Ocean Sci. Discuss., 8, 321–352, 2011
www.ocean-sci-discuss.net/8/321/2011/
doi:10.5194/osd-8-321-2011
© Author(s) 2011. CC Attribution 3.0 License.

Ocean Science
Discussions

This discussion paper is/has been under review for the journal Ocean Science (OS).
Please refer to the corresponding final paper in OS if available.

Seasonal and inter-annual temperature variability in the bottom waters over the Black Sea shelf

G. I. Shapiro[1,2], **F. Wobus**[1], **and D. L. Aleynik**[3,2]

[1]School of Marine Science and Engineering, University of Plymouth, Plymouth, UK
[2]P. P. Shirshov Institute of Oceanology, Moscow, Russia
[3]Scottish Association of Marine Science, Oban, UK

Received: 28 December 2010 – Accepted: 16 January 2011 – Published: 2 February 2011

Correspondence to: G. I. Shapiro (gshapiro@plymouth.ac.uk)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Long-term changes in the state of the Bottom Shelf Water (BSW) on the Western shelf of the Black Sea are assessed using analysis of intra- and inter-annual variations of temperature as well as their relations to physical parameters of both shelf and deep-sea waters. First, large data sets of in-situ observations over the 20th century are compiled into high-resolution monthly climatology at different depth levels. Then, the temperature anomalies from the climatic mean are calculated and aggregated into spatial compartments and seasonal bins to reveal temporal evolution of the BSW. For the purpose of this study the BSW is defined as such shelf water body between the seabed and the upper mixed layer (bounded by the $\sigma_\theta = 14.2$ isopycnal) which has limited ability to mix vertically with oxygen-rich surface waters during the warm season (May–November) due to the formation of a seasonal pycnocline. The effects of atmospheric processes at the surface on the BSW are hence suppressed as well as the action of the "biological pump". The vertical extent of the near- bottom waters is determined based on energy considerations and the structure of the seasonal pycnocline, whilst the horizontal extent is controlled by the shelf break, where strong along-slope currents hinder exchanges with the deep sea. The BSW is shown to occupy nearly half of the area of the shelf during the summer stratification period. The potential of the BSW to ventilate horizontally during the warm season with the deep-sea waters is assessed using isopycnic analysis of temperature variations. A long-term time series of temperature anomalies in the BSW is constructed from observations during the May–November period for the 2nd half of the 20th century. The results reveal a warm phase in the 1960s/70s, followed by cooling of the BSW during 1980–2001. The transition between the warm and cold periods coincides with a regime shift in the Black Sea ecosystem. While it was confirmed that the memory of winter convection events is well preserved over the following months in the deep sea, the signal of winter cooling in the Bottom Shelf Waters significantly reduces during the warm season. The time series of temperature in the BSW is highly correlated with the temperature of Cold Intermediate

Waters in the deep sea thus indicating that the isopycnal exchanges with the deep sea are more important for inter-annual/inter-decadal variability of the BSW on the Western Black Sea shelf than winter convection on the shelf itself.

1 Introduction

The coastal and shelf zones of the Black Sea are of immense economic significance, they contain biologically productive, diverse ecosystems that provide a vital habitat for many commercial and endangered species. Until mid-1980s, it supported fisheries almost five times richer than those of the neighbouring Mediterranean. In the end of the 20th century the Black Sea has experienced the worst environmental degradation of all of the world's major seas (Mee et al., 2005).

The environmental crisis and subsequent dramatic changes in the Black Sea's ecosystem are a direct effect of both natural and anthropogenic causes (Salihoglu, 2000). At the same time, significant changes in the physical environment have been reported (McQuatters-Gollop et al., 2008; Oğuz, 2005). There is growing understanding that changes in the Black Sea ecosystem are stronger influenced by climate change than previously thought (Daskalov, 2003; Oğuz, 2005).

The influence of changes in the physical environment on the ecosystem cannot be properly assessed without accurate analysis of the variability of the marine physical sub-system in its own right. The studies of long-term (inter-annual or inter-decadal) variations of physical parameters of the Black Sea are sparse, they are commonly restricted by analysis of the deep sea only, and usually deal with either sea surface temperature (Oğuz, 2005; McQuatters-Gollop et al., 2008) or temperature variations in the Cold Intermediate Water (CIW) of the deep basin (Ivanov et al., 2000; Belokopytov, 1998).

The link between the physical and biochemical parameters of the Black Sea has been established, in particular the connection between water density and vertical profiles of chemical parameters (Vinogradov and Nalbandov, 1990; Murray et al., 1995; Yakushev et al., 2005). The oxycline and the chemocline occur at the same depth intervals as the halocline, because of similarity in the mechanisms of vertical exchanges (Özsoy and Ünlüata, 1997). Supply of oxygen to the near-bottom waters, which is controlled by physical processes, is crucial for functioning of the benthic ecosystem (Yakushev et al., 2005). Habitats with normal levels of oxygen occur in the narrow coast zone from the shore to 7–10 m and in the deeper shelf zone from 40 m to the onset of permanently anoxic conditions at around 130 m (Zaitsev, 2006). While coastal areas are free from hydrogen sulphide, concentrations increase in the deeper parts of the shelf due to the restricted ventilation under the thermocline (Zaitsev et al., 2002).

The focus of this paper is on the long-term variation in the temperature of Bottom Shelf Water (BSW) on the productive Western shelf. For the purpose of this study the BSW is defined as such shelf water body between the seabed and the upper mixed layer which has limited ability to mix vertically with oxygen-rich surface waters during the warm season (May–November) due to the formation of a seasonal pycnocline. This water body has an arguably stronger influence on the deeper benthic communities of the outer shelf (depth range 40–130 m) than parameters at the sea surface. As we show later in Sect. 3, the areas occupied by the deeper shelf ecosystem coincide well with the spread of the BSW and hence knowledge of temporal variations in the physical state of BSW could help understand the decline and recovery cycles of the benthic ecosystem.

During the winter months the BSW on the extensive Black Sea shelf is subject to strong convective mixing with the surface waters and hence an intensive ventilation of the bottom waters occurs during the cold season. On the contrary, the heating of the surface waters during the warm season (here defined as May to November) weakens the link between the surface and bottom waters due to formation of a strong vertical density gradient that hampers vertical mixing and the bottom waters become isolated from the surface. It has been suggested that the strengthening of the seasonal pycnocline in summer is associated with the reduction of the oxygen supply to the bottom waters (Keondzhyan et al., 1990).

Suppression of vertical mixing does not mean that the BSW is completely arrested – they can still be involved in horizontal (more precisely – isopycnal) exchanges with deep sea waters. There is a number of ways in which horizontal exchanges contribute to communication between the shelf and the deep Black Sea, including transport by Rim Current meanders, mesoscale eddies, shelf edge cascading etc. (see e.g. Blatov et al., 1984; Gawarkiewicz et al., 1999). Horizontal shelf – deep sea exchanges are considered as one of the mechanism of formation of the Cold Intermediate Water in the deep Black Sea (e.g. Sorokin, 2002; Stanev et al., 2004). Shelf – deep sea interactions are known to have impact on the sea surface temperature over the shelf (Ginzburg et al., 2002), spatial distribution of chlorophyll (Oğuz et al., 2002; Shapiro et al., 2010b) and the state of the Black Sea ecosystem (Sur et al., 1996), however the strength of these exchanges was difficult to quantify and this issue has motivated the present study.

In this paper we use historic data sets to identify seasonal, inter-annual and inter-decadal variability in the temperature of bottom shelf waters over the Western Black Sea shelf. We also analyse the correlation of these changes with other physical parameters of the shelf and deep-sea waters, and the overlying atmosphere. Correlation between shelf and deep sea waters are used to examine potential role of lateral exchanges in variability of parameters and the ventilation of the BSW on the extensive western Black Sea shelf. We use temperature as an indicator for general physical conditions in the BSW. The physical reason for this is that inter-annual variations in the near-bottom temperature are directly related with the variations in the volume of cold waters (Ivanov et al., 2000) which are formed on the shelf and then exported into the deep sea. The other reason is that temperature variations in the BSW reflect variations in the vertical fluxes of heat and dissolved matter including oxygen.

2 Data and methods

The sources of data for this study are a combination of the temperature data subset from the World Ocean Database 2001 (Stephens et al., 2002), for the period 1900–2000, which includes 15517 individual stations, and a data set obtained from the Romanian Marine Research Institute (RMRI, 2362 stations covering the period 1963–2004). These combined data sets were used to calculate the high-resolution climatology and are hereafter referred to as "WOD+ROM" (see Shapiro et al., 2010a for a more detailed description of this data set). A further 26283 stations (for 1920–2001) from the Black Sea Digital Atlas of the Marine Hydrophysical Institute (Sevastopol, Ukraine) (Suvorov et al., 2004) were used for the calculation of an additional time series of temperature anomalies. This dataset will be referred to as "MHI". The temperature and salinity data for each individual station were linearly interpolated to 1 m vertical increments in z-coordinates.

In order to eliminate erroneous data points, the WOD+ROM data set was subject to a quality control using a two- step procedure as in Stephens et al. (2002). The data were subdivided geographically into 0.25° squares. Then the approximate values of the "first-guess" monthly mean states and standard deviations were calculated for 12 calendar months and all 0.25° degree squares at 26 standard hydrographic depth levels. Then, the outliers, i.e. the data points with more than 6 standard deviations away from the mean, were removed from the data base.

In contrast to many previous studies of inter-annual variability in the Black Sea, the temperature anomalies (i.e. deviations from monthly climatic averages) rather than the absolute values are used here as indicators of temporal changes. The advantage of using anomalies is that unlike the absolute temperatures, the temperature anomalies are highly correlated spatially at sampling points separated as far as 1200 km (Hansen and Lebedeff, 1987). This large correlation radius allows aggregating observational data over extended areas of the Black Sea and avoids bias caused by spatial inhomogeneity of sampling sites. In order to calculate deviations from climate, the mean (climatic) values over the period of 1910–2000 were calculated first.

cc BY

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
I◀ | ▶I
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

2.1 Climatology and inter-annual variability

Climatic averages are calculated using the adaptive grid method (Lozier et al., 1995; Shapiro et al., 2010a). The idea of this method is to use smaller grid sizes where the data is abundant and larger grids in the areas of sparse data. The Black Sea is split into $0.25^\circ \times 0.25^\circ$ squares, and the averages at each grid point and each depth level are calculated using a two-scale weighting function:

$$C(r)=\theta\left(\frac{r}{r_s}\right)\cdot\exp\left[-\left(\frac{r}{r_d}\right)^2\right] \qquad (1)$$

where $\theta\ (x)=1$ at $x \le 1$ and $\theta(x)=0$ at $x>1$. Parameters $r_s = 100\,\mathrm{km}$ and $r_d = 25\,\mathrm{km}$ are selected as in Shapiro et al. (2010a) to provide an optimum balance between horizontal resolution and statistical accuracy of the calculated mean values.

Then climatic values are spatially and temporally interpolated to the location and time of month of the actual measurements. Both profiles (measured and climatic) are interpolated in σ_θ-coordinates to density levels in $0.1\,\mathrm{kg\,m^{-3}}$ intervals. For stations where matching density levels are present in both actual $T(x,y,\sigma_\theta,t)$ and climatic $T_{\mathrm{clim}}(x,y,\sigma_\theta,t)$ profiles the temperature anomalies (T_{an}) are calculated at each density level σ_θ as:

$$T_{\mathrm{an}}(x,y,\sigma_\theta,t)=T(x,y,\sigma_\theta,t)-T_{c\,\mathrm{lim}}(x,y,\sigma_\theta,t) \qquad (2)$$

where t is the time of observation.

The anomalies are aggregated into two seasonal bins (cold period (“winter”): December to April, warm period (“summer”): May to November) and further aggregated spatially over each geographical compartment, either the western shelf or the western deep sea. The compartments are defined in the Western Black Sea over 41.05° N to 47° N and 27° E to 34° E (see Fig. 1). The shelf boundary is considered to be the 150 m depth contour which forms the lower limit of the deep benthic ecosystem on the shelf (Zaitsev, 2006). The bathymetry was taken from ETOPO2v2 (NGDC, 2006).

In order to estimate uncertainty related to combining data collected in different months of the warm season, the intra-annual variability is assessed using temporally and spatially averaged data for each calendar month and then compared to inter-annual variability of the same parameter. A similar procedure is used to assess temperature anomalies at specific density levels. The intra-annual variability during the months May to November (measured as standard deviation from the mean) is shown to be significantly smaller than the inter-annual variability (see Sect. 3.1), hence justifying the method of combining the data over the period May to November.

2.2 Mixing depth

The vertical extent of the bottom waters on the shelf can be defined by a number of ways: for example by setting a specific height above bottom or choosing a specific temperature/salinity/density level. For instance, the Cold Intermediate Layer (CIL) in the deep Black Sea is traditionally defined by the 8 °C isotherms (e.g. Blatov et al., 1984) or at its upper bounds by the isopycnic levels $\sigma_\theta = 14.2\,\mathrm{kg\,m^{-3}}$ (e.g. Ivanov et al., 2000, 2001). For the purpose of this study we are interested in the ability of water masses to mix under the action of mechanical forces. Following up ideas formulated by Simpson and Hunter (1974) and Ivanov et al. (2000) we employ the energy considerations to identify the boundaries between the water masses. In this section we show that the amount of mechanical energy needed to mix the pre-winter stratification from the surface down to a specified density level at different locations on the outer western Black Sea shelf is largely determined by the value of density itself irrespective of geographical location so that density levels can be used as “proxies” for mixing energy levels.

The energy needed for mixing down to a specific depth is calculated using the following scheme.

The potential energy (PE) of a stratified water column over a unit area is given as:

$$\mathrm{PE} = g \int_{z_1}^{0} \rho(z) z \, dz \qquad (3)$$

cc BY

Where g is the acceleration due to gravity, ρ is the density, z is the depth and z_1 is the depth of the water column (using a coordinate system with upward looking vertical axis).

The uniform density of the water column after mixing can be derived from the measured density profile (ρ_{before}) using conservation of mass,

$$\rho_{\text{after}} = -\frac{1}{z_1}\int_{z_1}^{0} \rho_{\text{before}}(z)dz \tag{4}$$

resulting in the potential energy of the well-mixed water column as:

$$\text{PE}_{\text{after}} = g\int_{z_1}^{0} \rho_{\text{after}}(z)z\,dz = \frac{g}{2}z_1\int_{z_1}^{0} \rho_{\text{before}}(z)dz \tag{5}$$

We consider here the work W_{mix} required to completely mix a water column from the surface to depth z_1 as the difference between the potential energy of the stratified and homogeneous water column:

$$W_{\text{mix}} = \text{PE}_{\text{after}} - \text{PE}_{\text{before}} \tag{6}$$

Substituting Eqs. (3) and (5) into Eq. (6) and rearranging the equation using the density σ_θ instead of ρ_{before}, the mixing energy W_{mix} (in J m^{-2}) can be linked to the pre-mixed density profile as:

$$W_{\text{mix}} = g\left[z_1\int_{z_1}^{0} \sigma_\theta(z)dz - 2\int_{z_1}^{0} \sigma_\theta(z)z\,dz\right] \tag{7}$$

The evaluation of depths z_1 from Eq. (7) for various W_{mix} gives an indication of how deep the effects of atmospheric processes penetrate into the water column.

A mean density profile (Fig. 2a) is obtained by combining climatic profiles located on the outer shelf (deep enough to reach the seasonal pycnocline) from 43° N, 28.5° E to 44.75° N, 33.25° E for the month of October representing stratification at the end of the summer period and before the beginning of winter convection. Calculations of the penetration depth of convective mixing are carried out using Eq. (7).

Figure 2b proves the robust link between density levels and mixing energy values. This fact provides a physical justification to the preferential use of density, rather than temperature and salinity, levels to define the boundaries of the BSW. According to 3.1b, if 10 KJ m^{-2} were applied to the surface of an average water column the resulting mixing would penetrate down to about $\sigma_\theta = 14.2\,\mathrm{kg\,m^{-3}}$ while 30 KJ m^{-2} would be required to penetrate to the level of $\sigma_\theta = 14.8\,\mathrm{kg\,m^{-3}}$, which corresponds to the core of the neighbouring CIL in the deep sea. These figures are consistent with results by Ivanov et al. (2000) who applied a similar method to measurements taken in October 1992 and showed that mixing energy of about 10–12 KJ m^{-2} would penetrate down to $\sigma_\theta = 14.3\,\mathrm{kg\,m^{-3}}$ in the western anticyclonic circulation of the deep Black Sea. Further in this study we use the same isopycnic surface $\sigma_\theta = 14.2\,\mathrm{kg\,m^{-3}}$ as in Ivanov et al. (2000) to define the upper boundary of the BSW.

3 Results

3.1 Climate and intra-annual variations

Analysis of climatic temperature profiles reveals that the water column during the winter convection period is well mixed on most parts of the shelf and therefore does not allow a meaningful identification of the pycnocline. Further analysis is therefore restricted to the warm season (defined here as May–November) when the shelf waters are strongly stratified.

The topography of the isopycnal level $\sigma_\theta = 14.2\,\mathrm{kg\,m^{-3}}$ is shown in 3.1 for the climatology in April (after the winter convection period) and October (after the summer

cc BY

stratification period). The spatial extent of the bottom shelf waters calculated for each calendar month within the warm season using climatic temperature and salinity profiles is shown in Fig. 4. The contours show the coverage of the BSW, which is largely isolated from vertical mixing from the surface until the following winter. The potential of these areas to be ventilated by horizontal exchanges during the warm period is discussed in Sect. 4.

Figure 5 shows that the area occupied by the BSW is fairly constant during May–November at around 38×10^3 km^2, which is 45% of the total shelf area, which occupies 83 300 km^2 from the coast to the depth of 150 m. The area of "locked" near-bottom waters varies from 30 300 km^2 in September to 40 500 km^2 in June. The volume of this water body varies from 900 km^3 in September to 1400 km^3 in June (the total volume of the shelf compartment is 4300 km^3). Figure 5 also shows the intra-annual variability of the depth of the upper boundary of the BSW as identified by the isopycnal at $\sigma_\theta = 14.2\,\mathrm{kg\,m^{-3}}$, which gives an average depth of 46 ± 4 m. The pycnocline deepens slightly (a few metres) during the warm season probably due to slow diapycnic mixing.

Figure 6 shows the values of spatially averaged climatic absolute temperatures within the BSW (i.e. averaged over the water body with $\sigma_\theta \geq 14.2\,\mathrm{kg\,m^{-3}}$ over the shelf up to the 150 m depth contour) for different months within the warm season. The intra-annual variability during the whole warm period shows a very small range from 7.5–8.2 °C with the mean value of 7.8 °C (Fig. 6). With the exception of June, there is a small but systematic warming of the BSW during the warm season from 7.5 °C in May to 8.1 °C in November. An unexpected small increase of average temperature in June is not statistically significant due to large scatter of data for this month.

For the same months the average temperature at the upper boundary of the BSW (defined as $\sigma_\theta = 14.2\,\mathrm{kg\,m^{-3}}$) was calculated as 8.3 °C (stdev = 0.35 °C) which closely coincides with the classical definition of the boundary of CIW as the 8 °C isotherm.

3.2 Inter-annual and inter-decadal variability

For reasons discussed in Sect. 2, inter-annual and inter-decadal variability is analysed using temperature anomalies rather than absolute values. A time series of temperature anomalies averaged spatially over the area and density range of the BSW (from $\sigma_\theta = 14.2\,\mathrm{kg\,m^{-3}}$ down to a depth of 150 m) and temporally over the warm season (May–November) of each year (Fig. 7) was constructed using methodology described above in Sect. 2.

The temperature anomalies range between −1.2° in 1996 and +1.7 °C in 1978. The inter-decadal variability is thus significantly greater than the than the small statistical uncertainty of less than 0.2 °C associated with this climatic data set (Shapiro et al., 2010a). It is also much greater than the intra-annual variability between May and November shown in Fig. 6, thus justifying temporal aggregation of temperature data in the BSW into a single seasonal value for the entire warm period of each year.

A warmer-than-average period is evident from the early 1960s to the early 1980s followed by a colder-than-average period from the early 1980s to the early 2000s. Figure 7 clearly shows 2 warming periods when the temperature rose, one lasted from the early 1960s to the early 1970s, the other started in the early 1990s and continued at least to the end of the 20s century. Despite their similarities there is an important difference between them: the first warming period (1960–70s) started from climatically "normal" condition ($T_{\mathrm{an}} = 0$), whilst the second one (1990–2000s) started from a colder than climatically averaged state ($T_{\mathrm{an}} = -0.7\,^\circ\mathrm{C}$) and did not reach the climatic mean temperatures even in 2001. These warming periods were separated by a 20-years-long cooling period from the early 1970s to 1990s.

The parameters of the BSW are influenced by neighbouring water masses and by the meteorological conditions particularly during the winter season when intensive vertical mixing with surface waters takes place. The correlations between the inter-annual variations of the BSW temperature and other local and remote parameters are analysed using Pearson correlation coefficients. In order to preserve comparability with the previous studies (Altman and Simonov, 1991; Belokopytov, 1998) correlations with external meteorological conditions are assessed using the long-term time series of the "winter severity index" Σt_a which is traditionally calculated as the sum of negative air temperatures during winter (November–April) from meteorological station at Odessa, Ochakov and Khorly along the North-Western shore of the Black Sea shelf (Fig. 8).

The effect of winter cooling is first felt at the sea surface and hence correlation between the winter sea surface temperature and the summer temperature in the BSW would show how well the effect of winter cooling is preserved in the shelf bottom waters. Inter-annual variability of the winter sea surface temperature of shelf waters is estimated similar to the bottom waters , i.e. by calculating temperature anomalies using Eq. (2) and then aggregating them over the shelf compartment (see Fig. 1) however temporal aggregation is done over the cold period (December–April) of each year (Fig. 8). In a similar way, the inter-annual variability was calculated for the temperature of CIW (defined by the density range $\sigma_\theta = 14.2 - 14.8\,\mathrm{kg\,m^{-3}}$, as in Ivanov et al. (1997)) during the warm season (May-November) in the deep part of the western Black Sea (Fig. 9). The temperature response of surface waters in the deep sea to winter cooling is characterised by a long-term series of the winter (December–March) mean sea surface temperature averaged over the interior basin with depths greater than 1500 m obtained from Oğuz et al. (2006) , see Fig. 9.

Figure 10 summarises the correlations (Pearson R-values) of long-term temperature time series of the winter severity index Σt_a, SST of the basin interior in winter, temperature anomaly (T_{an}) of the shelf surface in winter, T_{an} of Bottom Shelf Waters in summer and CIW in the deep sea in summer. In the next section, these correlations are used to discuss the links between various factors that influence the temperature response of the bottom waters on the western Black Sea shelf.

4 Discussion

In his study of the variability of sea surface temperature (SST) in the North Atlantic, Bjerknes (1964) suggested that SST variations on inter-annual timescale may solely be explained by a local forcing from the atmosphere. On the other hand, the explanation of inter-decadal temperature variations requires additional contribution from ocean dynamics, i.e. lateral exchanges (Eden and Willebrand, 2001). The Black Sea is much smaller than the North Atlantic, has a well developed basin- and sub-basin scale circulation pattern (Shapiro, 2008; Altman and Simonov, 1991; Özsoy and Ünlüata, 1997), so that one can expect that temperature reaction to lateral exchanges can be felt faster and be seen in inter-annual temperature variability. In earlier studies by Buesseler et al. (1991) and Özsoy and Ünlüata (1997) it was suggested that such lateral processes may play an essential role in the ventilation of the pycnocline. Temperature of surface waters responds fairly quickly (on a daily to weekly time scale) to the changes in the meteorological forcing (Stanev et al., 1995; Enriquez et al., 2005; Schrum et al., 2001). The near-bottom water body experiences only indirect influence from the atmosphere, and hence has greater inertia, so that time scales for local atmospheric forcing and lateral exchanges due to ocean dynamics become comparable (Ivanov et al., 2000). In this section we contrast and compare vertical and “horizontal” (isopycnic) communications of the bottom waters on the western Black Sea shelf.

We define the Bottom Shelf Water (BSW) as a near-bottom water body which is located below the upper mixed layer defined by a density level $\sigma_\theta = 14.2\,\mathrm{kg\,m^{-3}}$ down to the seabed. We show that the underlying physical reason that supports the use of an isopycnic surface as the upper boundary of the BSW is the close link between the amount of mixing energy applied during the winter season and the density level to which mixing occurs. The mixing-energy approach gives results which are close to the commonly used definition of the upper boundary of the CIW in the deep sea, i.e. the isotherm of 8 °C and density level of $\sigma_\theta = 14.2\,\mathrm{kg\,m^{-3}}$ (e.g. Ivanov et al., 1997, 2000, 2001; Özsoy and Ünlüata, 1997). Our calculations show that the near-bottom waters on the western Black Sea shelf below this density level remain largely “locked” i.e. isolated from the effects of surface processes from May to November.

The shelf bottom area covered by the “locked” bottom waters is at its smallest at the height of the winter convection period, when a well-mixed water column prevails over large parts of the shelf. As surface heating increasingly stratifies the water column in spring and summer, the “locked” shelf bottom areas reach their maximum extent during June–August, when nearly half the shelf bottom is occupied by the Bottom Shelf Waters.

Vertical mixing is suppressed by intense stratification during the summer. If only diapycnal (vertical) movement is considered the bottom shelf waters remain mainly locked until at least the following winter. However, the BSW can, in principle, move “horizontally”, predominantly along the constant density levels and get ventilated via isopycnal exchanges. Density surfaces in the Black Sea are dome-shaped (e.g. Özsoy and Ünlüata, 1997), so that the movements along sloping isopycnals towards the deep sea could bring bottom shelf waters upward. As a result, the BSW may in principle re-enter the euphotic zone over the deep sea where they could be biogeochemically re-ventilated. However, our isopycnic analysis shows (see Fig. 3, left panel) that surfacing of bottom shelf waters due to such mechanism can only happen in early spring (March–April). Later in the warm season a strong pycnocline prevents the $\sigma_\theta = 14.2\,\mathrm{kg\,m^{-3}}$ isopycnal from approaching the surface even in the deep sea (Fig. 3).

Not surprisingly, our calculations (see Fig. 10) reveal a strong influence of atmospheric conditions on the shelf surface temperature during the winter season. There is a fairly high correlation, $R = 0.69$, between the winter severity index Σt_a and the winter SST on the western Black Sea shelf. The time series of winter SST on the shelf is indicative of the temperature response of the entire shelf water body because the shelf is well-mixed during the winter (e.g. Sorokin, 2002). The effects of atmospheric processes therefore penetrate down to the benthic ecosystem during the cold season.

A high correlation ($R = 0.56$) is shown in Fig. 10 between the temperature anomalies of the bottom shelf waters and CIW in the adjacent deep sea. With the inception of the warm season and formation of the pycnocline, the influence of the weather on the bottom shelf waters is much reduced, creating a potential for the bottom shelf waters to preserve the memory of the winter conditions in the subsequent months. However the correlation coefficient between winter SST temperature on the shelf and summer temperatures in the BSW is as low as $R = 0.26$, showing that in reality the memory of the winter conditions is not well preserved in the bottom waters. The situation is quite different in the deep sea, where the winter SST is correlated with the summer temperatures of CIW at a moderate value of $R = 0.46$, revealing that the waters within the Cold Intermediate Layer keep a longer memory of the preceding winter.

Our analysis revises the findings by Ivanov et al. (2000), that traces of winter mixing events appear well preserved in the temperature-salinity structure, is only valid for the deep sea but not on the shelf. The different response of shelf waters can be attributed to their much smaller volume compared to the CIW in the deep sea. Furthermore the upper mixed layer is thinner in the deep sea compared to the shelf as a result of the doming of isopycnal surfaces (e.g. Özsoy and Ünlüata, 1997). It should be noted that the surface waters of the shelf and the deep sea regions appear to be in moderately strong communication giving an R-value of 0.43. The correlation between the severity of winters index, which is calculated using data from the costal stations, and the winter SST in the deep sea is very low ($R = 0.16$), confirming the previously reported decoupling between surface waters of shelf and deep sea regions to climate variations (Shapiro et al., 2010a).

The low vertical and higher lateral correlations of the shelf bottom waters in the summer suggest that the horizontal exchanges below the pycnocline across the shelf break are thus more significant than diapycnic mixing across the pycnocline. Horizontal processes thus appear to account for a substantial degree of inter-annual variability. These exchanges are thought to reduce the memory of winter mixing events on the shelf, while the CIW in the deep sea (which has a much larger volume and higher latency) buffers the traces of winter convection for longer, as observed by Ivanov et al. (2000).

The existence of horizontal exchanges has been suggested in a number of previous studies based on measurements from individual field campaigns. The mainly advective nature of CIW replenishment was probably first proposed by Kolesnikov (1953) and later by Filippov (1965, 1968) , however this view was challenged by other researchers (see e.g. Özsoy and Ünlüata, 1997; Zatsepin et al., 2003 for details). Blatov et al. (1984) introduced the concept of cold-water lenses which facilitate horizontal advection along isopycnal surfaces in the CIL. The exposure of the shelf break region to mesoscale circulation is well-established and shelf edge exchange processes can be driven by a number of mechanisms: meandering of the main Rim Current, formation of cross-shelf jets and filaments, transport by mesoscale eddies, dense water cascades, coastal upwelling events etc. (Stanev et al., 2004; Ginzburg et al., 2002; Oğuz et al., 2002; Zatsepin et al., 2003; Gawarkiewicz et al., 1999).

More recently, significant horizontal exchanges across the shelf break in the Black Sea by a mesoscale eddy have been quantified using satellite imagery to show that about 40% of the shelf waters was exchanged during the period from May to August 2005 (Shapiro et al., 2010b). The depth of penetration of a cross-shelf current induced by a mesoscale eddy can exceed 100 m and hence such eddies can be influential in maintaining a good correlation between summer temperatures below the $\sigma_\theta = 14.2$ isopycnal (Korotaev et al., 2006; Aleinik et al., 2007). Complex vertical and horizontal interactions of the BSW result in the inter-annual variability of the near-bottom temperature which mimics exactly neither the winter severity pattern nor the variations in the surface.

The inter-annual and inter-decadal variability of temperature in the Bottom Shelf Waters for the period 1955–2001 does not have a simple linear trend; instead it has an oscillating shape shown in Fig. 7. The range of inter-annual variations is as high as 2.9 °C and it significantly exceeds the range of intra-annual variations of 0.7 °C. The cold periods seen in the non-smoothed oscillations with a 2 year period indicate events of increased winter convection in agreement with Ivanov et al. (2000). It is thought that these events would also increase the oxygenation of the BSW, however we do not have

CC BY

sufficient chemical data to support this statistically. The 5-year running average suggests a cyclical oscillation with a period of approx. 20 years and an amplitude of ~2 °C. A similar periodicity was observed by Ivanov et al. (2000) in a temperature time series of various isohaline surfaces in the deep Black Sea, although the timing of the cooling phases does not coincide exactly. The BSW temperature is characterised by a warm period in the 1960s and 1970s followed by colder-than-usual conditions in 1980–2001. The warmer-than-usual period of 1970–80s coincided with the timing of significant eutrophication, whilst during the cold period the signs of ecosystem recovery have been observed (Mee et al., 2005). The 1990s belong to the colder-than-usual period, however the start of a warming tendency is evident from mid-1990s. There is no guarantee that future variations in the BSW temperature will repeat the oscillatory pattern of the past, but if they did we would have expected the current trend to have brought the BSW temperatures into the warmer-than-usual zone by about 2004 and the warming phase to last until approximately 2015.

5 Conclusions

The Bottom Shelf Water (BSW) is defined as located between the density surface $\sigma_\theta = 14.2\,\mathrm{kg\,m^{-3}}$ and the seabed on the western Black Sea shelf where the bathymetric depth less than 150 m. During the warm season from May to November it is isolated from exchanges with the surface layer and hence has a limited supply of oxygen due to a lack in diapycnic mixing. The area occupied by the “locked” bottom waters reaches 45% of the total shelf area during the summer months.

The use of anomalies rather than absolute temperature values allows aggregating the data spatially and reducing statistical uncertainties. The novelty of our result is that we now are able to show inter-annual/inter-decadal variability of bottom water temperatures and quantify the relative importance of horizontal (isopycnal) communications as compared to vertical mixing based on a very large data base spanning over more than 50 years.

There is little intra-annual (i.e. month-to-month) variation of the temperature of the BSW during May–November. To the contrary, the inter-annual variability is significant. The time line of the BSW temperature shows a warm phase (1960s–1980s) and a cold phase (1980s–2000s). Whilst the warm phase coincides with environmental deterioration, the colder-than-usual period coincides with signs of recovery of the Black Sea ecosystem.

The correlation analysis suggests that over the summer months the BSW generally loses memory of winter-time atmospheric forcing on the shelf, while traces of local winter cooling are reasonably well preserved in the deep sea. Lateral exchanges of the Bottom Shelf Water with the Cold Intermediate Waters from the deep sea are shown to be more important for controlling inter-annual temperature variations of the BSW than winter conditions on the shelf itself.

Acknowledgements. This study was partially supported by the following grants: EU FP6 SESAME, EU FP7 MyOcean, EU FP7 HYPOX, RFBR-07-05-00240 and the NATO Environmental Security Grant ESP.NUCR.CLG.982285.

References

Aleinik, D. D., Shapiro, G. I., Mee, L. D., and Lemeshko, E. M.: Using a lowered acoustic Doppler current profiler for measuring current velocities in the Black Sea, Oceanol., 47, 127–134, 2007.

Belokopytov, V. N.: Long-term variability of cold intermediate layer renewal conditions in the Black Sea, in: Ecosystem Modeling as a Management Tool for the Black Sea, NATO Science Series, 2, Environmental Security – 47, Vol. 2, edited by: Ivanov, L. I. and Oğuz, T., 2, Kluwer Academic Publishers, Dordrecht, NL, 47–52, 1998.

Bjerknes, J.: Atlantic air-sea interaction, in: Advances in Geophysics, Vol. 10, edited by: Landberg, H. E. and van Mieghem, J., Academic Press, New York, 1–82, 1964.

Blatov, A. S., Bulgakov, N. P., Ivanov, V. A., Kosarev, A. N., and Tuzhilkin, V. S.: Variability of Hydrophysical Fields of the Black Sea Gidrometeoizdat, Leningrad, 240 pp., 1984.

Buesseler, K. O., Livingston, H. D., and Casso, S. A.: Mixing between oxic and anoxic waters of the Black Sea as traced by Chernobyl cesium isotopes, Deep-Sea Res., 38, S725–S745, 1991.

Daskalov, G. M.: Long-term changes in fish abundance and environmental indices in the Black Sea, Mar. Ecol. Progr. Ser., 255, 259–270, 2003.

Eden, C. and Willebrand, J.: Mechanism of Interannual to Decadal Variability of the North Atlantic Circulation, J. Climate, 14, 2266–2280, 2001.

Enriquez, C. E., Shapiro, G. I., Souza, A. J., and Zatsepin, A. G.: Hydrodynamic modelling of mesoscale eddies in the Black Sea, Ocean Dyn., 55, 476–489, 2005.

Filippov, D. M.: The cold intermediate layer in the Black Sea, Oceanol., 5, 47–52, 1965.

Filippov, D. M.: Tsirkulyatsiya i structure vod Chernogo morya (Circulation and Structure of the Black Sea Water), Nauka, Moscow 136 pp., 1968.

Gawarkiewicz, G., Korotaev, G., Stanichny, S. V., Repetin, L., and Soloviev, D.: Synoptic upwelling and cross-shelf transport processes along the Crimean coast of the Black Sea, Cont. Shelf Res., 19, 977–1005, 1999.

Ginzburg, A. I., Kostianoy, A. G., Krivosheya, V. G., Nezlin, N. P., Soloviev, D. M., Stanichny, S. V., and Yakubenko, V. G.: Mesoscale eddies and related processes in the northeastern Black Sea, J. Mar. Syst., 32, 71–90, 2002.

Hansen, J. and Lebedeff, S.: Global trends of measured surface air temperature, J. Geophys. Res., 92, 345–372, 1987.

Ivanov, L. I., Beşiktepe, Ş. T., and Özsoy, E.: The Black Sea Cold Intermediate Layer, in: Sensitivity to Change: Black Sea, Baltic Sea and North Sea, edited by: Özsoy, E. and Mikaelyan, A., Kluwer Academic Publishers, Dordrecht, NL, 253–264, 1997.

Ivanov, L. I., Belokopytov, V. N., Özsoy, E., and Samodurov, A.: Ventilation of the Black Sea pycnocline on seasonal and interannual time scales, Mediterr. Mar. Sci., 1/2, 61–74, 2000.

Ivanov, L. I., Backhaus, J. O., Özsoy, E., and Wehde, H.: Convection in the Black Sea during cold winters, J. Mar. Syst., 31, 65–76, 2001.

Kolesnikov, A.: Seasonal course of temperature, stability and vertical turbulent heat exchange in the open part of the Black Sea, Tr. Mor. Gudrol. Inst. USSR AS, 3, 3–13, 1953.

Korotaev, G., Oğuz, T., and Riser, S.: Intermediate and deep currents of the Black Sea obtained from autonomous profiling floats, Deep-Sea Res. Pt. II, 53, 1901–1910, 2006.

Lozier, M. S., Owens, W. B., and Curry, R. G.: The climatology of the North Atlantic, Progr. Oceanogr., 36, 1–44, 1995.

McQuatters-Gollop, A., Mee, L. D., Raitsos, D. E., and Shapiro, G. I.: Non-linearities, regime shifts and recovery: The recent influence of climate on Black Sea chlorophyll, J. Mar. Syst., 74, 649–658, 2008.

Mee, L. D., Friedrich, J., and Gomoiu, M. T.: Restoring the Black Sea in times of uncertainty, Oceanogr., 18, 32–43, 2005.

Murray, J., W., Codispoti, L., A., and Friederich, G., E.: Oxidation-reduction environments. The suboxic zone in the Black Sea, in: Aquatic Chemistry: Interfacial and Interspecies Processes, ACS Advances in Chemistry Series vol. 244, edited by: Huang, C.-P., O'Melia, C. R., and Morgan, J. J., Advances in Chemistry, American Chemical Society, Washington, DC, 157–176, 1995.

ETOPO2v2 Global Gridded 2-minute Database, National Geophysical Data Center, National Oceanic and Atmospheric Administration: http://www.ngdc.noaa.gov/mgg/global/etopo2.html, 2006.

Oğuz, T.: Black Sea ecosystem response to climatic teleconnections, Oceanogr., 18, 122–133, 2005.

Oğuz, T., Malanotte-Rizzoli, P., Ducklow, H. W., and Murray, J. W.: Interdisciplinary studies integrating the Black Sea biogeochemistry and circulation dynamics, Oceanogr., 15, 4–11, 2002.

Oğuz, T., Dippner, J. W., and Kaymaz, Z.: Climatic regulation of the Black Sea hydro-meteorological and ecological properties at interannual-to-decadal time scales, J. Mar. Syst., 60, 235–254, 2006.

Özsoy, E. and Ünlüata, Ü.: Oceanography of the Black Sea: a review of some recent results, Earth-Sci. Rev., 42, 231–272, 1997.

Salihoglu, I.: Black Sea Integrated Coastal and Shelf Zone Monitoring and Modeling (INCOM) Program Science Plan, Report No. 248, NATO Committee on the Challenges of Modern Society (CCMS), 49, 2000.

Schrum, C., Staneva, J., Stanev, E., and Özsoy, E.: Air-sea exchange in the Black Sea estimated from atmospheric analysis for the period 1979–1993, J. Mar. Syst., 31, 3–19, 2001.

Shapiro, G. I.: Black Sea Circulation, in: Encyclopedia of Ocean Sciences, 2 Edn., edited by: Steele, J. H., Turekian, K. K., and Thorpe, S. A., Academic Press, Oxford, 3519–3532, 2008.

Shapiro, G. I., Aleynik, D. L., and Mee, L. D.: Long term trends in the sea surface temperature of the Black Sea, Ocean Sci., 6, 491–501, doi:10.5194/os-6-491-2010, 2010a.

Shapiro, G. I., Stanichny, S. V., and Stanychna, R. R.: Anatomy of shelf-deep sea exchanges by a mesoscale eddy in the North West Black Sea as derived from remotely sensed data,

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

cc BY

Remote Sens. Environ., 114, 867–875, 2010b.

Simpson, J. H. and Hunter, J. R.: Fronts in the Irish Sea, Nature, 250, 404–406, 1974.

Sorokin, Y. I.: The Black Sea: Ecology and Oceanography, Backhuys Publishers, Leiden, NL, 875 pp., 2002.

Stanev, E. V., Roussenov, V. M., Rachev, N. H., and Staneva, J. V.: Sea response to atmospheric variability. Model study for the Black Sea, J. Mar. Syst., 6, 241–267, 1995.

Stanev, E. V., Staneva, J. V., Bullister, J. L., and Murray, J. W.: Ventilation of the Black Sea pycnocline. Parameterization of convection, numerical simulations and validations against observed chlorofluorocarbon data, Deep-Sea Res. Pt. I, 51, 2137–2169, 2004.

Stephens, C., Antonov, J. I., Boyer, T. P., Conkright, M. E., Locarnini, R. A., O'Brien, T. D., and Garcia, H. E.: World Ocean Atlas 2001 Volume 1: Temperature, in: NOAA Atlas NESDIS 49, edited by: Levitus, S., US Government Printing Office, Washington, DC, 2002.

Sur, H. Ì., Özsoy, E., Ilyin, Y. P., and Ünlüata, Ü.: Coastal/deep ocean interactions in the Black Sea and their ecological/environmental impacts, J. Mar. Syst., 7, 293–320, 1996.

Suvorov, A. M., Eremeev, V. N., Belokopytov, V. N., Khaliulin, A. H., Godin, E. A., Ingerov, A. V., Palmer, D. R., and Levitus, S.: Digital atlas: Physical oceanography of the Black Sea, in: Environmental Control Systems, edited by: Eremeev, V. N., National Academy of Science of Ukraine, Sevastopol, 125–129, 2004.

Vinogradov, M. E. and Nalbandov, Y. R.: Effect of changes in water density on the profiles of physicochemical and biological characteristics in the pelagic ecosystem of the Black Sea, Oceanol., 30, 567–573, 1990.

Yakushev, E., Podymov, O., and Chasovnikov, V.: Seasonal Changes in Hydrochemical Structure of the Black Sea Redox Zone, Oceanogr., 18, 44–51, 2005.

Zaitsev, Y. P., Alexandrov, B. G., Berlinsky, N. A., and Zenetos, A.: Europe's biodiversity – biogeographical regions and seas: The Black Sea an oxygen-poor sea, EEA (European Environment Agency), Copenhagen 2002.

Zaitsev, Y. P.: Ecological consequences of anoxic events at the north-western Black Sea Shelf, in: Past and Present Water Column Anoxia. NATO Science Series, IV. Earth and Environmental Sciences, edited by: Neretin, L. N., 247–256, 2006.

Zatsepin, A. G., Ginzburg, A. I., Kostianoy, A. G., Kremenetskiy, V. V., Krivosheya, V. G., Stanichny, S. V., and Poulain, P.-M.: Observations of Black Sea mesoscale eddies and associated horizontal mixing, J. Geophys. Res. Oceans, 108, 3246–3274, 2003.

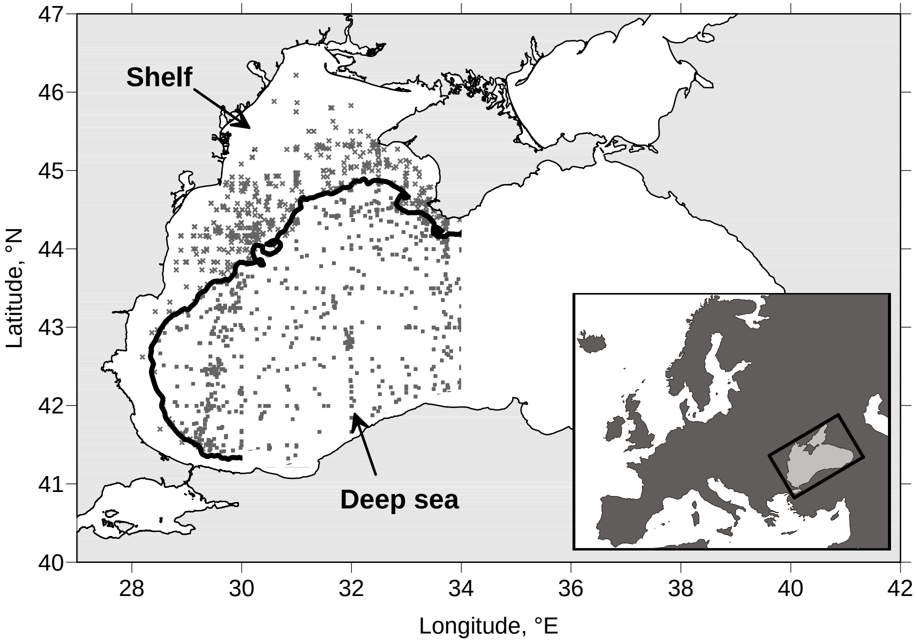

Fig. 1. Location map of the Black Sea and the boundaries of the shelf and deep sea compartments used in this study. The locations of stations where temperature anomalies in the BSW (i.e. between density level $\sigma_\theta = 14.2\,\mathrm{kg\,m^{-3}}$ and the bottom) were calculated are also shown (crosses: shelf compartment, squares: deep sea compartment).

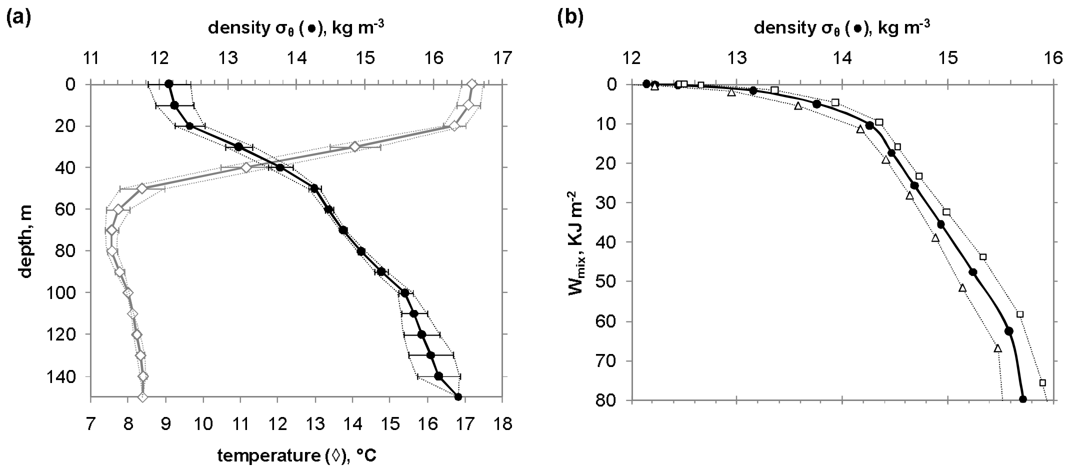

Fig. 2. Density and temperature profiles **(a)** and mixing energy penetration **(b)** from grid nodes along the shelf break (50–150 m) of the October climatology. The mean density profile for the outer shelf is shown in full circles. Error bars in **(a)** denote 1 standard deviation, while in **(b)** the mixing energy penetration is also shown for density profiles minus/plus 1 standard deviation (open triangles/open squares respectively).

cc BY

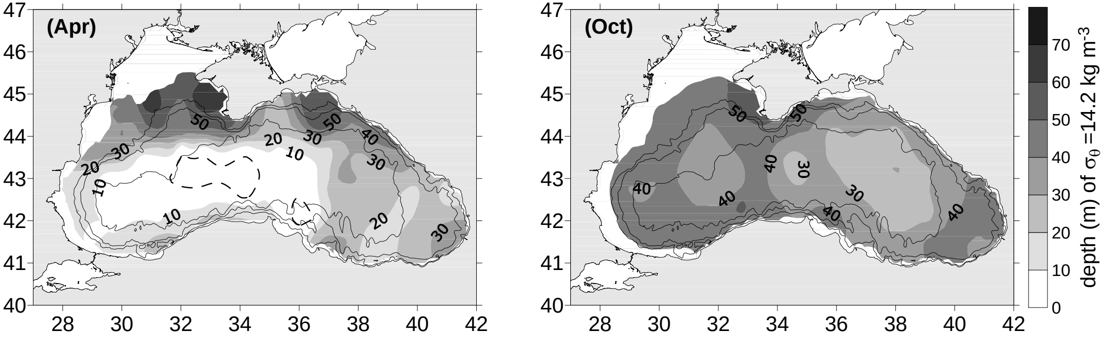

Fig. 3. Climatic topography in m below the sea surface in April and October of the σ_θ=14.2 kg m^{-3} isopycnal level. The isobaths are shown at 200, 1000 and 2000 m levels (solid lines). The April plot also shows the contour of this isopycnal along the sea surface (dashed line).

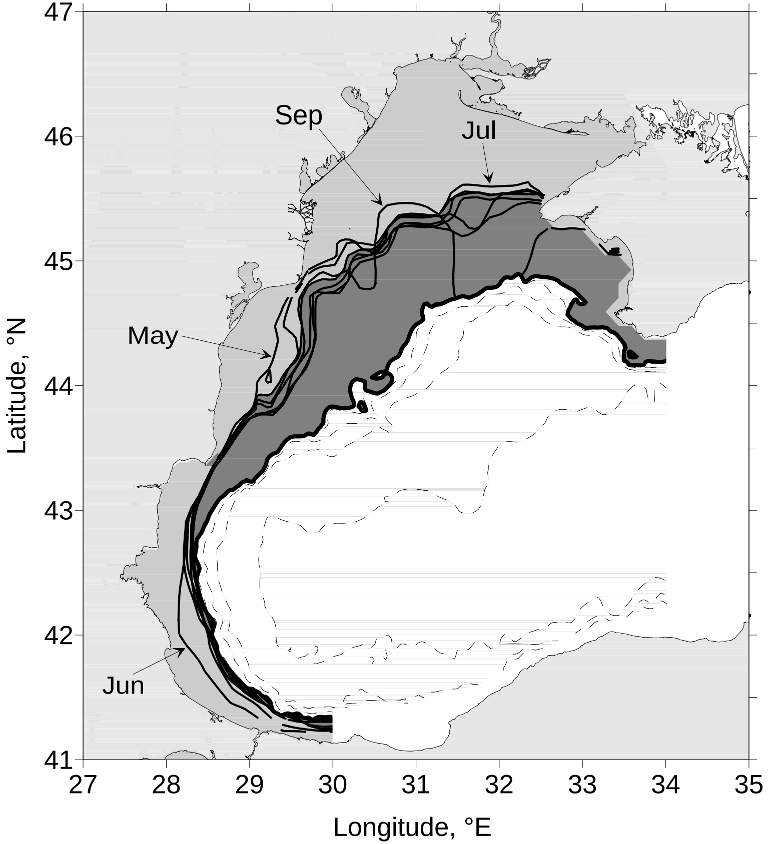

Fig. 4. Shelf area covered by "locked" Bottom Shelf Water ($\sigma_\theta \geq 14.2\,\mathrm{kg\,m^{-3}}$) for the individual months from May to November. The extent in August is shaded in dark grey, while the slight deviations in other months are shown by super-imposed contour lines, several of which are individually labelled.

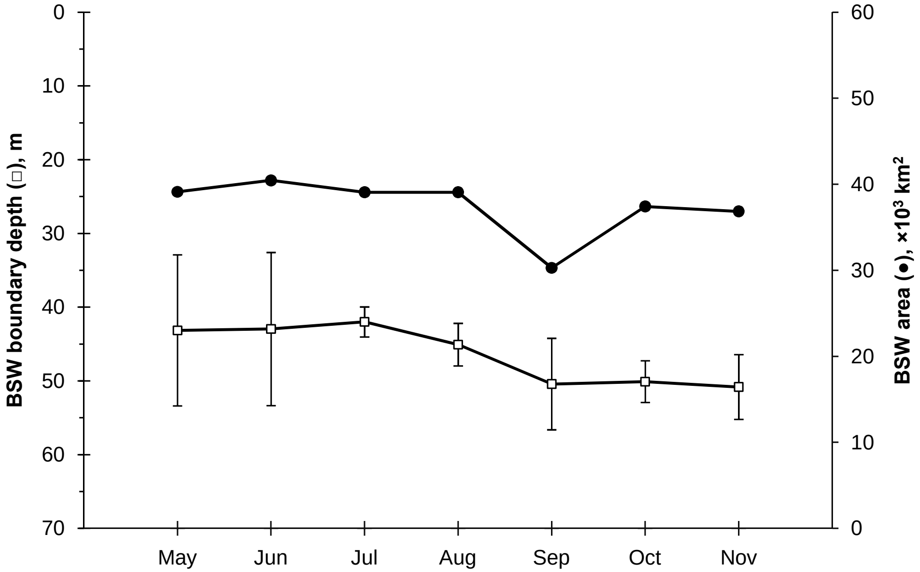

Fig. 5. Intra-annual variability (May–Nov) of the coverage (in $\times 10^3\,\mathrm{km}^2$) of "locked" Bottom Shelf Water (full circles) and the average depth of the BSW boundary at the isopycnal $\sigma_\theta = 14.2\,\mathrm{kg\,m}^{-3}$ for the same period (open squares). Error bars show 1 standard deviation.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

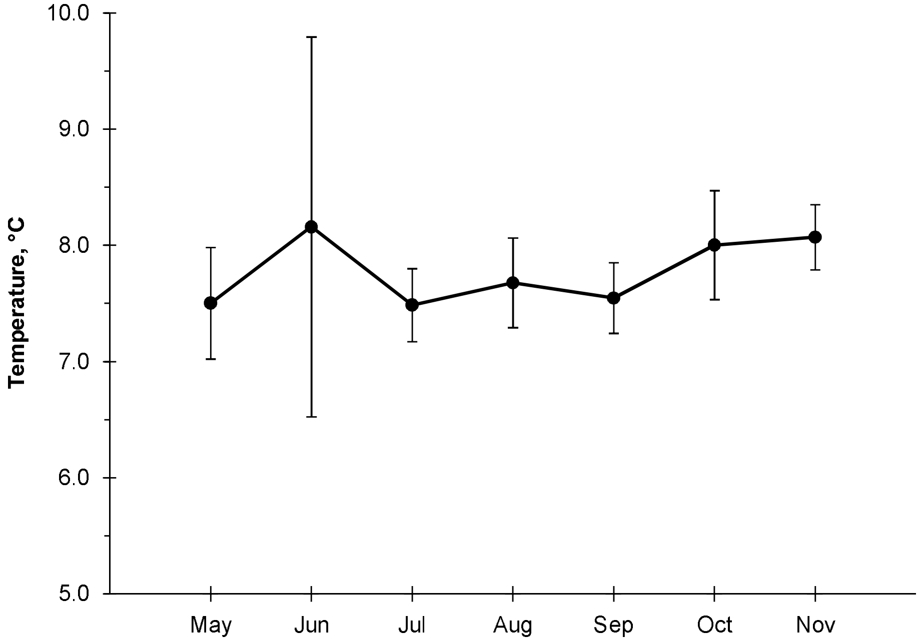

Fig. 6. Intra-annual variability (May–Nov) of absolute temperature (˚C) in the BSW. Error bars show 1 standard deviation due to variations of BSW temperature in individual nodes of the climate grid.

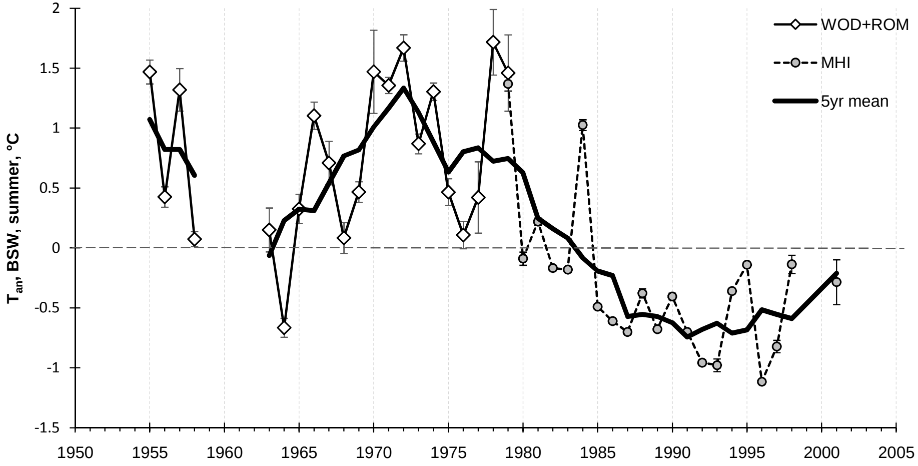

Fig. 7. Long-term time series of the temperature anomaly (˚C) of "locked" Bottom Shelf Water (thin solid line: WOD+ROM data set, thin dashed line: MHI data set) and the 5-year running mean (thick line) of the combined time series. Error bars show the standard error of the mean.

CC BY

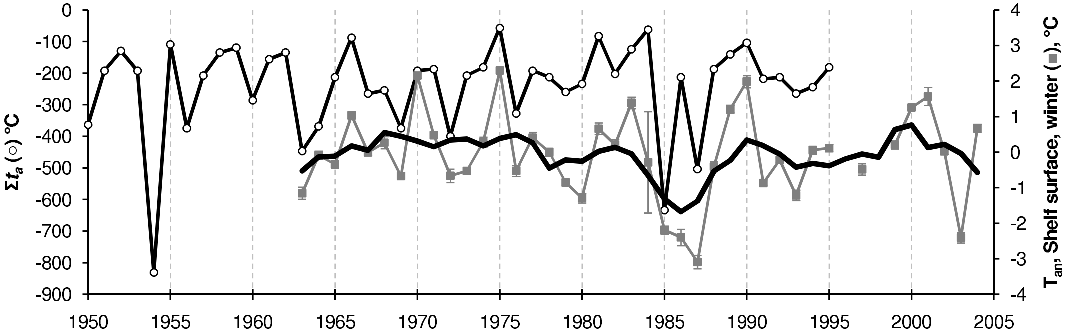

Fig. 8. Long-term time series of the winter severity index Σt_a (°C) for the North-Western part of the Black Sea (black line + circles, redrawn from Belokopytov, 1998) and time series of the winter (Dec–Apr) temperature anomaly (°C) of the shelf surface calculated using the WOD+ROM data set (grey line + squares), and the 5-year running mean (thick black line). Error bars show the standard error of the mean.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
I◀
▶I
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

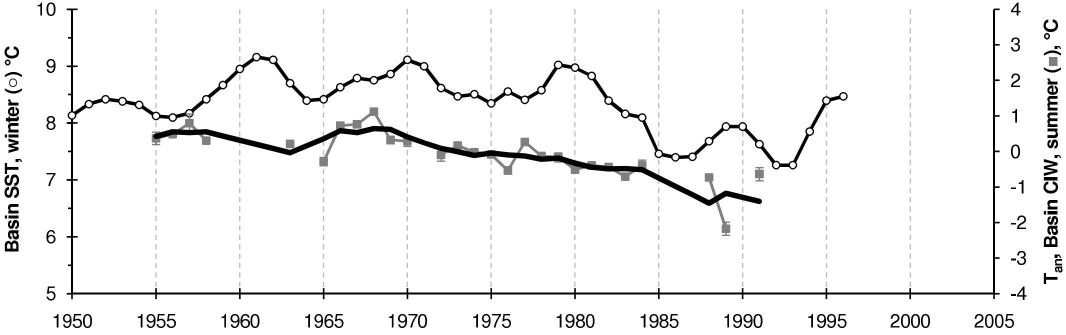

Fig. 9. Long-term time series of the mean sea surface temperature (˚C) in winter averaged over the interior basin with depths greater than 1500 m (thin black line + circles, redrawn from Oğuz et al., 2006) and time series of the summer (May–Nov) temperature anomaly (T_{an}, ˚C) of Cold Intermediate Water (CIW) (σ_θ = 14.2–14.8 kg m^{-3}) in the deep sea compartment (grey line + squares), and the 5-year running mean (thick black line). Error bars show the standard error of the mean.

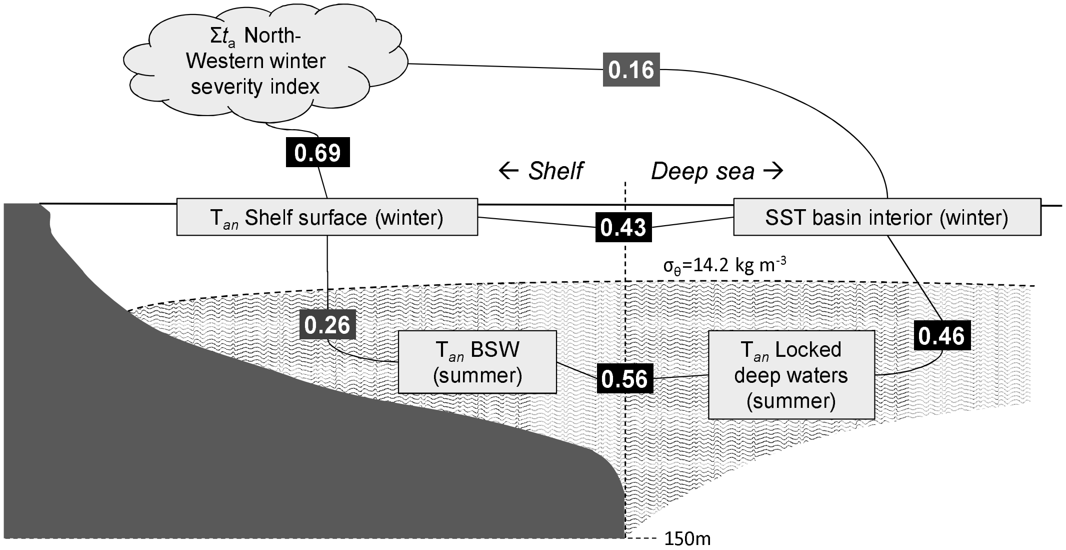

Fig. 10. Schematic of the Pearson correlation (R-values) between various long-term temperature time series. The shelf limit is the 150 m isobath, the locked Bottom Shelf Water is bounded by the σ_θ = 14.2 kg m^{-3} isopycnal and the seabed.