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# Long-Term (2001-2011) Temperature, Salinity and Chlorophyll-a Variations at a Southeastern Coastal Site of the Black Sea

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**Abstract**

Long-term measurements of temperature, salinity and chlorophyll-a concentration at a coastal site off Trabzon in the southeastern Black Sea document their monthly-to-interannual variabilities during 2001-2011. The data point to a general trend of warming with either negligible or absence of the Cold Intermediate Layer except for the relatively cold period of 2002-2004. The warming trend appears to be a continuation of the one started during the early 1990s. The data further documents enhanced anticyclonic type mesoscale features of the circulation system and its impacts on the local startification characteristics in terms of ventilation of the subsurface waters. The surface chlorophyll measurements show a rather sporadic relatively high plankton production events identified by the values greater than 2.0 mg $m^{-3}$. More importantly, relatively high chlorophyll concentrations prevail below the surface mixed layer up to 50 m depth throughouıt the years. The mesoscale physical processes occasionally spread this productivity well below the euphotic zone and support biological production at oxygen deficient waters of the upper layer water column. The data further point to quasi-lateral, most likely isopycnal, intrusions and ventilation of subsurface waters.

*Keywords*: Black sea, temperature, salinity, chlorophyll, cold intermediate layer, pycnocline, primary production.

**Karadeniz'in Güneydoğu Kıyısal Alanında Uzun Dönemli (2001-2011) Sıcaklık, Tuzluluk ve Klorofil-a Değişimleri**

**Özet**

Bu çalışmada, Güneydoğu Karadeniz'in Trabzon kıyılarında 2001-2011 dönemine ait uzun dönemli sıcaklık, tuzluluk ve klorofil-a konsantrasyonlarının aylık ve yıllık değişimleri incelenmiştir. Sıcaklık verileri, 2002-2004 göreceli soğuk dönem dışında, soğuk ara tabaka suyu oluşumunun yokluğu veya çok belirgin olmamasını göstermekte ve genel bir ısınma eğilimini işaret etmektedir. Söz konusu ısınma eğilimi 1990'lı yıllarda görülen ısınmanın devamı niteliğindedir. Bulgular, çalışma bölgesinde belirgin orta-ölçekli su sirkülasyonu hareketlerinin varlığına işaret etmektedir. Bu döngüler yaratmış oldukları dikey hareketler nedeniyle yaklaşık 100 m derinliğe kadar yöresel su kütlelerinin tabakalaşma özelliklerini etkileyebilmektedir. Yaklaşık 2 metre derinlikte gerçekleştirilen klorofil ölçümleri ise genellikle 2.0 mg $m^{-3}$'den büyük değerlerle tanımlanan göreceli yüksek plankton üretimlerine işaret etmektedir. Yüksek klorofil tabakası yıl boyunca yüzeyin hemen altındaki 50 m derinliğe kadar olan tabakada yer almakta, ancak orta ölçekli aktivitelere bağlı olarak zaman zaman daha derinlerdeki üretimi destekleyebilmektedir.

*Anahtar Kelimeler*: Karadeniz, sıcaklık, tuzluluk, klorofil, soğuk ara tabaka, piknoklin, birincil üretim.

## Introduction

Black Sea is one of the semi-enclosed basins of the world oceans subject to strong ecological degradation and major changes on the structure and functioning of the ecosystem under synergistic impacts of strong decadal-scale climatic changes, overexploitation of fish resources, intense-eutrophication, invasions by opportunistic species, and their density-dependent internal feedback processes in the 1970s and 1980s (Zaitsev and Mamaev, 1997; Gucu, 2002; Daskalov, 2003; Bilio and Niermann, 2004; Daskalov *et al*., 2007; Oguz and Gilbert, 2007; BSC, 2008; Yunev *et al*., 2009; Oguz and Velikova, 2010; Oguz *et al*., 2012a,b). The ecosystem degradation amplified starting by the 1970s as a result of large inputs of nutrients and contaminants into the northwestern shelf through the

Danube, Dniepr, and Dniestr Rivers. However, the way in which the Black Sea ecosystem has evolved in time is not known sufficiently well due to the lack of systematic observations with adequate temporal and spatial resolutions.

The analyses of multi-decadal, multi-disciplinary time series provided by Gunduz and Ozsoy (2005), Oguz *et al*. (2006), Kazmin and Zatsepin (2007), Kara *et al*. (2008), Ilyin *et al*. (2010), and many others emphasized the robust signature of low-frequency variability in physical and ecosystem properties. For example, the 1980s have been characterized by strong cooling of the upper layer water column, whereas the 1990s experienced considerable warming. As these warming-cooling cycles modify the seasonal flow, stratification and biogeochemical characteristics, further variability is introduced by mesoscale dynamics on the flow structure (Sur *et al*., 1996; Korotaev *et al*., 2003; Zatsepin *et al*., 2005) and the biogeochemical characteristics (Oguz and Salihoglu, 2000). In particular, Yunev *et al*. (2002) evaluated long-term changes of surface chlorophyll-a concentration for the deep basin of the Black Sea from 1980 to 1996. The results showed its pronounced interannual fluctuations but persistently higher values during October-March with respect to April-September.

To our knowledge, only few long-term measurements are currently available on the indicators of physical and ecosystem changes over the Black Sea. One of them is the measurements to the north of Constanta, Romania for which temperature, salinity and surface chlorophyll-a (Chl a) concentration variations during 2002-2010 are reported by Vasiliu *et al*. (2012). The other one is the ongoing weekly-to-monthly temperature and chlorophyll measurements at a coastal site along the southeastern Black Sea since 2001. The main objective of the present paper is to evaluate this data set in terms of the general trend of warming of upper layer waters since the early 1990s and availability of mesoscale features and their impacts on the local startification and biological characteristics. Below, section 2 describes the data sampling and processing methodology as well as the data quality issues. The results are presented in section 3 and a brief discussion, and conclusions are provided in section 4.

## Materials and Methods

The study site was in located 1.5 km away from the coast at 40º58′66.2″ N latitude and 39º51′27.5″ E longitude with a total depth of 200 m (Figure 1). Within 11 years measurent program (2001-2011), a total of 296 temperature and chlorophyll-a (Chl-a) concentration measurements was performed at a depth interval of roughly 1 m (Table 1). Some data gaps of several months exist during 2003, 2005, 2009 and 2010.

Depth, temperature and chlorophyll-a were measured with the Sea-Bird SBE 25 including SBE 29-1K model pressure sensor (0-1000 psi), SBE 3F temperature sensor (±0.001°C) and Wet Labs WS3S model flourometre sensor (±0,03 µg/L). These sensors were sent to the manufacturer for calibration on an irregular basis, usually one after several years. Failure of having systematic yearly calibration of the sensors appears to introduce problems in chlorophyll (Chl-a) measurements.

In situ temperature and chlorophyll measurements are complemented by the satellite Advanced Very High Resolution Radiometer (AVHRR) sea surface temperature (SST) and Sea-viewing Wide Field-of-view Sensor (SeaWiFS) chlorophyll data both for the close vicinity of measurement site (41.2°N, 40°E) and the averaged

**Figure 1.** The location map of measurement station in the Black Sea.

conditions of the Black Sea (characterized by 41-45°N latitutes and 28-42°E longitudes). The satellite chlorophyll data is based on 8 day average, 9 km resolution SEAWIFS Level 3 data set retrieved from http://gdata1.sci.gsfc.nasa.gov/daacbin/G3/gui.cgi? instance_id=ocean_month for the period of 01 Jan. 1998 - 11 Dec. 2010. The corresponding SST satellite data are retrieved from http://oceanwatch.pifsc.noaa. gov/las/servlets/ dataset?catitem=29.

The in situ Chl-a data reveal values up to 4 mg $m^{-3}$ at all depths even those greater than 100 m (Figure 2). Considering the fact that productivity in the Black Sea is limited to upper 50 m, and the depths below 100 m is well below the 1% light level and characterized by either suboxic or anoxic conditions, nonzero Chl-a values below 100 m can not reflect real conditions and should be associated with measurement errors, and need to be removed from the data. To improve the data quality, we first identified highest measured value within the 100-200 m depth range for each measurement set, and calibrated by subtracting it from the original measured values. This procedure removed well spikes in the data. No calibration is applied to the satellite Chl-a data. Further discussioın on the reliability of the chlorophyll measurements is provided in Discussion section.

## Results

### Temperature and Salinity Variations

The sea surface temperature, measured at 2 m depth (Figure 3a, 3b), undergoes sinusoidal changes from lowest values in the range of 7-10°C during March to the highest values 25-29°C during July-August for all the years. The bulk of minimum values are concentrated on 7.5-9.0°C interval. Considering that the layer of the Cold Intermediate Layer (CIL) is customarily characterized by temperatures less than

**Table 1.** The number of measurements performed at each monthly interval of 2001-2011 period

| Month/Year | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| January | 2 | 1 | x | 2 | 4 | 3 | 3 | 3 | 3 | x | 2 | 23 |
| February | 2 | 1 | x | 2 | 4 | 3 | 2 | 3 | 2 | x | 2 | 21 |
| March | 1 | 1 | x | 4 | 2 | 4 | 1 | 3 | 3 | x | 3 | 22 |
| April | 3 | 3 | x | 4 | 4 | 2 | 2 | 3 | 3 | x | 3 | 27 |
| May | 3 | 2 | x | 3 | 3 | 5 | 1 | 2 | 1 | 2 | 3 | 25 |
| June | 4 | 3 | 2 | 4 | 2 | 4 | 2 | 3 | x | x | 4 | 28 |
| July | 3 | 4 | 5 | 4 | 1 | 4 | 2 | 3 | x | x | 4 | 30 |
| August | 3 | 2 | x | 3 | 2 | 4 | 2 | 2 | x | x | 4 | 22 |
| September | 4 | 3 | 2 | 2 | x | 3 | 1 | 2 | x | 3 | 3 | 23 |
| October | 4 | 2 | 5 | 3 | x | 4 | 1 | 2 | x | 2 | 3 | 26 |
| November | 3 | 4 | 3 | 4 | x | 4 | 2 | 3 | x | 4 | 4 | 31 |
| December | 2 | x | 3 | 3 | x | 2 | 2 | 2 | x | 1 | 3 | 18 |
| Total | 34 | 26 | 20 | 38 | 22 | 42 | 21 | 31 | 12 | 12 | 38 | 296 |

x: sign indicates no measurements

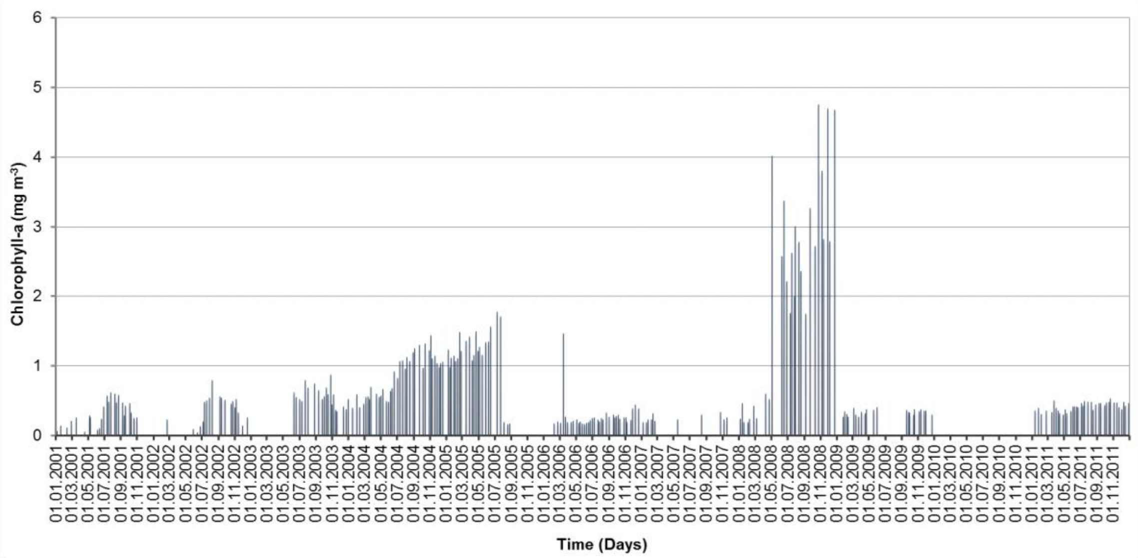


**Figure 2.** Observed Chl-a distribution at 150m depth based on the unclibrated data. Such high values prevail for all the water column and are considered as the measurement error. Thus, threy are subtracted from the original data.

8°C, the observed range of temperatures indicates persistence of a decade-long relatively warm winters in regards to the formation and persistence of CIL during the measurement period. The warmest temperatures are generally confined at 25-27°C interval. Temperatures are subject to almost linear increase/decrease betweeen the periods of these two extreme ranges of values. According to the monthly averaged data, the years 2001 and 2010 turns out to be characterized by the warmest winter and summer conditions and the years 2002-2004 the coldest winter and summer conditions (Figure 3b). Their difference may be as high as 2-3°C. The montly averaged data conform well with the corresponding monthly averaged AVHRR satellite data (Figure 3c).

More interestingly, temperature variations at 50 m depth (Figure 4) may occasionally exhibit relatively high values, even in excess of 15°C. They imply

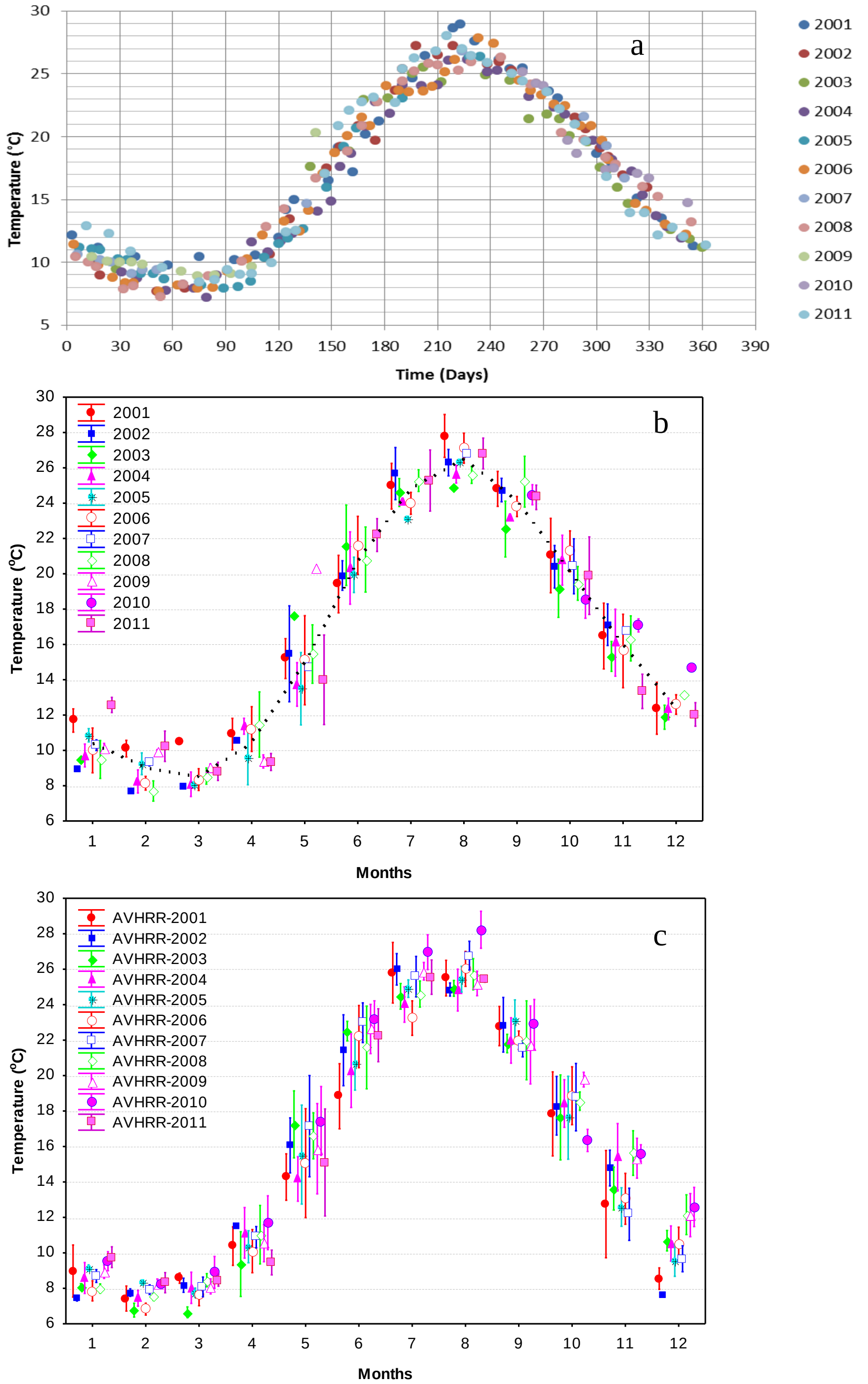


**Figure 3.** Annual variations of temperature for the years 2001-2011 obtained from (a) compilation of all measurements at 2m depth, (b) monthly-averaging of the available measurements for all years, and (c) monthly averaged AVHRR satellite data. The dash line in figure 3b shows the monthly averaged variations obtained from the entire data set.

occasional deepening of the mixed layer by either strong wind events or passage of anticyclonic eddies from the measurement site. The fact that majority of these events are accompanied with relatively low salinity values (about 17.5 psu) implies the prevalent role of anticyclonic eddies for such relatively deep and broad thermocline/halocline structures. These events are more typical during autumn months and followed by rapid cooling and abrupt temperature drops back to the low values during the subsequent winter seasons.

Two contrasting cases for the temporal evolution of vertical temperature structure may be illustrated for periods of 2003 and 2010-2011 (Figure 5a and 5b). The former data set corresponds to a particularly cold year (as inferred for the entire sea from the AVHRR data), but the measurements cover only the second part of the year (Figure 5a). Nevertheless, the available summer-autumn data deliniate a well-defined broad CIL with temperatures between 7°C and 8°C extending to about 100m depth. This layer is situated below the surface mixed layer with temperatures in excess of 20°C within the upper 20m and the subsequent thermocline zone with a thickness of 15-20 m. The CIL is preserved for the entire summer-autumn period but shallows towards the end of the year due to accumulating effect of vertical mixing across the base of the seasonal thermocline. We note that the relatively warm and shallow surface mixed layer is maintained until the end of October, and then temperature drops from 18°C at the end of October to 13°C during the first week of December. These temperature changes accompany with deepening of the mixed layer in response to a strong cooling of surface waters.

The temperature structure for the year 2003 appears to be the only case within the entire data set for representing a well-preserved CIL structure during the year. The rest of the data shows a contrasting structure with either its weak or no development, for which a typical example is shown for 2010-2011 in Figure 5b. Starting by the early October, the surface mixed layer undergoes a gradual cooling with temperature dropping to 12°C by the end of December. At the same time, it deepens gradually with the lowest temperature of 10°C isotherm located roughly at 75 m by the end of January, and 9°C isotherm at 100 m by the end of February 2011. March 2011 offers an interesting case of a well-homogeneous layer within the entire 200 m deep water column. It was caused by a weak-to-moderate but persistent cooling that brought the upper 100 m layer temperature to 8.5°C and made it comparable to the ambient temperatures of the subsurface layer further below. Starting by mid-April, warming of surface waters gradually builds up the seasonal thermocline with similar features developing as described before for the case of summer-autumn 2003. The major difference, however, is the absence of the CIL below the thermocline except a bulk of water with relatively cold temperatures between 7.6-8.0°C limited to April-May, 2011. It should be related to quasi-lateral protrusion of a relatively cold water parcel from offshore regions by means of the meandering Rim Current structure.

Contrary to the case of 2003, the winter 2001 reveals one of the warmest winters of the recent decades in the Black Sea (Oguz, 2011). This is also supported by the present measurements (Figure 5c) which report winter (February-March) temperatures being higher than 9°C. the coldest temperatures with 7.9°C extends roughly between 75 m and 100 m as a remnant of the previous year. The subsequent winter of 2002 offers an intermediate case of the CIL

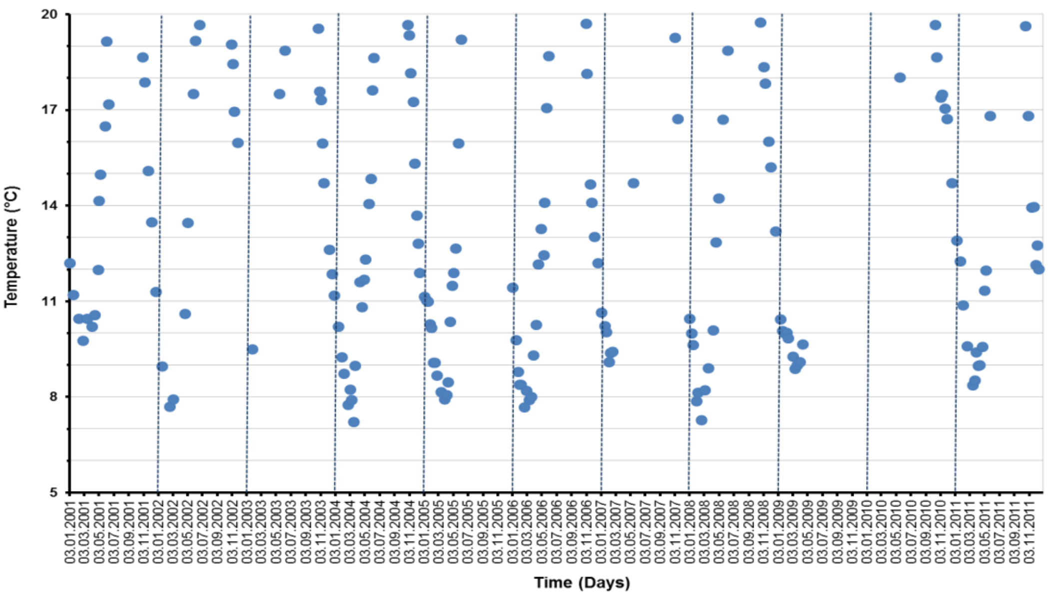


**Figure 4.** Annual variations of temperature at 50m depth for the years 2001-2011. Such a broad range of variations is rather unexpect and has not been reported before, to our knowledge.

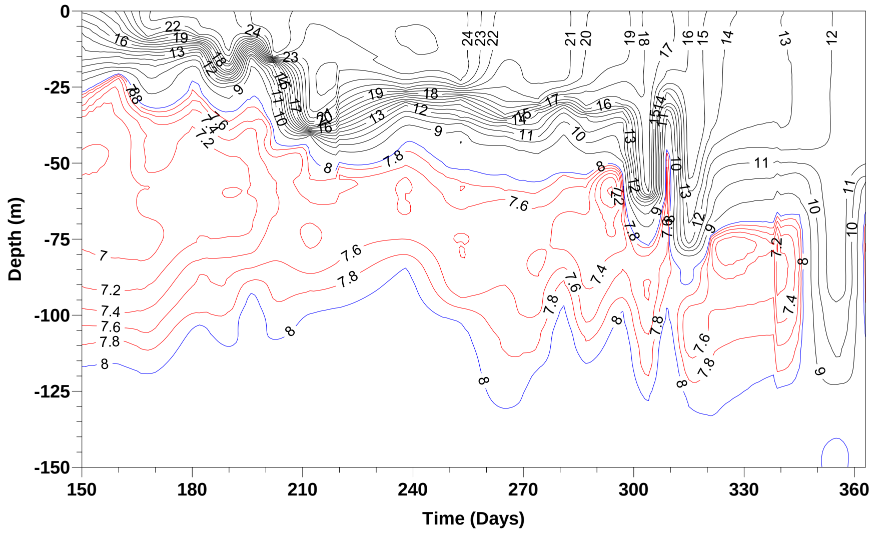


**Figure 5a.** Temperature (°C) variations within 150 m layer during June-December 2003. For temperatures greater than 8°C, the contours are shown in black color at an interval of 1°C. The 8°C contours, representing the upper and lower boundaries of the CIL is shown in blue, and lower values in red at an interval 0.2°C.

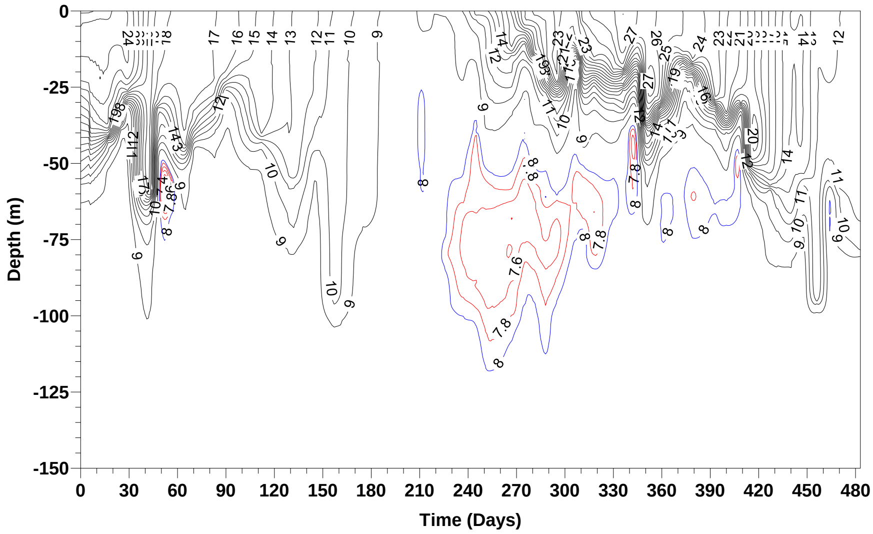


**Figure 5b.** Temperature (°C) variations within 150 m layer from September 2010 to December 2011. Countors are drawn as in Figure 5a.

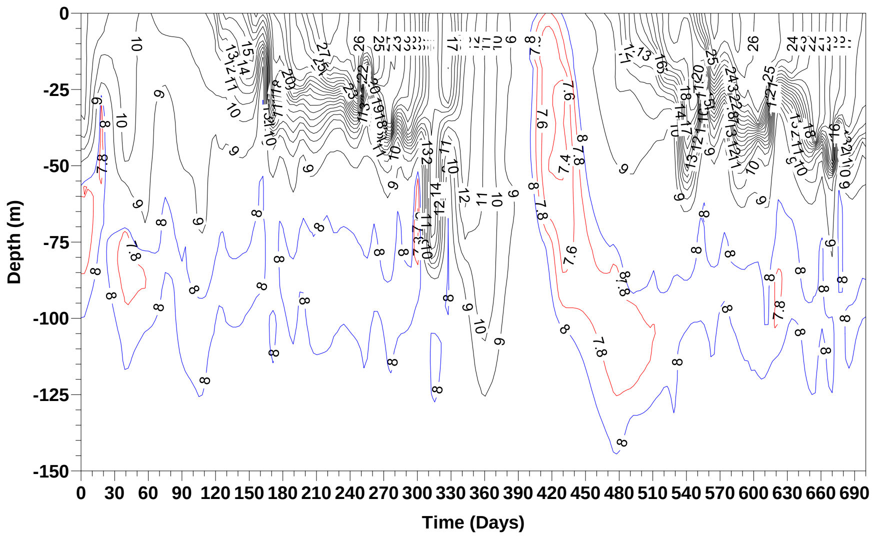


**Figure 5c.** Temperature (°C) variations within 150 m layer from January 2001 to November 2002. Countors are drawn as in Figure 5a.

formation with T~7.5°C within the upper 100 m layer. This layer is preserved during rest of the year. Figure 5c further suggests considerable weakening of the temperature stratification within the upper 200 m layer during December 2001 which possibly arise due to an anticyclonic eddy temporally residing within the measurement site. A further supporting evidence for such an eddy is the presence of relatively low salinity (less than 18 psu) within the upper 100 m (Figure 6a).

The surface mixed layer is characterized by salinity values between 17.5 and 18.0 psu, whereas the sharp temperature gradient across the seasonal thermocline zone is accompanied with a homogeneous layer of salinity between 18.0 and 18.5 psu (Figure 6a). The CIL and further below attain much stronger salinity variations that roughly increases to 20.5 psu at 150 m depth. The density variations resemble more closely to those of the temperature as evident by the presence of a strong seasonal pycnocline accompanying with the seasonal thermocline (Figure 6b). 14.0 kg $m^{-3}$ isopycnal level characterize the base of this pycnocline. On the other hand, the layer between 75 m and 150m depths possesses high density stratification between 14.5 and 16.0 kg $m^{-3}$ corresponding to sharp salinity changes and represents the permanent pycnocline zone of the

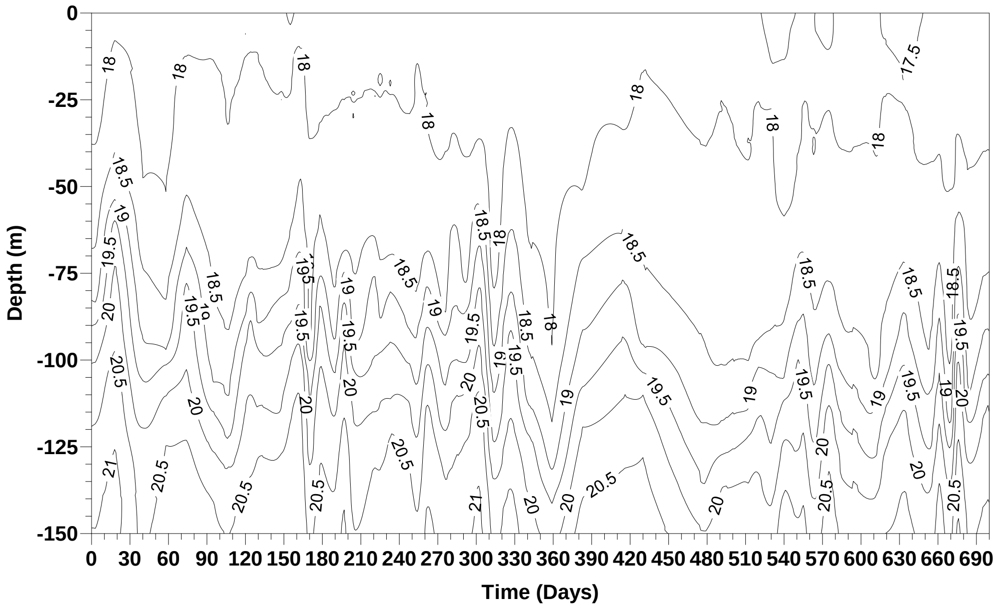


**Figure 6a.** Salinity (psu) variations within 150 m layer from January 2001 to November 2002. The countours are drawn at an interval of 0.5 psu.

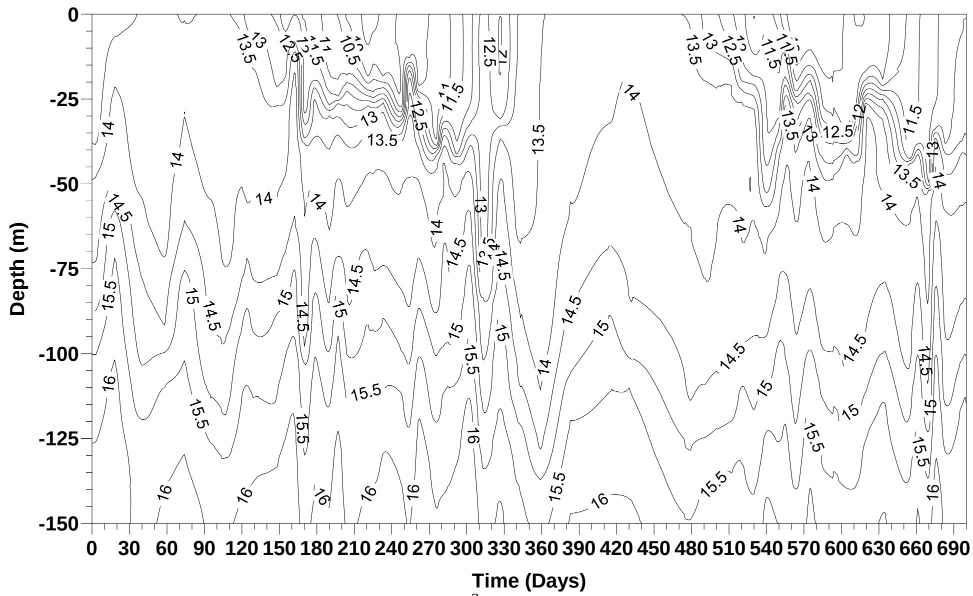


**Figure 6b.** Density variations, in terms of sigma-t (kg/$m^3$), within 150 m layer during 2001-2002. The countours are drawn at an interval of 0.5 kg/$m^3$.

Black Sea (Figure 6b). The vertical density structure supports a preferential anticyclonic character of the measurements site.

### Chlorophyll-a Variations

The surface chlorophyll measurements at 2m depth show a rather sporadic relatively high values greater than 2.0 mg m$^{-3}$ (Figure 7). While the measurements can hardly illustrate a systematic annual structure, the accompanying data set retrieved from the SeaWiFS satellite sensor both for near the measurement site and averaged over the Black Sea suggest comparable values that may suggest a likely open ocean character of the measurement site rather than a more productive coastal one. They display a regular annual structure of chlorophyll-a cencentrations varying in the range of 0.5 and 2.0 mg m$^{-3}$ that repeates systematically almost every year (Figure 7). It reveals a robust structure of high chlorophyll-a concentrations during autumn followed by declining concentrations in winter and two subsequent secondary peaks in late winter-early spring (mostly end of February-early March) and early summer (mostly in June).

The chlorophyll transects for various years (Figure 8a-c) reveal some important features. The first one is a year around, relatively high subsurface chlorophyll concentrations greater than 1 mg m$^{-3}$ that are generally confined within the layer between the depths of 20 m and 50 m. They further infer that the chlorophyll-rich euphotic zone typically extends to 40-50 m depth, but may deepen occasionally to more than 75 m by the physical processes the most important of which is the mesoscale anticyclonic formations within the measurement site.

## Discussion and Concluding Remarks

A decade long measurements during 2001-2011 at a coastal site along the southeastern Black Sea (off Trabzon) documents persistently warm winters except a relatively cold winter period during 2002-2004. Another characteristic feature of the site is its anticyclonic character identified by the position of isopycnal levels almost twice deeper with respect to those within the cyclonically-dominated interior basin. This structure was also modified temporally by the passages of anticyclonic eddies. They were observed more persistently during autumn months that is known to be dominated by a turbulent regime over the basin (Korotaev *et al*., 2003). The region is indeed known to be characterized by a generally strong Rim Current system that flows eastward over the steep topography with a typical speed of 50 cm s$^{-1}$ near the surface (Oguz *et al*., 1992).

In one occasion, the measurement site is subject to quasi-lateral protrusion of a relatively cold and more dense water parcels from offshore regions by means of the meandering Rim Current structure. A broad range of temperature variations between 8°C and 20$^o$C is a rather unexpect feature and, to our knowledge has not been reported before, and may have serious biological implications because it also implies ventilation of deeper levels with higher oxygen concentrations. A striking feature is the lack of Cold Intermediate Layer during this period. Instead, relatively warm surface tempertures around 8.0-8.5°C, comparable to those observed below 75-100 m, often gave rise to a vertically homogeneous layer over for the entire water column (150-200 m). This homogeneous layer is however not observed in

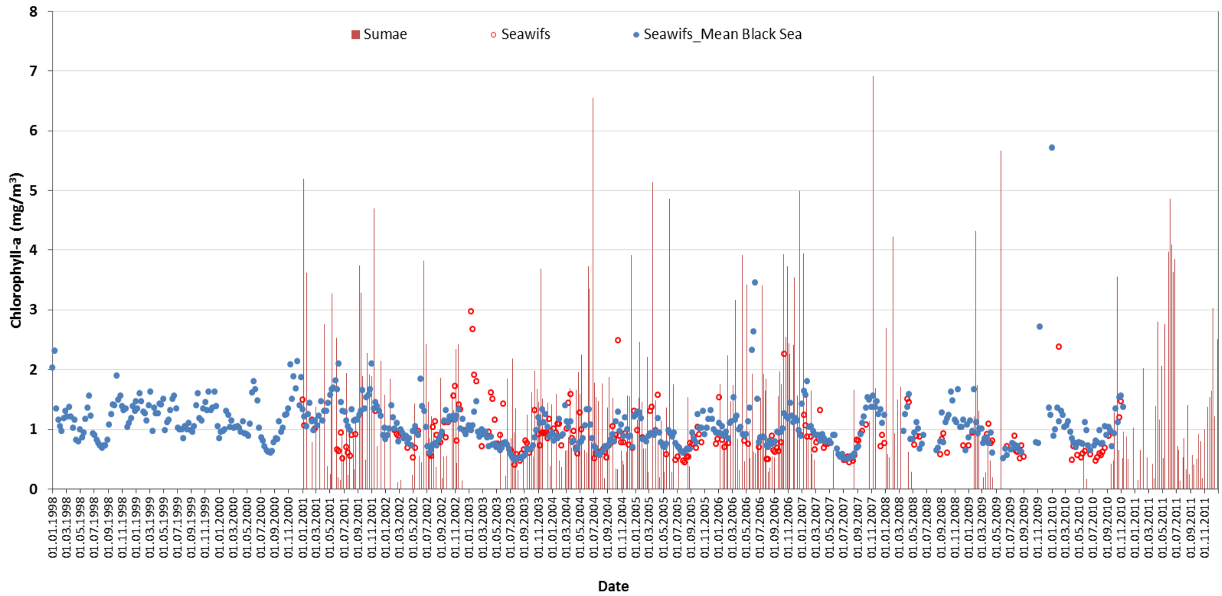


**Figure 7.** Variations of chlorophyll-a concentration measured at 2m depth at the measurement site during 2001-2011 perio (vertical bars), and surface chlorohyll concentrations retrieved from 8-days average SeaWiFS satellite sensor at 41$^o$N and 40$^o$I (red dots) and averaged for the Black Sea between 41$^o$ and 45$^o$N latitudes and 28$^o$ and 42$^o$E longitudes (blue dots).

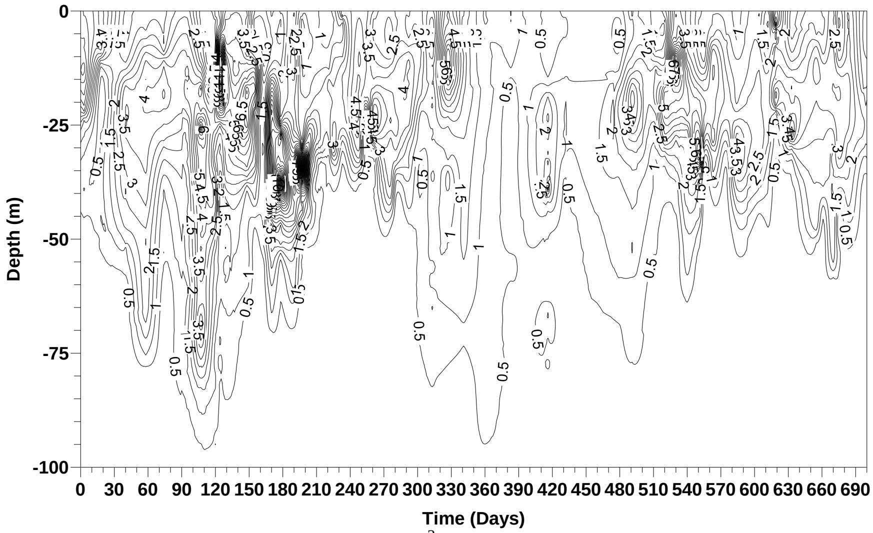


**Figure 8a.** Variations of chlorophyll-a concentration (mg m$^{-3}$) within 150 m layer from January 2001 to November 2002. Contours are drawn at every 0.5 mg m$^{-3}$ and possess relatively high values up to 4.0 mg m$^{-3}$ except winter 2002.

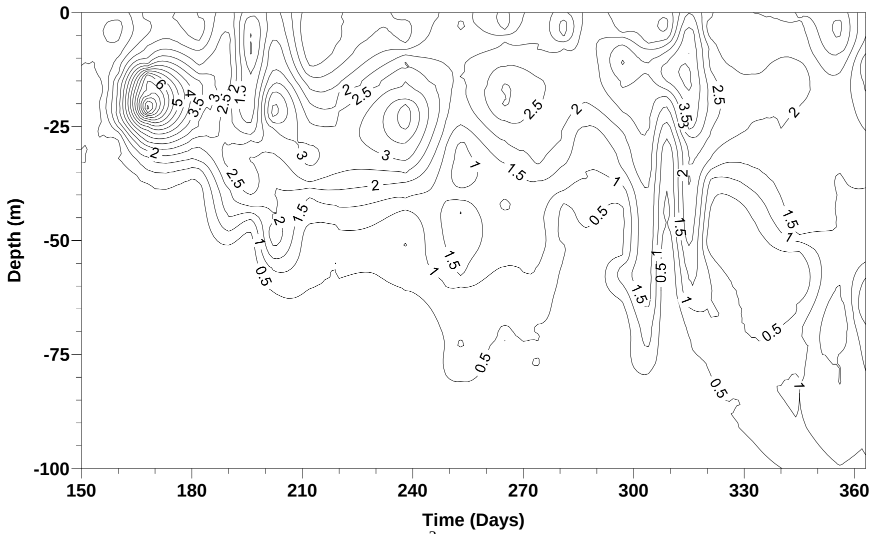


**Figure 8b.** Variations of chlorophyll-a concentration (mg m$^{-3}$) within 150 m layer during June-December 2003. Contours are drawn at every 0.5 mg m$^{-3}$.

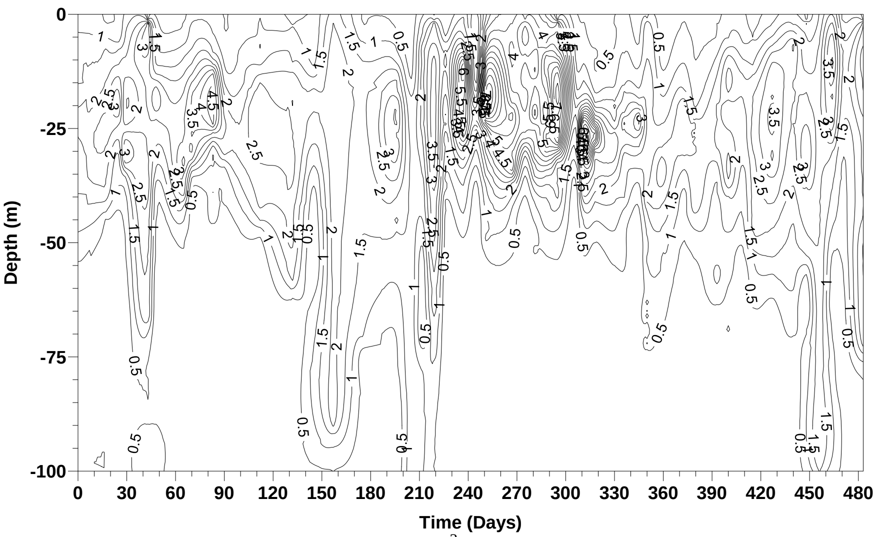


**Figure 8c.** Variations of chlorophyll-a concentration (mg m$^{-3}$) within 150 m layer from September 2010 to December 2011. Contours are drawn at every 0.5 mg m$^{-3}$.

salinity and density and should not be related to the homogeneisation due to strong vertical mixing. Instead, it was promoted by the downward vertical motion associated with anticyclonic character of the region. In the absence of regular cold winters, vertical mixing was limited to episodic, short-term strong wind events.

The observed temperature variations may be argued to control, to some extent, the total anchovy catch in the southeastern Black Sea. For example, relatively warm autumn temperatures (particularly for November) during 2008-2010 is correlated well with the relatively low anchovy catch, whereas relatively low temperatures during 2002-2004 may be effective on relatively high anchovy catch due to longer fishing season. We further argue that the observed lowest anchovy catch during 2005 may be caused by the availability of relatively high bonito catch instead of physical causes.

The *in situ* chlorophyll data and its satellite counterpart at the measurement site involve background concentrations on the order of 0.5 mg $m^{-3}$ that may be related to biases on the measurements rather than pointing to a year around plankton production. We further note that the Black Sea is known to be a case two type water for which the chlorophyll-a concentration can not be estimated with sufficient reliability with the global satellite chlorophyll algorithm. The existing studies suggest a factor two overestimation when computed using the global SeaWiFS chlorophyll algorithm with respect to direct measurements (e.g. Oguz and Ediger, 2006). Even for the case of such an overestimation, the satellite-based estimates are still lower than *in situ* values, indicating either considerable error on the flouresence measurements or some uncertainty on the global - to - local conversion of the satellite-based chlorophyll estimates. On the other hand, subtructing the bias ($\approx$ 0.5 mg $m^{-3}$) and dividing the values by two lead to the satellite-based chlorophyll values less than maximally 0.75 mg $m^{-3}$ that may be acceptable for the interior Black Sea conditions (Yunev *et al*., 2002), but quite low for the coastal regions even though chlorophyll values at the measurement site attains are comparable with the basin-averaged estimates. On the other hand, the long-term measurements along the Romanian coast sugggest an order of magnitude higher (about 6.0 mg $m^{-3}$) long-term (2002-2010) mean value (Vasiliu *et al*., 2012). Various data sets at different sites along the Turkish coast also suggests long-term mean values greater than 1.0 mg $m^{-3}$ (BSC; chapter 2, 2008). Thus, the chlorophyll estimations on the measurement site appear to be questionable.

Irrespective of the true chlorophyll-a values over the water column, the flourescence measurements illustrate an almost year-around production over the uppermost 30-50 m layer and episodic ventilation of the subsurface levels deeper than 75 m in the presence of transient anticyclonic eddies over the region. The mesoscale physical processes may often spread this productivity well below the euphotic zone and may promote a more efficient recycling of nutrients over the water column above the anoxic interface. In addition, the biological production prevailing persistently below the mixed layer is, in reality, more than appreciated by the satellite data and may be the reason to support the long-lasting high fishery within the southeastern Black Sea (Oguz *et al.*, 2012b).

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