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VENTILATION OF THE BLACK SEA PYCNOCLINE ON A SEASONAL AND INTERANNUAL TIME SCALES AND WATER MASS FORMATION

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ABSTRACT

The Black Sea is an apparent example of estuary type basin. Saline underflow (salinity>36) originates from the Sea of Marmara. About 300 cub km per year of Marmara Sea water forming Bosporus undercurrent, after exiting from the straits, spread over slanting sea bed along underwater canyons and grooves and get mixed with the ambient water in approximate proportion 1 to 9 forming a plume. Plume water permeates into and below the permanent pycnocline, a layer of about 100 m thickness separating lower warmer, more saline, anoxic and relatively homogeneous water mass from the upper less saline, oxygenated and highly variable upper layer waters. In the surface layer, rivers and precipitation exert freshening influence and upper less saline waters (salinity>18) form the Bosporus surface outflow. The resultant strong stratification within the pycnocline effectively inhibits vertical mixing and aeration of the lower layer leading to the occurrence of anoxic conditions within 90 per cent of the entire volume of the sea.

The Black Sea being globally the largest body of anoxic waters, presently, is facing environmental degradation. Scientific assessment of its present state and prediction of its future implies better understanding of the processes maintaining its vertical structure on seasonal, interannual and longer time scales. In particular, the problem of a balance between vertical advection resulting from the transverse vertical circulation and diffusive mixing within the pycnocline may be considered as one of the pivotal and still debatable issues of Black Sea oceanography. Its solution applies to oceanographic issues of general interest (such as assessment of the role of different processes in vertical exchange, water mass formation and of the ocean climate) as well as to regional environmental problems. For example, a profound knowledge of the mixing mechanisms and rates in the Black Sea pycnocline is needed for correct parameterisation of mixing processes in GCM. It is also essential for better understanding of the impact of mixing on transport of pollutants and of organic matter, evolution of the suboxic layer and of the chemocline, and on the entrainment of nutrients from the pycnocline into the euphotic zone.

Despite its importance, changes of the Black Sea pycnocline could not be examined in detail in the past because of the lack of synoptic data covering the entire basin. O ur preliminary analysis based on the recent high-resolution, full-basin and partial hydrographic data sets, revealed significant interannual variability in the basin averaged vertical position and structure of the halocline, showing a balance which is sen sitive to climatic variability.

In the paper we present basic results of recent studies of the processes of ventilation of the Black Sea. The specific objectives of this work were (1) to reveal space-time variability of the thermohaline structure of the py cnocline layer discerning responses to seasonal and interannual changes in external conditions as well as the role of the Bosporus effluent in maintaining the observed structure of the thermohalocline, (2) to provide quantitative estimates of ventilation rates due to different mechanisms (discerning lateral and vertical exchange processes), (3) to reveal relationship between ventilation mechanisms and water mass formation in the Black Sea.

Data and methods.
To meet the objectives the focus was on the analysis of long term changes in temperature/salinity structure of the Black Sea pycnocline, based on annual mean data sets, prior to 1984 and starting from 1923, and on recent fine resolution data sets depicting normal, severe and mild winter conditions in the Black Sea since 1984 (more than 50 basin wide and partial hydrographic surveys). Seasonal fluctuations were resolved with monthly averages using all historical data. Temporal and spatial variability is analysed versus depth as well as salinity and density co-ordinates. Though spatial variability on a density scale is much less pronounced than on a depth scale, still some differences exists, basically, between the regions of cyclonic and anticyclonic circulation. Therefore, to minimise possible errors related to variations in the stations network for different surveys and to emphasise regional peculiarities, recent data were also averaged separately for the areas of cyclonic and anticyclonic circulation.

Starting from 1990, co-ordinated multi-institutional surveys within the context of the joint Turkish - USSR, CoMSBlack and NATO TU - Black Sea programs have resulted in high quality, intercalibrated, pooled data sets providing a unique opportunity to study variations of the Black Sea pycnocline structure in detail. Basin-wide surveys: in September of 1991, July 1992; and partial surveys: October 1990, April 1993, May 1994, March-April 1995 are used for the analysis and comparison with other data.

One of the conclusions from the studies is that the magnitude of seasonal fluctuations within the mid and lower pycnocline may be considered negligible in comparison with the magnitude of long-term changes and that allowed to use annual means or data of different seasons for the analysis of long-term fluctuations of the thermahaline structure of the pycnocline. Winter air temperatures from coastal meteorological stations as well as basin-averaged daily wind speed, wind stress and of the wind stress (vorticity) have been used to characterise interannual variability in thermal conditions for the Black Sea region for selected years.

For quantitative estimates of mixing rates we used data on depth dependant decease of the magnitude of seasonal and long-term thermohaline fluctuations and vertical phase lag of the changes. Also, a stationary one dimensional model of Bosporus water mixing and transformation in the Black Sea based on the balance of mass, salt and heat is used for description of mixing properties and mechanisms. It is assumed that the process of transformation of the Bosporus effluent goes in three phases: (1) entrainment of the upper layer ambient fluid to Bosporus inflow, (2) exfoliating of the down flow and ispycnal intrusion of the plume water into the ambient fluid, (3) a flow down of a of the plume into the bottom homogeneous layer. The influence of the plume on the processes of entrainment - advection are realised in the form of boundary conditions. The solution gives expressions for vertical distribution of vertical diffusion coefficient as well as for vertical velocity for the entire basin. All calculations are based on real data.

Basic Results.

It is shown that traces of winter mixing events appear well preserved in the temperature-salinity structure, particularly due to the peculiarities of the Black Sea pycnocline where temperature acts as a passive tracer with a smaller contribution to density as compared to salinity. Vertical distribution of the magnitudes of temperature oscillations within the pycnocline layer indicates that the convection events have limited effects in modifying the structure of the main pycnocline on a seasonal time scale. However, long term (5 to 10 years period) fluctuations of the thermal structure of the pycnocline are well recognised from both basin wide and limited area surveys. In recent years, gradual cooling of the pycnocline essentially occurred in response to three major cooling events in 1985, 1987, 1993. The data reveal magnitudes and phases of these fluctuations as a functions of depth, salinity and/or density. The results are used for estimation of the mixing rates.

Regional peculiarities in physical responses to variable winter conditions allow to infer that the lower pycnocline of the Black Sea is continuouslyventilated through lateral (isopycnal) injection of waters of the Bosporus plume, whereas, an effective ventilation of the upper pycnocline occurs episodically (once in two to ten years) due to extreme winter cooling at the surface.

The latter mechanism takes place in the central part of the basin and, in much extent, is enhanced by intensification in general circulation. Shoaling of the pycnocline in the central part of the basin due to Ekman pumping has at least two important consequences related to cold intermediate water mass formation. 1) It exposes the upper pycnocline to wind induced mixing resulting from wave breaking and velocity shears related to Ekman and inertia currents. 2) In speculative manner, it may be also suggested that the negative vertical velocity enhances the efficiency of winter convection.

Intensive winter convection exerts a proxy impact on ventilation of the lower pycnocline changing characteristics of the waters which are entrained to Bosporus inflow. In this manner, fluctuations in the lower pycnocline may be explained by variations that occur within the upper layer but, then, conveyed downward due to the process of entrainment. Temperature and salinity basin averages for the period from 1923 to now reveal a linear segment of the T, S diagram (or a segment of constant density ratio values), approximately, between 15 and 15.5 sigma-t surfaces. Actually, that provides additional proof to the concept of different ventilation regimes for the upper and lower pycnocline. For the long term variations, the estimates of mixing rates roughly depict the specific case of basin average temperature decrease after 1993 winter cooling. At the same time, when analysing data on decrease in the magnitude and on the time lag for temperature variations with increasing depth one may suggest lower mixing rates for the central part of the basin. From a general point of view, the conclusion seems reasonable because it gives a proxy evidence to a logically obvious suggestion that variations in mixing rates on a large scale depend upon large scale shear currents.

The solution for the one dimensional stationary model of vertical exchange within the pycnocline gives expressions for vertical distribution of vertical diffusion coefficient as well as for vertical velocity for the entire basin. It is shown that the total upward heat flux from the Black Sea thermocline considerably exceeds the value for the geothermal heat flux revealing dependence of the thermal conditions of the pycnocline layer on Bosporus inflow. However, thermal regime below the pycnocline is controlled by geothermal heat flux spent to warm water of the plume which is a cold water pattern when compared to the temperatures of the ambient fluid. As a result a quisi-isothermal interfacial layer is formed, approximately, from 500 to 650 m. The results of the model were checked against the results of data analysis.

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ABSTRACTS

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