Mediterranean Marine Science

Vol 1, No 2 (2000)

Ventilation of the Black Sea pycnocline on seasonal and interannual time scales

L.I. IVANOV, V.N. BELOKOPYTOV, E. OZSOY, A.S. SAMODUROV

doi: [10.12681/mms.290](https://doi.org/10.12681/mms.290)

Mediterranean Marine Science
Vol. 1/2, 2000, 61-74

Ventilation of the Black Sea pycnocline on seasonal and interannual time scales

L.I. IVANOV[1], V. BELOKOPYTOV[1], E. OZSOY[2] and A. SAMODUROV[1]

[1] Marine Hydrophysical Institute, Ukrainian NAS
2, Kapitanskaya st., Sevastopol, 335000, Ukraine
e-mail: max777@ukrcom.sebastopol.ua

[2] Institute of Marine Sciences, Middle East Technical University
P.K. 28 Erdemli - Icel 33731 Turkey

Manuscript received: 18 August 1999; accepted in revised form: 6 June 2000

Abstract

The paper is a description of temporal variability of winter cooling conditions and estimation of effective cross-isopycnal mixing rates in the Black Sea. Data averaging versus salinity / sigma-t scale was used to filter effects of local dynamics. It is shown that traces of winter mixing events appear well preserved in the temperature-salinity structure, due to the peculiarities of the Black Sea where temperature often acts as a passive tracer with a smaller contribution to density as compared to salinity. Vertical distribution of the magnitudes of temperature oscillations indicates that the convection events have limited effects in modifying the structure of the middle and lower pycnocline on a seasonal time scale. However, long-term fluctuations are well recognised. The magnitudes of the seasonal and long-term temperature fluctuations are comparable only in the upper pycnocline. Three major cooling events can be distinguished from the record of the pycnocline temperature for the past 75 years. The intensive cooling occurred in the late 1920s - early 1930s, early 1950s and late 1980s - early 1990s. Partial renewal of the water of the cold intermediate layer core took place approximately once in two years. The period when convection causes erosion of the pycnocline lasts for only a week. It is shown that a lateral source of heat and salt exists for the upper pycnocline, where it is the cold intermediate water, and for the lower pycnocline, the layer below $S \cong 20.5$*, where this lateral source of salt and heat is maintained by disintegrating Bosphorus plume.*

Keywords: Pycnocline, Winter Convection, Mixing, Thermal Structure, Seasonal and Long-term Variability.

Introduction

The Black Sea is an apparent example of an estuary basin. The saline underflow (salinity ≈ 36) originates from the Sea of Marmara. About 300 cubic kilometres per year of Marmara Sea water forms the Bosphorus undercurrent (UNLUATA *et al.,* 1990). In the surface layer, rivers and precipitation exert freshening influence, and the near surface less saline water (salinity ≈ 18) forms the Bosphorus outflow. The resultant strong stratification effectively inhibits vertical mixing and aeration of the lower layer. This is the main reason for the occurrence of anoxic conditions within 90 per cent of the entire volume of the sea.

The Black Sea permanent pycnocline (thermohalocline) is a layer of about 100 m thickness separating relatively warm, more saline, anoxic and homogeneous water mass of the lower layer from the water of the less saline, oxygenated, highly variable and relatively thin upper layer. The pycnocline is dome shaped with the shallowest position in the centre of the basin (~50 m) and the deepest position over the continental slope (~ 150 m). After exiting from the straits the Bosphorus effluent spreads over the slanting seabed of the adjacent shelf along underwater canyons and grooves, entrains the ambient water and gets mixed with it in the approximate proportion 1 to 9 (BUESSELER *et al.,* 1991; OZSOY *et al.,* 1993) forming a plume. The water of the Bosphorus plume, being generally denser than the ambient Black Sea water, permeates into and below the permanent pycnocline providing gradual ventilation of the Black Sea water body. The plume is thus the main source of salt and heat for the lower layer of the sea. Since the residual heat flux within the Black Sea pycnocline is always upward and the source of colder water is above the pycnocline, any cooling / warming at a particular depth indicates an increase / decrease in the ventilation rate. In this manner any changes in the intensity of vertical heat flux across the pycnocline can be seen from temperature time series.

The Black Sea being globally the largest body of anoxic waters is facing environmental problems, and the 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, 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 in the Black Sea pycnocline could not be examined in detail in the past because of the lack of synoptic data covering the entire basin. Our 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 sensitive to climatic variability (IVANOV *et al.,* 1997a; IVANOV *et al.,* 1998). Regional peculiarities in physical and chemical response to variable winter conditions allowed to infer (IVANOV *et al.,* 1998) that the lower pycnocline of the Black Sea is continuously ventilated through lateral (isopycnal) injection of waters of the Bosphorus plume. An effective ventilation of the upper pycnocline however occurs episodically (once in several years) in response to extreme winter cooling at the surface.

The latter mechanism takes place in the central part of the basin with predominantly cyclonic type of general circulation (OVCHINNIKOV, 1984) and, in much extent, it is enhanced by intensification in general circulation (IVANOV *et al.,* 1998; IVANOV, BESIKTEPE, 1998). Shoaling of the pycnocline that occurs in the central part of the basin due to Ekman pumping has at least one important consequence related to aeration of the upper thermohalocline. The process exposes the upper portion of this layer to wind induced mixing resulting from breaking surface waves and velocity shears related to Ekman and inertia currents. In this paper we address the question of space-time scales of this process.

Intensive winter convection exerts a proxy impact on ventilation of the lower pycnocline by changing characteristics of the water entrained to Bosphorus inflow (IVANOV *et al.,* 1998). In this manner, fluctuations in the lower pycnocline may be explained by variations that occur within the upper layer but, then, are conveyed downward due to entrainment and subsequent downward penetration of the plume. In the paper, among other issues, we examine influence of the Bosphorus effluent on water mass formation on the basin-wide space scale and on a century time scale.

In the paper we present basic results of recent studies of the processes of ventilation of the Black Sea pycnocline. The specific objectives of this study are to describe space-time variability of the thermohaline structure of the pycnocline, discerning responses to seasonal and interannual changes in external conditions; to evaluate the role of lateral fluxes in altering the thermal structure of the pycnocline; to estimate the cross-pycnocline heat flux; and to find a relationship between ventilation mechanisms and processes of 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. We used annual mean data sets for the period from 1923 to 1984, and data of recent fine resolution hydrographic surveys depicting normal, severe and mild winter conditions in the Black Sea since 1984 (more than 50 hydrographic surveys) (IVANOV, BESIKTEPE, 1998). 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. The basin-wide surveys: in September of 1991, July 1992; and the partial surveys: October 1990, April 1993, May 1994, March-April 1995 are used for the analysis and comparison with other data. It is important that such comparison showed general consistency of former and recent data sets.

However, there is one critical point about merging annual mean temperature values for the period of 1923 - 1984 and analogous average values but for specific surveys of the ensuing period. The problem is that estimates of annual means made on the basis of historical data with coarse time resolution may comprise random 'errors' emerging as a result of the effect of seasonal fluctuations. So one of the reasons of special interest to study parameters of seasonal variability was to make an estimate of the uncertainty in estimates of the annual averages. The magnitude of seasonal fluctuations within the middle and lower pycnocline appeared to be negligible in comparison with the magnitude of long-term changes. This made possible to consider, with the estimated uncertainty, data for different seasons for the analysis of long-term fluctuations.

Temporal and spatial variability was analysed versus depth as well as versus salinity and density co-ordinates. The latter method has been applied to filter the effects of local dynamics. The temperatures in the pycnocline were calculated as mean values for a survey area (or for a year) for fixed salinity ranges (0.1). Such non-traditional approach was used to filter also, to an extent possible, random bias related to errors in measuring the depth. Indeed, for the data collected by means of Nansen bottles, the depth was the most inaccurately measured parameter compared to temperature and salinity. Thus, the advantage of the approach is that averaging within a salinity range eliminates any uncertainties related to measuring the depth. Any changes in salinity are considered negligible compared to temperature.

Though not all of the cruises provided basin wide coverage we did not find much scattering in temperature variability revealing that mean values do not depend much upon the area of the survey. Actually, this is not a surprising result because the main differences in temperature for isopycnal surfaces are observed between the cyclonic gyre and anticyclonic eddies (IVANOV *et al.*, 1997b). The horizontal scale of the transition zone associated with the Rim Current is about 20 to 40 kilometres. The horizontal dimensions of anticyclonic eddies in the Black Sea range from 30 to 70 km (BLATOV, 1981). At the same time most of the surveys were designed to investigate spatial inhomogenity of oceanographic fields within the Rim Current and to resolve basic mesoscale features. Therefore, estimates of average temperatures, even for the surveys of relatively small regions, or for cross current transacts, are close to the corresponding basin wide estimates. Though spatial variability on the density scale is much less pronounced than on the depth scale still some differences exists, basically, between the regions of cyclonic and anticyclonic circulation. To minimise possible errors, related to variations in the station networks for different surveys, and to emphasise regional peculiarities, recent data were also averaged separately for the areas of cyclonic and anticyclonic circulation.

For quantitative estimates of the cross-pycnocline mixing rates we used data on depth dependence of the magnitude and phase lag of seasonal and long-term temperature fluctuations. Quality of the data series, however, does not make possible to resolve mixing coefficient as a function of depth. Therefore, our estimates were then used to verify results of a stationary 1.5-dimensional model of vertical exchange in the Black Sea that was applied to describe mixing properties and mechanisms (SAMODUROV, IVANOV, 1998). The model is the solution to the inverse problem, when characteristics of sources and sinks are found from the known $T(z)$, $S(z)$ distributions. It is based on the existing balance of mass, salt and heat for the Black Sea. Influence of the Bosphorus plume on the processes of entrainment - advection is realised in the form of boundary conditions. The solution gives expression for the vertical distribution of the vertical diffusion coefficient as well as for vertical velocity for the entire basin. The steady state thermal, haline and density stratification is considered a known function, which was derived from the available hydrographic data, i.e. as a by-product of data analysis presented in the paper.

To reveal impacts of external meteorological conditions we used long-term time series of the winter severity index (AL'TMAN, SIMONOV, 1991; BELOKOPYTOV, 1998) traditionally calculated as the sum of negative air temperatures, Σt_a, for meteorological stations of Odessa, Ochakov and Khorly.

Results and discussion

Variability of the pycnocline thermal structure

The time series of temperature in the halocline is presented in Figure 1. The salinity range, for which temperatures are given in the figure, spans the entire pycnocline and part of the lower layer or, approxi-

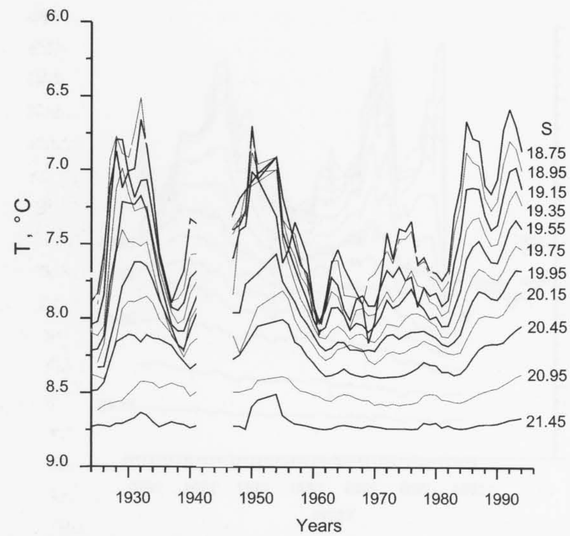

Fig. 1: Temperature variations for the fixed salini ty ranges, 18.6-18.7,..., 21.4-21.5 for the period from 1923 to 1997. The time series is smoothed by running average with the 3-point window.

mately, 14.8 to 16.6 sigma-t range. It should be emphasised that, in general, temperature variations could result not only from variable cooling conditions at the top boundary of the pycnocline but also from changing mixing rate within the pycnocline itself because mixing rate controls the heat and salt fluxes. In temperature - salinity coordinates, however, the main reason of the observed temperature variability is changing external conditions, since turbulent mixing effects salinity in the same manner as temperature. Under conditions of increased mixing rate, for example, both temperature and salinity at a fixed depth will tend to decrease. Any point of the T,S diagram in this case will thus shift along the curve towards lower temperature and lower salinity leaving the form of the curve and temperature for a fixed salinity unchanged.

At the same time it may be suggested that deep winter convection enhances mixing in the pycnocline. Though no conclusive evidence can be provided from data analysis, the suggestion seems quite reasonable because winter convection conveys dynamical atmospheric impact from the sea surface to the upper boundary of the pycnocline. If in general this is true one may conclude that an estimate of the magnitude of temperature variations at a fixed depth should exceed similar estimate for a fixed salinity. We neglect the difference considering that it is small compared with the overall range of temperature variability. To check this assumption we calculated average positions of isohaline surfaces using the data of recent basin-wide surveys. The estimated range of variations in the position of the halocline appeared to be about 5 meters. Thus, magnitudes of temperature variations may be underestimated by 15%.

Three major cooling events can be distinguished from the record of temperature in the pycnocline for the past 75 years. The intensive cooling occurred, approximately, in late 1920s - early 1930s, early 1950s and late 1980s - early 1990s. On the average, temperature of the upper part of the pycnocline was about 1 degree lower during these periods than during the predominantly warm periods that correspond to late 1930s, almost entire period of 1960s, and the first half of 1980s. The magnitude of temperature variations decreases with increasing depth. Less pronounced cooling anomalies

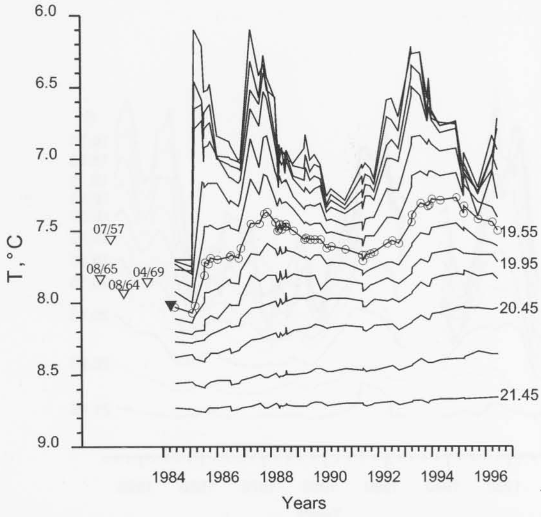

Fig. 2: Temperature variations for the fixed salinity ranges as in Figure 1. Circles at S = 19.55 reveal timing of the surveys, open triangles reveal temperature at 19.55 salinity for some surveys of previous years (dates shown).

correspond to the beginning of 1940s and middle 1970s. Thus, an approximate periodicity of the occurrence of the most appreciable cooling conditions is 20 years. Even a cursory examination of the temperature data series shows that notable cooling in the pycnocline occurs only if cold winters come in succession, perhaps with an exception of the beginning of 1950s, for which almost simultaneous cooling throughout the water column has been registered. For any other changes a one-three years delay in response of the lower layers is a well noticeable feature of cooling events.

Depth dependence of the phase lag is better seen for the period after 1984, for which the data series has better discreteness (Fig. 2). The period starting from 1984 and until 1997 was characterised by gradual cooling of the pycnocline waters in response to three notable cooling events: 1985, 1987 and 1993. Partial renewal of water of the cold intermediate layer core (the level of 14.2-14.8 isopycnal surfaces) took place in 1989, 1991 and 1992. Thus, residence time of the cold intermediate water was about two years for this period. It can be easily verified from the figures that depth penetration of cooling signals depends upon the period of fluctuations. Abrupt changes, even if their magnitude is quite appreciable, like intense cooling that occurred in March of 1985, are confined to the upper pycnocline (salinity lower than 19.0-19.5), and they are negligible in terms of modifying temperature structure of deeper layers. Cooling that occurred in 1987 added to the effect of the intense event of 1985, and this signal penetrated downward reaching at least the level of 16.0 sigma-t surface. Cooling signal of the beginning of 1990s reached approximately the same sigma-t surface with a two to three years delay, and a cycle of the variation in the thermal structure of the pycnocline with the period of six to eight years is well seen from the data.

Effective vertical mixing in the Black Sea pycnocline

Figure 3 shows depth dependence of the magnitudes of temperature oscillations of different periods (about 20 years, 6 to 8 years and seasonal). In general, the ampli-

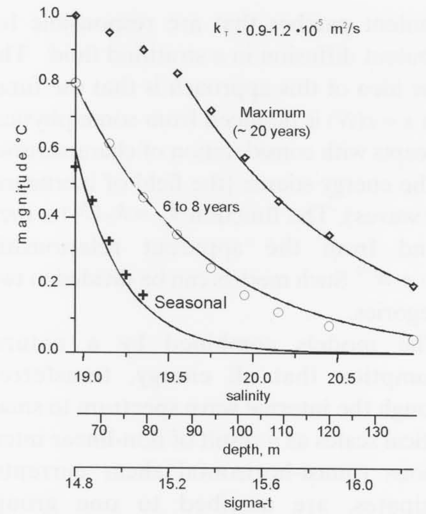

Fig. 3: Depth dependence of the magnitudes of temperature fluctuations of different periods.

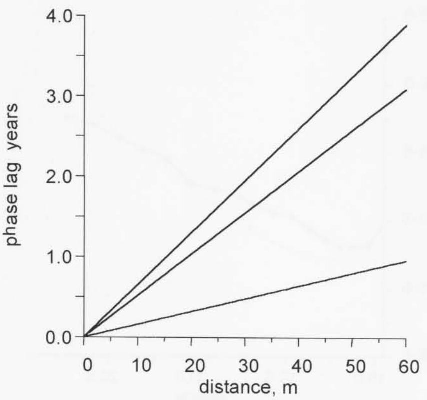

Fig. 4: Depth dependence of the phase lag of temperature fluctuations with 20-years (the upper line), 8-years and 1-year periods propagating from a harmonic source, calculated with $k_T = 1 \cdot 10^{-5}\, m^2 s^{-1}$.

tudes of the fluctuations, starting from certain salinity, decrease with increasing depth in accordance with the exponential law. Typically, $A(z)$ decreases exponentially below salinity 19, but for the extreme events this exponential decrease commences at a deeper level. The relationships $A = A(z)$ have been approximated by the solutions of the diffusion equation $\frac{\partial T}{\partial t} = k_T \frac{\partial^2 T}{\partial z^2}$ that describes thermal wave propagation from a harmonic source, $A(z) = A_0 \exp(-\sqrt{\frac{\pi}{k_T \cdot \tau}})$, where k_T is the average effective mixing coefficient for the middle and lower part of the pycnocline and τ is the period of oscillations. The best fits were achieved with the $k_T = 0.9 \div 1.2 \cdot 10^{-5}\, m^2 s^{-1}$. The relationship between the phase lag and depth, $\varphi = \sqrt{\frac{\pi}{k_T \cdot \tau}} \cdot z$, (relative to the top boundary of the layer) is shown in Figure 4. It confirms that, for the long-term fluctuations (20 years and 6 to 8 years), the delay in penetration of the signal across the pycnocline should be about three years. Typically, fluctuations at about 20 m depth lag behind those at the top boundary of the layer for one year. The estimates roughly depict the specific case of basin average temperature decrease after the 1993 winter cooling event (IVANOV *et al.*, 1997a; IVANOV *et al.*, 1998). In 1994, the magnitude of temperature anomaly at 15.4 sigma-t interface was about 0.3°C and, the next year, it diminished to about 0.1°C reaching 16.0 sigma-t surface, the level about 25 to 30 meters below 15.4 sigma-t). At the same time, when analysing data on depth dependence of the magnitude and on the time lag for temperature variations for different regions of the sea, one may suggest lower mixing rates for the central part of the basin. Amplitudes dwindle faster with increasing depth and the phase lag is better noticeable in this region than along the periphery of the basin. From a general viewpoint, the conclusion seems quite reasonable because it gives proxy evidence to a logically obvious suggestion that variations in mixing rates on a large scale depend upon large-scale shear currents.

The numerical value of the effective mixing coefficient agrees well with the results of the 1,5-dimensional model of vertical exchange in the Black Sea (SAMODUROV, IVANOV, 1998) that gives details of the k_T distribution in the vertical (Fig. 5). The effec-

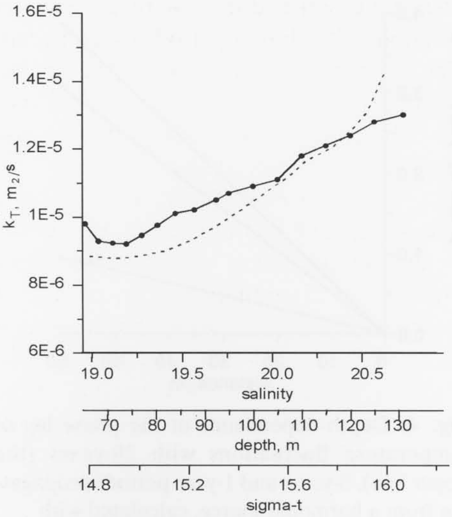

Fig. 5: Depth dependence of the turbulent mixing coefficient derived from the model of vertical exchange in the Black Sea (SAMODUROV, IVANOV, 1998). The dashed line shows the $k_T = a \cdot N^{-1}$ relationship.

tive mixing coefficient increases with increasing depth from about $0.9 \cdot 10^{-5}\, m^2 s^{-1}$ in the upper part of the pycnocline to $1.3 \cdot 10^{-5}\, m^2 s^{-1}$ in its lower part, i.e. in accordance with the commonly accepted hypothesis (GARGETT, 1984; SAMODUROV *et al.*, 1994) on its dependence on stratification. An easy and reliable way to check the figure for the upper pycnocline is to make an estimate of the upward diffusive salt flux and to compare its value with additional salt inputs into the basin. Taking at the top pycnocline boundary $(S \approx 19)$ $\frac{\partial S}{\partial z} = 0.05\ m^{-1}$ and $k_T = 9 \cdot 10^{-6}\, m^2 s^{-1}$, we obtain the value of about 170 tons of salt per second for the additional inputs. The figure perfectly corresponds with the volume, about 300 km^3 per year, of the Bosphorus inflow (UNLUATA *et al.*, 1990).

At present, few results suggesting dependence of k_T on basic parameters in the framework of the $\varepsilon - k$ model are available. The Brunt-Vaisala frequency, $N(z)$, is usually considered as a primary parameter. Here, ε is a specific rate of energy dissipation within turbulent patches that are responsible for turbulent diffusion in a stratified fluid. The basic idea of this approach is that the function $\varepsilon = \varepsilon(N)$ is deduced from some physical concepts with consideration of characteristics of the energy source (the field of inertiagravity waves). The function $k_T = k_T(N)$ is then found from the apparent relationship $k_T \sim \varepsilon \cdot N^{-2}$ Such models can be divided in two categories.

The models combined by a natural assumption that all energy, transferred through the internal wave spectrum to small vertical scales as a result of non-linear interactions (quasi-horizontal shear currents) dissipates, are ascribed to one group. However, this does not mean that all energy is dissipated within patches of turbulence. A mechanism of energy dissipation within patches of turbulence in some form is taken into account for another group of models. In a case, when breaking of internal waves is connected with an integral impact of a broad band wave spectrum, energy dissipation rate is considered proportional to $N^{-1/2}$. When a general source of turbulence is a narrow band internal wave breaking $\varepsilon \sim N^{-1}$. The narrow band model of GARGETT (GARGETT, 1984), $k_T = a \cdot N^{-1}$ ($a = const$), is considered as the most reliable among specialists. The model has been verified using extensive experimental data. Similar dependence of k_T on density stratification within upper pycnocline (strong stratification) has been obtained on the basis of another approach in the model of SAMODUROV *et al.* (SAMODUROV *et al.*, 1994).

The process of formation of turbulent patches depends on background velocity shears. For the open ocean, where shears are basically associated with internal waves, and mixing seems to result mainly from breaking internal waves, the value of N implicitly reflects intensity of the internal wave field as parameterised by GARRET and MUNK. In the Black Sea however, the intensity of the background internal wave field is less than in the ocean due to the absence of tidal motions, and thus large-scale velocity shears must play major role. In such case, the function $k_T(z) = a \cdot N^{-1}$ does not any more imply dependence of mixing on background velocity shears and therefore differs from the real distribution (Fig. 5).

Spatial peculiarities of ventilation properties

In general, temperature variations in the pycnocline correlate with the winter severity index (Fig. 6). Indeed, the Σt_a series indicates that the discussed temperature anomalies (negative) in the pycnocline took place after the severe winters of 1928 and 1929, 1954, 1985 and 1987. For some periods, however, correlation between pycnocline and air temperatures is rather low. For example, the winter of 1993, which was registered as an intensive-cooling episode in terms of effecting thermal structure of the pycnocline, has moderate severity index. The period of 1960s that corresponds to notable positive temperature anomaly in the pycnocline does not differ much from other decades in terms of the winter severity index. The continuation of the cooling period of late 1980s should not be expected either. Surprisingly, the winter severity index time series does not reveal distinct variations with similar periods as the pycnocline temperature time series. These examples imply that cooling at the surface is not the only process that controls penetration depth of winter convection.

As it has been shown in (IVANOV, BESIKTEPE, 1998) stratification above the pycnocline, in much extent, determines effectiveness of ventilation in the process of convective mixing. There is direct and tight relationship between penetration of convection in terms of sigma-t and position of the upper boundary of the pycnocline. To illustrate this CTD data of one of the surveys conducted in the north-western part of the basin in October 1992 were used to calculate values of Potential Energy hypothetically spent to mix the water column with existing stratification down to a certain depth or sigma-t level.

The results of calculations are shown in Figure 7. From the figure, it can be verified that approximately same amount of energy (~ 10000 J/m2) should be spent to mix the water column down to 40 m within the western cyclonic gyre (43°30'N, depth of the 14.8 sigma-t surface is about 40 m) and down to 70 m in the Sevastopol anticyclonic eddy (44°30'N, depth of the 14.8 sigma-t surface is about 85 m). The results were

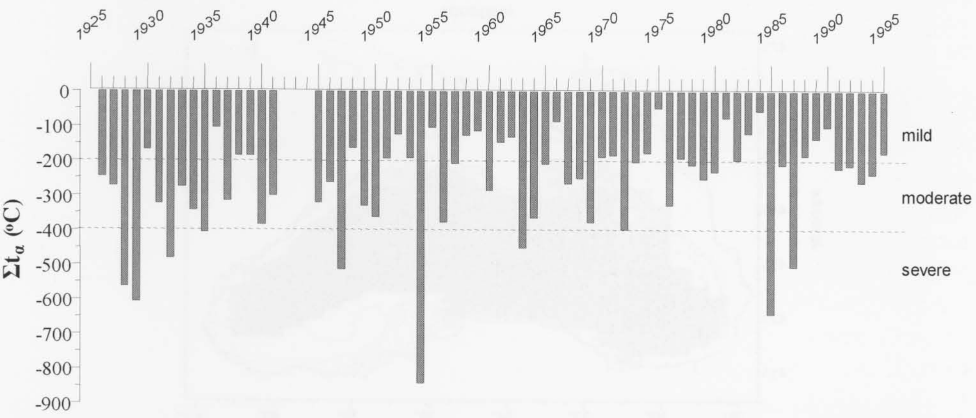

Fig. 6: The winter severity index time series: Σt_a, for meteorological stations of Odessa, Ochakov and Khorly.

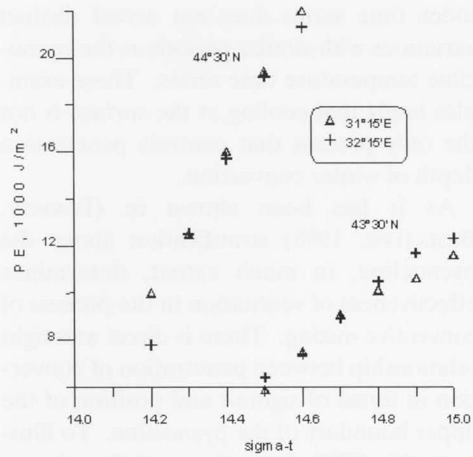

Fig. 7: Potential Energy hypothetically spent to mix the water column with the real stratification for October 1992 down to selected sigma-t surfaces in the centre of the western cyclonic gyre (43°30'N) and over the continental slope west off Crimea.

then compared with the real data that describe situation after the winter of 1992-93. Convective mixing during the winter of 1992-93 eroded the pycnocline in the cyclonic domain where its upper boundary was situated 30 - 40 meters below the sea surface. A patch of low temperature in the central part of the western basin coincides with the dome of the pycnocline (Fig. 8). Within anticyclonic eddies convection is deeper in terms of depth but much "shallower" in terms of sigma-t. The result could be predicted from the October 1992 data with the known estimate of energy spent for mixing. Indeed, Figure 7 shows that if about $10 \div 12 \cdot 10^3 \ J/m^2$ were spent for mixing convection would penetrate down to 14.8-15.0 sigma-t in the centre of the western cyclonic

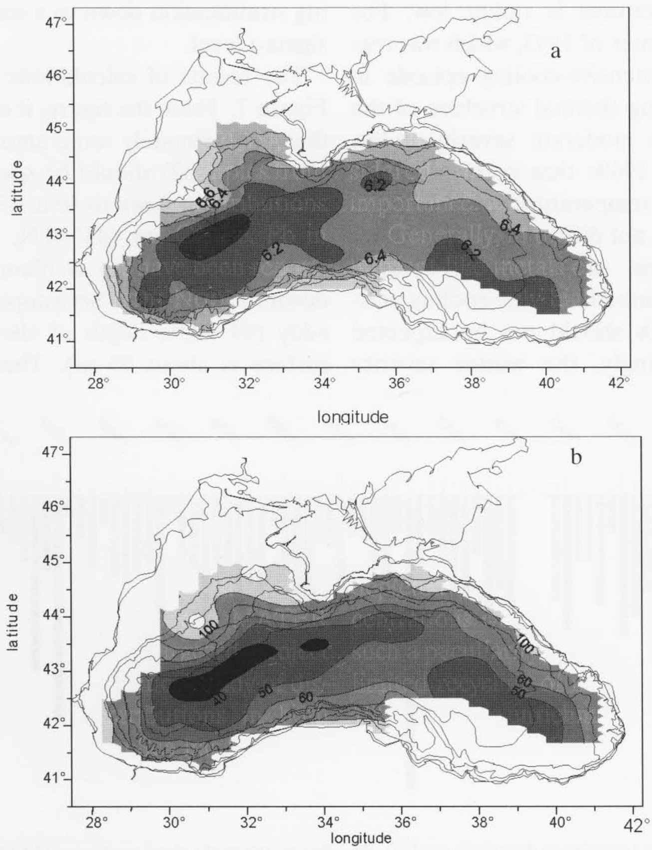

Fig. 8: Spatial distribution of temperature at 14.8 sigma-t surface (a) and topography of the 14.8 sigma-t surface (b).

gyre and only down to 14.3 sigma-t in the area of anticyclonic circulation. Actually, it reveals that, even with a spatially uniform surface fluxes, the characteristic inhomogenity in the thickness of the cold intermediate layer is formed due to horizontal inhomogeneity in stratification of the upper layer.

Interestingly, vertical distribution of the magnitudes of extreme temperature fluctuations (Fig. 3) implies that under certain conditions convective mixing penetrated down to 15.2 sigma-t surface. Figure 7 indicates that this might happen either in response to extreme weather conditions, like in 1954, or as a result of anomalous shoaling of the pycnocline.

Estimates of the cross-pycnocline heat flux

In the Black Sea, due to existence of the perennial feature of the Cold Intermediate Layer, the upward heat flux out of the thermohalocline is limited to short winter periods of rough and cold weather when the layer is exposed to atmospheric forcing. In other words, it happens when the CIL core is completely eroded, and convection reaches the upper boundary of the pycnocline in the centres of the large-scale cyclonic gyres. The shallower the upper pycnocline boundary the longer is the period of the pycnocline exposure to erosion. On intuitive grounds, the area where convection reaches the pycnocline must be quite small because, within a seasonal cycle, the layer deepens due to diffusion. This also suggests that the pycnocline may not be exposed to erosion every winter. Hydrographic data of recent basin wide monitoring surveys allow to make estimates of the magnitude of heat losses from below the level of the temperature minimum.

Calculations of heat losses below the CIL core during the cooling period gave an estimate of $4 \div 6 \cdot 10^7 \, J/m^2$. At the same time typical negative heat flux at the sea surface

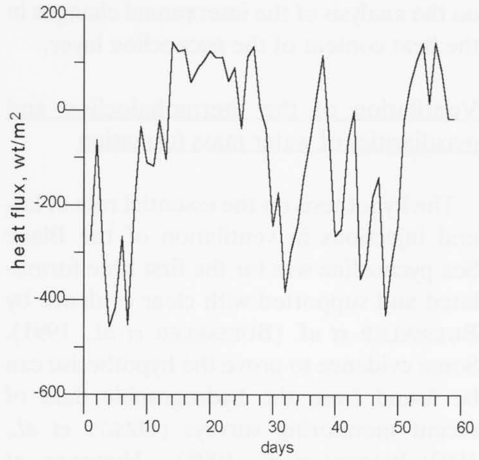

Fig. 9: Sea surface heat flux during January - February 1993 in the area of the western Black Sea cyclonic gyre.

during winter storms can be estimated about $300 \; wt/m^2$ (Fig. 9). Hence, space-time scale of the atmospheric impact on the main pycnocline can be estimated as 40 - 60 hours *times* fraction of the area where the pycnocline is eroded. The profile for 1994 shows redistribution of heat within the pycnocline for a warm year, i.e. for a year when convection was confined to the layer above the remnant CIL core. Spatial distribution of temperature in the upper pycnocline in April of 1993 (Fig. 8, a) implies that convection eroded the pycnocline over 50 - 60 % of the area of the deep basin. Thus, the period when convection reaches the upper boundary of the pycnocline is rather short, it lasts for about a week, and on the average such conditions occur once in two years.

The cross-pycnocline heat flux can be also estimated using the effective mixing coefficient derived from the analysis of the peculiarities of the pycnocline thermal structure variability. Taking $k_T = 9 \cdot 10^{-6} m^2 s^{-1}$ and $\frac{\partial T}{\partial z} = 0.03°C \cdot m^{-1}$ at about 70 m depth (salinity about 19.2) we get $F^T \cdot c_P = 1.1 \; wt/m^2$ for the diffusive upward heat flux, or $7.1 \cdot 10^7 \, J/m^2$ for a period of two years, which is in good agreement with the former estimate based on the analysis of the interannual changes in the heat content of the pycnocline layer.

Ventilation of the thermohalocline and peculiarities of water mass formation

The hypothesis on the essential role of lateral injections in ventilation of the Black Sea pycnocline was for the first time formulated and supported with clear evidence by BUESSELER *et al.* (BUESSELER *et al.,* 1991). Some evidence to prove the hypothesise can be found from the hydrographic data of recent monitoring surveys (OZSOY *et al.,* 1993; IVANOV *et al.,* 1998). However, at least one issue remains unclear from the analysis of sporadic data. The question can be formulated in the following form. At what depth, on the average, does disintegration of the sinking plume commence? Interestingly, but the answer to the question can be found from the analysis of an average T,S diagram drawn with the use of all available hydrographic data, i.e. basin-wide average on a century time scale (Fig. 10).

Temperature and salinity basin-wide averages for the period from 1923 to 1997 reveal a linear segment of the T, S diagram (or a segment of constant density ratio values), approximately, between 19.0 and 20.5 isohaline surfaces. Non-linear segments of the T,S curve correspond to the layers below

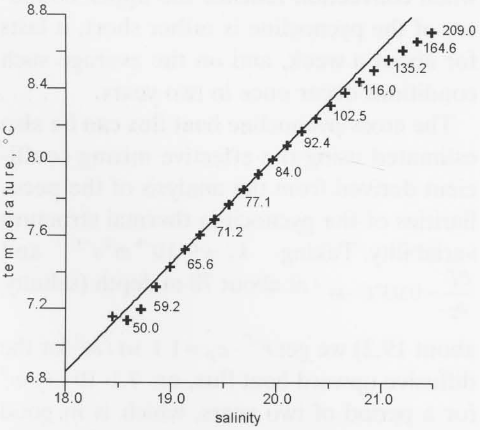

Fig. 10: Mean T,S diagram for the Black Sea.

20.5 and above 19.0 isohaline surfaces. If to accept that the mean T,S diagram shown in the figure reflects the Black Sea steady state conditions then we must conclude that there are lateral sources of salt and heat in the layers above salinity surface 19.0 (~65 m) and below salinity surface 20.5 (~100 m). The water mass in between is the result of two end-member mixing, a mixture of the upper and lower pycnocline waters, and there is no evidence to suggest any lateral source of heat or salt for this layer. For the upper layer this lateral source is the cold intermediate water formed due to winter convective mixing. For the lower layer the lateral source of salt and heat is the cascading and disintegrating Bosphorus plume. That provides additional proof to the concept of different ventilation regimes for the upper and lower pycnocline.

Applying the hypothesis of BUESSELER *et al.* (BUESSELER *et al.,* 1991) for explanation of spatial variability of thermohaline structure, one may come to conclusion that waters of the Bosphorus plume effectively contribute to cross-pycnocline exchange in the Black Sea. Intensive near-surface winter convection exerts a proxy impact on thermal characteristics of the lower pycnocline changing temperature of the water entrained to Bosphorus inflow. Thus, fluctuations in the lower pycnocline may be partially caused by variations that occur within the upper layer, but then are conveyed downward due to entrainment and subsequent disintegration of the cascading plume.

Conclusions

It is shown that three major cooling events can be distinguished from the record of the pycnocline temperature for the past 75 years. The intensive cooling occurred in late 1920s-early 1930s, early 1950s and late 1980s-early 1990s. Partial renewal of water of the cold intermediate layer core took place approximately once in two years.

Thus, the events of the pycnocline erosion do not happen every year and they last for only about a week. Depth dependence of temperature fluctuations in the pycnocline is well described by exponential decrease. The functions $A = A(z)$ are the solutions to the diffusion problem with an assumption of a constant mixing coefficient. The best fits are achieved with $k_T = 0.9 \div 1.2 \cdot 10^{-5} m^2 s^{-1}$. The estimated value for the effective cross-pycnocline mixing coefficient seems quite reasonable since it provides a realistic estimate for salt and heat fluxes in the pycnocline.

Lateral source of heat and salt exists for the upper pycnocline, where it is the cold intermediate water formed within confined areas over the dome of the pycnocline, and for the lower pycnocline, the layer below $S \cong 20.5$ where this lateral source of salt and heat is maintained by disintegrating Bosphorus plume. Within the framework of this approach, three layers are distinguished in terms of physical mechanisms of water mass formation. The formation of the upper pycnocline water is influenced by penetrative winter convection. Events of pycnocline erosion happen quite rarely, once in a couple of years and the patches of mixing are confined to the domes of the pycnocline. The water mass of the middle part of the pycnocline, the layer between 65 and 100-m depth, is formed due to two end-member vertical mixing. The water mass of the lower pycnocline is formed under the influence of lateral sources of heat and salt, presumably maintained by Bosphorus effluent.

Acknowledgements

The study has become possible through the support coming from the EC INCO COPERNICUS Project "Ventilation of the Black Sea Anoxic Waters" (IC15CT96-113). Much of data pooling has been done in the framework of the NATO TU Black Sea Project.

References

ALTMAN, E.N. & SIMONOV, A.I. (eds), 1991. Hydrometeorology and hydrochemistry of USSR seas, Vol. IV The Black Sea, 428 p., Gidrometeoizdat, St. Petesburg.

BELOKOPYTOV, V., 1998. On Hydrometeorological Conditions of Cold Intermediate Water Renewal in Northern Part of the Black Sea. In: L.Ivanov, T.Oguz (eds.) Ecosystem Modelling as a Management Tool for the Black Sea, Kluwer Academic Publishes, Dordrecht, Vol.2, 47-52.

BLATOV, A.S. 1981. Hydrological structure and energy storage of the Main Black Sea Current eddies, *Meteorologia i Gydrologia* 7, 86-93.

BUESSELER, K.O., LIVINGSTON, H.D. & CASSO, S.A., 1991. Mixing between oxic and anoxic waters of the Black Sea as traced by Chernobyl cesium isotopes. *Deep-Sea Res.* 38, suppl.2A, 725 - 746.

GARGETT, A.E., 1984. Vertical eddy diffusivity in the ocean interior. *J.Mar.res.*, 42, 359-393.

IVANOV, L.I., BESIKTEPE, S. & OZSOY, E., 1997. Physical Oceanography Variability in the Black Sea Pycnocline, in A.Mikaelyan and E.,Ozsoy (eds.), Sensitivity to change: Black Sea, Baltic Sea and North Sea, Kluwer Academic Publishes, Dordrecht, NATO ASI Series, 265-274.

IVANOV, L.I., BESIKTEPE, S. & OZSOY, E., 1997. Black Sea Cold Intermediate Layer. In: E.Ozsoy and A.Mikaelyan (eds.), Sensitivity to change: Black Sea, Baltic Sea and North Sea, Kluwer Academic Publishes, Dordrecht, NATO ASI Series, 253-264.

IVANOV, L.I., KONOVALOV, S., BELOKOPYTOV, V. & OZSOY, E., 1998. Regional Peculiarities of Physical and Chemical Responses to Changes in External Conditions Within the Black Sea Pycnocline: Cooling Phase. In: L.Ivanov, T.Oguz (eds.) NATO TU-Black Sea Project: Ecosystem Modelling as a Management Tool for the Black Sea, Symposium on Scientific Results. Kluwer Academic Publishes, Dordrecht, NATO ASI Series. Vol.2, 53-68.

IVANOV, L.I., & BESIKTEPE, S., 1998. Black Sea Cold Intermediate Water Mass Volumetric Structure and Its Variability. In: Oceanic Fronts and Related Phenomena. Konstantin Fedorov memorial Symposium. St. Petersburg, Pushkin, 18-22 May, 1998.

OVCHINNIKOV, I.M., 1984. To the question of cold intermediate layer formation in the Black sea, *DAN SSSR* 279, 986-988.

OZSOY, E., UNLUATA, U. & TOP, Z., 1993. The Mediterranean Water Evolution, Material Transport by Double Diffusive Intrusions, and Interior Mixing in the Black Sea. *Progress in Oceanography.* 31, 275-320.

SAMODUROV, A.S., LYUBITSKY, A.A. & PANTELEEV, N.A., 1994. A contribution of the overturning internal waves to the structures formation, energy dissipation and vertical diffusion in the ocean. *Marine Hydrophysical Journal*, N 3, 14-27.

SAMODUROV, A.S. & IVANOV, L.I., 1998. Processes of Ventilation of the Black Sea Related to Water Exchange through the Bosphorus. In: L.Ivanov, T.Oguz (eds.) NATO TU-Black Sea project: Ecosystem Modelling as a Management Tool for the Black Sea, Symposium on Scientific Results. Kluwer Academic Publishes, Dordrecht, NATO ASI Series. Vol.2, 221-236.

UNLUATA, U., OGUZ, T., M.A., LATIF, E., OZSOY (1990) On the Physical Oceanography of the Turkish Straits. In L.J.Pratt (ed.), The Physical Oceanography of Sea Straits, NATO/ASI Series, Kluwer Academic Publishes, Dordrecht., 25-60.