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Are trends in SST, surface Chlorophyll-a, primary production and wind stress similar or different over the decadal scale in the south-eastern Black Sea?

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Abstract: A 10-year time series of *in-situ* sea surface temperature (SST), chlorophyll-a concentration and wind stress from 2002 to 2011 was used to examine temporal changes in the South-Eastern Black Sea, together with primary production rates (PP) calculated empirically. Satellite-derived SST was used to support the *in-situ SST,* and showed a good agreement. The yearly averaged trend for *in-situ* and satellite-derived winter SST revealed a statistically significant warming over the last decade in the region of interest. Statistically significant correlation between winter NAO and winter averaged SST suggested that winter SST in the South-Eastern Black Sea is influenced by NAO climatic trends. A consistent decrease in wind stress was observed throughout the time series. Inverse relationship between winter averages of SST and wind stress suggested that SST is forced by wind speed. Chl-*a* and PP fluctuations during the study period revealed that the system is dominated by nanoplankton with some additional contribution from larger species. We concluded that SST in the South-Eastern Black Sea has increased over the decade, whereas the trend in Chl-*a* and PP rates were not straightforward. Hence, these conditions with respect to other parameters will need to be considered in future studies for the Black Sea ecosystem.

Résumé : *L'évolution de la température de surface, de la chlorophylle* a *de surface, de la production primaire et de la tension due au vent est-elle similaire à l'échelle décennale dans la partie sud-est de la Mer Noire ?* Une série temporelle de 10 ans de mesures *in situ* de la température de surface de la mer (SST), de la concentration de chlorophylle *a* et de la tension due au vent, de 2002 à 2012, est analysée pour comprendre les variations temporelles de la partie sud-est de la Mer Noire, associée à une estimation de la production primaire (PP). Les données satellitales de SST ont été utilisées pour valider les données *in situ* de SST. La tendance moyenne annuelle des deux séries révèle un réchauffement significatif au cours de cette période dans la région. La corrélation significative entre l'indice NOA en hiver et les SST moyennes hivernales suggère que les SST hivernales de la partie sud-est de la Mer Noire sont sous l'influence des tendances climatiques de la NAO. Une diminution cohérente de la tension due au vent a été observée tout au long de la série temporelle. La corrélation négative entre les moyennes hivernales de la SST et de la tension due au vent suggère que la SST est forcée par la vitesse du vent. Les fluctuations de chlorophylle *a* et de PP pendant cette période montrent que le système est dominé par le nanoplancton et la contribution de plus grosses espèces. Nous concluons que la SST de cette région a augmenté au cours de cette période alors que la tendance pour la chlorophylle *a* et la PP n'est pas évidente. Par conséquent, ces résultats devront être pris en compte dans de futures études de l'écosystème de la Mer Noire.

Keywords: Black Sea ● Chlorophyll-*a* ● Sea Surface Temperature ● Wind Stress ● Primary Production

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Introduction

Marine ecosystems respond to climate changes in terms of many aspects (e.g. growth, life history traits, and population dynamics) from primary producers to herbivores to top predators (Stenseth et al., 2002). However, phytoplankton are the most sensitive groups in the ecosystem. Additionally, phytoplankton are closely coupled to environmental change (Hays et al., 2005), making them sensitive indicators of environmental disturbance. Therefore, changes in phytoplankton community composition and primary production may have severe ecological consequences for higher trophic levels (Edwards & Richardson, 2004). In our changing climate, it is important to monitor and document changes occurring in the phytoplankton to increase our understanding of the interactions between climate and phytoplankton. This can be done by investigating events occurring on inter-annual and inter-decadal time scales, in order to help in forecasting how marine ecosystems will respond to future scenarios of climate change (Head & Pepin, 2010). Increasing temperature and enhanced stratification could affect the amount and production of phytoplankton. Since these pelagic microalgae are responsible for removing CO_2 from the atmosphere and transferring the carbon to higher trophic levels. Any change in the timing, abundance or species composition of these primary producers will have consequences on the rest of the marine food web (Anadon et al., 2007).

The Black Sea holds one of the most anoxic marine ecosystems among the world oceans. The Black Sea, nearly enclosed and isolated environment, has suffered from severe ecological changes during the last three decades (Oguz, 2005). Several factors may play key role in these changes: excessive nutrient and pollutant input (Mee, 1992; Zaitsev & Mamaev, 1997), outbursts of the alien ctenophore species *Mnemiopsis leidyi* (Shiganova, 1998; Kideys & Romanova, 2001; Kideys, 2002), overfishing (Prodanov et al., 1997; Daskalov, 2002; Gucu, 2002), and climate changes (Daskalov et al., 2003). Changes in climate may affect productivity in the Black Sea, shifting physical structure of the water column, temperature, wind patterns, and riverine inputs; however the spatial variation of impact, the extent of change to the pelagic ecosystem and the exact mechanisms through which change will occur are not fully understood (McQuatter-Gollop et al., 2008).

Although oceanic algal production is an important component of the marine ecosystems, limited long-term biological data sets exist for the South-Eastern part of the Black Sea. Available data on plankton is collected mostly from near-shore monitoring programmes or occasional research cruises for particular areas (Feyzioglu, 1994; Uysal & Sur, 1995; Uysal et al., 1998; Eker et al., 1999; Eker-Develi & Kideys, 2003; Feyzioglu & Seyhan, 2007). Therefore, a time-series of *in-situ* and satellite data is used to address the recent changes in sea surface temperature, Chl-*a* concentration, primary production and wind stress at one monitoring station along the continental shelf area of the South-Eastern Black Sea. We used 10 years of Chl-*a* and SST, wind stress and primary production obtained from an empirical model of primary production based on surface Chl-*a* (applicable to remote sensing). We also analysed these changes in relation to climatic indices.

Materials and Methods

Study area and sampling regime

The dataset used in this study cover a time series of *in-situ* measurement carried out at one monitoring station in the South-Eastern Black Sea coast (Fig. 1). Samplings were conducted monthly interval on board R/V KTU DENAR-I.

Monthly SST data, encompassing a period between 2002 and 2011, were obtained from *in-situ* measurement by using IDRONAUT Ocean Seven 316 Plus CTD (Conductivity, Temperature and Depth) probe. In addition to *in-sit*u SST, it was also used averaged monthly satellite-derived SST from the Giovanni online data system, developed and maintained by the NASA GES DISC (Acker & Leptoukh, 2007). The monthly data product of Sea Surface Temperature (obtained from the 11 µm band night data) was used from the NASA MODIS-AQUA at 9 km spatial resolution, averaged over a rectangular box surrounding the coastal station.

Monthly wind speed data were provided from Turkish Meteorological Service. Wind speed was converted into wind stress, which is a function of wind speed, non-dimensional drag coefficient and boundary layer air density

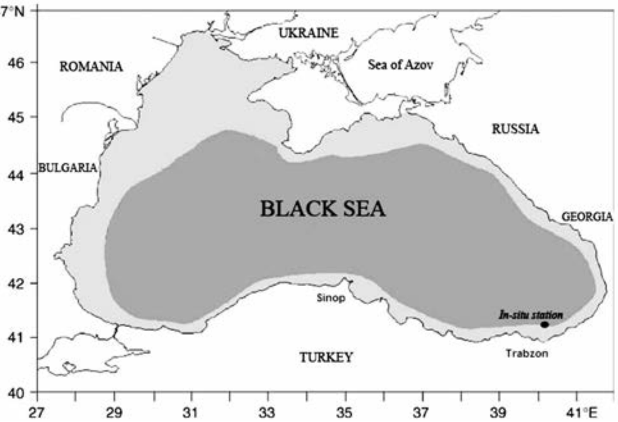

Figure 1. Study area and location of the *in-situ* sampling station.

(Pond & Pickard, 1978). Wind stress was calculated via:

$$\tau = \rho_{air} \times Cd \times W^2 \quad (1)$$

where τ is wind stress (N.m^{-2}), ρ_{air} is air density (1.22 kg.m^{-3}), Cd is the wind-drag coefficient and W is wind speed (m.s^{-1}). Cd was calculated following Smith (1988).

In-situ Chl-*a* samples were collected from surface using 5-L Niskin bottles mounted on a SBE 32 Carousel water sampler. The samples were concentrated onto GF/F filters by filtering 2 L of seawater. Chl-*a* was extracted in 90% acetone solution. The intensity of clear extracts was then measured (Parsons et al., 1984), using a Shimadzu 2550 Model spectrophotometer. A commercially available Chl-*a* Standard (Sigma) was used for calibration purposes (JGOFS, 1994).

In addition to comparing Chl-*a* and SST trends, we also empirically calculated primary production (PP) based on surface log transformed Chl-*a* over the years (Behrenfeld et al., 1998). The empirical model of Behrenfeld et al (1998) uses Chl-*a* to derive PP as follows:

$$Log_{10}\, PP = 0.559 \times log_{10} Chl\text{-}a + 2.793 \quad (2)$$

Statistics

The multiannual trends were evaluated by using linear regression analysis on SST data. One way analysis of variance (ANOVA) was used to test significant trend of linear regressions in Chl-*a* concentrations and SST values for each year. The ANOVA critical significance value P, was given in the text to indicate the level of difference. Pearson rank correlation was used to test for significant differences in the parameters (i.e. *in-situ* SST, satellite derived SST, Chl-*a*, wind speed and NAO).

Results and Discussion

The data set presented here allows us to visualize the differences in the temporal variability of SST (*in-situ* and satellite-derived), wind stress, Chl-*a* and PP in the continental shelf area of the South-Eastern Black Sea (Fig. 2-11).

Sea Surface Temperature (SST)

Changes in *in-situ*- measured SST along the South-Eastern Black Sea coasts exhibited a sinusoidal seasonal pattern reaching a maximum of 28.1°C in summer and decreasing to a minimum of 7.9°C in winter throughout the study period (Fig. 2). Satellite-derived SST also displayed the same pattern as *in-situ* measured SST for the time series, ranged from 6.6 to 27.9°C (Fig. 2). Moreover, *in-situ* measured SST is well correlated with satellite-derived SST (Pearson rank correlation = 0.97, $p < 0.001$), indicates consistency among the measurements. The yearly averaged trend for *in-situ* and satellite-derived winter SST (Fig. 3) revealed a significant warming over the last decade along the South-Eastern Black Sea coasts (r = 0.59, $p < 0.05$ and r = 0.79, $p < 0.05$ for *in-situ* and satellite derived SST, respectively). The warming trend in winter SST is almost apparent in every year, except for between 2005 and 2008, implying that the change is driven by seasonality. The most pronounced increasing in this time series occurred after 2008. The warming trend in yearly averaged of summer SST was also apparent, however, the trend was not significant ($p > 0.05$).

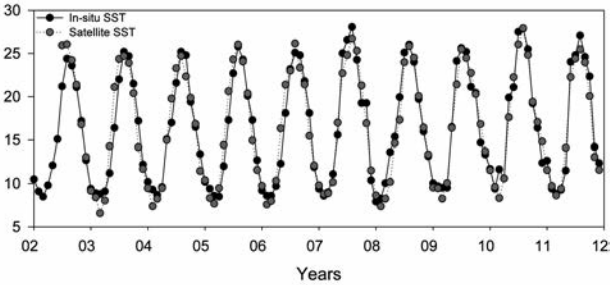

Figure 2. Time series of *in-situ* (black dots) and satellite derived (red dots) SST (°C) from 2002 to 2011 along the continental shelf area of the South Eastern Black Sea.

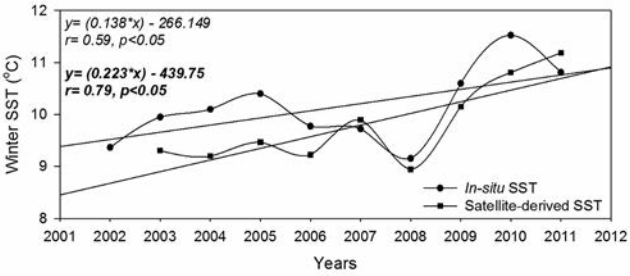

Figure 3. Linear trend of winter (December-March) SST (°C), yearly averages from 2002 to 2011 along the continental shelf area of the South-Eastern Black Sea. Black and the red solid line denote the linear regression for *in-situ* and satellite-derived SST, respectively. The equation for trends is shown on the plot.

In order to examine whether the observed trends is a regional characteristic or part of the current global warming trend, we compared winter NAO with winter (December-March) averaged SST (Fig. 4). Statistically significant correlation obtained between winter NAO and winter averaged SST (Pearson rank correlation = -0.84, $p = 0.002$; Fig. 4) revealed that winter SST in the South-Eastern Black Sea is influenced by NAO climatic trends. A positive winter NAO index is associated with the strong pressure gradient between Azores high-pressure and Iceland low-pressure

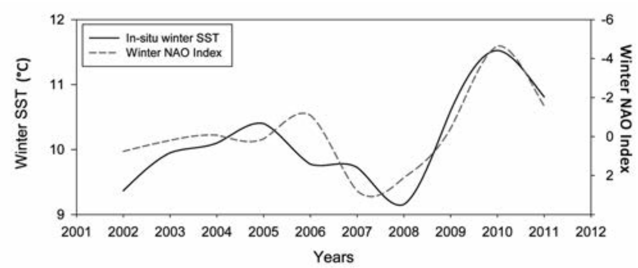

Figure 4. Changes of winter averaged *in-situ* SST (°C) for the continental shelf area of the South Eastern Black Sea and the North Atlantic Oscillation (NAO) climatic index.

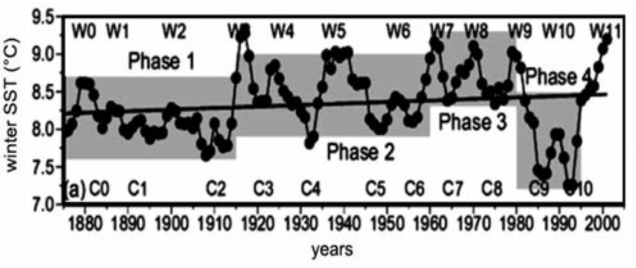

Figure 5. Long-term variations in winter SST (°C) along the Black Sea whole basin (Oguz et al., 2006).

systems, bringing cold and dry air masses with strong westerly winds to southern Europe and the Black Sea region (Hurrell et al., 2003). Conversely, a negative NAO index implies a weaker surface atmospheric pressure values and milder winters, with warmer air temperatures and less dry/more wet atmospheric conditions over the Black Sea (Oguz, 2005). A close relationship between the local climate and hemispherical atmospheric motions is apparent in Figure 4 by the association of 2005-2008 cooling period with increasing trends of NAO climatic index. The subsequent warming cycle is explained by decreasing mode of the NAO indices up to 2010, after which the NAO climatic index explain the Black Sea SST variations well. In general, the observed consistency supports the presence of a relationship between the regional atmospheric conditions and the NAO-driven large scale atmospheric motion. On the contrary, no significant correlation was found between summer averaged SST and NAO for study area (Pearson rank correlation = -0.140, $p = 0.699$).

Earlier studies report that an evidence of abrupt increasing in SST for the Black Sea in the last decades (Oguz, 2005; Alkan et al., 2012), thus the regional warming trend observed in this study is apparently part of a wide spread warming. Long-term (1880-2000) winter SST revealed fluctuations over the decades (Oguz et al., 2006). These authors reported that the warming trend was apparent along the basin, except for phases 1 and 4 (Fig. 5). Strong cooling trend during the 1980-1990s was obvious, whereas warming trend after the 90's was most pronounced. Winter SST in the interior basin of the Black Sea displayed considerable fluctuation over the last century, with a rise of 0.25°C, except from 1980-2000 (Oguz et al., 2006). The enclosed seas have noticeably undergone far more dramatic changes than open seas during the past decades. Relatively small changes in the frequency of inflow (as in the Baltic Sea) or in temperature (as in the Eastern Mediterranean and Black Sea) had a strong effect on large parts of the ecosystem, indicating the high sensitivity of these enclosed systems to climate change (Anadón et al., 2007). Furthermore, increasing SST inhibits mixing, reducing the upward nutrient supply and lowering productivity (Doney, 2006; Henson et al., 2010) and consequently fisheries (Kideys, 1994). Our analysis suggests that the South-Eastern Black Sea is sensitive to environmental changes.

Chl-a

Chl-*a* concentration, an index of phytoplankton biomass, was obtained from *in-situ* measurements for the study area, and fluctuated throughout the time (Fig. 6). A large range fluctuation in Chl-*a* concentration was observed along the study area, ranged from 0.01 to 2.58 mg.m^{-3}. While the lowest Chl-*a* concentrations, around the 0.5 mg.m^{-3}, were recorded at the beginning of the study period, the highest ones, up to 2 mg.m^{-3}, were observed between 2008 and 2011. In the present study, *in-situ* Chl-*a* was also compared with satellite-derived Chl-*a* (MODIS Aqua at 9 km), however, no significant correlation (Pearson rank correlation = 0.113, $p = 0.233$) was found among them; so the satellite data are not presented here. Using the operational chlorophyll satellite data products that are designed for clear open oceanic waters, especially for the coastal regions of the Black Sea, can be problematic due to water optical properties, mainly the high coloured dissolved organic matter (CDOM) and total suspended matter (TSM), which can cause errors in Chl-*a* (Oguz & Ediger, 2006).

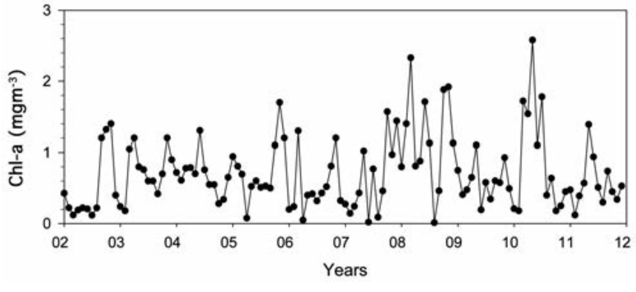

Figure 6. Time series of *in-situ* Chl-*a* (mg.m^{-3}) obtained from 2002 to 2011 along the continental shelf area of the South Eastern Black Sea.

Previous studies state that inter-annual fluctuations in Chl-*a* are more pronounced among seasons. The average Chl-*a* concentration in the open parts of the Black Sea for the period of 1978-1991 was reported as 0.97-1.52 mg.m^{-3} during winter months and 0.28-0.38 mg.m^{-3} during summer months (Vedernikov & Demidov, 1993). Besides, changes in Chl-*a* in the open and shelf areas of the Black Sea coincided with SST increase, which affect the whole pelagic ecosystem, especially over the last 2 decades (Yunev et al., 2002). Moreover, a decreasing trend in Chl-*a* concentration since 1995 was reported for the open parts of the Black Sea with increasing SST and decreased nutrient loading (Oguz & Gilbert, 2007).

The knowledge on Chl-*a* concentration of the phytoplankton and its variation also gives idea about the trophic status for a given area. Here, the *in-situ* Chl-*a* data were partitioned according to approximate trophic status: oligotrophic (picoplankton, Chl-*a* < 0.25 mg.m^{-3}), mesotrophic (nanoplankton, Chl-*a* > 0.25-1.2 mg.m^{-3}) and eutrophic (microplankton, Chl-*a* > 1.2 mg.m^{-3}) (Aiken et al., 2009). There were notable differences in trophic status of the area over the decade (Fig. 7). At the beginning of the period (between 2002 and 2003), the area was mainly characterized by oligotrophic conditions and elevated to a relatively mesotrophic level from 2003 to 2011, the eutrophic level prevailed in the area in 2008 and 2010, in which the most prominent increase in SST was recorded (see Fig. 3). The system was generally dominated by nanoplankton with some additional contribution from larger species during two more productive and warm years (i.e. 2008 and 2010). The shifting of trophic status towards mesotrophic plus eutrophic level over the decade also coincided with increasing of SST (see Fig. 3). Similarly, increasing of the eutrophication overlapped with increasing trend in Chl-*a* concentration during 2008-2011 periods (see Fig. 6).

Primary Production

Primary production (PP) was calculated empirically by using surface log transformed Chl-*a* data (Fig. 8). Due to using the same Chl-*a* data set, PP rates displayed almost the same pattern as Chl-*a* trend, ranged from 24 to 1055 mgC.m^{-2}.d^{-1}. PP rates fluctuated throughout the time; the highest values were obtained during 2008 and 2010 period.

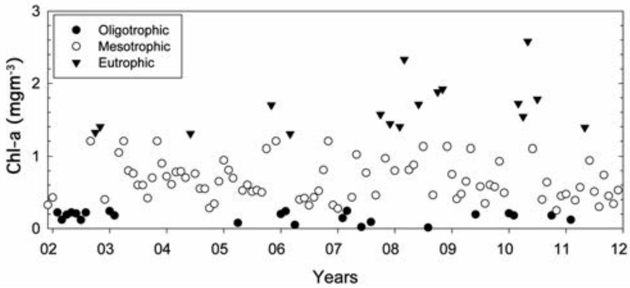

Figure 7. The variation of trophic level from 2002 to 2011 along the continental shelf area of the South Eastern Black Sea.

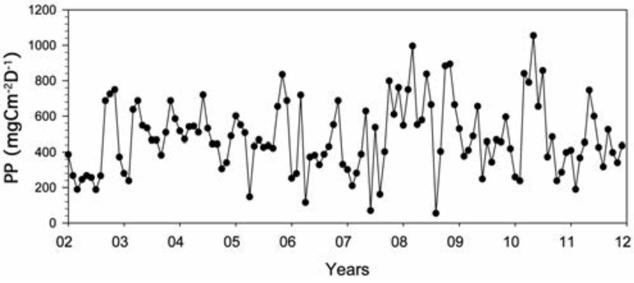

Figure 8. Time series of empirical PP (mgC.m^{-2}.d^{-1}) obtained from 2002 to 2011 along the continental shelf area of the South Eastern Black Sea.

The primary production rates reported from earlier studies were relatively high in NW shelf of the Black Sea ranged from 570 to 1200 mgC.m^{-2}.d^{-1}, whereas values varied from 320 to 500 mgC.m^{-2}.d^{-1} in the regions of continental slope, 100 to 370 mgC.m^{-2}.d^{-1} in the central deep-sea regions during 1960-1991 (Bologa 1986; Vedernikov & Demidov 1993; Demidov 2008). On the other hand, production rates for the southern coasts of the Black Sea were estimated as 247-1925 mgC.m^{-2}.d^{-1} for spring and 405-687 mgC.m^{-2}.d^{-1} for summer-autumn period during 1995-1996 (Yilmaz et al., 2006). In the present work, calculated production rates fall within the ranges those reported from previous studies performed in other parts of the Black Sea. Even though, these findings do not reflect a general feature of the Black Sea ecosystem, relatively higher production rates may arise from using only surface Chl-*a* data and model parameters in the present study. The differences in the production rates along the different parts of the Black Sea clearly emphasis that physical conditions (e.g. CDOM, TSM, riverine input etc.) are main factor in the study area.

Wind stress

Wind stress in the study area revealed a decreasing pattern over the time series (Fig. 9). The highest wind stress was recorded generally during the period of 2002-2006. Yearly averaged wind stress also suggested a statistically significant decreasing trend throughout the study period (Fig. 10). Moreover, we also observed a strong negative correlation between wind stress and yearly averaged SST in the study area (Pearson rank correlation= -0.83, $p < 0.05$; Fig. 11). Whereas no significant correlation was reported from earlier studies between SST or wind stress in the shelf regions of the Black Sea (McQuatter-Gollop et al., 2008).

Wind stress regulates the dynamics of the boundary layer, and is connected to the production of wind-driven

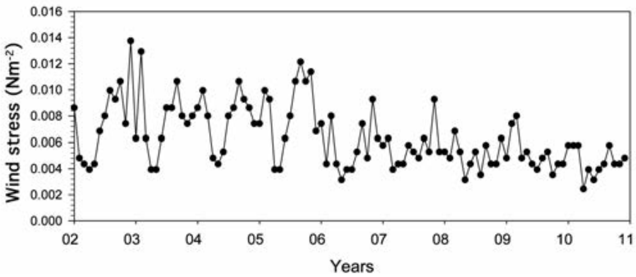

Figure 9. Time series of wind stress (N.m-2) obtained from 2002 to 2011 along the continental shelf area of the South Eastern Black Sea.

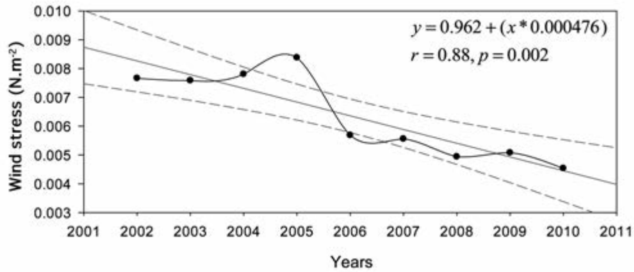

Figure 10. Linear trend of wind stress (Nm-2), yearly averages from 2002 to 2011 along the continental shelf area of the South Eastern Black Sea.

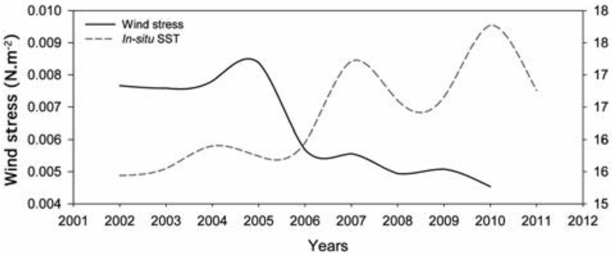

Figure 11. The changes of yearly averaged wind stress (N.m-2) and SST (°C) along the continental shelf area of the South Eastern Black Sea.

surface currents, the generation of surface waves and upper-ocean mixing (Pond & Pickard, 1978). Therefore, low wind stress contributes to formation of highly stratified waters (McQuatters-Gollop et al., 2008). Enhanced stratification reduced vertical mixing of water column and retention of nutrients to upper layers (Edwards et al., 2013). It is worth noting that, especially, weak winds at the end of spring and in the beginning of summer may also ensure the formation of thermocline that cuts off upper layers where the zone of low concentrations of nutrients is formed (Silkin et al., 2013). Observations along the western English Channel revealed that the most prominent increases in SST followed by a period of reduced wind speeds and enhanced surface irradiation (Smyth et al., 2010). Similarly, the warm and stratified conditions were also reported from the Black Sea due to low wind stress resulted alterations to phytoplankton bloom pattern along the Black Sea (McQuatter-Gollop et al., 2008). Earlier studies during the end of 1980s and the begging of 1990s in the Black Sea reported that windy and cold winters enhance extensive spring/summer blooms due to vertical mixing and upwelling (Oguz, 2005). The increases in wind speed result in deepening the mixing-layer depth; consequently cause to move phytoplankton from surface to depths without sufficient light to grow. This situation can limit phytoplankton growth and primary production. Moreover, low wind speed provides the stratification necessary for a bloom to develop, whereas strong wind mixing prevents stratification (Collins et al., 2009). On the other hand, the increases in diatom species along the North Sea over the last decade have been associated with increasing wind intensity (Hinder et al., 2012). In the present study, the decreasing trend in wind stress especially after 2005 brought on increases in Chl-*a* and SST along the study area. Similarly, low wind speeds also led to high PP (see Fig. 9) along the study area. In general, obtained wind regime for the study area is generally low when compared to the other parts of the Black Sea. Despite this, any changes in wind regime can impact water column stratification, nutrient availability and PP, which may in turn potentially affect the fishery.

Concluding Remarks

Using a long-term time series data revealed that how important ecosystem properties have changed during the last decade in the continental shelf area of the South-Eastern Black Sea. Temporal analysis of *in-situ* and satellite-derived SST showed that the warming is apparent in the study area. Correlation between winter SST and with winter NAO also suggested that the increasing in SST is not only a local phenomenon but also affected by large-scale atmospheric circulation patterns. Inverse relationship between SST and wind stress suggested that low frequency of wind stress affect the SST in the study area and appear to be coupled to both local meteorological forcing and changes in NAO.

The results obtained from present study, illustrate oscillations over a decade which are too short to evaluate climate-driven effects on the South-Eastern Black Sea ecosystem. We aware that the 10-year time series of measurements insufficient to unambiguously characterize long-term trends. This short term analysis, however, revealed that the South-Eastern Black Sea is going through and intense warming trend. The data showed well-defined oscillations during the last decade and we do not know whether the trends we report will continue in the same sense. Further studies to elucidate the trends and their causes on the shifts in Black Sea ecosystem are required.

The present paper suggests that climate played key role in the South-Eastern Black Sea ecosystem during the study period. This work also permitted, for the first time, a long-term comparison for SST, Chl-*a*, wind stress and model based PP trend in the study area. Moreover, this brings a step closer towards reporting and understanding a temperature change seen in the South-Eastern Black Sea. However, the question as which factor has triggered this alteration remains unanswered. The warming may have a direct or indirect impact on marine entities and ecosystems, thus, there is need to asses further available past biological data (e.g. phytoplankton, zooplankton, fisheries etc) for potential responses to the new thermal state, and to closely monitor the South-Eastern Black Sea ecosystem.

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