PHYSICAL OCEANOGRAPHY VARIABILITY IN THE BLACK SEA PYCNOCLINE

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Abstract. Local variability of the Black Sea permanent pycnocline position is caused, basically, by dynamical processes: Ekman pumping, meandering of the Rim current, mesoscale eddies, etc. Recent CTD measurements allow to filter local effects and to study variations of the pycnocline structure in detail with the focus on understanding of the role of different mechanisms which cause these variations. Gradual deepening of the isopycnal interfaces since 1991 as well as cooling (freshening) tendency has been registered. The total range of migration of the sigma-t interfaces within the pycnocline was 9 - 11 meters, with the shallowest position in 1990-91 and the deepest position in 1994. In the particular case, both cooling and freshening during 1991 - 1994 period, to some extent, occurred in response to changing vertical velocity. Cooling in this sense may not coincide with respective variation of annual mean air temperatures. In speculative manner, there should be a balance between combined variations of the basin's water balance, winter meteorological conditions and the thermohaline structure of the pycnocline layer. Weather conditions for the warm part of the year complicate the response in the pycnocline.

1. Introduction

The Black Sea is globally the largest body of anoxic waters facing rapid environmental deterioration under the impact of increasing contaminant inputs [17]. The evolution of the basin density and chemical stratification in the last few millennia results from the invasion of the Black Sea by the Mediterranean waters [6]; yet very little is known of the short term, interannual variability of the halocline or chemocline. Because the chemical changes including the transition from oxic to anoxic waters (i.e. the chemocline and the oxycline) coincide with the permanent halocline, its shoaling would imply adverse changes.

Claims of oxycline shoaling [7,11,18], supposedly in response to decreased freshwater inputs [18], have been contested and proved to be premature by more recent

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results [3,4,9]. The former hypothesis of a rising oxycline could not be supported with positive proof, because comparisons based on depth profiles of oxygen, hydrogen sulfide or other chemical properties in a given region and time period could not isolate vertical displacements associated with local dynamical variability of currents (the meandering Rim Current, eddies, etc.) from processes of irreversible diapycnal mixing or chemical transformation. Typically, when comparisons are made with respect to density, so as to exclude variability resulting from dynamical effects, no justification remains to argue for a recent trend in the depth of the oxycline [2,9,10,24]. However, purely chemical changes can not be excluded; for example in nutrients [2,25] and possibly in the suboxic zone [4, 18, 20], in relation to eutrophication.

The observed stationarity of the present chemocline position with respect to density coordinates [2,9,10,25], raises the question of whether the density stratification itself is stationary on interannual time scales. Any foresight to this end has been limited in the past by the availability of data covering the entire basin.

The upper part of the pycnocline is ventilated effectively by wintertime convective cooling resulting in the formation of the Cold Intermediate Layer (CIL), residing below a warm layer in summer, and above the deep waters where temperature increases with depth [14].The deep waters of the Black Sea have striking stability in physical and chemical properties, as a result of limited turbulent energy penetration into the deep waters [19,23].

Direct ventilation appears to be confined to the layer above the pycnocline (above the 14.5 - 14.7 sigma-t interface) where convection and subsequent isopycnal injection supposedly are the major mechanisms of water mass formation [14,19]. Similarly, ventilation of the lower pycnocline occurs due to entrainment of the Cold Intermediate water (CIW) into the Mediterranean Water near the Bosporus and its subsequent injection in the lower pycnocline region (sigma-t = 15.8 - 16.2) by intrusions of the shelf modified waters [8, 23].

The interannual variations in the thermohaline structure of the pycnocline, acquired from the comparative analysis of the Atlantis II 1969 and Knorr 1988 data were reported in [19] with a suggestion, in a speculative manner, that possible causes for changes in the structure could be increased heat flux to the atmosphere and decreased freshwater input. On the other hand, permanent shifts in the position or structure of the pycnocline are not evident in recent data [9]. This brings into question the existence of possible short term (on a time scale of several years) variations in the pycnocline structure. Our analyses below reveal significant interannual variability in the vertical position and structure of the halocline (pycnocline) [15].

2. Data and Analysis Methodology

Recent CTD measurements (basin-wide and partial surveys within the context of the CoMsBlack program and TU-Black Sea project) in the Black Sea provide a unique opportunity to study variations of the pycnocline structure in detail, and to understand the role of different mechanisms which cause these variations. The data set includes

intercalibrated CTD data from basin wide surveys in September 1991, July 1992 [1,21] and surveys with 40-70 percent coverage of the sea (western part of the sea, mostly, with 10 to 20 miles between the hydrographic stations) conducted in the framework of the CoMSBlack and TU-Black Sea programs in April 1993, May 1994 and March-April 1995. To characterize an overall range of pycnocline temperature variations, the une 1984 data (approximately 60 percent of the whole basin coverage, western and central part, on 20 x 20 miles grid [12]) as well as the data from the joint MHI ASU - IMS METU October 1990 basin wide survey [22] were also included.

Data averaging over the survey area was used to filter effects of local dynamics. Since typical spatial scales of a mesoscale features in the Black Sea are on the order of 50 nm [5], such averaging procedure implies efficient filtering of a mesoscale fluctuations and therefore the averaged data depict the general features of the water body.

3. Results

Temperatures in the core of the CIL, as well as meteorological data reveal a decrease in winter averaged temperatures for the region in 1991 - 1993 [14,26]. The winter of 1994 was warmer (CIL core temperatures in May of 1994 were, approximately, 0.2°C warmer than in April of 1993) and the 1995 winter could be characterized as anomalously warm [14].

Averaged positions of the selected sigma-t surfaces and the temperatures at those surfaces for the 1991 - 1994 period are presented in [15]. The updated results are shown in figures 1a,b, revealing that the deepest position of the pycnocline occurred in 1994. Note that the deepening of the pycnocline did not coincide with the time of maximum surface cooling. Only the 1995 data showed a tendency of reversal in the vertical migration of the interfaces, and the cooling appreciably lagged behind, with increasing lag with depth. The slanted dashed line in fig. 1,b reveals the vertical phase shift in the temperature fluctuations. For the upper pycnocline (14.8 sigma-t), the lowest temperature occurred in 1993, but the cooling in the lower part of the pycnocline continued at least until March 1995 in the form of a delayed response to the earlier surface cooling. Since the only source for water with lower temperatures is at the surface, cooling at the sigma-t interfaces of the pycnocline implies ventilation of the layer continuing in the second and the third years after the extreme surface cooling.

Referring to the analysis of climatological data [16] and individual data sets for one specific year [13], it can be easily shown that the seasonal warming (same for winter cooling) is confined mostly to the layer above the core of the CIL and intraanual changes of temperature and salinity at 75 m and below are small (respectively less than 0.04°C and 0.05 [16]) when compared with interannual variability (see fig.1). Therefore, the recent data obviously show appreciable interannual changes within the pycnocline. Such a comparison also provides confirmation to the claim that various properties are well preserved within the pycnocline region on a seasonal time scale, i.e. the results of the present study are not much affected by seasonal variability.

The total range of excursion of the sigma-t interfaces within the pycnocline was 9 - 11 meters, with the shallowest position in 1990-91 and the deepest position in 1994. The combined effect of the downward pycnocline migration and of the cooling resulted in a considerable changes in the position of the lower CIL boundary [Ivanov et al., this volume], revealing appreciable interannual changes from 77 meters in June 1984 (the warmest year) to 107 meters in 1994 (especially large when compared with the negligible seasonal changes [16]). This fact strongly contests the claim on intraannual stationarity of the total volume of water above the lower boundary of the CIL [16].

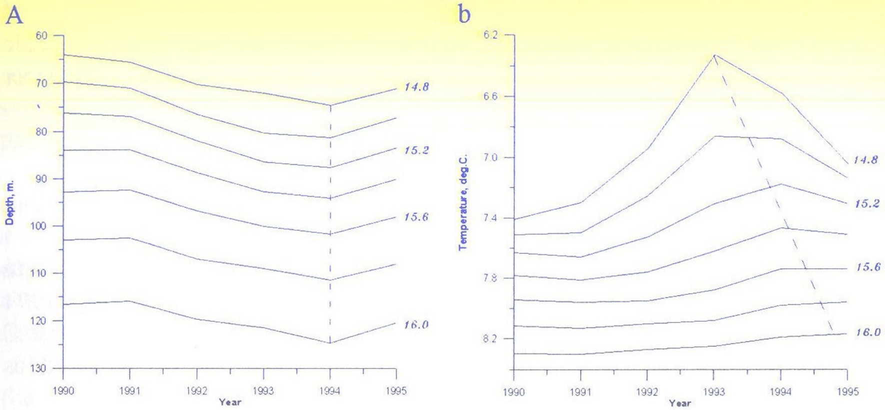

Figure 1. Positions of the 14.8 - 16.0 sigma-t interfaces and temperatures at those surfaces.

The average T,S curves for 1984 and 1990 - 1994 (downward migration phase of the pycnocline) in figure 2 illustrate the overall temperature and salinity variations in the pycnocline region. The arrowhead lines in fig.2 show successive changes in T,S at 70 and 90 m depths. On the T,S plane, 'points' for the 1984 - 1991 period 'shifted' towards denser position since cooling and salinity increase occurred at a fixed depths.

Figures 1 & 2 depict T,S variability of the averaged data. Figure 3 shows the overall range of variations in the position and temperature of the 15.6 sigma-t interface throughout the survey areas for June 1984, September 1991 and May 1994 periods, revealing a consistent decrease in temperature in all regions of the sea.

In June 1984 and May 1994, the temperature distribution has asymmetry, with some data revealing the existence of anomalously (compared to the averaged values) cold water. Water with low temperatures (low salinities) originates from near the Bosphorus region, where mixing of the Mediterranean waters with CIW and the subsequent lateral injection into the basins interior takes place [8,23]. Similar cold water patterns can be seen on other interfaces in the range of 15.2 - 16.2 sigma-t.

Vertical profiles of temperature and salinity vertical gradients for the 1991 - 1994 surveys are shown in figures 4 a,b. It can easily be verified that the temperature gradient varies in much broader range than the salinity gradient, and the same is also valid for the second derivatives. Because the computation of second derivatives proved to be noisy, order of magnitude estimates were made by dividing the profiles to three

density intervals of sigma-t = 14.8 - 15.4, 15.4 - 15.8 and 15.8 - 16.2 respectively, representing the upper, middle and lower pycnocline, so that the second derivatives are calculated at the middle part.

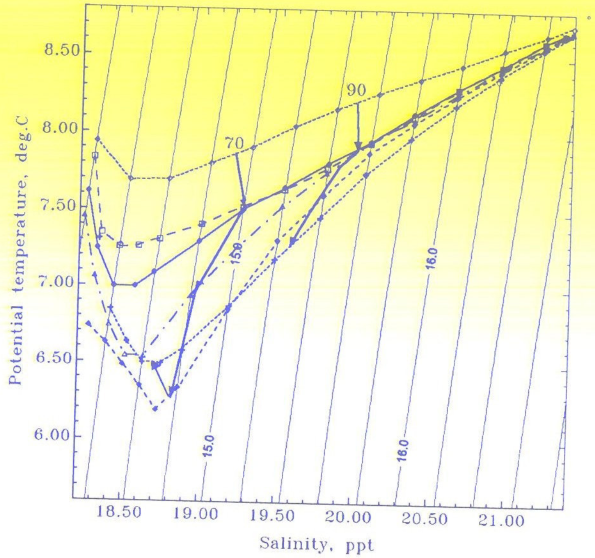

Figure 2. Averaged T,S diagrams for the 1984, 1990-94 surveys. Arrowhead lines show them in succession.

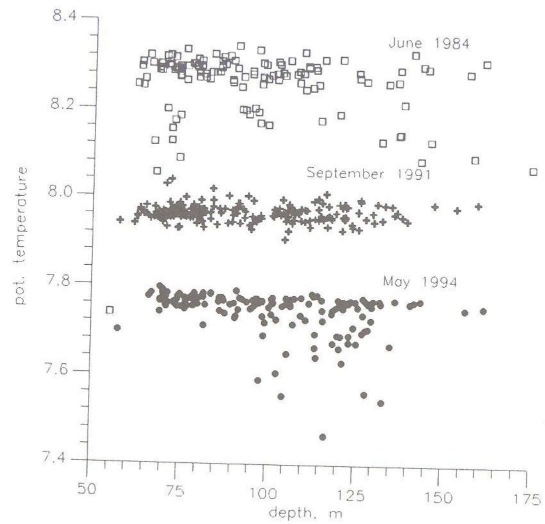

Figure 3. Scatter distribution of potential temperature at 15.6 sigma-t interface for different years.

For the 1991 - 1994 period, cooling and decrease in salinity were observed, resulting in a net deepening of the density surfaces (salinity changes overcompensated the decrease in temperature), proportional to the difference between salinity ($\beta\Delta S$) and temperature ($\alpha\Delta T$) contributions to density variations. The decrease in salinity was more uniform with depth than the decrease in temperature (fig.4,a,b). In the vertical, values of $\Delta T/\Delta t$ decrease faster than $\Delta S/\Delta t$ (t is time) so that the vectors characterizing T,S variations on the T,S plane veer towards isopycnal orientation in the upper layers (see fig.2). The divergence of these vectors in the pycnocline region characterizes changes in density stratification, i.e. a downward 'migration' (in terms of density) of pycnocline (i.e. the layer of maximum vertical density gradient). In 1991, the maximum density gradient was confined to the 14.9 sigma-t level and it shifted to the 15.3 level in May 1994. Variations in density structure can be very important for the Black Sea from a dynamical point of view, since they would also characterize changes in potential vorticity; this last issue is beyond the scope of the present paper.

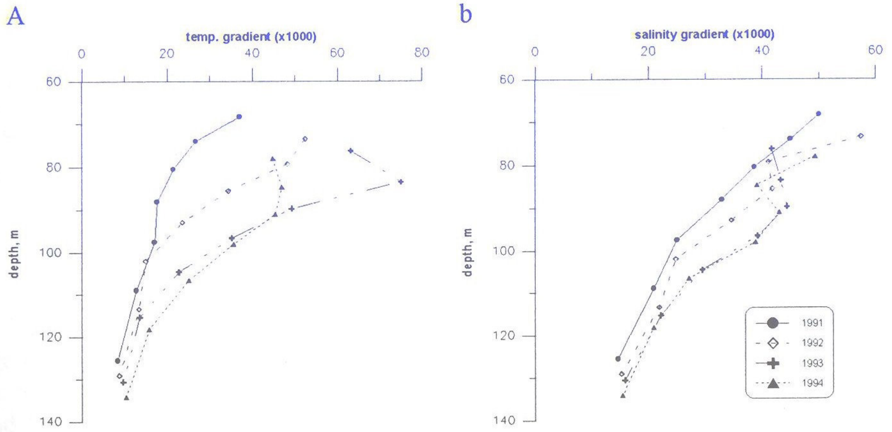

Figure 4. Vertical temperature (a) and salinity (b) gradients versus depth for the 1991 - 1994 period.

4. Discussion

In the following section, we shall scrutinize recent temporal changes in temperature and salinity. Both for temperature and salinity, we may write the following equations which characterize the balance between vertical diffusion, vertical advection and temporal variations:

$$\partial T/\partial t + W\,\partial T/\partial z = k_T\,(\partial^2 T/\partial z^2); \qquad (4.1)$$
$$\partial S/\partial t + W\,\partial S/\partial z = k_S\,(\partial^2 S/\partial z^2),$$

where W is the vertical velocity, k_T and k_S are the vertical diffusion coefficients.

It is assumed, for simplicity, that, vertical variations of the diffusive coefficients within the pycnocline depth range are much less important than variations of vertical

temperature and salinity gradients. Since we consider mean values for the whole Black Sea, horizontal advection is neglected.

4.1. AN ESTIMATE OF VERTICAL VELOCITY

With the existing data, it is difficult to estimate the amount of laterally injected waters, which actually affect the W value, but, for a first order approximation, it is possible to assume that that the ratio of entrainment to Bosphorus inflow varies from about 6-11 [8,24] in the upper pycnocline to 3.3 [19] in the deep layer. The volume of Bosphorus effluent is 312 km^3 per year [27] and, with an averaged (in the vertical) entrainment ratio of about 7, the total volume of intrusions can be estimated as 2.3 x 10^3 km^3 per year and the resulting upward velocity is then 2.1 x 10^{-7}m/s. Most probably this is a lower limit estimate for W, because in [23,24] it was explicitly shown that intrusions resulting from the near bottom mixing of the inflowing Mediterranean waters are confined mostly to the upper layer, which would result in higher values for W in the pycnocline layer.

4.2. AN ESTIMATE OF DIFFUSIVE COEFFICIENTS

There are two equations (4.1) with three unknowns (W, k_T, k_S) and to solve them a certain hypothesis should be applied. We can use the estimate of W made above. Substituting this value (W = -2.1 x 10^{-7}m/s) into (4.1), we obtain k_T and k_S close to (1.2-1.5) $10^{-5}m^2/s$ and (1.0-1.2) $10^{-5}m^2/s$, respectively. Another approach is also possible: We could assume $k_T = k_S$, as it is often considered for the pycnocline region where diffusive coefficients are typically two orders of magnitude larger than those for molecular diffusion. This yields estimatesin the ranges of W = (-3 - -5) 10^{-7}m/s and $k_T = k_S$ = (2-3) $10^{-5}m^2/s$.

4.3. POSSIBLE TIME VARIATIONS OF TERMS

Temporal variations in the pycnocline can occur as a result of changes in vertical velocity, vertical gradients, second derivatives or the diffusion rate. It should be emphasized that basin averaged vertical velocity (excluding the side boundary layers) for the Black Sea is always negative (z axis pointing downward) and its value depends upon total water balance of the basin. An increase in the absolute value of W results in warming and subsequent increase in salinity at a certain depth level.

In the above section it has been revealed that downward migration of density interfaces was also associated with 'deepening' of the profiles of temperature and salinity with respect to density and not only depth. Since the vertical gradient term is accompanied by the vertical velocity W in equations (4.1), its increase (decrease) is equivalent to the effect of an increase (decrease) in vertical velocity. In our further speculations we shall therefore take into consideration the combined effects of W and $\partial S/\partial z$, $\partial T/\partial z$ changes, referring to it as the effect caused by the W variation. Note, that the changes in salinity vertical gradients were for the most time insignificant; hence, we basically observed a decrease in vertical velocity during 1991 - 1994, rather than the effect of $\partial S/\partial z$, $\partial T/\partial z$ variations. If changes in W were constant in time, the effect would be greater in 1993-94, when the gradients were higher, rather than in 1991-92.

Figure 4 implies appreciable temporal changes in second derivative of temperature and small changes in salinity. For simplicity we consider the diffusive coefficients to be constant.

4.3.1. Changing vertical velocity

Based on a basic balance between diffusive and advective effects, it can be argued that diffusion effects will depress the pycnocline when advective effects recede, or *vice versa*. Note, further, that the variations in the vertical first and second derivatives of temperature are usually larger than that of salinity, as may be verified by figures 4a,b, and the temporal change of salinity gradient at the pycnocline is relatively constant with depth. The latter situation could correspond to vertical shifts of the salinity profile due to changes in vertical velocity.

The decrease in vertical velocity in the 1991-94 period amounts to 15-30 % of the average value. Changes of W affect the temperature, but, for the upper and middle pycnocline, in much less extent than salinity and density. Therefore, the variations of pycnocline position are mostly governed by changes in W. Such variations in vertical velocity affect the profiles of all the other properties (vertical distribution of nutrients, dissolved oxygen, hydrogen sulfide, etc.) in much the same way as salinity, density and temperature profiles, giving an explanation for the observed stationarity of the present chemocline position with respect to density coordinates.

4.3.2. The role of heat flux

Variation in vertical advection has resulted in deepening of the halocline (pycnocline) approximately by 9 - 11 m in 1991-1994 (see fig.1). Using this estimate, and the mean temperature gradients in figure 4a, the mid-pycnocline (90-100 m depth) temperature change accounted by advection during the same period is estimated to be on the order of 0.3^{0}C, or 45 % of the total variance. The remaining part is explained by diffusion of heat.

4.3.3 Comparison with other data

To check consistency of the present observations with the hypothesis claiming long term stability of the Black Sea pycnocline [9], data from the 1969 Atlantis II and the 1988 Knorr surveys [19] can be used for comparison with present results. The 1969 T,S relationship lies somewhere in between the 1984 and 1991 extremes in Figure 1, and the 1988 T,S relationship approximately coincides with the 1992 curve, showing that both cases are within the range of the discussed thermohaline variability from 1984 to 1994. Most probably, there was a cooling phase from 1984 to 1988, followed by subsequent warming before 1990, and the last cooling episode of 1991-94 described in this paper. The observations suggest interannual and interdecadal variations in the pycnocline.

Note, that the cooling may not necessarily coincide with the respective variations of annual mean air temperature. In a speculative manner, more general influences should be expected, involving combined effects of the basin's water balance, the time history of winter meteorological conditions including other variables such as the wind stress, basin averaged surface fluxes, and the averaged curl of wind stress, driving the system through either direct or proxy relationships.

5. Summary

Substantial interannual variability is shown to exist in the pycnocline structure. In the period from 1991 to 1994, appreciable deepening of the pycnocline region occurred mostly due to a decrease in the upward vertical velocity. This result in itself sheds light on the question of remarkable stationarity displayed by the present chemocline [2,4,9,10,24]. Variations in vertical velocity affect all other profiles (vertical distribution of nutrients, dissolved oxygen, hydrogen sulfide, etc.) in the same way as salinity, and temperature profiles, giving an explanation for the observed stationarity of the present chemocline position with respect to density coordinates.

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