern part of the Black Sea, the winter is warmer than over its western part and the monthly sum of precipitation is correspondingly several times higher.

The recurrence of the principal types of synoptic processes over the sea area and the related dominating wind directions in the lower troposphere vary during the year (Fig. 2).

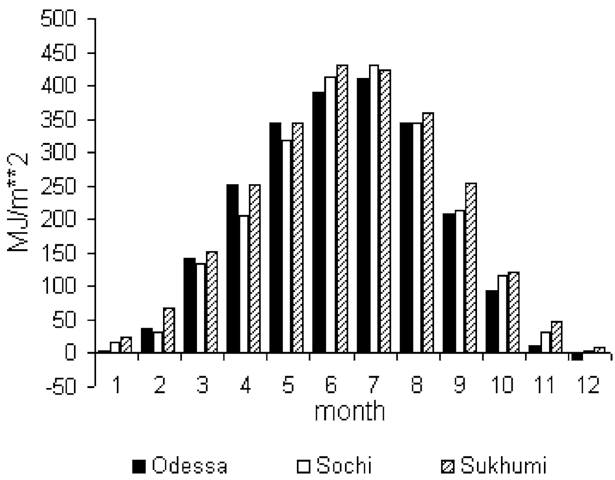

Fig. 1 Monthly values of the irradiance balance, MJ/m^2

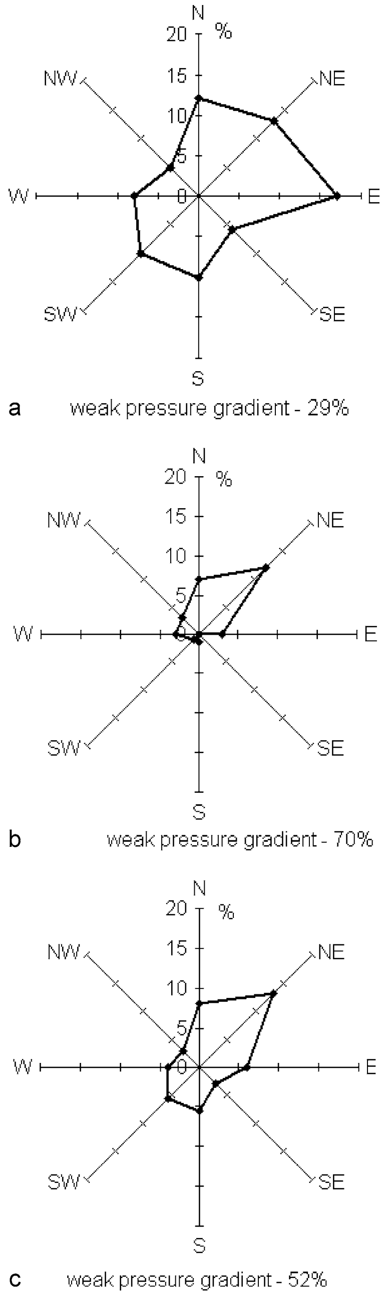

Fig. 2 Recurrence of synoptic processes, %, **a** in February, **b** in August, and **c** throughout the year. The names of the synoptic processes corresponding to the directions of the winds in the lower troposphere that dominate during the process. In the line below, the recurrences of the situations with low-gradient baric field are indicated

At the northerly processes, the Black Sea finds itself at the southeastern periphery of a vast anticyclone centered over Europe and Scandinavia. The strongest northerly winds accompany rapid displacement of the anticyclone from the region of the Balkan Peninsula in the course of the development of salinity activity over the Caucasus, the Caspian Sea, and, more rare, over the eastern part of the Black Sea. In these cases, the rate of atmosphere pressure growth in the western section of the Black Sea may reach 3–5 hPa during 3 h.

At the northeasterly synoptic process in the Black Sea region, the center of the anticyclone is located over the western regions of the European part of Russia. Owing to the advection of cold air from the north and northeast, the cyclonic activity over the southeastern part of the Black Sea is intensified. The passage of cyclones over the southern part of the Black Sea is accompanied by strong easterly and northeasterly winds, especially in the northeast of the Black Sea and off the western coast of the Crimea. At the same time, the southeastern part of the sea is usually dominated by weak and moderate winds of different directions.

For the easterly type of processes, it is characteristic of the anticyclone to be centered over the central regions of the European part of Russia. Meanwhile, the cyclonic activity also develops over the Mediterranean Sea and Turkey. In so doing, the Mediterranean cyclones tend to the southern regions of the Black Sea and result in a significant strengthening of easterly winds over the major part of its area.

The northerly, northeasterly, and easterly processes noticeably dominate in the wintertime and generally throughout the entire year.

The southeasterly processes are also observed mostly during the cold time of the year; they are related to the situation when the high-pressure area is located over the east of the European part of Russia and Kazakhstan, while its spur extends into the western regions of the European part of Russia. In so doing, the Balkan Peninsula and the Mediterranean Sea experience the influence of a low-pressure area while the Mediterranean cyclones displace to the southwest of the Black Sea and favor the strengthening of the southeasterly wind in its eastern part. While this process develops, the airflows mostly feature an easterly direction over the northwest of the sea and a southerly direction over its southwestern part.

The southwesterly processes develop in the situation when the depression of the air pressure in the lower troposphere is directed from the Baltic Sea toward the Balkan Peninsula. The cyclone development in this depression results in the strengthening of southerly and southwesterly winds over the Black Sea.

The cyclonic activity over the central part of the European part of Russia leads to the development of westerly winds over the Black Sea. In this case, the strongest winds are observed under the passages of deep Scandinavian cyclones over the south of the Ukraine and in the rear parts of the Mediterranean cyclones.

The northwesterly type of synoptic processes is related to the development of the cyclonic activity in the southeast of the European part of Russia and to an anticyclone over Europe with a spur toward the Balkan Peninsula. Similar to the westerly type of the process, the strongest winds are observed at the displacement of Scandinavian cyclones to the southeast of the European part of Russia across the southern part of the Ukraine in the rear of the Mediterranean cyclones.

In the case where a cyclone is located over the central part of the Black Sea, strong easterly and westerly winds dominate over its northern and southern parts, respectively. At this time, an anticyclone is usually located over the European part of Russia.

Local winds. Local (mesoscale) circulations and winds such as breezes, mountain–valley circulation, slope winds, foehns, boras, etc., along with the atmospheric processes on synoptic scale, play an important role in the formation of the climate on the coasts of the Black Sea.

The development of breezes, mountain–valley circulation, and slope winds is best favored by synoptic situations low-gradient baric field and low velocities of the main flow in the lower troposphere. In these cases, a distinctly manifested diurnal variation in all the meteorological parameters is observed [2, 3].

Breezes are induced by temperature contrasts between land and sea; they are characteristic of the entire Black Sea coast. The greatest recurrence of breezes universally fall in the period from March to October; on the southern coast of the Black Sea, they are probable throughout the entire year.

The greatest number of days with breezes (more than 50 days/year, at places up to 190 days/year) is noted on the southern coast of the Crimea, where the temperature contrast between land and sea is best expressed. Along the Caucasian coast, the recurrence of breezes increases from the north to the south from 18 to 50 days/year. Breezes are most rarely encountered on the western and northwestern coasts of the Black Sea and in the Kerch region.

The durations of the offshore and onshore breezes during the day are approximately equal (11–12 h). The morning and evening changes in the breeze direction occur very quickly—during 15–20 min. The onshore breeze is changed by the offshore one approximately in 2.5 h after the sunrise; the opposite change occurs almost simultaneously with the sunset [4].

The speed of breezes is relatively low. For the offshore breezes, its average value is 3–5 m/s; for the onshore breezes, it is 1–3 m/s. Speed increases may be observed in the regions where mountains approach the coastline and the orientation of mountain and river valleys coincides with the dominating direction of the breezes. In such cases, the breezes are enhanced by slope winds or due to the mountain–valley circulation.

Within the mountainous portions of the coast, foehns are often developed. They represent strong and gusty winds, which cause sharp changes in the temperature and moisture contents. They may last from a few hours to a few days. In the wintertime, they are more common than in the summer. The generation of foehns is related to the air masses that have overcome the mountain ridge. On the windward side of the ridge, the air upwells, the water vapor condenses, and clouds ("foehn bar") are formed; it reaches the crest of the ridge and sharply terminates on the leeward side. On the leeward side, an intensive downwelling airflow is induced, which, at the foot of the mountains, may reach characteristics similar to a hurricane. When warm foehns develop, the air descending downhill is adiabatically heated, which causes a sharp (sometimes up to 10–15 °C) temperature growth and a drop in the moisture content at the foot of the ridge. These kinds of foehns are characteristic of the Crimean and Caucasian mountains.

In the region of Novorossiisk, especially in the wintertime, bora (Nordost) is often observed, which represents a cold foehn accompanied by a sharp temperature drop and significant wind speeds (up to 40 m/s). During a bora, the cold air that has overridden the low (600–700 m) Markotkh Ridge extended along the shore flows downhill. The high wind speed values are caused by the large density differences between the still warm air over the sea surface and the cold air; the latter downwells from the ridge as a waterfall featuring strong acceleration. The topography of the ridge may provide an additional bora enhancement. Similar to a fluid, the air moves over the lines of least resistance; therefore, boras are stronger on the ridge passes.

The Novorossiisk boras most often emerge when the center of the European part of Russia is occupied by an intensive cold anticyclone, at the southern margin of which strong northeasterly winds develop. Often, boras are induced in the rear parts of the so-called "diving cyclones" that travel from Scandinavia and Karelia to the Lower Volga or Southern Urals. In all these cases, the boras on the Black Sea coasts are related to the penetration of cold air into the southern part of the European part of Russia. Usually, boras are observed in the wintertime, while the most intensive events are confined to the end of the fall to the beginning of the winter, when the sea is still warm as in the summer, while invasions of very cold Arctic air from the continent are already possible.

The wind speed during bora events may reach 25–30 m/s; in selected cases on mountain passes it is as high as 60 m/s. Boras result in icing-over of ships and port constructions since seawater splashes immediately freeze over their surfaces. Many ships couldn't withstand the attack of bora and went down under the ice load and hurricane winds.

Wind speed. Over the open sea, the wind speed is greater than that on the coasts throughout the year. In all the months, the highest speed values are noted in the northern part of the sea except for the southeastern coasts of the Crimean Peninsula. The least values are observed in the southeastern part of the sea. According to the data of meteorological stations, weak winds with speeds less than 5 m/s dominate throughout the year over the major part of the coasts. The number of days with strong winds (> 15 m/s) is the greatest on the northeastern and southwestern coasts (34–35 days per year). The least number of such days (20–22 days per year) are characteristic of the southern coast of the Crimea and the southeastern regions of the Caucasian coast. On average, the mean annual wind speed over the sea increases from the south to the north and comprises 4–6 m/s. The highest wind speed over the open sea probable once per 100 years makes 40 m/s. Almost everywhere, the annual trend of the wind speed is characterized by an increase in the cold period and a decrease in the warm period of the year (Fig. 3).

Atmospheric pressure. The regime of the atmospheric pressure over the Black Sea is defined by the influence of the Azores and Asian anticyclones, by the area of the wintertime cyclonic activity over the Mediterranean Sea, and by the summertime thermal depression over North Africa and Asia Anterior. Seasonal changes in the air and sea surface temperatures additionally affect the pressure field. In addition, cyclone passages may cause rather rapid and significant aperiodic changes it atmospheric pressure.

The annual trends of the atmosphere pressure feature a regularity common of the entire Black Sea and represented by a distinctly manifested low in the summertime (July) and an insignificant secondary low in the spring, in April (Fig. 4). During the winter half of the year, the general pressure background is elevated and is rather similar over the entire Black Sea. Pressure growth is most rapid in August and September and lasts until January; later, the pressure begins to irregularly decrease.

During the period from May to October, mean pressure values over the western part of the sea are higher than those over its eastern part. In other months, the pressure low is mostly observed over the central parts of the sea. The variability of the atmospheric pressure throughout the year is the highest in the northern part of the sea and the lowest in its southeastern part.

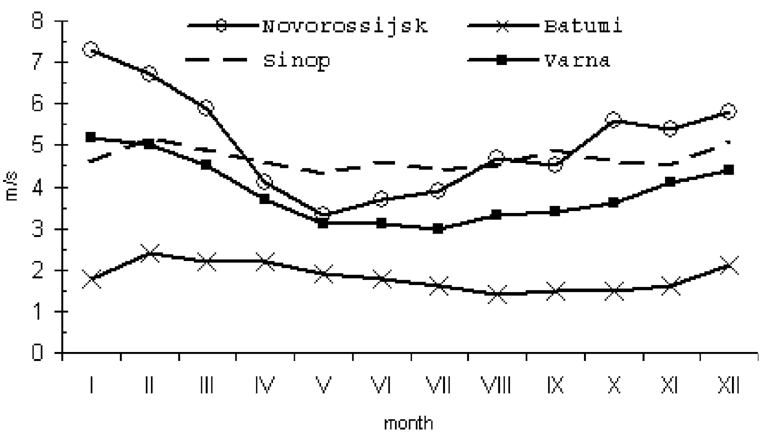

Fig. 3 Mean monthly wind speed, m/s

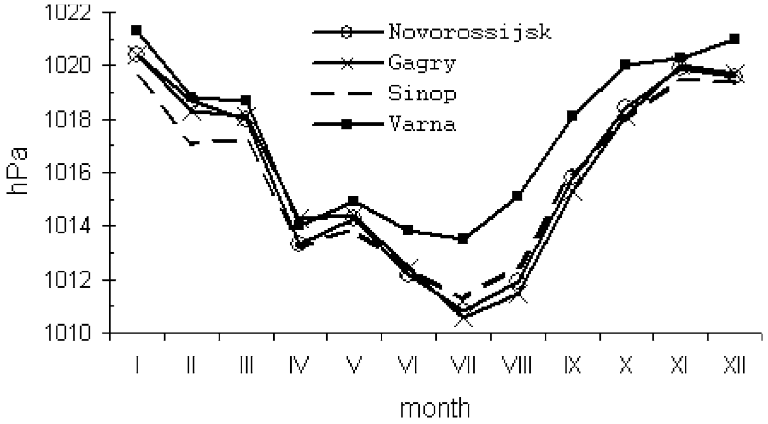

Fig. 4 Mean monthly atmosphere pressure at hydrometeorlogical stations, hPa

Air temperature. The mean annual air temperature over the Black Sea ranges from 10 °C in the northwest to 14–15 °C in the southeast. From August to March, the air temperatures over the open sea are higher than on the coasts. In the spring the situation changes. Owing to the increase in the solar irradiance flux, the land is rapidly heated and becomes warmer than the sea, which has greater heat capacity and, during the summer, accumulates a large amount of heat. Due to the effect of the sea, the variability of the air temperatures on the coasts is greater than that over the open sea. The greatest annual temperature variations are characteristic of the northwestern part of the sea, while the central and southeastern parts feature the least variations.

From September to March, the air temperature distribution over the sea is quasi-zonal. The highest temperatures are noted in the southeast and southwest of the sea in the regions with great sea depths. The lowest mean monthly temperature (down to negative average values of –1 to –2 °C), are observed in February in the northwest; the highest values (up to 24 °C) were registered in August off the Caucasian coast (Fig. 5b).

The differences in the annual temperature trends over the sea are best expressed in the wintertime, when the mean monthly values in February range from – 2 °C in the northwest to 7.5 °C in the southeast. During the warm season, the differences are not so great (Fig. 6) – the mean values for August vary from 21.5 °C in the northwest up to 24.0 °C in the southeast.

The low mean daily air temperatures (–23 to –25 °C) are noted under the northerly, northeasterly, and easterly synoptic processes in January and February. When these processes give place to the southeasterly, southerly, and southwesterly ones, the temperature growth may be rather rapid, reaching 8–10 °C per day. On the whole, negative temperatures occur over the entire sea area; they are mostly noted in January and February with highest recurrences over the northwestern and northeastern parts of the sea—in these

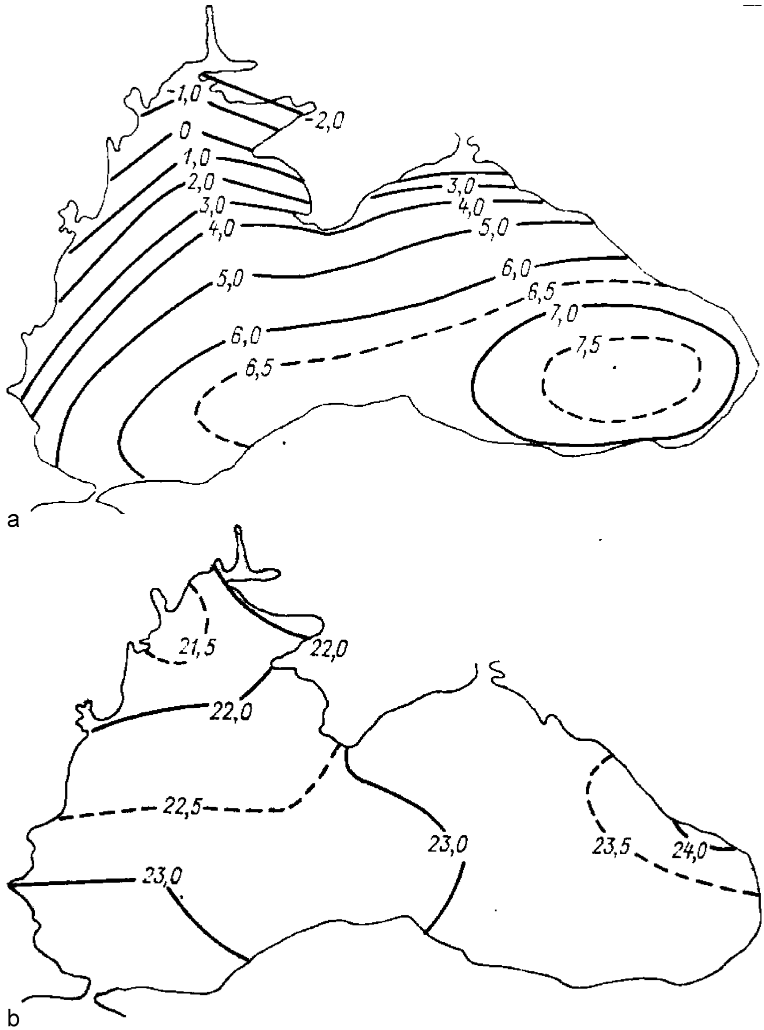

Fig. 5 Mean air temperature, °C, **a** in February and **b** in August

regions, from 6 to 10 days per month with temperatures from 0.0 to – 4.9 °C are registered. In selected years, the number of days with negative air temperatures may reach 22–26 in January and February and 13–15 in December and March.

The warmest regions are the Caucasian and Anatolian coasts of the Black Sea. There, air temperatures rarely drop below zero. In selected years, the number of such days may comprise 5–8 in January and February and 1–2 13–15 in December and March. In these regions, mean daily temperatures below –5 °C are noted once per 10–20 years, on the average. On the southern coast of

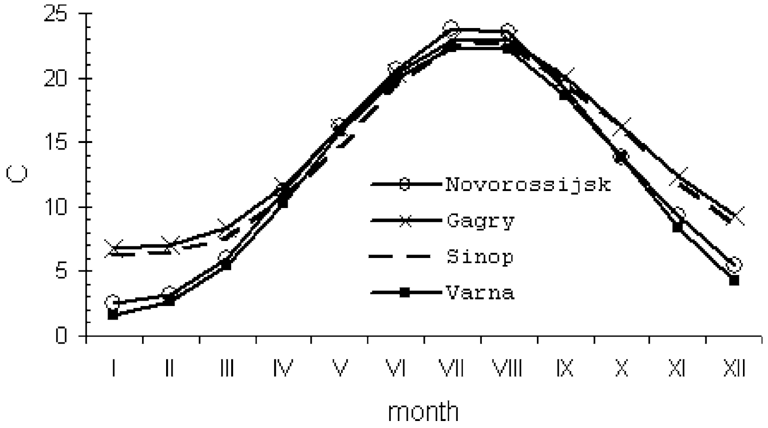

Fig. 6 Mean monthly temperature, °C

the Crimea, where mountains prevent cold from penetrating from the north, air temperatures below 0 °C are also rare: on the average, 3–4 days in January and February (up to 13–15 days in selected years) and 1–2 days in December and March.

On the coast, mean air temperatures below –10 °C are observed but not every year. Only in the northwest and northeast of the sea may these temperatures be observed during 7–14 days in January and February, 5–8 days in December, and 2–3 days in March. On the southern coast of the Crimea, over the past 75 years, only two cases were registered when the mean daily air temperature dropped below –10 °C.

Against the background of temperatures below 10 °C, sharp warmings are possible,which are caused by the warm air advection from the south in the process of cyclonic activity. In mountainous parts of the coast, warmings related to the foehn events are especially sharp. In these cases, the temperature growth rate may reach 15 °C per day and more. On the contrary, during the bora events, one observes a sharp temperature drop by 10–15 °C as compared to the temperature before the beginning of this wind.

The period with a stable mean daily air temperature of 20 °C and higher is the shortest in the northwest of the sea; here, lasts it from the end of June to the beginning of September. Its average duration in this region comprises 70–80 day; toward the southeast of the sea, it grows up to 100–110 days per year. Over the major part of the coasts, mean daily temperatures higher than 30 °C are possible in the summertime. Meanwhile, the mean daily temperature threshold of 35 °C was never overcome. The number of moderately hot days with a mean daily temperature from 20 to 25 °C is especially great in July and August and, on average, comprise 20 days per month (up to 25 days per month on the Anatolian and the southern part of the Caucasian coasts). Hot weather with a mean daily temperature higher than 25 °C is observed over

3–9 days per month in the north of the Black Sea coast, 10–11 days on the southern coast of the Crimea, and 2–7 days in the southern part of the Caucasian coast. Over the entire coast, the greatest recurrences of hot days are confined to July and August. At mean daily temperatures of 30 °C and higher, the maximum temperature values may reach 35–40 °C.

Daily trends of coastal air temperatures feature maximum values at 13–16 h; in the summertime, the peak is observed later than in the winter. The temperature minimum is observed early in the morning at sunrise. The extreme temperature values in the open sea are delayed by 1–2 h as compared to the coastal areas. In mountainous parts of the coast, against the background of the nighttime temperature decrease, its short-term peaks (by 0.5–5 °C during a few tens of minutes) are sometimes observed [4]. The reason for this kind of foehn effect lies in the irregular pulse character of the air downwelling at a nighttime mountain wind and its adiabatic heating. In this process, the moisture content may drop by 5–10%.

Over the entire sea, the daily amplitudes of the temperature variations in the winter period are greater than those in the summertime, except for the eastern region, where it is greatest in the fall. In so doing, the daily amplitudes grow from the southeast to the northwest. The inter-daily temperature variability generally decreases from the north to the south; in the cold season, it is 2–3 times as great as in the warm season. On average, coolings are more intensive than warmings: inter-daily temperature drops may reach 10–15 °C, while temperature rises rarely exceed 10 °C.

Moisture content. The regime of the moisture content over the sea is determined by the processes of interaction between the air and the sea surface. In coastal regions, the diurnal variations in the moisture content are additionally affected by the breeze circulation. The daytime breeze supplies humid air from the sea to land areas. In contrast, the nighttime breeze delivers dry air to the sea surface. The flux of relatively dry air is also provided by foehns and boras.

The intraannual changes in the water vapor partial pressure follow the annual trend of the air temperature over the sea (Fig. 7a). The lowest values are observed in January and February, while the highest are confined to July and August. During the entire year, the spatial distribution of the water vapor contents also corresponds to the air temperature distribution. The lowest values of the partial pressure of water vapor are noted in the northwest of the Black Sea (4.7–20 hPa on the coast and 5.0–21.0 hPa over the sea). The water vapor content grows in the southeastern direction (7.2–23.4 hPa on the coast and 8.0–24.0 hPa over the sea).

The annual trend of the relative moisture content over the greater part of the Black Sea shows its maximum values in the cold season of the year and the lowest values in the warm period. The humid subtropical areas of the eastern coast are characterized by a somewhat distinct regime; here, the highest values are observed in the summer and the intra-annual variations are in-

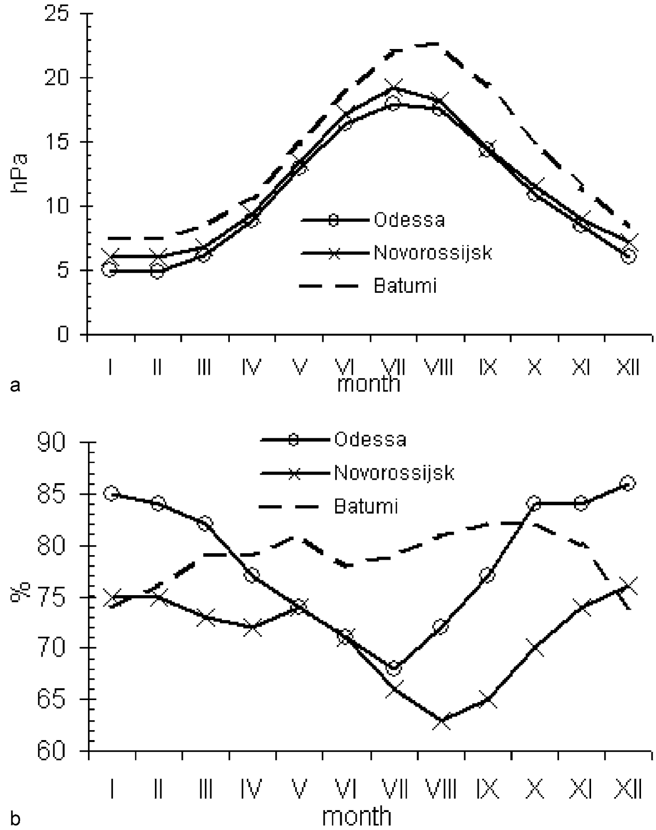

Fig. 7 Annual trends of the **a** partial pressure of water vapor, hPa and **b** relative moisture content, %

significant (Fig. 7b). The regularities of the spatial distribution of the relative moisture content over the Black Sea in the summer season are similar to those of the distribution of the water vapor partial pressure. The lowest values of the relative moisture content are characteristic of the northwestern areas, while the highest values are confined to the southeastern and southwestern parts of the sea. On the contrary, in the wintertime, the relative moisture content grows from the southeast to the northwest.

Atmospheric precipitation. Atmospheric precipitation over the Black Sea is mostly related to the cyclonic activity. The convective process plays a noticeable role only it near-shore band and on the coasts. An additional influence is provided by the topography of the coastal zone. Throughout the year, the precipitation amount grows from the northwest (380–420 mm/year) to the southeast, where the Caucasian ridges approach the coastline and are oriented across the principal moisture-bearing airflows (up to 1500–2500 mm/year) (Fig. 8). The greatest number of days with precipita-

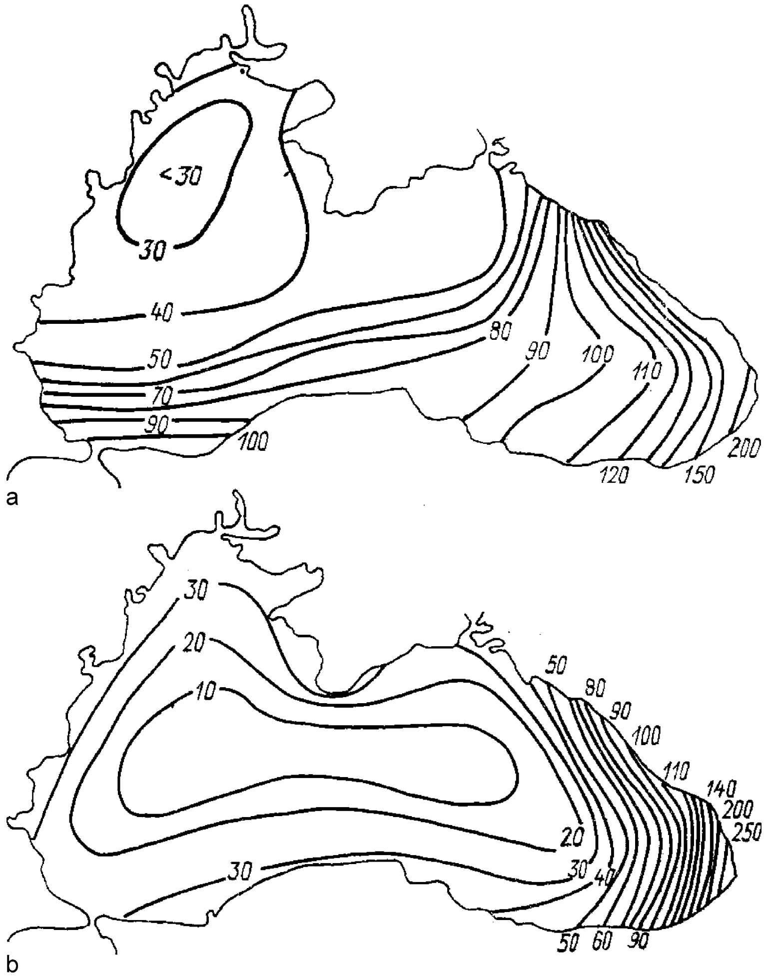

Fig. 8 Mean monthly precipitation, mm/month, in **a** February and **b** August

tion is observed in the same regions where the precipitation proper is the highest. In the southeast, the annual number of days with precipitation is 100–170, while on the northwestern and Crimean coasts it equals 100–125 with a maximum in the region of the southern coast of the Crimea. In the summertime, the precipitation intensity is greater. In the winter season, especially on the northern coast of the sea, precipitation may take the form of a snowfall, though no stable snow cover can be formed. On average, during the winter, 25–40 days with a snow cover on the northwestern coast, 15–25 days in the Crimea (on its southern coast, not greater than 15 days), 14–17 days in the northeast, and less than 15 days in the southeast are observed.

3 Wind Waves

According to the character of the wind activity over the sea, heavy waves develop mostly in the autumn and winter in the northwestern, northeastern, and central parts of the sea. In the sea, depending on the wind speed and wave vector distance, waves with heights of 1–3 m dominate. In open sea regions, the maximum wave heights may reach 7 m; at strong storms, they may be even higher. The southwestern and southeastern parts of the sea are the calmest; here, strong winds are rare and usually wave heights do not exceed 3 m even at storms.

The wind wave regime of the Black Sea is poorly studied, since there were virtually no regular instrumental observations of waves in the open part of the sea. The principal characteristics of the waves were determined using calculations; this also refers to the wave heights cited above. Meanwhile, under extreme conditions, the wave height may be significant. For example, on November 14, 1854, during the Crimean war, in the region of Balaklava, the joint English–French squadron of 34 battleships sunk; the losses reached 1500 seamen. Later, such extreme storms were registered in November of 1969, 1981, and 1992. In these cases, the maximum wave heights in the open part of the sea may reach 14–15 m.

The strong waves that develop during storms create serious obstacles for practical activities in the sea and on the coasts, such as dangers for navigation, destruction of coastal constructions, and, recently, from losses at the prospecting and extraction of hydrocarbon resources. In some cases, the storm activity is enhanced by local winds owing to the orographic effects.

One of the most hazardous aftereffects related to the wind wave action is the appearance of the so-called tyagun phenomenon in selected ports of the Caucasian coast. In these cases, the ships in the ports both moored and anchored start to spontaneously move; they are pressed to the piers or, on the contrary, moved away from the moorings breaking their fastening ropes. This phenomenon may last a day or longer, the reason being supposedly related to the generation of a resonance of natural oscillations of the water mass in the basin of the port caused by the penetration of the long swell waves into it with the free oscillations of the ship moored. The tyagun is most frequently observed in the port of Tuapse (up to 20 cases per year) and in the ports of Poti and Batumi (5–7 cases per year) [1, 5].

4 Water Balance

Calculations of the water balance of the Black Sea were performed by many scientists and their results are naturally slightly different. This depends on the values of the data taken as the basis for the calculations and of the periods of averaging. The component most difficult for its estimation is the water exchange via the Bosporus Strait, due to its strong variability and lack of instrumental data. Here, the information on the water balance mostly corresponds to the most complete dataset for the period 1923–1985 presented in [1]. Meanwhile, recently V.N. Mikhailov obtained refined data on the riverine runoff to the Black Sea (see corresponding chapter), which yields a value 16 km^3/year greater than the commonly accepted one [1]. Due to this, we slightly corrected the loss component of the water exchange via the Bosporus Strait.

The receipt part of the water balance of the Black Sea consists of the riverine runoff, atmospheric precipitation, and marine water supply via the Bosporus and Kerch Straits. A small contribution is also provided by the ground water delivery. The expenditure part of the balance includes evaporation from the water surface and the removal of the Black Sea waters via the Bosporus and Kerch Straits. The mean annual value of these components of the balance (under certain assumptions) comprises about 816 km^3/year, that is, only 0.15% of the total volume of the Black Sea waters. Approximately 354 km^3 of riverine waters is annually supplied to the sea; of them, up to 200 km^3 is contributed by the Danube River. The atmosphere precipitation in the form of rain and snow provides 237 km^3 of water. The lower current via the Bosporus Strait annually delivers about 175 km^3 of saline waters of the Sea of Marmara, while the Kerch Strait supplies approximately 50 km^3 from the Sea of Azov. The mean annual water expenditure for evaporation comprises up to 396 km^3; the upper current in the Bosporus Strait removes about 385 km^3 of the Black Sea water to the Sea of Marmara, and the water removal via the Kerch Strait to the Sea of Azov makes up to 35 km^3. Thus, the receipt part of the balance mostly consists of riverine waters, which comprise about 40% of all the water supplied. This component is characterized by a strong variability. The expenditure part of the balance consists of evaporation and water removal via the Bosporus. Meanwhile, evaporation features a low variability and thus has no significant effect on the variations in the water regime.

The distribution of the waters supplied over the sea area is quite irregular. The riverine runoff is mainly concentrated in the northwestern part of the sea (up to 80%) and, to a smaller extent, in the southeast. The waters of the Sea of Azov with a salinity of 10–14 psu flow via the Kerch Strait to the northeastern part of the Black Sea. They feature a low density and propagate with currents in the upper sea layer. The saline (about 30 psu) waters of the Sea of Marmara are delivered with the lower Bosporus current to the southwestern part of the sea at a level of about 50 m.

The degree of the desalination of the upper water layer of the sea throughout the year mostly depends on the volume of the riverine runoff and its distribution over the sea area. In the spring–summer season, the sea receives about 60% of the annual runoff volume. On average, the maximal and minimal runoff values are noted in May and September, respectively. The seasonal and interannual changes in the components of the water balance finally affect the sea level and the water exchange via the Bosporus Strait.

In the above-described version of the water balance, we assumed equilibrium between its receipt and expenditure parts, which is rather conventional. For example, owing to the sea level rise recently observed in the Black Sea (see this chapter), the water supply should exceed the water loss by approximately 2 km^3/year (or even more). However, the tendencies of the sea level changes at different sites of the coast are different and not everywhere registered. Therefore, in order to generally estimate the water regime, we found it reasonable to present the water balance rather than the water "budget" of the Black Sea.

5
Sea Level

The observations of the Black Sea level started in the middle of the 19th century. The longest observation series are available in Romania for the ports of Constanta and Sulin (since 1858), in the Ukraine (Ochakov, since 1874; Odessa and Sevastopol, since 1875), and Georgia (Poti, since 1874 and Batumi, since 1882). At present, the observation network of the Black Sea level includes 30 stations (of them, 13 in the Ukraine, five in the Russian Federation, four in Bulgaria, three in Romania, three in Turkey, and two in Georgia). During the past decade, the sea level is also studied with the use of satellites.

Multiannual sea level changes. An analysis of the data of observations of the Black Sea level over the last century allowed one to recognize to stages in its multiannual variability [6]. At the first stage (from the beginning of the observations up to the middle 1920s), the level was relatively stable with a slight tendency to fall. Subsequently, it began to rise at an average rate of 0.16 cm/year (Table 1); during selected intervals, this rate was significantly higher. For example, at the Tuapse hydrometeorological station, the general tendency over the entire period of observations is 0.23 cm/year, while during the last decade of the past century, it comprised 1.2 cm/year (Fig. 9).

The present-day rise of the Black Sea level is most often explained by the variability of the components of water balance of this basin [7, 8]. Among the other reasons for this phenomenon one should note the general level rise in the Atlantic Ocean [9].

In the multiannual variability of the Black Sea level, in addition to the tendency to the sea level rise, we can distinguish some reliable interannual periods: 2.5, 3.5–4, and 10–20 years (Fig. 10). These sea level oscillations are most often explained by the changes in the freshwater balance of the Black Sea [9].

Table 1 Tendencies in the sea level changes at different points of the Black Sea

Hydrometeorological station	Observation period	Tendency, cm/year	Standard deviation, cm/year
Odessa*	1923–1995	0.44	
Khorly*	1923–1995	0.14	
Blacksea*	1927–1995	0.17	
Evpatoriya*	1923–1995	0.18	
Yalta*	1927–1995	0.19	
Sevastopol	1910–1994	0.13	0.028
Feodosiya*	1923–1995	0.14	
Anapa*	1923–1995	0.13	
Novorossiisk*	1923–1995	0.13	
Tuapse	1917–2002	0.23	0.027
Sukhumi*	1926–1995	0.12	
Batumi	1882–1996	0.18	0.021
Burgas	1929–1995	0.16	0.043
Varna	1930–1996	0.14	0.044
Constanta	1933–1996	0.13	0.051

(* after [12])

Seasonal sea level oscillations. Interannual level changes in the Black Sea are mainly defined by the variations in the water balance components, seawater density, and atmospheric pressure.

On average, the range of the seasonal sea level oscillations at the coastal hydrometeorological stations reach values of 15–20 cm; in so doing, the highest level is observed in June–July, and the lowest sea level standing is confined to October–November (Fig. 11).

The level changes caused by the atmospheric pressure variations (the inverse barometer effect) comprise approximately 7–8 cm with a maximum in July and a minimum in November–January [1].

The ranges of the steric sea level oscillations related to the changes in the seawater density are different over the Black Sea area [10]. The highest annual ranges of the steric oscillations are observed in the central (up to 20 cm) and southeastern (up to 16 cm) regions; their lowest values are characteristic of the center of the eastern part of the sea. The explanation of this kind of spatial pattern may be found while assessing the phases of the annual harmonics of the total level and its temperature and salinity components.

The maximum of the temperature component of the annual harmonic of the steric sea level is observed approximately simultaneously over the entire sea (in August) because of the location of the Black Sea in the single climatic zone. Meanwhile, the phases of the maximum of the salinity component in different regions of the sea differ by a few months. For example, in the near-

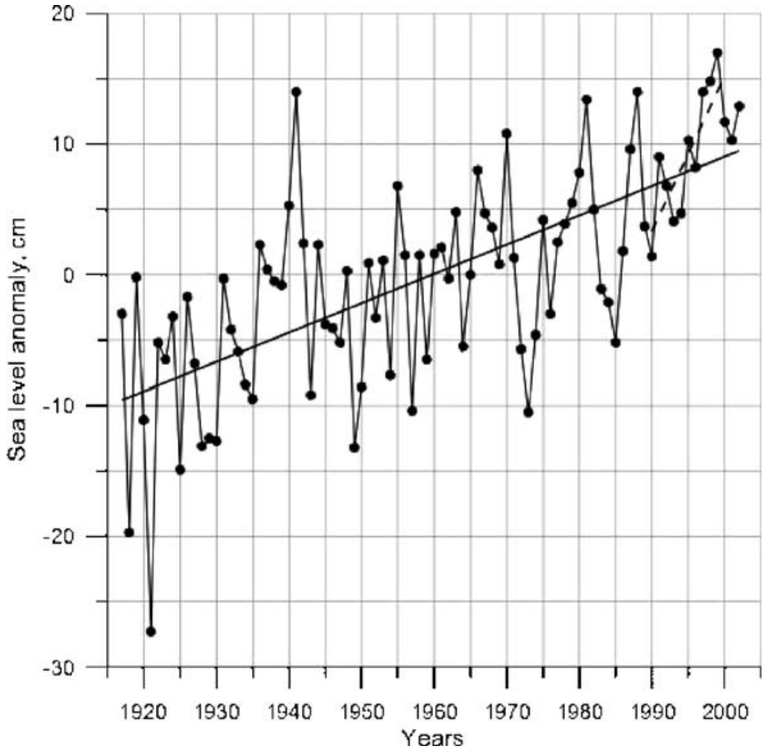

Fig. 9 Mean annual sea level anomalies in Tuapse according to the data of the PSMSL (Permanent Service for Mean Sea Level). The *solid line* shows the linear trend for the entire observation series; the *dashed line* represents the data for 1990–2000. Sea level anomalies were calculated with respect to the mean value over the entire time of observations at the hydrometeorlogical station

shore areas, the range maximum of this component is observed in the spring period, which is related to the riverine runoff, while in the central parts of the sea, the maximum is observed in August, which is the period of the lowest intensity of the cyclonic circulation. In the regions in which these phases coincide, their coupled range is equal to the total range; phase shifts result in discrepancies between these ranges (for example, the southwestern region).

Storm surges. These significant nonperiodical sea level oscillations are caused by coastal winds. In so doing, their range and duration depend on numerous factors such as the time of forcing, the wind direction and speed, the outlines of the coastline, the shelf depth, and the water stratification. The most complete characteristics of the storm surges in the Black Sea are presented in [1, 11].

It was shown that the most significant storm surges are noted off the western and northwestern coasts of the sea over small sea depths near the shore. Here, the storm surges are formed during the cold period of the year. In

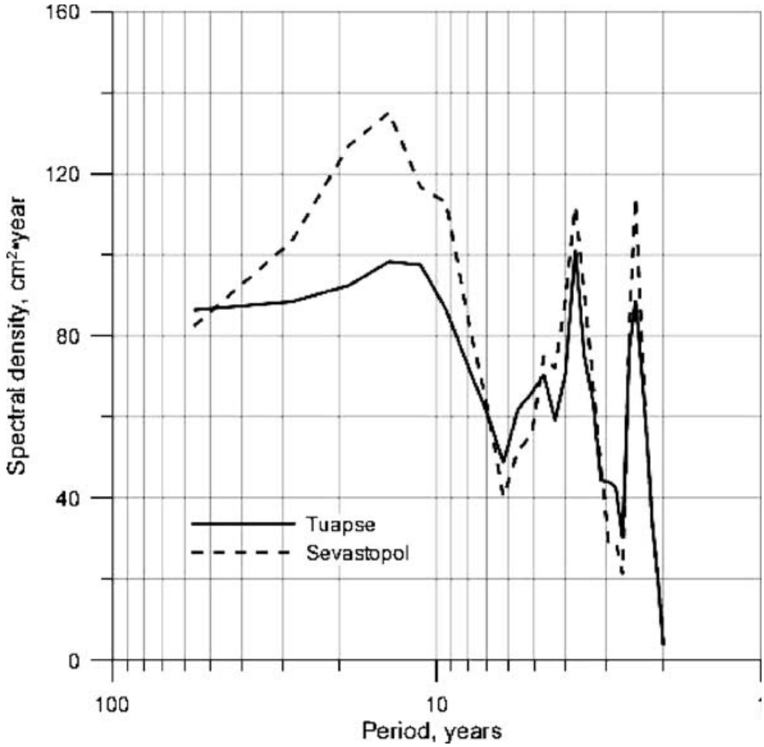

Fig. 10 Spectral density of the mean annual sea level in Tuapse and Sevastopol for 1917–2002

most cases, their values are about 30–40 cm. Storm surges with values greater than 40 cm are rarely observed; they are mostly confined to the autumn–winter period. Information about the maximum and minimum values of storm surges is shown in Table 2. For instance, near Primorskoe, the maximum height (115 cm) of storm surge was observed in the winter season. In the Odessa area it was about 100 cm in autumn. Off the Crimean coasts, the storm surges are small, while off the Caucasian coast their amplitudes may reach 70–90 cm.

The duration of the storm surge events varies over a wide range (2–57 h) and depends on the duration of the wind forcing and on the stability of the wind direction; in the shallow-water northwestern parts of the sea it is lower than in the deeper areas off the Crimean and Caucasian coasts.

Seiche sea level oscillations. The level of any basin, being turned out of its equilibrium state by a certain force, returns to its initial position performing decaying oscillations with respect to one or several horizontal lines (nodal lines) until their energy is expended for bottom and coastal friction. These free oscillations are known as seiches (uninodal or multinodal depending on

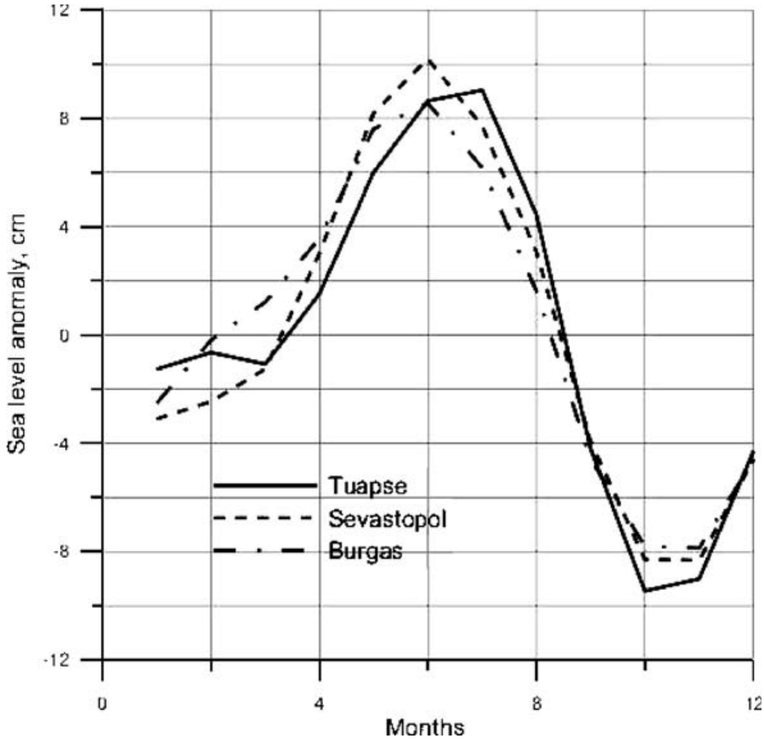

Fig. 11 Mean seasonal sea level variability (cm) in Tuapse, Sevastopol and Burgas

the number of nodal lines). The range of seiche oscillations is defined by the energy of the impact upon the surface of the basin. On nodal lines, no oscillations occur. Their maximal ranges are observed near the coasts of the basin most remote from the nodal lines. The mechanisms of the seiche generation are different for completely closed and semi-enclosed basins. In closed basins, seiches are induced owing to direct impact of an external force (wind, atmospheric pressure, etc.), while in bays and bights seiches are mainly excited directly through the open boundary.

In the Black Sea, the ranges of the seiche oscillations of the basin as a whole are low (up to 7 cm), while in bights and bays they may reach 50 cm [6]. The period of the seiche oscillations depends on the mode of the natural oscillation, the size of the basin, and its depth. For the entire sea, it comprises a few hours (for ten first modes), for bays the periods may be as small as a few minutes up to 1–2 h. The duration of the seiche oscillations, in most of the cases, comprises 6–10 h.

In order to study the spatial structure of seiches and to estimate their periods in the Black Sea, the corresponding sets of equations of fluid motion were numerically simulated. In [13] it was shown that the greatest period

Table 2 Maximal values (cm) of storm surges with respect to the mean monthly level position in 1880–1985 [12]

Site	Month											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
	Storm surges											
Vilkovo	111	151	94	62	65	69	69	55	55	71	74	80
	77	77	78	78	53	56	50	69	56	66	54	67
Izmail	189	193	192	157	168	184	186	207	225	233	216	190
	177	178	229	161	165	179	174	126	108	125	148	161
Primorskoe	89	125	107	58	41	31	43	47	50	88	56	91
	64	67	48	41	34	45	36	48	76	89	72	48
Belgorod Dnestrovskii	62	49	46	55	57	50	42	42	54	59	71	64
	56	55	66	59	58	50	43	43	73	60	91	59
Il'ichevsk	72	74	70	57	67	41	38	43	59	92	106	57
	75	71	72	62	39	46	42	59	56	60	101	63
Odessa	106	95	96	87	93	67	66	75	79	120	109	99
	114	113	77	69	88	74	66	70	68	84	174	98
Ochakov	71	68	61	66	63	50	45	40	56	61	78	74
	83	94	83	69	58	48	37	75	52	62	80	79
Nikolaev	91	96	108	79	90	67	99	89	76	77	125	124
	90	94	110	100	72	74	58	60	70	73	105	99
Kherson	96	76	92	148	267	155	83	72	71	89	90	99
	82	87	97	96	113	61	52	38	67	72	88	137
Poti	78	84	65	55	55	53	49	52	53	71	74	85
	67	75	70	69	63	56	60	67	71	77	82	65
Batumi	65	57	91	43	44	39	44	40	55	82	90	102
	35	50	41	39	33	29	40	44	37	36	33	35

of the seiche oscillations in the Black Sea equals 9.7 h. This seiche is represented by a uninodal oscillation with the nodal line running over the seaward edge of the shelf that serves as a natural boundary between the shallow-water northwestern and the deep-water parts of the sea. The greatest ranges of seiche oscillations are observed on the shelf of the northwestern part of the sea, especially in Odessa bay.

Tidal sea level oscillations. In the Black Sea, tides are formed under the action of the tidal forces in the basin proper, which is limited in size; therefore, the tides are small. Over the entire sea area, tides feature a semidiurnal or irregular semidiurnal character. The prevalence of this type of tides is related to the closeness of the semidiurnal period to that of the first mode of free oscillations in the Black Sea (uninodal seishe).

Table 3 Mean and maximal tidal ranges in the Black Sea, cm [3]

Station	Mean values		Maximal tide
	Spring tide	Neap tide	
Poti	9, 6	2, 4	12, 1
Tuapse	3, 5	0, 2	4, 7
Novorossiisk	4, 9	1, 8	6, 3
Il'ichevsk	11, 6	4, 6	14, 5
Batumi	10, 0	2, 0	13, 0
Odessa	14, 0	2, 8	17, 0
Yalta	∼ 0	∼ 0	∼ 0
Sevastopol	∼ 0	∼ 0	∼ 0
Varna	3, 6	0, 2	4, 7
Burgas	8, 2	3, 0	11, 2

The spatiotemporal distribution of the tidal energy over the Black Sea proves the correctness of the inference on the seiche-like character of the Black Sea tides. For example, the tides in the western and eastern parts of the sea are almost precisely in antiphase. In doing so, the highest tides are observed in the northwestern and southeastern parts of the sea. Meanwhile, off the Crimean coast, almost no tides are noted.

The highest tides in the Black Sea are noted in Odessa Bay (up to 17 cm) and in the Poti–Batumi region (up to 13 cm) (Table 3).

Level oscillations caused by tsunamis. Tsunamis are sea waves generated by strong underwater earthquakes or intensive landslides. In the region of the Black Sea, several strong earthquakes accompanied by tsunami wave generation were noted. They include, for example, the Yalta earthquake on September 11–12, 1927, the Turkish earthquake on December 27, 1939, and the Anapa earthquake on July 12, 1966. The height of the wave generated by the Turkish earthquake reached 50 cm in Sevastopol, 53 cm in Novorossiisk, and 40 cm in Tuapse. The tsunamis observed were not hazardous. However, it is supposed that a strong earthquake (such as the Turkish one) with its epicenter located in the sea may generate a tsunami wave a few meters high.

6 Sea Ice

The Black Sea is a partly freezing basin. Ice is formed only in a narrow band in its northwestern part. Even in severe winters, it covers no more than 5% of the sea area, while in moderate winters the coverage comprises 0.5–1.5% of the area. In extremely severe winters, fast ice extends along the western coast to the south up to Constanta and floating ice may driven as far as to the Bosporus Strait. Over the past 150 years, ice flows in the strait were observed five times. In mild winters, only lagoons and selected bights are covered with ice.

In moderate winters, the boundary of the resting ice in the northwestern part of the sea runs at a distance of 10 km from the coast from Dniester Lagoon to the Tendrovskaya Spit. Farther, the ice edge crosses Karkinitskii Bay and reaches the middle part of the Tarkhankut Peninsula. The average thickness of the ice never exceeds 15 cm, but in severe winters it can reach 50 cm. In the Kerch Strait, the ice appears every year. The northern part of the strait up to the Tuzla Spit together with Taman' Bay is its most icy part. Here, the ice is most stable and has a thickness reaching 30 cm. In the southern part of the Kerch Strait, floating ice is observed in the middle–terminal winter period, while local ice is rarely formed. During the winter, the strait may be repeatedly opened and frozen. At strong northerly and northeasterly winds, large masses of compact and hummocky ice are accumulated at the northern entrance to the strait preventing from ship navigation. Meanwhile, under southerly winds, the strait is quickly released from compact ice.

Usually, the ice formation in the sea starts in mid-December while the maximum ice extension is observed in February. The sea is released from ice in March (early release at the beginning of March and late release at the beginning of April). The duration of the ice period ranges from 130 days in extremely severe winters to 40 days in mild winters.

The ice cover of the Black Sea is characterized by instability. In different regions of the northwestern part of the sea, ice can repeatedly appear and disappear. The number of such releases per winter is 2–4 times on average and may reach ten times or more. The ice coverage of the northwestern part of the Black Sea is well correlated with the air temperature in this region [1].

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