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MARINE PHYSICS

Temperature and Salinity Variations in Caspian Sea Waters in the 20th Century

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Abstract—One the most complete megadatabases for the period of 1914–2010 is used to study the interannual dynamics of salinity and temperature of Caspian Sea waters. Periods with relatively stable sea levels but different climatic conditions are considered. Average interannual climatic salinity and temperature profiles of water and corresponding anomalies are analyzed. Quantitative and qualitative changes in the structure of seawater that took place during the 20th century are described. Schemes of water exchange between particular sea regions for different sea levels are proposed.

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INTRODUCTION

There are several stages of the Caspian Sea level that can be distinguished throughout the 20th century (Fig. 1c): high stand (–26 m before 1934), drop (down to –28.9 m by 1977), growth (up to 1992), and stabilization at a relatively high level (about –27 m until 2000). After 2010, a slow drop in sea level began, which, given ongoing climate change, may lead to restructuring of the sea's entire hydrological regime.

In the 19th–21st centuries, a number of comprehensive studies were carried out in the Caspian Sea, the main results of which were published in monographs and general reference books on climate [3–21, 24–27]. The main regularities in the seasonal and interannual dynamics of the elements of the sea's hydrological regime were revealed. Meanwhile, virtually the whole time, the initial primary data underlying these studies were unavailable to a broad range of users, while the cartographic data were compiled into schematic charts.

It should be noted that the mentioned publications utilized the data obtained in different years, with different processing methods, and this lack of unity influences interpretation of the results, especially when comparing publications considering different periods. For example, salinity studies in the Northern Caspian Sea in the period of lowest sea level stand (1977–1978) led specialists to ambiguous conclusions: (a) by 1977, there was almost no difference between salinity in the western and eastern parts of the sea [5]; (b) from 1945 to 1980, salinity in the western part remained much higher than in the eastern [28]; (c) salinity in the eastern part approached that of the western part, even exceeding it in 1977 [14].

In the 20th century, informational and technological support for these studies considerably improved. Manual data-processing methods and physical paper storage were replaced by automated observation systems and digital databases. Information technologies which tested and broadly used in geographic sciences allow researchers to document (or digitize) historical data with retention of measurement systems and cartographic projections, which is especially important for constant sea level variations in the Caspian Sea and, therefore, changes of its shoreline.

The creation of a digital database of initial oceanographic data for the Caspian Sea, taking into consideration world-level standards on its design, storage, and distribution of information, has the goal of saving and reconstructing study results that have accumulated from long-term instrumental observations. In addition, such a database is subsequently used to obtain new conclusions and generalizations.

In the present work, we attempted to reveal and analyze the main peculiarities of seasonal, spatial, and

† Deceased.

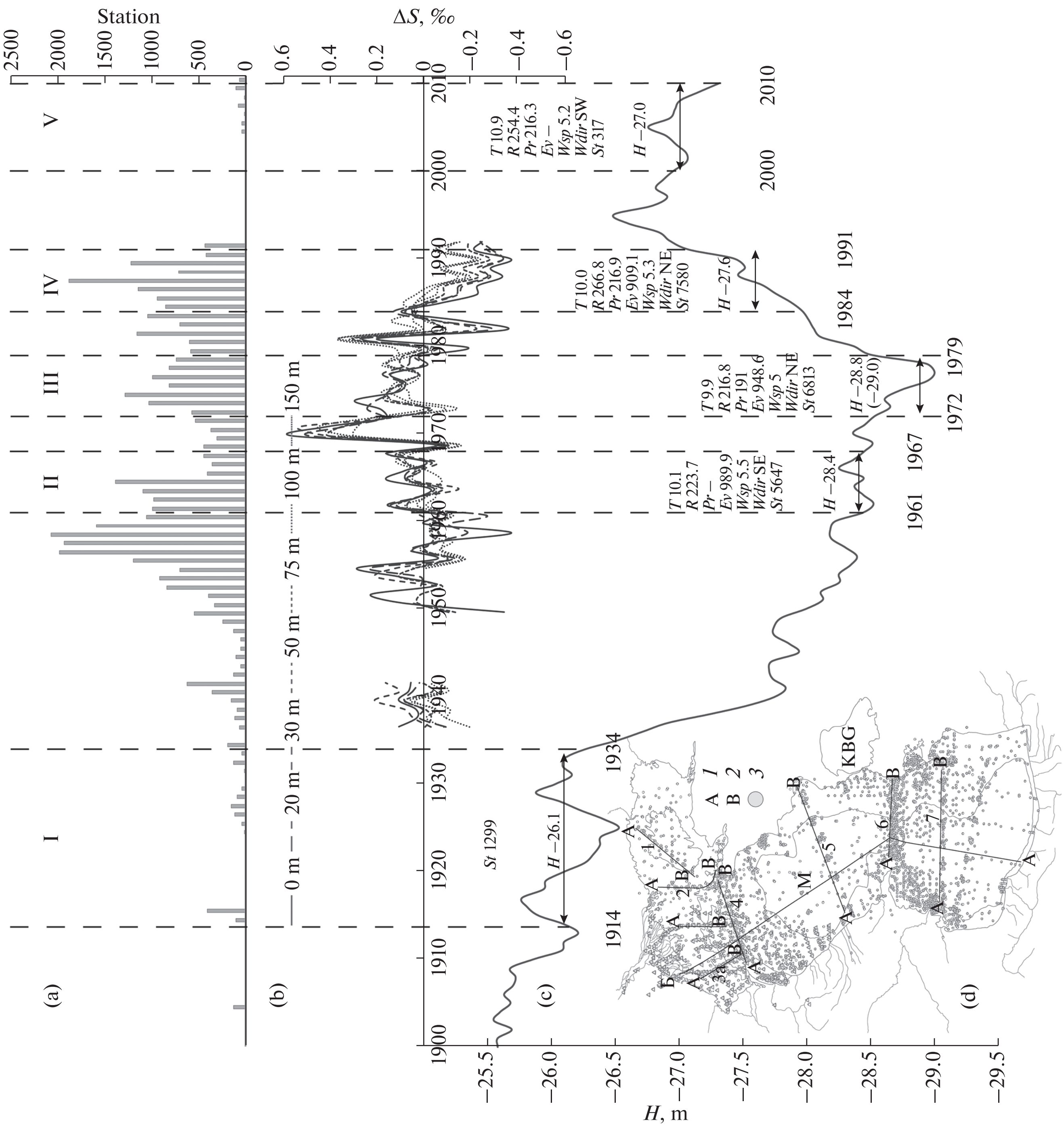

Fig. 1. Interannual variations of Caspian Sea level in selected period: (a) distribution of stations presented in database by year; (b) water salinity anomalies (ΔS, ‰) relative to mean interannual value along profile 6; (c) interannual variations of Caspian Sea level; (d) spatial distribution of data in database and locations of centennial profiles: (*1*) starting point of profile, (*2*) end point of profile, (*3*) observation data. *T*, mean interannual temperature (°C) according to Astrakhan meteorological station; *R*, mean interannual river discharge (km^3/yr) in Verkhnee Lebyazh'e River section; *Pr*, mean interannual precipitation (mm) according to Astrakhan meteorological station; *Ev*, mean interannual evaporation (mm/yr; after R. Wardlow [36, 37]); *Wsp*, mean interannual wind speed, based on reanalysis data (m/s); *Wdir*, mean interannual wind direction based on reanalysis data; *St*, total number of stations employed in period; *H*, sea level (m) in Makhachkala; –, no data. Hereinafter, KBG stands for Kara Bogaz Gol Gulf.

interannual temperature and salinity variations in Caspian Sea waters for a nearly 100-year observation period using a combined methodological approach and the currently available database.

MATERIALS AND METHODS

The factual basis of the work was the archive of initial oceanological and meteorological data for the period from 1897 to 2013 from 43 333 marine stations [1, 35]

(Figs. 1a, 1d). The data sources were archives of the US National Ocean and Atmospheric Administration (NOAA), United Ocean Data System (ESIMO), and particular publications, including the scientific results of expeditions conducted by the Southern Scientific Centre, Russian Academy of Sciences (SSC RAS). All these data passed a multistage quality control system in accordance with the approaches elaborated in [22, 29–34].

Today this database is probably the most complete among those commonly accessible. Free access is provided by NOAA (http://data.nodc.noaa.gov/woa/DATA_ANALYSIS/LME_supplementary/) and SSC RAS (http://atlas.ssc-ras.ru/). The data registry on the Caspian Sea, organized in the framework of the Caspian Environmental Program (CEP), contain metadata on 88 311 marine stations, but these data were available at different organizations. In his doctoral dissertation, V.S. Tuzhilkin [26] referred to a database that included more than 60 000 marine stations, but its today access status is unknown.

Studies in the Caspian Sea are almost always carried out along so-called centennial hydrological profiles (Fig. 1d) [9, 18], where marine observation stations are usually located. This is exactly why we consider profiles in our study to reveal interannual and seasonal temperature and salinity variability in Caspian Sea waters. The vertical temperature and salinity distributions for these profiles have been constructed, averaged over the entire observation period—so called "climatic norms" published in climate atlases [1, 35]—and for particular periods; the corresponding seasonal and interannual variability curves have calculated. Additionally, we considered the meridional profile across the deepest parts of the sea running from the south to the Volga River delta.

The data were averaged as follows [30]. On a regular grid with 15 × 15 cells (squares), we considered only squares that crossed the sections. In this case, each square within the limits of the profile almost always contains one standard station.

At the first stage, the data within each square were averaged at standard depths of 0, 5, 10, 20, ..., 900 m for each month of every year. The extreme (minimum and maximum) values were rejected. Thus, one square of each month of every year is characterized by single temperature and salinity values (the mean for all stations falls within the square).

At the second stage, the data for the entire considered period were averaged within months and squares at the mentioned standard horizons. Note that observations in years when such parameters as air temperature, wind speed, precipitation, evaporation, and water discharge of the Volga River had anomalous mean annual values were not used in calculating the mean climatic norm.

To analyze interannual water salinity and temperature variability, five time periods were distinguished based on combined consideration of graphs showing sea level changes, mentioned meteorological parameters, and water discharge of the Volga River (see Fig. 1 and its explanation). Within each time period, data for each month and square were averaged over the standard depths.

Thus, the vertical distributions for all centennial profiles were constructed for mean climatic conditions and characteristic periods with relatively stable sea levels (Fig. 1). We used ArcGIS ESRI software to visualize the results.

Plots of the seasonal water salinity and temperature variability at the standard depths were constructed for each square along the centennial and meridional profiles; however, in the next section, we take into account only the central squares of all sections, because they had the most abundant observation data [30].

RESULTS AND DISCUSSION

In the 20th century, the climatic conditions and water budget regime of the Caspian Sea changed considerably. Salinity and its centennial fluctuations can be considered indicators when estimating changes in water exchange in the sea [2, 23]. Below, we demonstrate that when salinity is considered in the centennial profiles, it shows a complex interannual variability with a certain cyclicity in the background. The same is applicable to the interannual water temperature dynamics. Remarkably, in some areas, interannual changes are synchronous, but not always unidirectional.

1961–1967

For the eastern part of the Northern Caspian Sea [9, 18] and the area of Kulaly sill, the period of 1961–1967 was characterized by a salinity that decreased by 1‰ compared to the mean climatic norm. The minimum salinity values in the eastern part were reported in May, when almost the entire region is filled by water with salinity less than 3.5‰. Vertical salinity stratification is absent in all months. In April, July, and October, clusters of colder (by 1°C relative to the surrounding water) and saltier (by 0.5‰) water formed above the Ural Furrow. The northern area of the Kulaly sill is occupied by waters with salinity up to 3.5‰ from May to July. Waters with salinity more than 12‰ are not reported to the north of Kulaly Island. The smallest variations are observed in the near-bottom central part of profile 4. Salinity here is lower than the mean interannual value by 0.1–0.2‰. Inflow of transformed Middle Caspian waters with salinity more than 12.5‰ into the Northern Caspian Sea took place in the layer lower than 10 m. Near the eastern coast, Middle Caspian waters wedged up to the surface (Fig. 2, profile 4).

In the period of 1961–1967, salinity in the Middle and Southern Caspian [9, 18] beyond the offshore zone was the same, 12.8 and 12.9‰, respectively (Fig. 2, profile M). Near the eastern coast, salinity reached 13.1‰. In the narrow zone along the western coast of the Middle Caspian, the influence of water inflow from the Volga River becomes noticeable. Compared to the period of 1914–1934, water below 100 m in the area of the Apsheron sill warmed by 1°C and became 0.1‰ saltier, probably because of the changed in the water exchange mechanism for the deep basins (Figs. 2, 3, profiles 6 and M).

1972–1979

In the eastern part of the Northern Caspian Sea, vertical water stratification is absent. Similarly to the period of 1961–1967, in particular months, if the volume of supplied Middle Caspian water is large enough, clusters of higher salinity (by ≈0.5‰ relative to the overlying layers) formed in the area of the Ural Furrow. Notably, in the interannual regime, this area is marked by the highest salinity variability (Fig. 2). In the period of 1972–1979, due to minimum water discharge and increased compensatory inflow from the Middle Caspian, salinity increased by 2.5–3.0‰, reaching 10.1‰ in the area of the Ural Furrow (the average value for the entire profile is 9.2‰) [2]. Thus, salinity in the eastern and western parts were almost equalized (9.2 and 10.6‰, respectively), although salinity in the western part was higher.

Interannual variations in salinity in the Northern Caspian Sea demonstrate two peaks, in 1974–1976 and 1982–1983. The former is related to a significant decrease in river water discharge, precipitation, and lower wind speeds; the latter, to an increase in air temperature and evaporation, combined with higher wind speeds and greater river water discharge. As shown below, relative freshening is seen in all horizons after 1983.

On the background of a decreasing volume of river discharge and precipitation, the 1970s were marked by significant freshening of the northern part of profile 3a and salinization of the southern, which could have been caused by redistribution of Volga River discharge through arms. With respect to the drop in sea level and shallowing of significant areas near the delta, the main water discharge volume was directed to the western river arm. In the same time, the southern part of the section was marked by the presence of saltier (compared to the mean interannual regime) Middle Caspian water. Thus, the profile 3a in this period is characterized by significant horizontal gradients in all months. Shallowing of the water area led to impeded water exchange between the Northern and Middle Caspian. Middle Caspian water masses flowed in along the coast of the Mangyshlak Peninsula and then across the northern part of the Kulaly sill, forming a vast frontal zone. Water flowed out through the strait between Kulaly Island and the Mangyshlak Peninsula. The influence of discharge currents along the entire extent of profile 4 (Chechen Island–Mangyshlak Peninsula) in the high water period abruptly increased. In June, the salinity peak quickly spreads to the eastern terminus of the profile, but the influence of high water also quickly disappears. In August, traces of fresh water are noticeable only near the Agrakhan Peninsula. Under mean interannual conditions, the minimum salinity near the Mangyshlak Peninsula was reported in August in the periods that preceded and followed. Notably, water temperature in the areas of profiles 1, 2, and 3 increased in all months, with the exception of June, when river water discharge was maximum. Water temperature in the area of the Agrakhan Peninsula and Chechen Island, also increased. Intensive supply of cooler and more salty Middle Caspian waters occurs only into the central and eastern parts of the Northern Caspian Sea.

In the entire water area of the Middle and Southern Caspian Sea, vertical stratification of waters intensified owing to freshening of the surface layer and salinization of the lower ones (Fig. 2, profile M). This phenomenon was caused by redistribution of Volga River water discharge through its arms and by intensification of the western arm of the Volga River. The influence of river water discharge on salinity on the western shelf of the Middle Caspian Sea abruptly increased. The seasonal salinity variation pattern also changed along the profile 6 (Fig. 4).

Due to convective mixing, seasonal freshening began to reach layers deeper than 50 m. In the intermediate layer and in the near-bottom horizons, salinity increased by 0.5–1.1‰, while vice versa, in the layer above 50 m depth, it decreased by 0.2–0.3‰ (maximum change by 0.4‰ in June) with respect to the previous period. Near the eastern shelf, a slight increase in salinity is observed; therefore, the background salinity along profiles 4 and 6 remained higher compared to the 1950s. As shown by the calculations in [2], the mean salinity values along profile 4 were 11.9‰ in 1951–1965 and 12.4‰ in 1974–1980. Along profile 6, they were 12.8 and 12.9‰, respectively. In the 10–30 m layer, the mean salinity also increased.

The seasonal pattern of water temperature variations calculated for squares in the central parts of profiles over periods (Fig. 5) shows that the temperature increased by up to 1°C in summer within the near-surface layer in the 1970s. As seen in the profiles (Fig. 3), the vertical temperature distribution in the Middle and Southern Caspian demonstrated no significant qualitative and quantitative changes after the 1930s.

1984–1991

The main volume of freshwater discharge from the Volga River reached the Northern Caspian Sea through the western arm. A characteristic feature of interannual variations in freshwater discharge for the eastern part of the Northern Caspian is an abrupt decrease in salinity at all horizons after 1982 in April, June, and October, and an increase in the difference

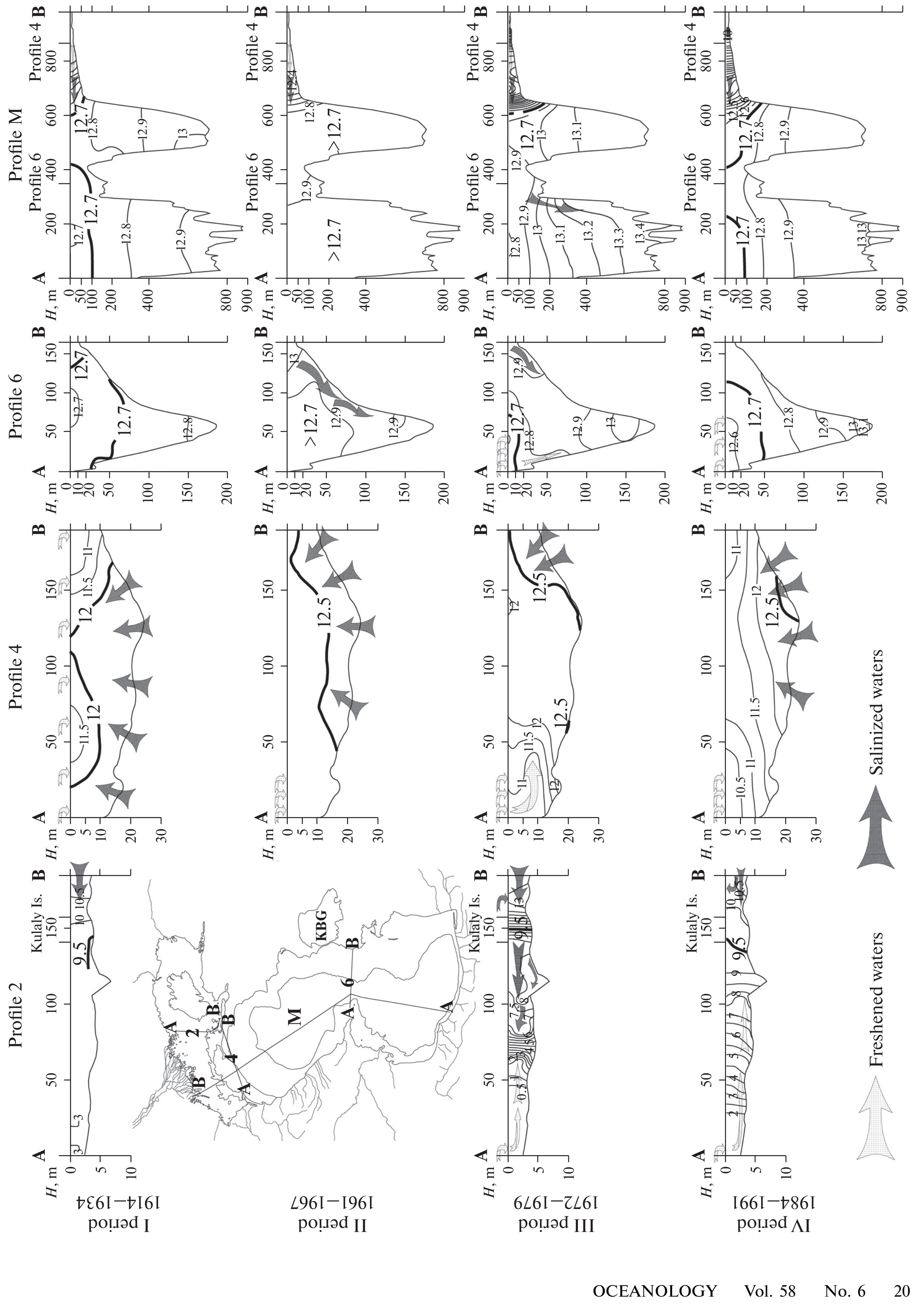

Fig. 2. Vertical distribution of salinity (‰) in Caspian Sea for characteristic periods (August).

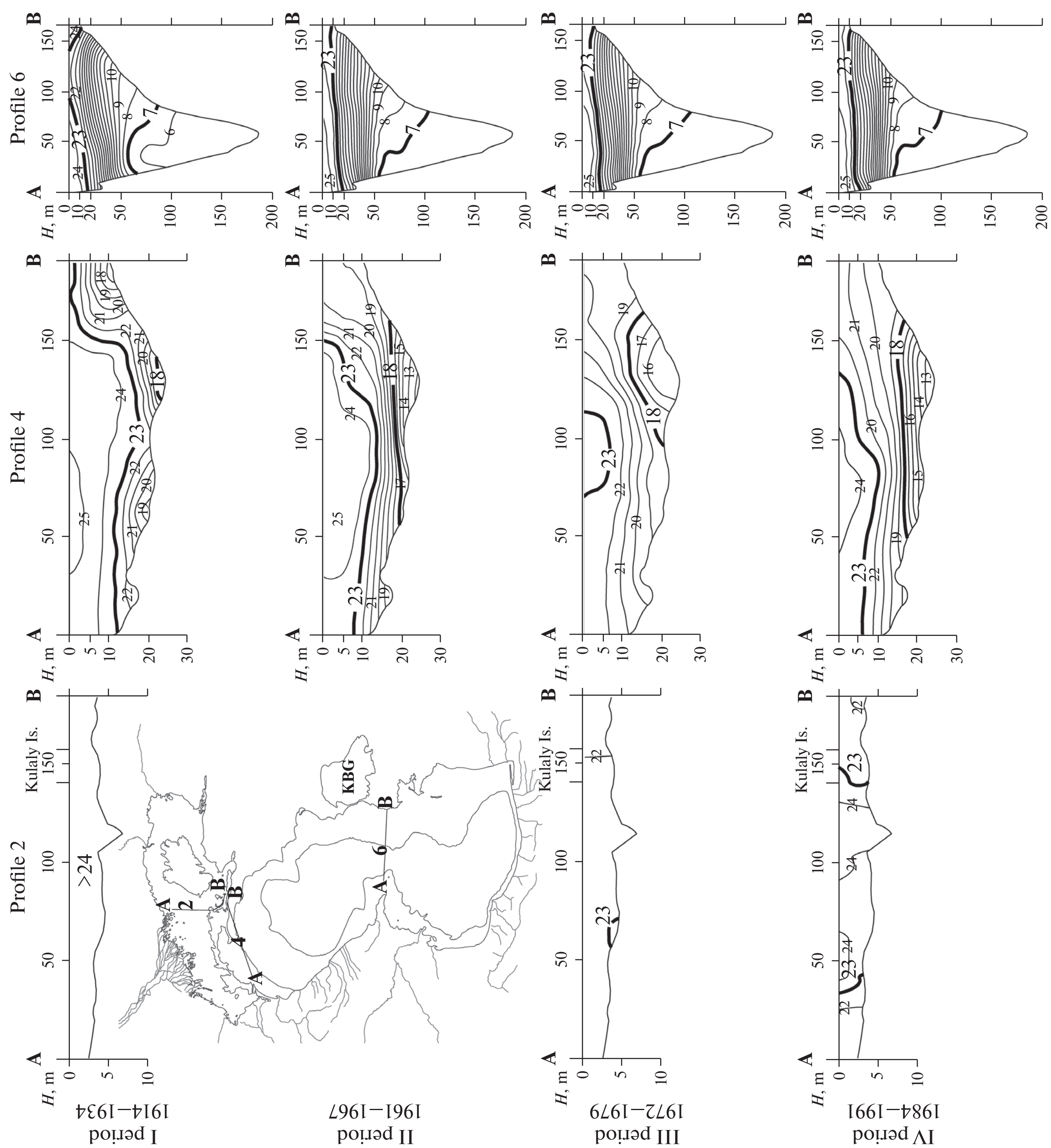

Fig. 3. Vertical distribution of water temperature (°C) in Caspian Sea for characteristic periods (August).

between surface and near-bottom horizons. A similar dynamics is observed in August at the nearshore area of the Ural River; however, no trend (either positive or negative) is seen within the limits of the Ural Furrow (>5 m depth). Only in 1991 did salinity slightly decrease in the entire water column.

In the western part of the Northern Caspian, fresh water propagated in the near-surface sea layer rather than in the usual manner along the coast. South of the continental slope, water all along profile 4 is stratified year round (Fig. 2). The same phenomenon was noted earlier [25] only in summer months in the southwestern part of the Northern Caspian. Such a change in vertical stratification and expansion of the surface freshening zone at the boundary between the Northern and Middle Caspian could have been caused by the

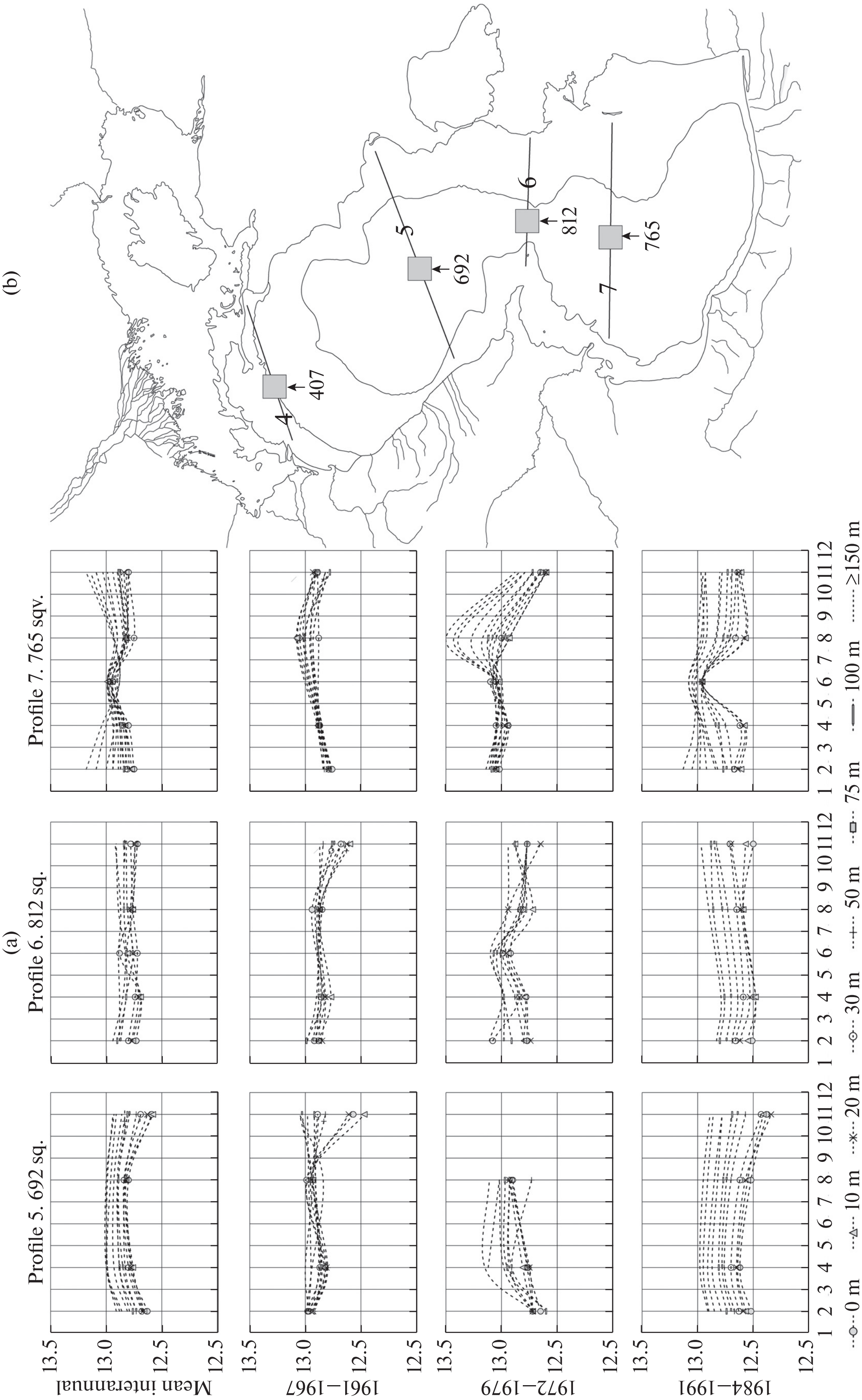

Fig. 4. Mean interannual seasonal distribution of salinity (‰) in central squares along profiles: mean interannual norm and values for selected periods: (a) salinity distribution, (b) locations of squares.

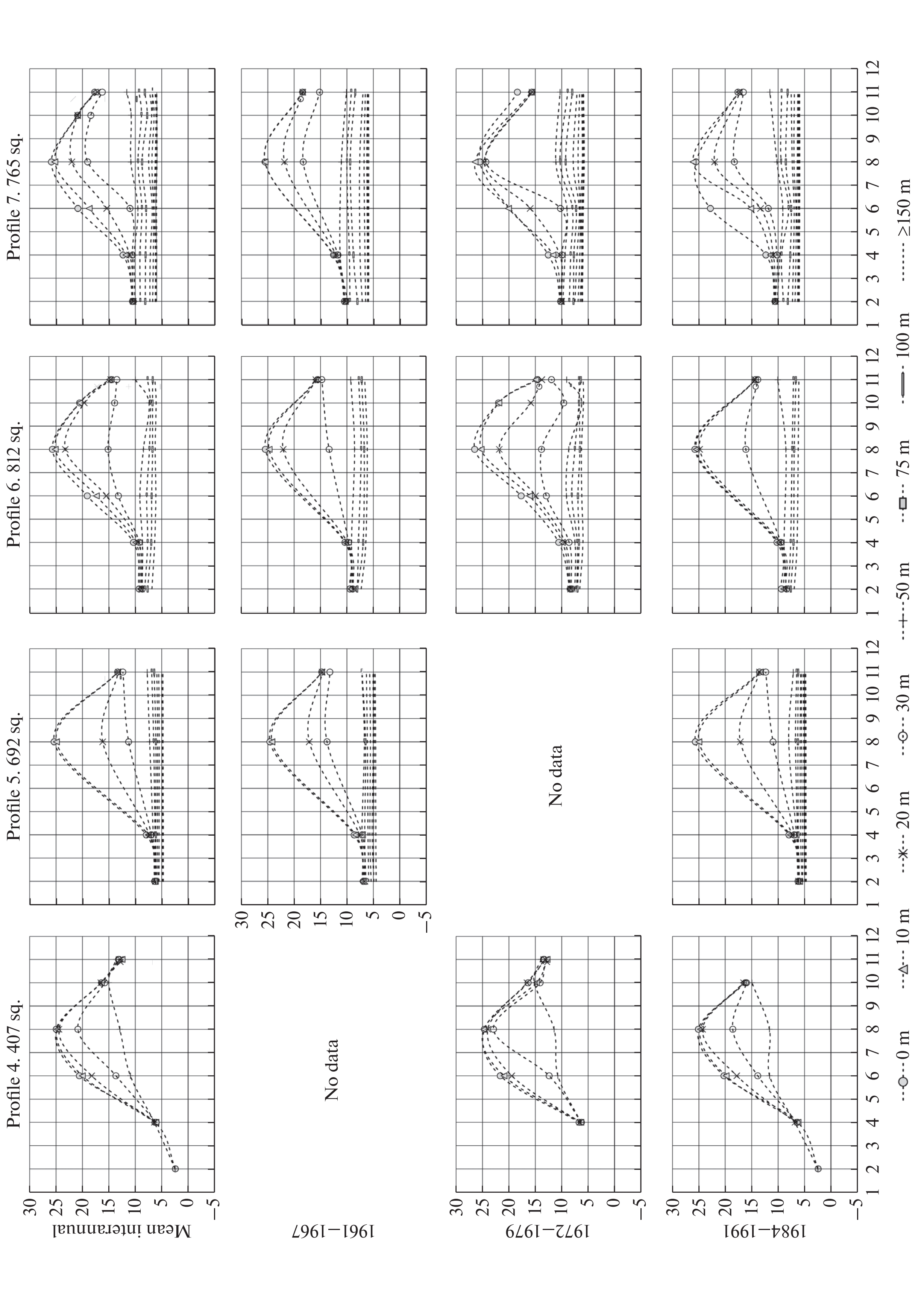

Fig. 5. Seasonal distribution of water temperature (°C) in central squares along profiles: mean interannual norm and values for selected periods. For locations of squares, see Fig. 4b.

changed wind direction and increase in wind speed, as well as by a larger volume of river water discharge. These factors together could lead to freshening of the near-surface layer in the Northern Caspian and intensification of the near-bottom compensatory current that could be traced from the evolution of the vertical temperature and salinity fields. Inflow of Middle Caspian waters takes place in the near-bottom part of profile 4, running farther into the eastern part, along Kulaly Island. Water temperature increases but does not reach 1914–1934 values.

A sea level rise in 1984–1991 caused freshening of Caspian Sea waters [23]. Vertical stratification of waters in the areas of the Apsheron and Mangyshlak peninsulas intensified. Salinity in the Middle and Southern Caspian basins decreased and did not exceed 12.8‰ (Fig. 2, profile M). The difference between the eastern and western coasts became smaller. Formation of saline waters and their subsequent flow down the slope of the eastern coast are not observed. At the boundary with the Southern Caspian Sea, water masses with salinity up to 12.7‰ formed at depths down to 50 m (Fig. 2, profile M); this phenomenon was reported earlier only at the beginning of the 20th century [17].

It should be noted that significant changes in temperature of Caspian Sea waters were characteristic only of the northern part and were most likely related to redirection of flows in the 1970s (Fig. 3). Only in the Southern Caspian Sea does temperature in the layers below 300 m significantly increase by 0.3–0.5°C in 1978–2000. It is also possible to see warming of layers below 100 m in the area of the Apsheron sill by 1.0°C. These results agree with those obtained earlier in [26].

CONCLUSIONS

Analysis of vertical profiles has allowed us to reveal some important regularities in the salinity and temperature variability of Caspian Sea waters.

In 1914–1934, stable salinity stratification was reported [17]. Waters from the Middle Caspian flowed to North Caspian all along profile 4. Later, in the 1960s, on the background of a drop in sea level by 2 m, a homohaline structure of the water column had formed. In 1972–1979, vertical inhomogeneity of water masses intensified. Notably, the mean annual salinity values, calculated based on information from the database for centennial profiles in the 0–100 m layer, demonstrate a gradual decrease at a rate 0.02–0.06‰ per year on average, despite the continuing drop in sea level and relatively small water discharge. In 1980, an abrupt surge of salinity occurred again (by 0.3‰ per year in profile 6), then it dropped again at rates faster than in the previous period; the cause was an increase in water discharge combined with sea level rise by almost 1.5 m. In the recent period (2000–2010), in the northwestern part of the sea, salinity decreased by 2.1‰ compared to the period of the lowest sea level [2] and a clear stable vertical stratification was noted. Thus, after more than 30 years of increase and change in the type of *TS* stratification of waters, the salinity regime was almost completely restored to its initial state (beginning of the 20th century).

For the shallow Northern Caspian Sea basin, interannual variations in sea level and, therefore, changes in morphometric conditions are some of the key factors forming the temperature and salinity fields. Intensity of water exchange between the eastern and western parts of the sea over the Kulaly sill, as well as the scheme of water flows itself, depends on them. Significant changes in the hydrological regime of the deep-water Middle and Southern Caspian are primarily caused by the complex effect of climatic and anthropogenic factors in the catchment area. The submeridional orientation of the sea also contributes to a certain degree; sea level oscillations, only in part. This can be seen from the fact that after the abrupt drop in sea level in 1929 and until the late 1940s, the published study results mentioned no anomalies in the salinity regime.

A change in the salinity regime in the Middle and Southern Caspian, accompanied by intensified vertical stratification, freshening of the surface horizon, and salinization of the deeper layers in the 1970s, as well as the mechanism itself that caused these transformations, were not characteristic of the Northern Caspian. In the 1970s, a drop in sea level in the Northern Caspian Sea was accompanied by salinization, which was especially noticeable in the eastern part. This was related to redistribution of discharged river and Middle Caspian waters, as supported by the order of observed changes.

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