UPPER MIXED LAYER (UML)

Upper mixed layer on temperature, salinity and density is distinctly enough detected in the Black sea in all seasons of year by that from below it is resricted with layers, which have big vertical gradients of the above mentioned thermodynamic parameters of sea water: in the spring, in the summer and in the autumn - a layer of seasonal pycnocline, in the winter - a layer of main pycnocline. The border between these layers, as a rule, is well appreciable on a sharp break of a vertical structure of density (fig. 1).

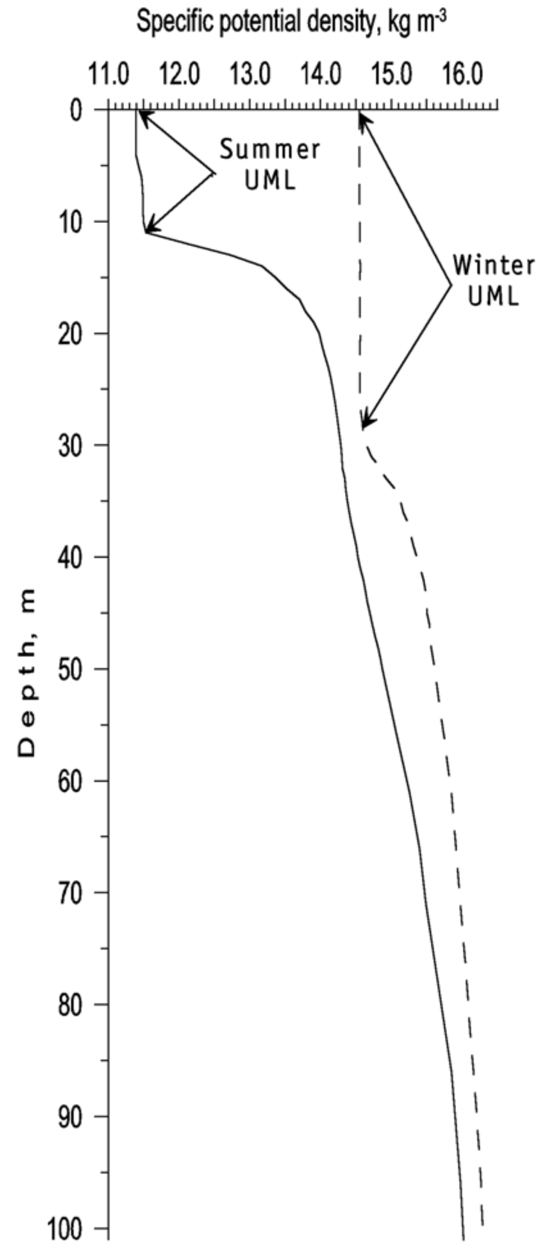
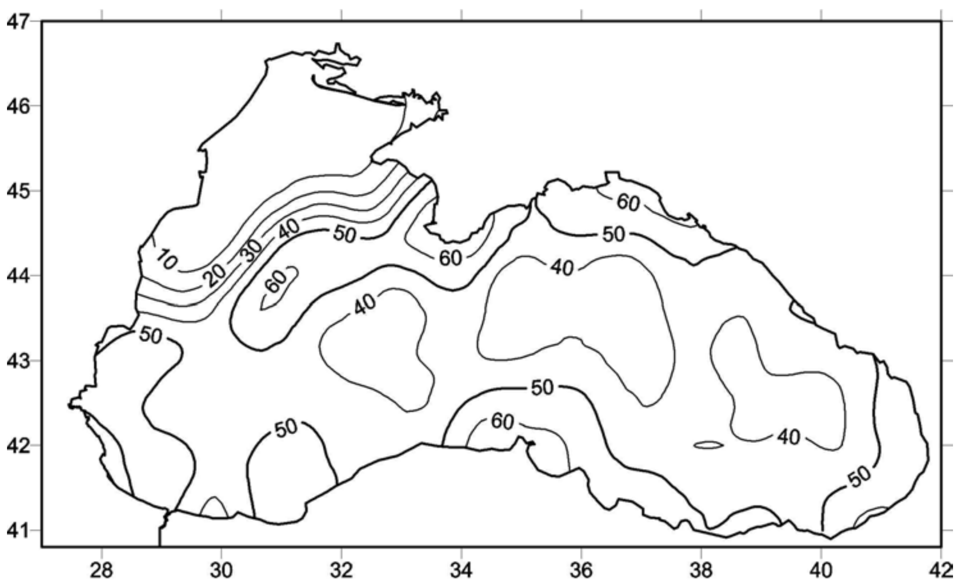


Fig. 1 - Typical vertical structures of potential density in top 100-meters layer of the central area of the Black sea (43.5N, 36.0E) in February and August.

The annual cycle of variability of bottom depth (that is thickness) of UML, basically is defined by fluxes of heat, freshwater and momentum, which is proportional to speed of wind, through a surface of the sea, that is local external forcing. As their seasonal variability is homogeneous enough within the limits of water area of the Black sea, also intra-annual variations of UML thickness are so horizontally homogeneous (Blatov et al., 1984). The maximal values (40-60m) it reaches in February. In May it decreases almost up to zero as a result of spring warming up and formation of seasonal pycnocline. To August UML thickness slightly grows up to 5-10 m. Then with development of autumn-winter convectively mixing there is a fast increase UML thickness of due to destruction of underlying seasonal pycnocline(fig. 2).

a)



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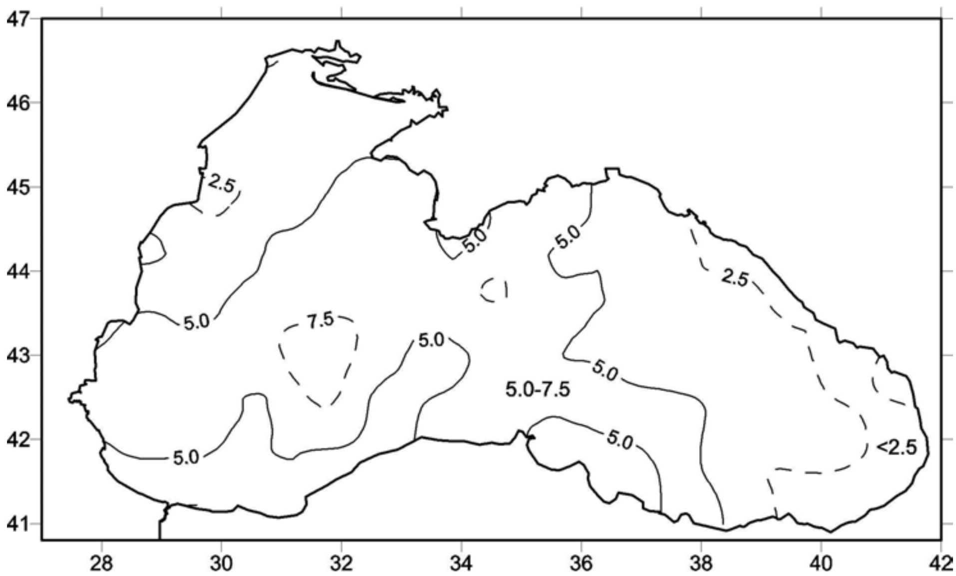

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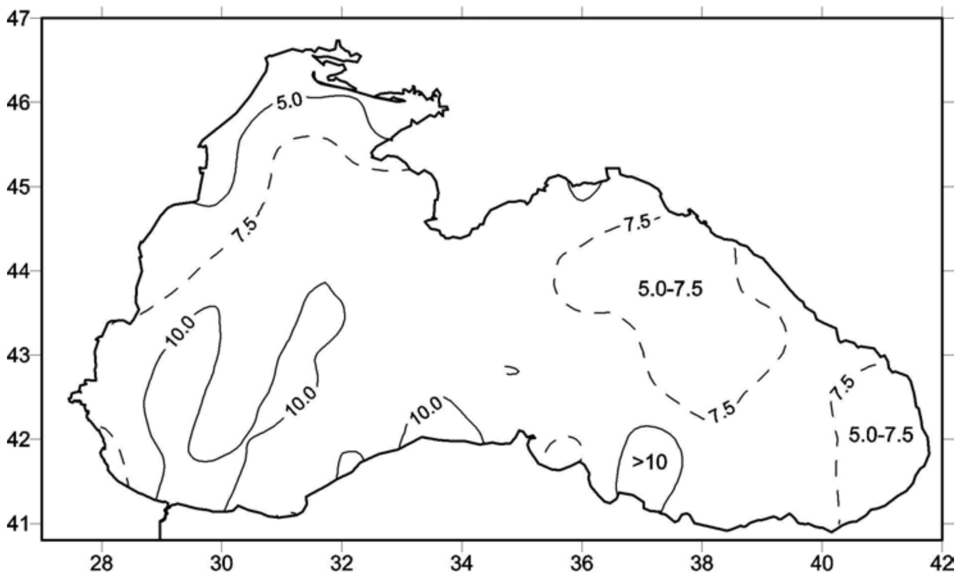

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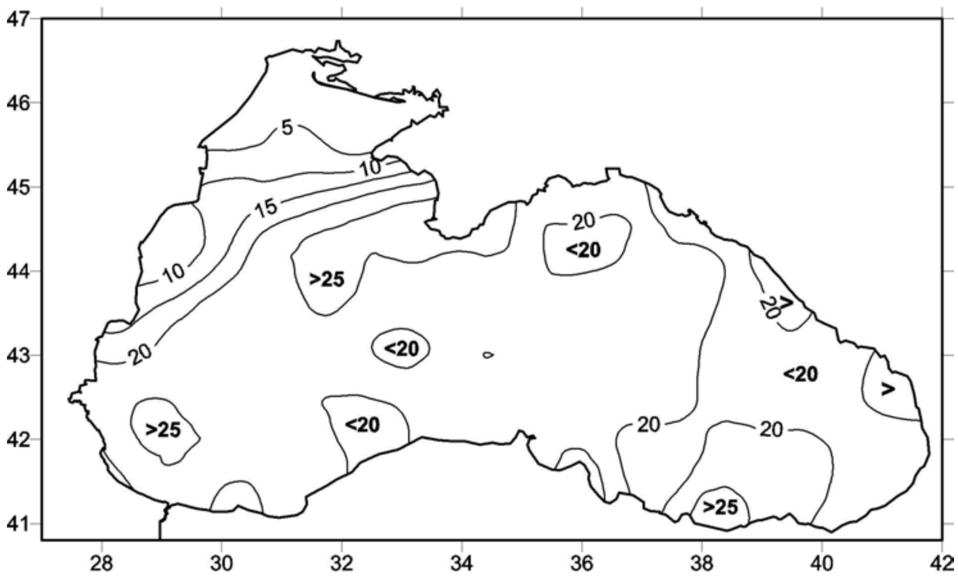


Fig. 2 - Climatic fields of thickness of UML (m) in the Black sea in February (a), May (b), August (c) and November (d).

In various areas of the Black sea of a deviation from the described scheme are observed only in details (absolute values of thickness of UML, its temperature, salinity, speed of their changes and so on).

Winter distribution of UML thickness to fig. 2a has the greatest spatial heterogeneity. The maximal values (50-60m) it reaches in a coastal zone of the Black sea and along north-western shelf break. In the winter this area almost is not exposed to riverine freshening and the cold air outbreak freely getting here from the north and northeast. Additionally there is the winter climatic maximum of speed of a wind (with monthly average speeds of 8.0-8.5 m/s) here. Smaller values of UML thickness in the central areas of the Black sea in the winter are connected with upward water motions corresponding to cyclonic general circulaton.

In the spring it is formed seasonal pycnocline as a result of warming up of the upper layers. In areas where surface freshening is less significant and stability in seasonal pycnocline is defined basically by thermal stratification, UML thickness in May makes 5-8 m. In the areas subject to influence of river discharge UML thickness is less than 5 m (fig. 2b).

To August seasonal pycnocline deepens on the average on 2-3 m (fig. 2в). It is connected with increase in speeds of a wind above the sea and reduction of inflow of heat and a freshwater from an atmosphere. Displacement of maximums of UML thickness to southern coast of the Black sea is caused by increase of a role of wave mixing in formation of UML. Maximums of wave mixing in southern areas of the sea correspond to the greatest waves fetch for northern and northeast winds, which have the increased repeatability above the Black Sea in the summer.

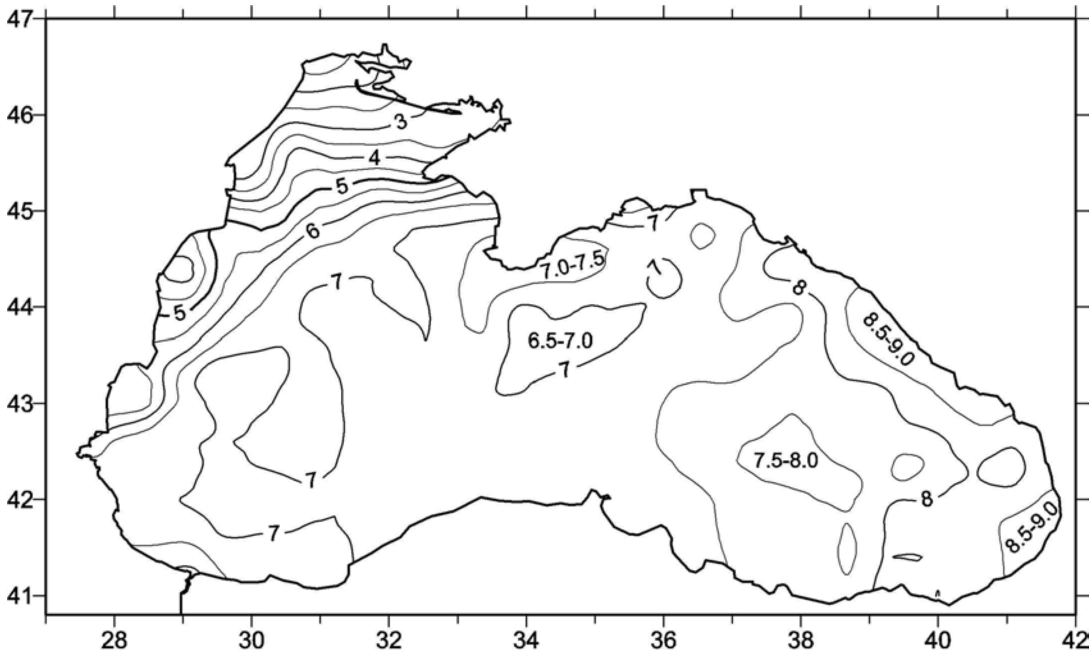
In November to wave mixing is added thermal convection. In the Southwest of the Crimea is formed the area with UML thickness more than 25 m (fig. 2d). At southern coast of the Black sea cumulative action of wind wave mixing and convection causes the same values of UML thickness to the end of autumn. As a whole the horizontal configuration of an autumn field of thickness of UML are similar to whose in the winter.

Shallowness of northwest part of the Black sea and its significant freshening by the river discharge defines the minimal values of UML thickness within all year (fig. 2).

From stated above follows, that the annual cycle of UML thickness especially closely (in inverse proportion) is connected with seasonal variability of its temperature, but its spatial variations - mainly with horizontal heterogeneity of vertical components of the general circulation of waters (in the autumn and in the winter) and salinity (in the spring and in the summer) (Eremeev et al., 1992).

The water temperature of UML of the Black sea (fig.3) the year round raises from northwest on a southeast. Its greatest horizontal heterogeneity takes place in the winter (fig. 3a) that is during a season of the minimal values, the least - in the summer (fig. 3b) when warming up of UML is maximal.

a)



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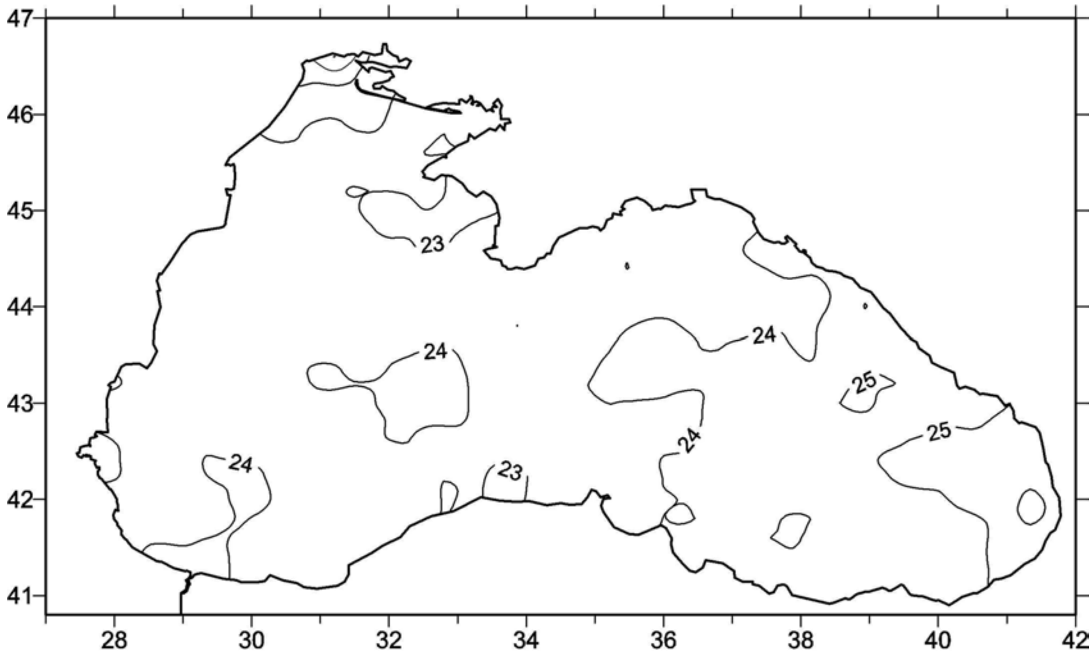
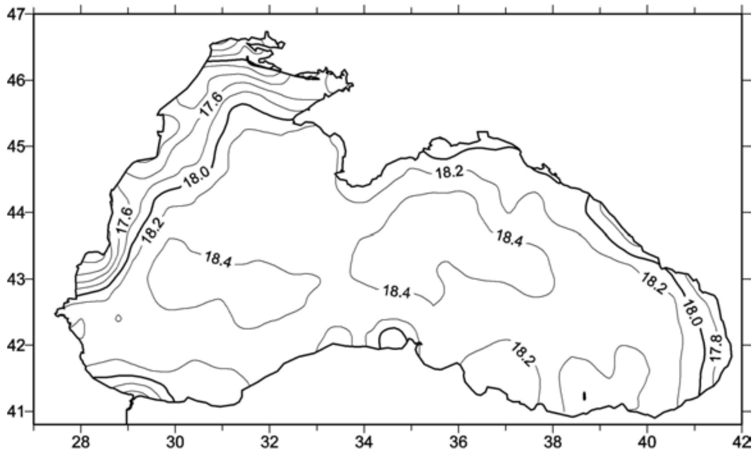


Fig. 3 - Climatic fields of temperature of water (ºC) of UML in the Black sea in February (a) and August (b).

Areas of maximal freshening of waters of UML year round are located in northwest and southeast coastal zones of the Black sea (fig. 4). From that areas the wedges of the lowered salinity spread, respectively along the western and northeast coasts of the Black Sea. The maximal freshening takes place in the end of spring - in the beginning of summer (fig. 4b). Exception is made with a coastal zone of the Crimea and the central areas of the Black sea which the wave of freshening reaches in August (fig. 4c). The minimal freshening everywhere takes place in the winter (fig. 4a).

a)



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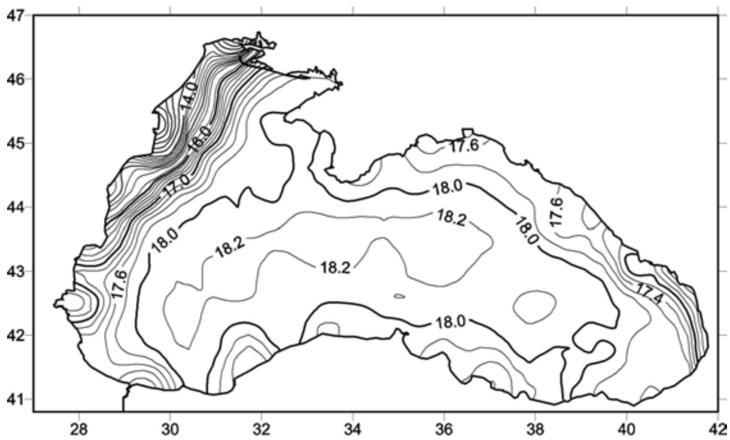

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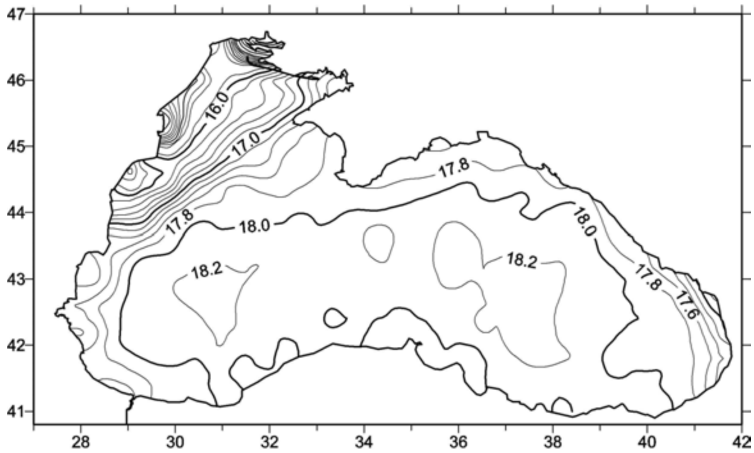

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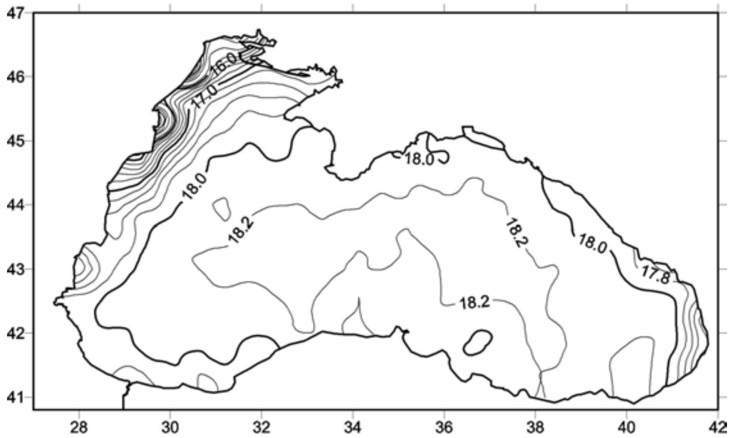
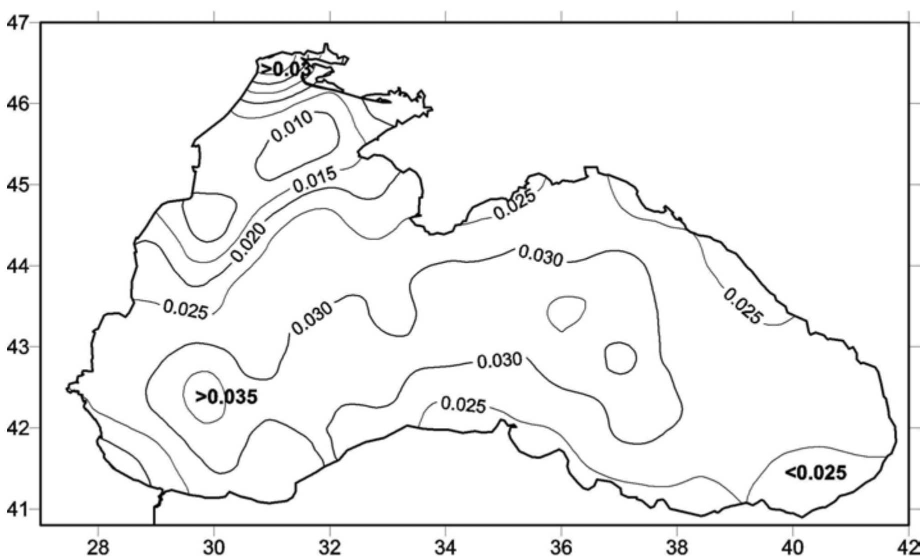


Fig. 4 - Climatic fields of salinity of water (psu) of UML in the Black sea in February (a), May (b), August (c) and November (d).

The maximal vertical gradients of density of water $(d\rho/dz)_{max}$ in pycnocline, underlying UML, increase from winter to the summer on the order of values (fig. 5): from 10^{-2} up to 10^{-1} kg/m^4. In these seasons their maximal values settle down in the central areas and in a northwest part. The central maximums are connected with the upward movements of waters compressing a pycnocline (as in winter), the northwest maximum is caused by influence of a river discharge. In the spring (it is not shown) here too take place the maximal values (up to 0.35 kg/m^4). On other water area the values $d\rho/dz$ are homogeneous (about 0.1 kg/m^4). Also is homogeneous the field $(d\rho/dz)_{max}$ in pycnocline in the autumn (in November everywhere about 0.05 kg/m^4).

a)



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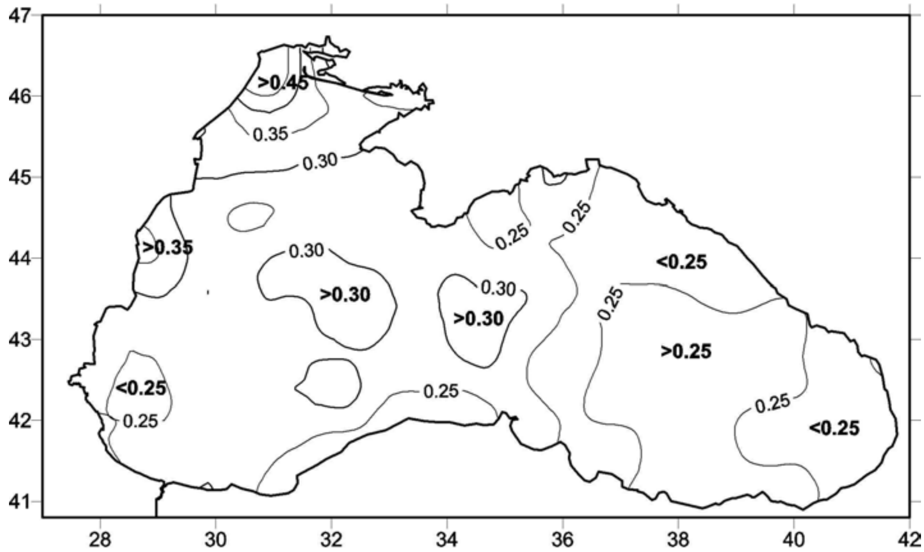

Fig. 5 - Climatic fields of the maximal vertical gradients of density (kg/m^4) of UML in the Black sea in February (a) and August (b).

UML is area of formation upper and cold intermediate water(CIW) water of the Black sea. Cold waters are formed in UML during the autumn-winter period. In the end of winter - the beginning of spring occurs them subduction under newly formed seasonal pycnocline. Then CIW spread on Black sea in a layer from 50 up to 100-150 m owing to advection currents and to horizontal mixing (Blatov et al., 1984). Thus subsurface layers of the Black sea are ventilated. Below cold intermediate layer direct ventilation is absent in the Black Sea.

The rate of subduction (S) was calculated in (Tuzhilkin and Nakolushkin, 1999) as the vertical velocity of motion of a particle relative to the base of UML (vertical coordinate axis is directed downwards) by the formula of Marshall-Nurser:

$$S = w_h - \partial h/\partial t - (u_h \bullet \partial h/\partial x + v_h \bullet \partial h/\partial y) \qquad (1)$$

This formula (1) includes vertical velocity of a particle on the base of UML - w_h, local temporary change of depth of the base of UML - $\partial h/\partial t$ (see fig. 2), and vertical displacement of a particle relative to the base of UML causing by horizontal non-uniformity of its depth - ($u_h \bullet \partial h/\partial x + v_h \bullet \partial h/\partial y$), where u_h and v_h are the horizontal components of velocity of motion of a particle on the base of UML. Three current velocity component were numerically simulated in (Trukchev et al., 1995). The monthly volumes of subducted waters were calculated from the rates of subduction in each cell.

The calculations are carried out for the effective time of subduction i.e. the time the waters flow from UML to the Black sea main pycnocline. In the Black sea the effective time of subduction is from February to April. Out of this time range waters flow from UML to the Black sea seasonal pycnocline and then are caught again by the upper mixed layer forming in the next winter.

In a climatic mode for given time range volumes of subduction are 28.3×10^3 km^3 (in February - 8.0×10^3 km^3, in March - 15.5×10^3 km^3 and in April - 6.8×10^3 km^3) that is in accordance with the known estimations of volumes of CIL waters (Hydrometeorology …, 1991). In the region of the northwestern shelf and continental slope of the Black sea (about 15% of the total Black Sea area) volume of subduction is 9.6×10^3 km^3 (32%). The southeastern region of the Black sea gives - 4.6×10^3 km^3, the region of a southern coast of the Crimea (from Sevastopol to Yalta) - 3.8×10^3 km^3 and the northeastern region - 3.1×10^3 km^3.

The average rate of subduction in those regions is about 60 m per month. About 45% in average of this quantity is given by a sum of the last two terms of S in (1), 33% - the first term on the right side of (1) (w_h), 22 % - the second term ($\partial h/\partial t$). Such proportion is typical for the estimations by the formula (1). At the same time in some regions it differs from the mean essentially. In the northwestern region the part of $\partial h/\partial t$ increases up to 40% while the part of w_h decreases. In the Crimea region, on the contrary, the part of w_h increases up to 50% because of reduction of $\partial h/\partial t$. In the southeastern region the last term (1) contributes 55-60%.

The total contribution of regions along a continental slope from the southernmost point of the Crimea to the Burgas Gulf is 55-60%.

The waters subducted in these regions in February and March have the temperature and salinity, which are typical for CIL in summer and autumn (fig. 6). Therefore, given region of the Black sea may be recognized as the main area of late winter subduction of waters from UML to CIL. In April the temperature of UML is too high and its waters are subducted at levels above the CIL.

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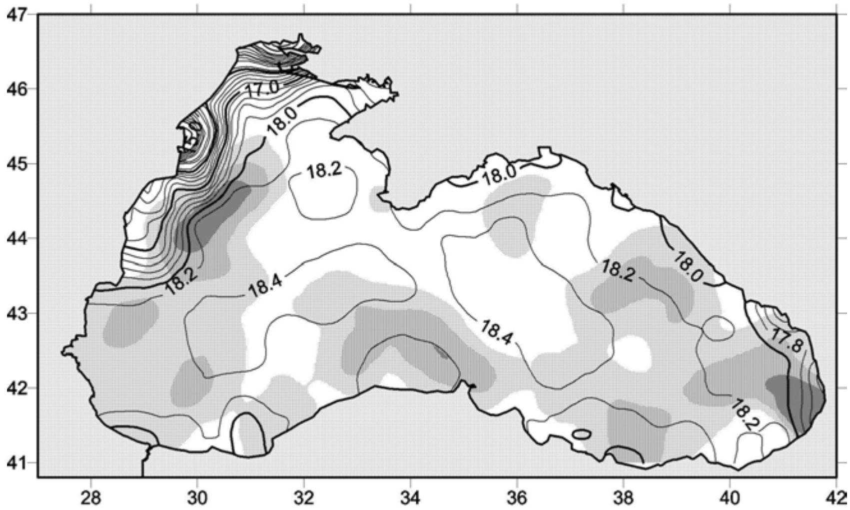
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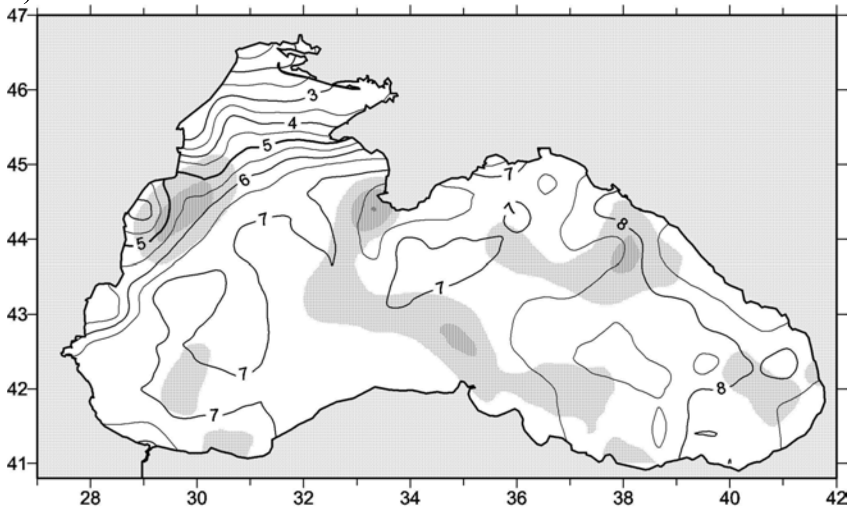
b)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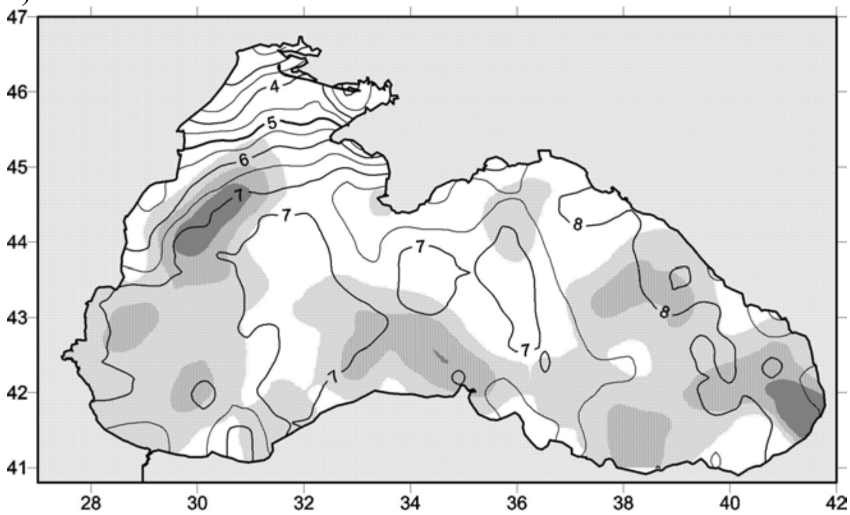
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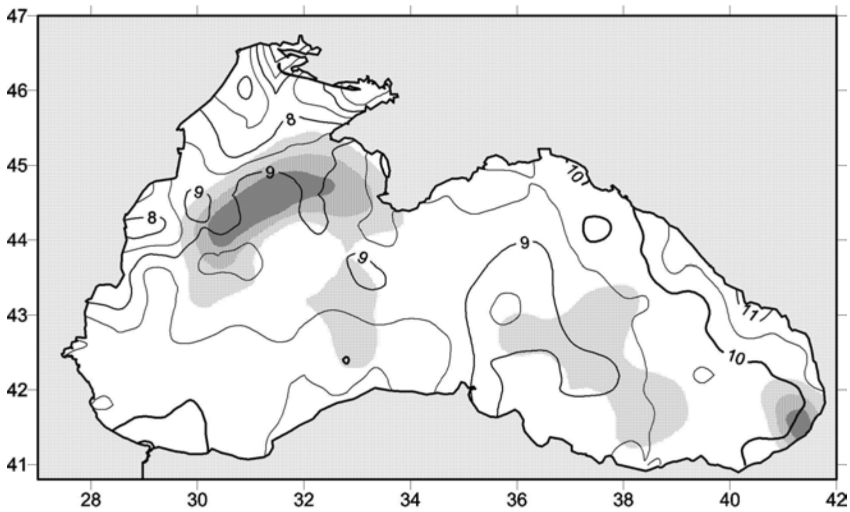

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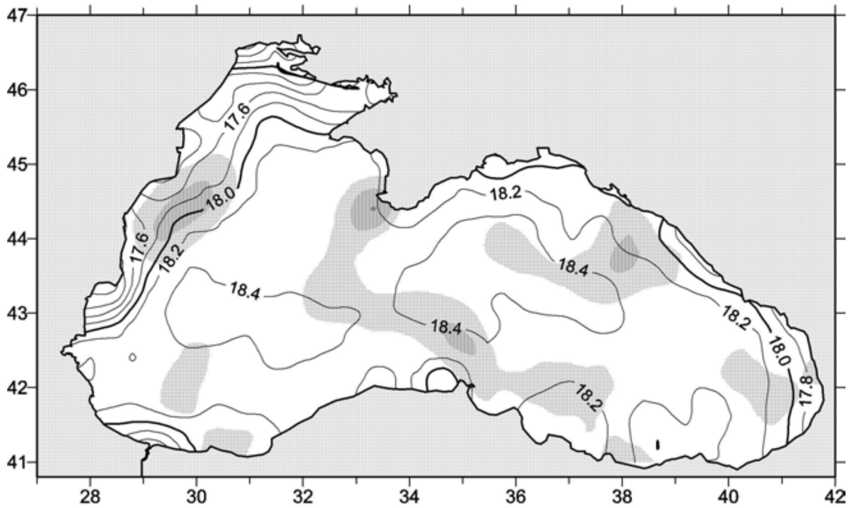

Fig. 6 – Climatic fields of water temperature (ºC, a-c) and salinity (psu, d-f) in Black Sea UML in February (a, d), March (b, e) and April (c, f). Shaded areas are the regions of high water subduction from UML to main pycnocline. The darker shaded area the higher rate of subduction.

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