www.trjfas.org
ISSN 1303-2712
Turkish Journal of Fisheries and Aquatic Sciences 17: 981-994 (2017)
DOI: 10.4194/1303-2712-v17_5_13

PROOF

RESEARCH PAPER

Contrasting Wind Regimes Cause Differences in Primary Production in the Black Sea Eastern and Western Gyres

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Received 19 February 2017
Accepted 27 February 2017

Abstract

A 12-year time series of SeaWiFS chlorophyll a (Chl-a), primary production (PP), sea surface temperature (SST), and meteorological wind speed were used to examine decadal changes in these parameters in the eastern and western Gyres of the Black Sea. In both Gyres, low wind speeds and SST led to higher PP. After 2004, there was a progressive decrease in PP and Chl-a, which co-varied with increasing SST. Chl-a and PP were significantly higher in the western Gyre compared to the eastern Gyre, especially from 1998 to 2004. Wind speed negatively correlated with PP in both Gyres, but the higher wind speed prior to relaxation in the western Gyre led to higher PP during spring and autumn. Variability in annual PP in both Gyres was coupled to fluctuations in the Multivariate ENSO Index (MEI), which affected the wind regime more in the eastern than in the western Gyre. The data suggest that localised wind regimes in the western gyre that are uncoupled from MEI, sustains higher PP in this area.

Keywords: Black Sea, Chlorophyll-a, Sea Surface Temperature, Primary Production, SeaWiFS

Introduction

Many different trophic levels of the marine ecosystem, from primary producers to herbivores to top predators, are affected by climate change which can alter growth, life history traits and population dynamics (Stensth et al., 2002). Due to their short life cycles, phytoplankton is the most sensitive group and therefore acts as an indicator of disturbances in the natural environment (Hays et al., 2005). This can cause changes in phytoplankton composition and photo-physiology and ultimately primary production, which can potentially cascade to impact higher levels of the marine food web (Edwards & Richardson, 2004; Anadon et al., 2007). In addition, climate change can result in a number of different stressors that can potentially affect algal growth; increasing temperature affects phytoplankton photo-physiology, enhanced stratification affects the availability of nutrients, primary production (PP) and elevated CO_2 can alter pH and the availability of inorganic carbon in the sea. Currently global warming is causing approximately a 0.2^0C rise per decade in sea surface temperature in many tropical and subtropical seas (IPCC, 2007). This is expected to increase over the next decade when the planet could become warmer than any other period over the past million years (Hansen, 2006). In a changing climate, it is important to monitor inter-annual and inter-decadal changes in the phytoplankton (Head et al., 2010, Rykaczewski & Dunne, 2011).

The Black Sea is one of the largest anoxic marine ecosystems in the global ocean (Tolmazin, 1985). It is a semi-enclosed and isolated environment, which has suffered from severe ecological changes over the last three decades (Zaitsev & Mamaev, 1997; Oguz, 2005). Excessive nutrient and pollutant input (Mee, 1992; Zaitsev & Mamaev, 1997), the introduction of the alien ctenophore species *Mnemiopsis leidyi* (Shiganova, 1998; Kideys & Romanova, 2001; Kideys, 2002), overfishing (Prodanov et al., 1997; Daskalov, 2002; Gucu, 2002) and recent changes in the physical structure of the water column as a result of climate change (Daskalov, 2003) have had a major impact on this ecosystem. The Black Sea supports a large-scale commercial fishery for countries that border the basin (Kideys, 2002; Agirbas et al., 2010). Until 1988, the fishery was almost five times richer than the neighbouring Mediterranean Sea (Anonymous, 2000; Kideys, 1994). In recent years there have been some signs of recovery of the fishery (Yunev et al., 2002; Bodeanu et al., 2004; Mee, 2006), though the reasons for this have not been properly quantified.

Changes in Chl-a and PP have been monitored in different regions of the Black Sea for several decades (Finenko, 1967; Vedernikov et al., 1980, 1983; Yunev, 1989; Krupatkina et al., 1990, 1991; Berseneva, 1993; Vedernikov & Demidov, 1993; Yilmaz et al., 1998; Bologa et al., 1999; Demidov, 1999; Kopelevich et al., 2002; Yunev et al., 2002). Spatial and seasonal variations in Chl-a in the Black Sea were assessed using CZCS satellite data from 1978 to 1986, before the onset of dramatic changes in Chl-a biomass during the late 1980's (Vedernikov & Demidov, 1993). Changes in basin-wide Chl-a were also assessed from 1997 using Sea-viewing Wide Field of view Sensor (SeaWiFS) (McQuatters-Gollop et al., 2008), which illustrated that open ocean and coastal areas of the Black Sea were controlled by different factors. Whereas coastal ecosystems are mainly regulated by freshwater inflow and climatic processes (Bodeanu, 2002, 2004), open-ocean areas of the Black Sea are controlled by a combination of upwelling and stratification (Sorokin, 2002). McQuatters-Gollop et al. (2008) indicated that the recent recovery of the Black Sea ecosystem was potentially influenced by climatic changes. Other studies have suggested that under the influence of global warming, the strength of upwelling could decrease and the degree of water column stratification potentially increases (Doney, 2006), which in turn affects the availability of nutrients and hence primary production. Few long-term data sets of primary production exist for the Black Sea, especially in the south eastern Gyre (Yilmaz et al., 1998; Yayla et al., 2001).

The aim of this study was to assess recent changes in phytoplankton biomass, primary production, sea surface temperature and wind speed in the eastern and western Gyres of the Black Sea. We used 12 years of SeaWiFS Chl-a, a proxy for phytoplankton biomass, primary production, AVHRR SST and wind speed data from the eastern and western Gyres to quantify temporal differences between them. We also analyse these changes in relation climate forcing indices.

Material and Methods

Study Area

The location of the eastern and western Gyres in the Black Sea is given in Figure 1. Mean monthly satellite AVHRR SST, SeaWiFS Chl-a and PP and wind speeds provided by the Turkish Meteorological Office were extracted from 1998 to 2010. Data for the eastern Gyre were extracted from an elliptical shape that did not include coastal regions or the Sea of Azov, with a centre point at 41.64°N, 37.44°E; the easterly edge of the elipse was at 39.63°E; the westerly edge was at 35.07°E; the Northerly edge was at 44.26°N and the Southerly edge was at 41.92°N. Data for the western Gyre was extracted from an elliptical shape that similarly excluded coastal regions and the Sea of Marmara Centre with a centre point at 41.64°N, 31.43°E; the eastern edge at 33.98°E; the western edge at 29.23°E; the northern edge at 44.26°N, and the southern edge at 41.92°N (see Fig.1 for further details).

Satellite Data

AVHRR Sea Surface Temperature

Mean monthly SST from Advanced Very High Resolution Radiometer (AVHRR) 4-km grid Pathfinder v2009 data were downloaded from NOAA.

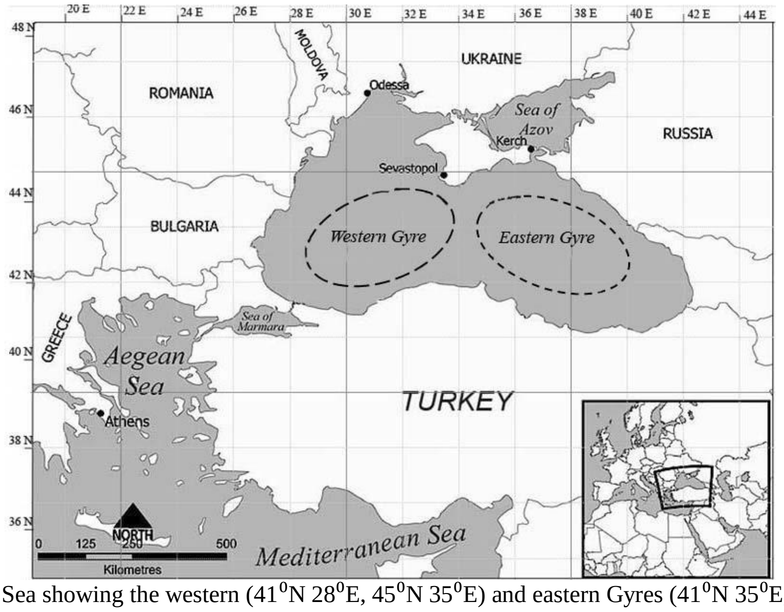

Figure 1. The Black Sea showing the western (41^{0}N 28^{0}E, 45^{0}N 35^{0}E) and eastern Gyres (41^{0}N 35^{0}E, 45^{0}N, 42^{0}E).

SeaWiFS OC4v6

Monthly composite of SeaWiFS level-3 data, with 9 km spatial resolution, from September 1997 to December April 2010, were downloaded from GSFC-NASA (http://oceancolor.gsfc.nasa.gov/cgi/l3).

Primary Production

A wavelength resolving PP model (Morel, 1991) was implemented following Smyth et al. (2005) using mean monthly 9 km NASA SeaWiFS OC4v4 Chl-a and Pathfinder v2009 AVHRR SST data re-gridded to 9 km, to generate mean monthly satellite maps of PP from 1997 to 2010. The maximum quantum yield for growth (ϕ_m) and the maximum phytoplankton Chl-a specific absorption coefficient (a^*_{max}) were parameterized using Chl-a following Morel et al. (1996) from SeaWiFS and the model was forced with monthly satellite fields of Chl-a and SST. The model of Gregg and Carder was used to generate PAR instead of being derived from satellite, since this model can resolve PAR at 30 min intervals so that PP can be integrated over the day. The light field was propagated through the water column by calculating the spectral attenuation coefficient for downwelling irradiance following the methods of Morel (1988) as outlined in Tilstone et al. (2005). Hourly rates of PP were weighted to the water column light field and carbon fixation was integrated over the light hours for each day down to 1% irradiance depth. Integration was performed over all daylight hours, for wavelengths 400–700 nm and computed through the iterative approach of Morel and Berthon (1989). The model was run using surface Chl-a and temperature assuming a homogenous water column profile of Chl-a, a^*_{max} and ϕ_m, since this is what is available from satellite. PUR irradiance was derived from Gregg and Carder (1990) using meteorological data. PP_{WRM} was calculated as follows:

$$\sum PP_{WRM} = 12\, a^*_{\max}\, \phi_m \int_0^D \int_0^{z_{eu}} \int_{400}^{700} Chla(z)\, PUR(z,t,\lambda)\, f(x(z,t))\, d\lambda\, dz\, dt \quad (1)$$

This model has proved to be the most accurate satellite PP model for the Atlantic Ocean where modelled values are within 20% of in situ (Tilstone et al., 2009). During recent NASA PP inter-comparisons, Carr et al. (2006) and Saba et al. (2011) found that this model was the most accurate in eight out of ten regions of the global ocean and within ~30% of in situ values.

Data Analysis

Anomalies were calculated by subtracting from each monthly value the corresponding monthly average for the time series from 1998 to 2010. Linear regression was fitted to the anomalies to assess inter-annual trends and Pearson correlation coefficients (r) and levels of significance (P) were used to evaluate significant trends. The cumulative sums method was applied to the anomalies to further decompose the signal to highlight major changes in monthly data values along the time-series. Successive positive anomalies produce an increasing slope, while successive negative anomalies produce a decreasing slope (McQuatters-Gollop et al., 2008). One way analysis of variance (ANOVA), paired t-tests and Pearson rank correlation were used on normally distributed data to test for significant differences in wind speed, SST, Chl-a and PP between Gyres. The ANOVA critical significance value P, is given in the text to indicate the level of difference.

Results

Sea Surface Temperature

Changes in SST in both Gyres exhibited a sinusoidal seasonal pattern reaching a maximum of 27.8-28.0^{0}C in summer and decreasing to a minimum of 5.9-7.1^{0}C in winter for western and eastern Gyres, respectively (Figs. 2A-B). There was no statistically significant difference in SST between western and eastern Gyres ($P>0.05$). Cumulative sum of the SST anomalies indicated a decreasing trend in SST from 1998 in the western and eastern Gyre which continued in both Gyres until 2007. This decrease in SST was greater in the western Gyre compared to the eastern Gyre over this period. After 2007, there was an increase in the mean monthly cumulative sums of the anomalies in SST in both Gyres, but the magnitude of this was greater in western Gyre compared to the eastern Gyre (Fig. 2C-D).

Wind Speed

There was a similar trend in wind speed in both Gyres with higher values in winter and lower values during spring and autumn. Wind speeds in the western Gyre were however significantly higher than in the eastern Gyre ($P<0.001$; Figs. 3A-B) and in the western Gyre, the wind speed was highest from 2007-2008. The cumulative sum of the anomalies illustrates the differences in trends between Gyres (Figs. 3C-D). Wind speed in the western Gyre (Fig. 3C) decreased from 1997 to 2007, after which time it increased again. Concurrently, in the western Gyre, a decrease in wind speed caused an increase in SST (Fig. 2C). By comparison, in the eastern Gyre, wind speed increased to 2007 and then decreased to 2010 (Fig. 3D) which was mirrored by a decrease in the cumulative sum anomalies in SST to 2007 and an increase to 2010 (Fig. 2D).

Chl-a Time Series

SeaWiFS Chl-a was slightly higher in the western Gyre (0.78 mg.m^{-3}) compared to the eastern

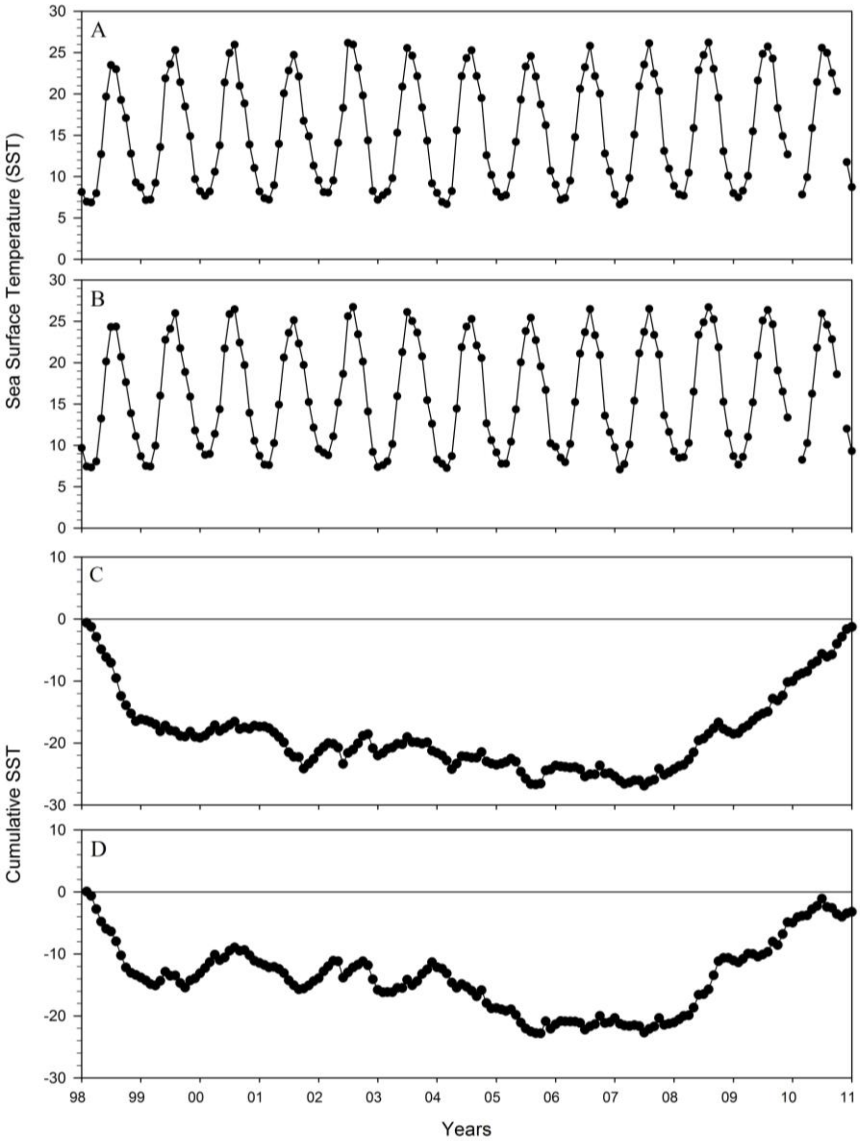

Figure 2. Advanced Very High Resolution Radiometer Sea Surface Temperature (SST) data from 1998 to 2011 for the western (A) and eastern Gyre (B) of the Black Sea and cumulative sum of the anomalies in SST for the western (C) and eastern Gyre (D).

Gyre (0.77 mg.m^{-3}; P>0.05). In the western Gyre, the highest Chl-a was recorded from 1999-2003 (1.86 mg.m^{-3}) and 2008-2010 (1.28 mg.m^{-3}), which corresponded with the lowest wind speeds (Fig 4A). By comparison, SeaWiFS Chl-a in the eastern Gyre was relatively stable from 2002 to 2008. From 1998-2002 the highest Chl-a concentrations (1.84 mg.m^{-3}) were recorded (Fig 4B). The cumulative sum of the Chl-a anomalies indicated that Chl-a increased in both Gyres until 2003, which was followed by a downward trend (Fig. 4C-D). The magnitude of the trend was greater in the western (Fig. 4C) compared to the eastern Gyre (Fig. 4D).

Primary Production Time Series

A time series derived from the Wavelength Resolving Model (WRM) from 1998 to 2011 using SeaWiFS data to assess inter-annual variations in PP in the Black Sea (Fig. 5). Mean annual PP values (mgCm^{-2}d^{-1}) in the Black Sea illustrate both spatial and temporal variations in PP. PP was significantly high in the western Gyre (110-2196 mgCm^{-2}d^{-1}) compared to the eastern Gyre (111-1806 mgCm^{-2}d^{-1}), especially from 1999 to 2001 (paired t-test, P<0.001; Fig. 5 A, B). Similar to Chl-a and wind speed, PP in the western Gyre was always higher than in the eastern Gyre. There was also a clear cumulative increase in PP until 2004 in both Gyres. After this period, there was a decrease in the cumulative sum of the PP anomalies from 2004 to 2010 in both Gyres (Fig. 5C-D).

To illustrate the magnitude of the spatio-temporal differences PP maps were generated for the Black Sea (Fig. 6). Mean annual satellite maps of PP indicated that the eastern Gyre had a higher annual PP

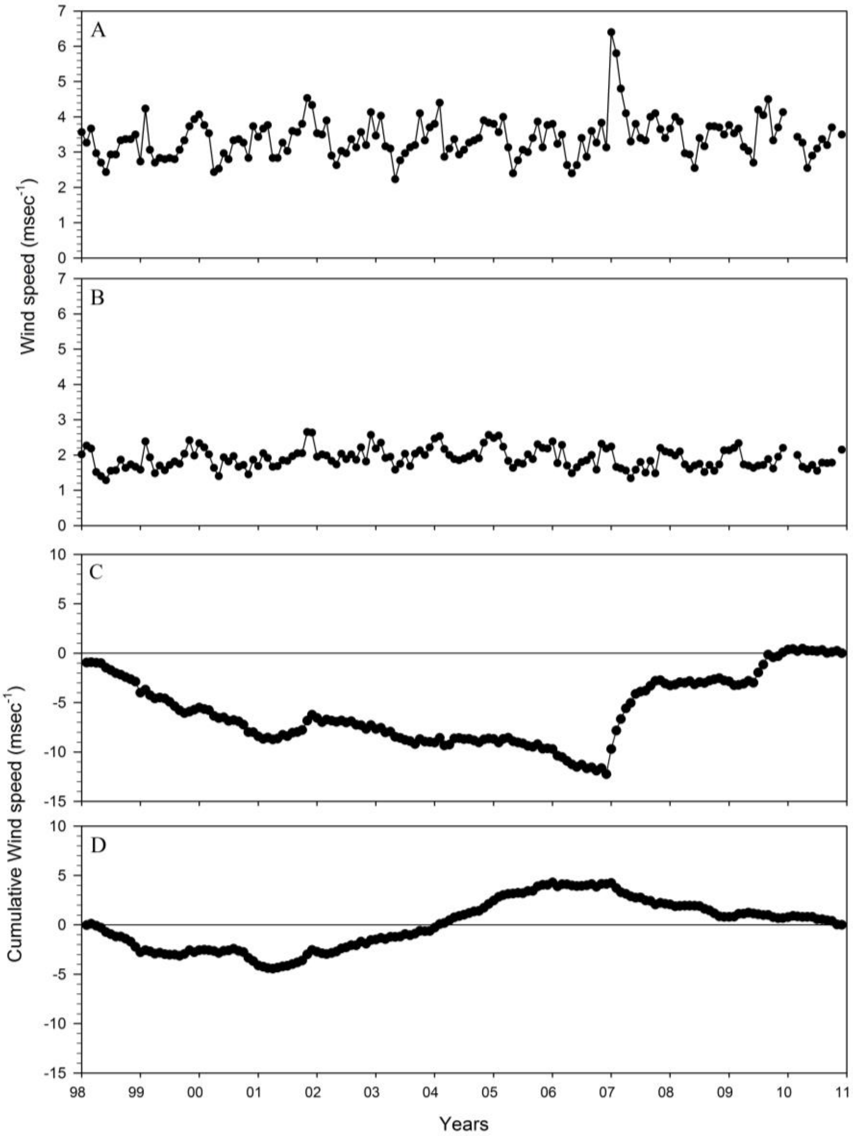

Figure 3. Wind speed data from 1998 to 2011 for the western Gyre (A) and eastern Gyre (B) of the Black Sea and cumulative sum of the anomalies in wind speed for the western (C) and eastern Gyre (D).

than the western Gyre from 1998-1999. Annual PP of both Gyres increased in 2000 and was greater in the western Gyre compared to the eastern Gyre. From 2001 to 2010, the western Gyre consistently had a higher annual PP than the eastern Gyre.

There was significant negative correlation between PP and wind speed in both Gyres, (western Gyre r=0.45, P<0.001; eastern Gyre r=0.53, P<0.001). Low wind speeds led to high PP in both Gyres (Fig. 7A-B). PP in the western Gyre was higher than in the eastern Gyre due to the higher wind speeds, which when they decreased led to higher PP in the western Gyre (Fig 2A, 7A). Similarly, significant negative correlations between SST and wind speed in both Gyres was observed (Fig. 7C-D), and high wind speed resulted in a decrease in SST. In addition, there were significant positive correlations between PP and SST (Fig. 7E-F). In the western Gyre, PP was higher even though the range in SST was similar to the eastern Gyre, indicating that the difference in wind speed causes the difference in PP.

Discussions

Temporal Trends in Chl-a and PP

During the past few decades, the Black Sea has experienced high inter-annual variation in Chl-a, which was attributed to eutrophication (Kideys, 1994; Vinogradov et al., 1999; McQuatters-Gollop et al., 2008, Mikaelyan et al., 2013). Historic studies of primary production from 1960-1991 reported values of 570-1200 mgCm^{-2}d^{-1} along the NW shelf, 320-500 mgCm^{-2}d^{-1} along the continental slope, and 100-370 mgCm^{-2}d^{-1} in deep-sea regions of the Black Sea (Vedernikov & Demidov, 1993; Bologa, 1986; Demidov, 2008). Primary production for the southern coast of the Black Sea has been estimated to be 247-

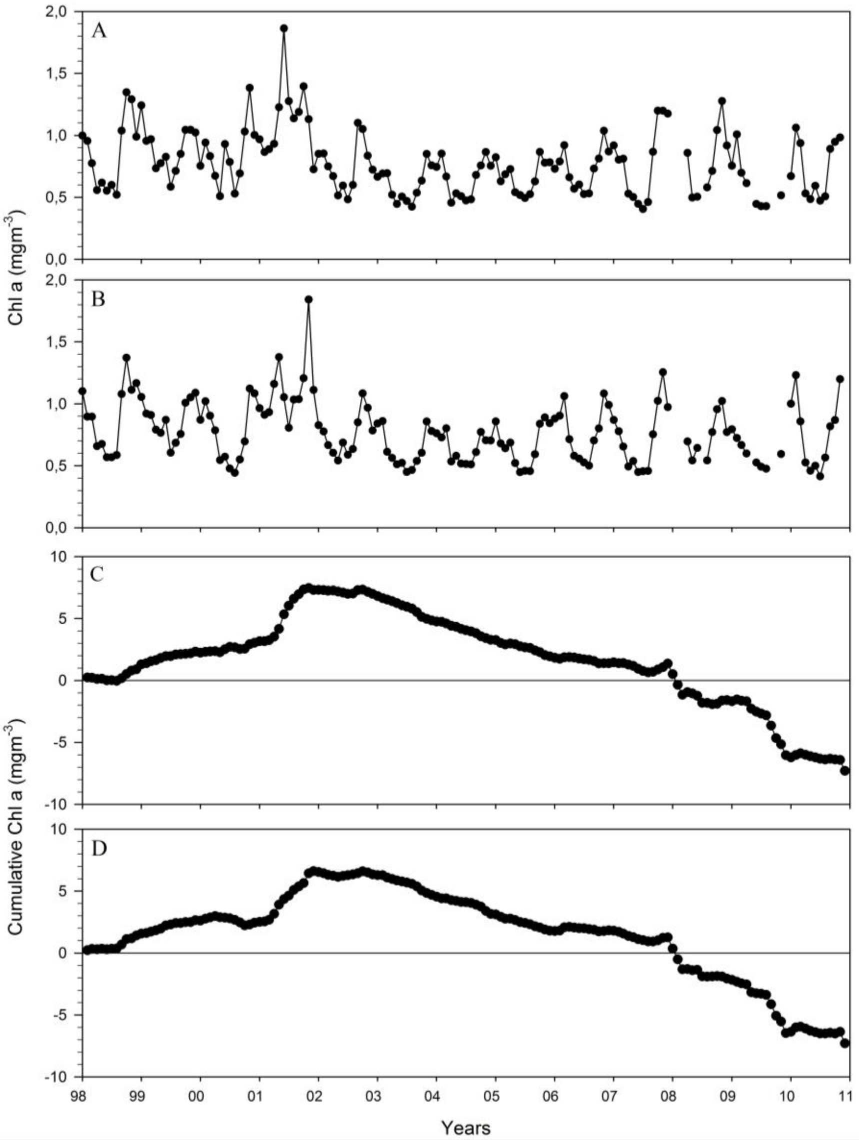

Figure 4. SeaWiFS Chlorophyll-a (Chl-a) from 1998 to 2011 for the western (A) and eastern Gyre (B) of the Black Sea and cumulative sum of the anomalies in Chl-a for the western (C) and eastern Gyre (D).

1925 mgCm^{-2}d^{-1} during spring and 405-687 mgCm^{-2}d^{-1} during summer and autumn from 1995-1996 (Yilmaz et al., 2006). The differences in PP values between coastal, shelf and deep-sea are thought to be due to the riverine discharge of nutrients (Cociasu et al., 1997).

Open ocean areas of the Black Sea experience Chl-a maxima during autumn and winter and minima during the summer (Vinogradov et al., 1999). Mean Chl-a in the open Black Sea from 1978-1991 was reported to be 0.97-1.52 mgm^{-3} during winter and 0.28–0.38 mgm^{-3} during summer (Vedernikov & Demidov, 1993). Since 1995, there has been a decrease in Chl-a in the open Black Sea, which correlated with an increase in temperature and a decrease in nutrient load (Oguz & Gilbert, 2007). The reasons for the differences between the eastern and western parts of the Black Sea are not entirely clear but may be attributed to regional differences in the physics of the Gyres and variability in the rim current at the edge of the Black Sea (Zatsepin et al., 2003; Enriquez et al., 2005).

The seasonal cycle of Chl-a, however, is not spatially uniform across the Black Sea (McQuatters-Gollop et al., 2008). In the shelf region, Chl-a minima occur during winter, when the River Danube discharge is lowest and shelf waters are well mixed and cool (McQuatters-Gollop et al., 2008). Kopelevich et al. (2002) reported marked differences in monthly mean CZCS Chl-a from 1978-1986 between western shelf regions and the open Black Sea. The western Gyre of the Black Sea appears to be the most stable region, with bloom events and underlying hydrodynamic conditions that persist for longer duration than either the shelf or eastern Gyre (McQuatters-Gollop et al., 2008). Using satellite data in the coastal regions of the Black Sea however can be problematic because of the high CDOM

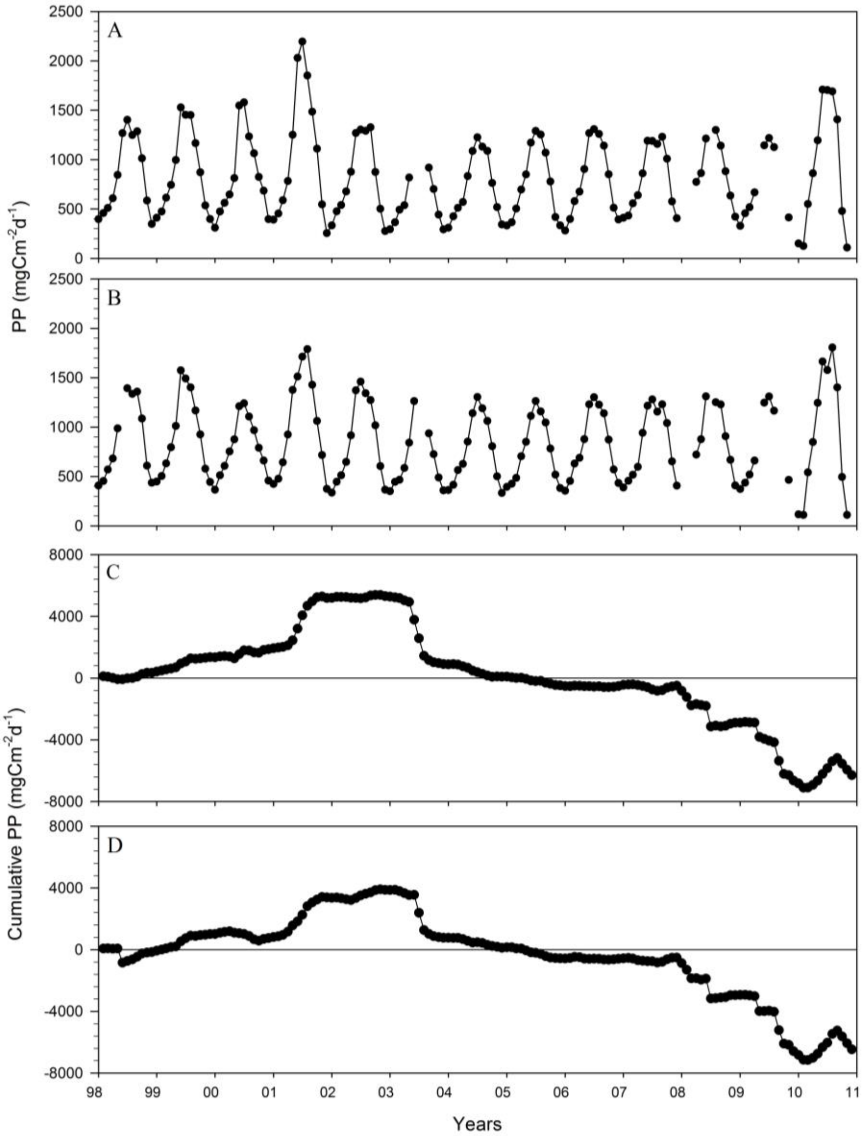

Figure 5. SeaWiFS derived Primary Production (PP) using the Wavelength Resolving Model of Smyth et al (2005) from 1998 to 2011 for the western (A) and eastern Gyre (B) of the Black Sea and cumulative sum of the anomalies in PP for the western (C) and eastern Gyre (D).

absorption, which can cause errors in Chl-a (Oguz & Ediger, 2006) and primary production estimates (Tilstone et al., 2005), which can be corrected for as long as the total suspended matter (TSM) and absorption by coloured dissolved organic material (a_{CDOM}) is known. The open Black Sea, where we extracted data from, is principally case 1 (Cokacar et al., 2004), suggesting that phytoplankton principally dominate the absorption properties. We therefore focused only on open ocean areas of the Black Sea (see Fig.1 for further details) where the errors in SeaWiFS Chl-a are likely to be small due to low or minimal TSM and a_{CDOM}. We also deployed one of the most accurate PP satellite models based on recent NASA inter-comparisons (Carr et al. 2006; Saba et al. 2011).

There are two maxima in PP along the Black Sea; highest values occur in early spring with a secondary peak in autumn (Sorokin, 1983; Vedernikov & Demidov, 1993). Recently, additional summer blooms have been observed in both the coastal and open sea areas (Hay & Honjo, 1989; Hay et al., 1990, 1991; Sur et al., 1996). From 1998-2011, we found that primary production was higher in the western Gyre compared to the eastern Gyre as a result of contrasting wind regimes. This could be because atmospheric events that deepen the surface mixed layer in the western Black Sea, that supply nutrients to the photic zone from below the upper boundary of the Cold Intermediate Layer (CIL), are more persistent and lead to blooms of longer duration (Yunev et al., 2005; Oguz & Ediger, 2006). By comparison, blooms in the eastern Gyre are considerably shorter and can decrease rapidly (McQuatters-Gollop et al., 2008). The spatial variability in PP throughout the Black Sea is

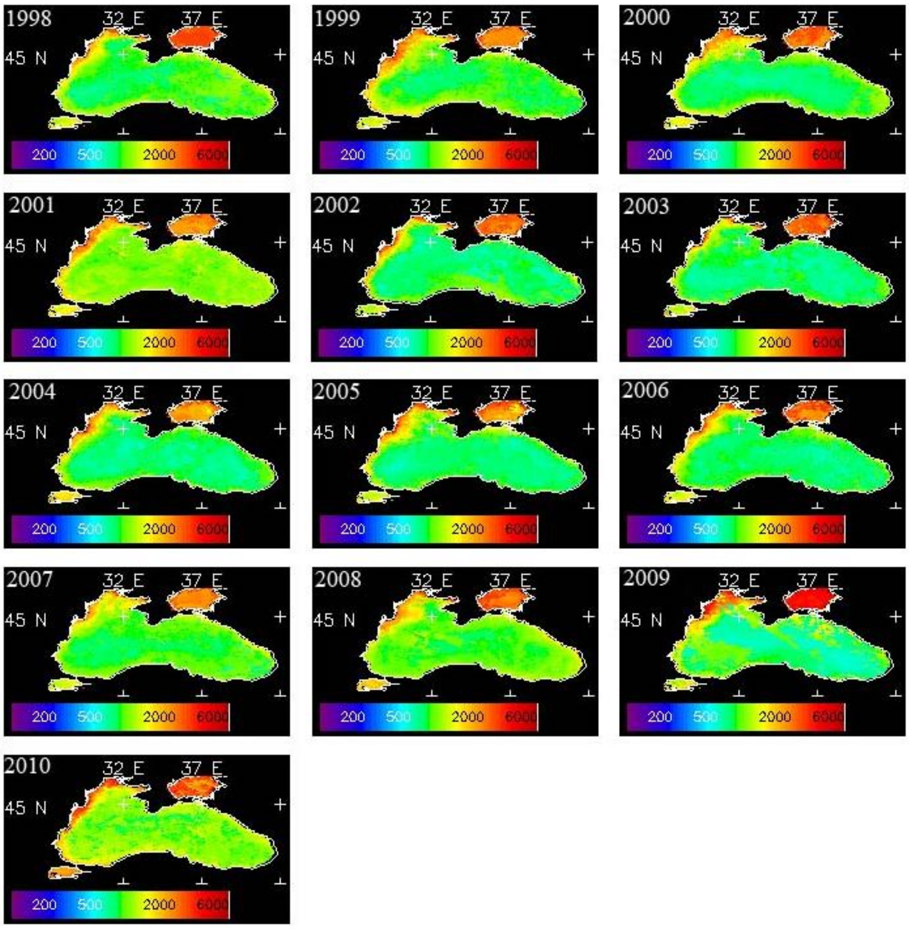

Figure 6. Maps of mean annual primary production (mgCm^{-2}d^{-1}) derived from the Wavelength Resolving Model (WRM) of Smyth et al (2005) from 1998 to 2011 for the Black Sea.

determined by the cyclonic boundary Rim current and frontal jet instabilities between the Rim current and the interior eddy fields (Yilmaz et al., 1998). The rim current forms a biogeochemical barrier between coastal and offshore waters (Oguz et al., 1994). The formation of the Batumi anti-cyclone, which occurs as warm core rings during summer (Oguz et al., 1993), may also lead to a decrease in PP and a decline in fish stocks in the eastern Gyre. The anchovy fishery is important for both the economy and as a food for the Turkish inhabitants of the Black Sea coastal regions (Kideys, 1994). Our data suggest that subtle changes in the wind regime of the Black Sea region can impact the PP, which may in turn potentially affect the fishery. Years with high wind speeds in winter, followed by a relaxation of the wind speeds in spring and autumn, potentially lead to higher PP and theoretically, to a higher fish catch. No studies however have been conducted so far on the validation of satellite algorithms for PP in the Black Sea. Further work is required in this direction.

Recent Changes in PP and Chl-a in the Black Sea

The Black Sea has experienced severe ecological destruction over the past three decades. Persistent eutrophication over the past few decades drastically altered the phytoplankton community structure in the region (Kideys, 1994; Uysal, 1995; Feyzioglu & Seyhan, 2007; Bat et al., 2011; Mikaelyan et al., 2013). Global atmospheric changes after 1980s resulted in changes in river runoff, salinity, sea and air temperature, atmospheric pressure, precipitation and the strength of westerly winds throughout the northern hemisphere (Ozsoy & Unluata, 1997; Niermann et al., 1999). The reasons for the change in phytoplankton community structure during the end of the 1980s and the beginning of the 1990s are still under discussion (Yunev et al., 2002). In recent years however, the Black Sea has shown some signs of recovery, attributed to a reduction in nutrient loading (McQuatter-Gollop et al., 2008).

Winter SST in the interior basin of the Black Sea has exhibited considerable fluctuation over the last century, with a rise of 0.25 ^{0}C, except from 1980-2000 (Oguz et al., 2006). The highest increase in temperature was from 1998. Over the past two decades there has also been paralleled changes in Chl-a in the open sea and shelf areas of the Black Sea (Yunev et al., 2002). Our data suggest that over the past decade that there has been a decline in PP from 2004 to 2010, in both the eastern and western Gyres,

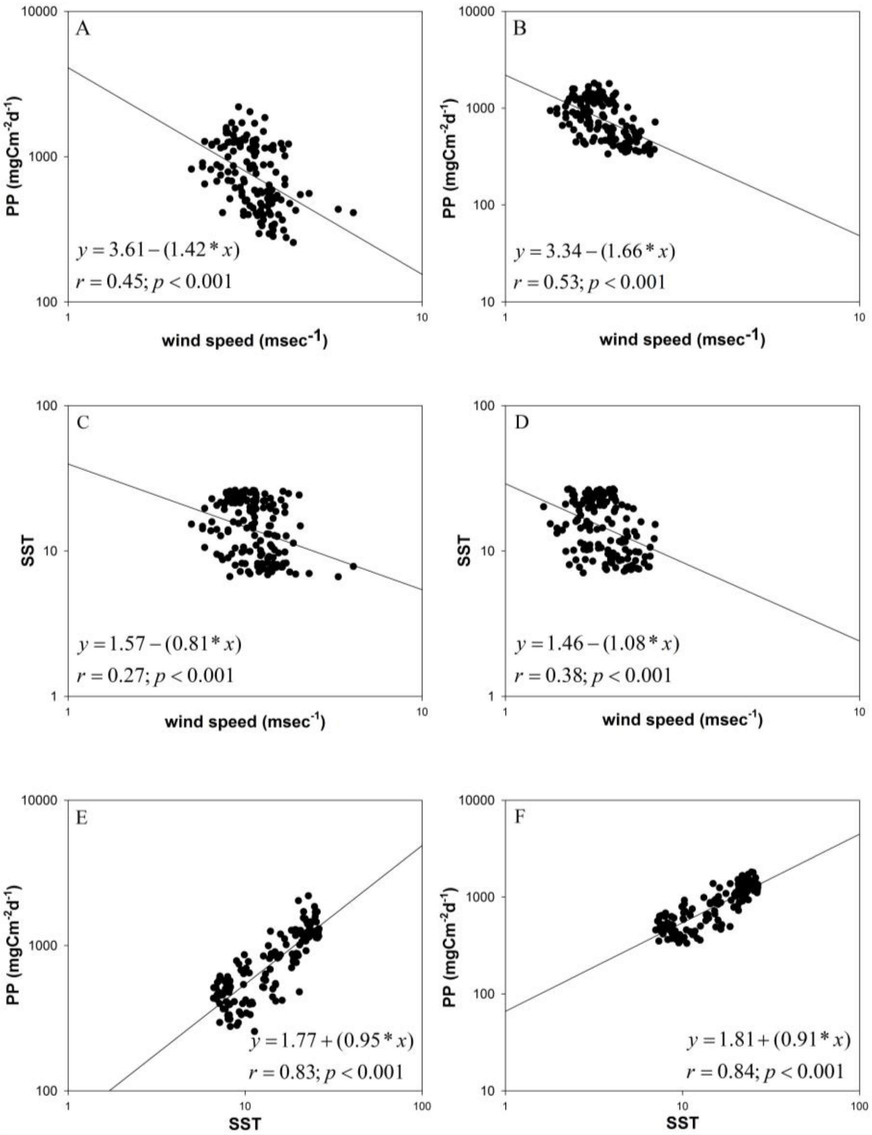

Figure 7. Linear regression between PP and wind speed (A), wind speed and SST (C) and PP and SST (E) for the western Gyre and PP and wind speed (B), wind speed and SST (D) and PP and SST (F) for the eastern Gyre of the Black Sea.

which was linked to changes in the wind regime. Similarly, earlier studies conducted during the end of 1980s and beginning of 1990s in the Black Sea reported prolonged spring & summer blooms due to higher wind speeds and lower temperatures during winter, which lead to greater vertical mixing and upwelling (Oguz, 2005). By contrast, McQuatter-Gollop et al. (2008) reported no significant correlation between SST or wind stress and annual mean Chl-a concentrations or annual Chl-a anomalies in the Gyres and shelf regions of the Black Sea. This could be due to non-linear relationships between phytoplankton biomass and environmental conditions, indicating that parameters other than SST such as nutrient input and water column stability may have a greater regulatory effect on Chl-a (McQuatter-Gollop et al., 2008). They did observe that warm, stratified conditions resulting from low wind stress altered the timing and magnitude of phytoplankton blooms in the Black Sea (McQuatter-Gollop et al., 2008). Future research should investigate the nutrient regimes of the open ocean western and eastern Gyres in spring and autumn in relation to winter and summer wind regimes.

Our analysis of SeaWiFS data from 1998 to 2003 showed that wind speeds decreased and PP increased, especially in the western Gyre. A decrease in global PP from 1998 to 2006 has been reported due to an increase in global SST as a result of the shift in ENSO index (Behrenfeld et al., 2006). We also observed a strong negative correlation between the mean annual cumulative sums of primary production and Multivariate ENSO Index (MEI) in both the western (Pearson rank correlation=-0.69, P=0.009; Fig. 8A) and the eastern Gyres (Pearson rank correlation=-0.73, P=0.004 Fig. 8B) of the Black Sea.

The mean annual cumulative sum of the anomalies in PP were also negatively correlated with

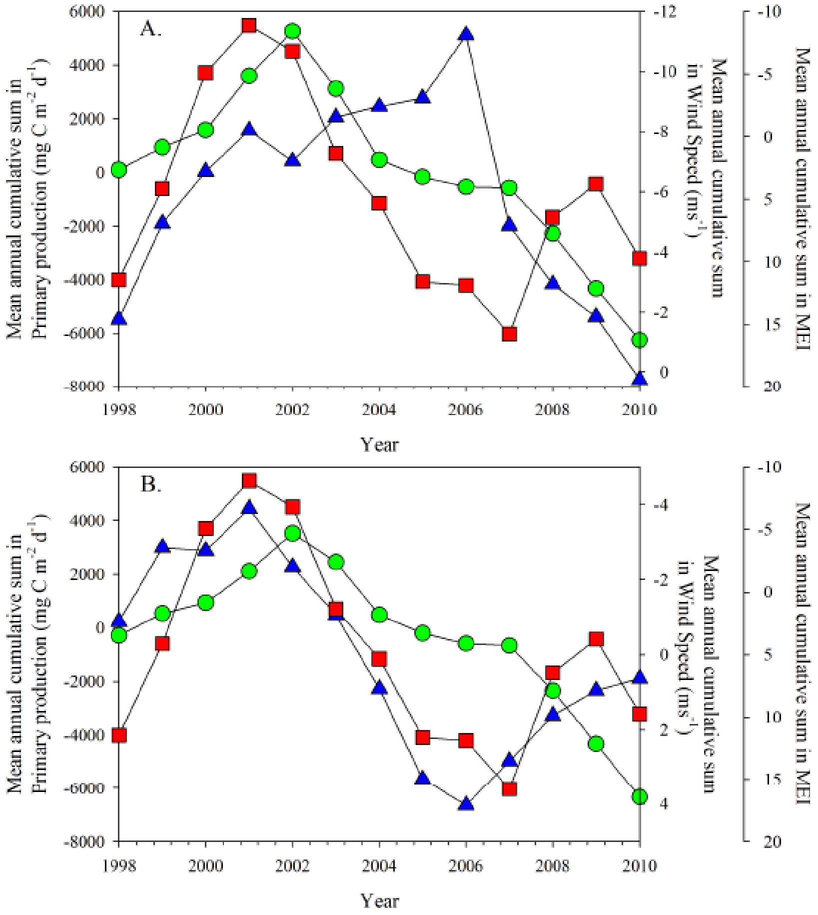

Figure 8. Mean annual cumulative sums in primary production, wind speed and Multivariate ENSO index for the western (A) and eastern (B) Gyres. Primary production is green circles, Multivariate ENSO index is red squares and wind speed is blue triangles (note reversal of range for MEI and wind speed).

the mean annual cumulative sum of the anomalies in wind speed in both the western (Pearson rank correlation=-0.58, P=0.038; Fig. 8A) and eastern (Pearson rank correlation=-0.69, P=0.009; Fig. 8B) Gyres. The mean annual cumulative sums of wind speed were highly correlated with MEI in the eastern Gyre (Pearson rank correlation=0.82, P<0.001; Fig. 8B), but uncorrelated with wind speed in the western Gyre (Pearson rank correlation=0.21, P=0.49; Fig. 8A). This suggests that strong la Niña (negative MEI) from 1998-2003 and 2009-2010 caused an increase in PP which affected patterns in PP more in the eastern Gyre, and that el Niño (positive MEI) from 2004-2008, caused a decrease in PP. MEI affects the wind regime more in the eastern Gyre than in the western Gyre. The data suggest that localised wind regimes affect PP in the western gyre, than the effects of MEI. This decoupling of the annual winds in the western Gyre from fluctuations in MEI, sustains a higher PP. Behrenfeld et al. (2001) also reported that increases in PP were pronounced in tropical regions where ENSO impacts upwelling and nutrient availability. By contrast, globally terrestrial PP did not exhibit a clear ENSO response, although regional effects do occur (Behrenfeld et al., 2001). Global changes in ocean circulation, the physical and chemical structure, and phytoplankton depth distribution and production, appear to be coupled to both local meteorological forcing and changes in ENSO (Mackey et al., 1997; Behrenfeld et al., 2006). For example, Boyce et al. (2010) found that yearly Chl-a anomalies were strongly negatively correlated with the bivariate ENSO index in the Equatorial Pacific. Positive ENSO phases are associated with warming SST, increased stratification and a deeper nutricline, leading to negative Chl-a anomalies in the Equatorial Pacific (Behrenfeld et al., 2006; Martinez et al., 2009).

Enclosed seas have undergone more dramatic changes in physics and biology than the open ocean over recent decades. For example, changes in the frequency of inflow have occurred in the Baltic Sea (Matthäus & Frank, 1992; Matthäus, 2006) and higher increases in temperature in the eastern Mediterranean and Black Sea have occurred compared to the neighbouring Atlantic Ocean (Danovaro et al., 2001; Oguz et al., 2006). Enclosed seas therefore potentially have a greater sensitivity to changing environmental effects than the open ocean (Anadon et al., 2007). Our analysis suggests that the western Gyre is more sensitive to shifts in wind and temperature regimes than the eastern Gyre. Recent decadal shifts in these parameters have caused a greater increase in PP in the western than eastern Gyre.

The analysis we present, only illustrates oscillations over a decade, which is too short to assess climate-induced effects on phytoplankton and the resulting productivity. This short term analysis, however indicates that the western Gyre is more productive than the eastern Gyre, due to a stronger wind regime, which when it relaxes, sustains a higher productivity. This is possibly due to nutrients being available for longer time due to deeper mixing in the western Gyre compared to the eastern Gyre. Further studies to elucidate the physico-chemical forcing on phytoplankton between Gyres are required. The variations in PP in both Gyres are coupled to fluctuations in the ENSO, but this affects the annual wind regime in the eastern Gyre more than in the western Gyre. Ecosystem properties have been found to oscillate quasi-synchronously ranging from inter-annual (~1 to 5 years) to decadal (10 to 12 years) and inter-decadal (~20 to 30 years) periods (Daskalov, 2003). Longer-term analyses of PP are required to establish the reasons for the shift in wind regimes in the Black Sea and knock on effects through the ecosystem, which may be linked to the short term recovery of the fish stocks (Oguz et al., 2012).

Conclusions

Decadal satellite data from 1998 to 2011 showed that the western Black Sea Gyre has a higher primary production than the eastern Gyre. The differences in PP are caused by higher wind speeds in the western Gyre, which during wind relaxation, sustain a higher productivity. Both Gyres exhibited an increase in PP from 1998 to 2004 followed by a decrease from 2004 to 2011, which was greater in the western compared to the eastern Gyre. Variability in annual PP in both Gyres was coupled to fluctuations in the MEI, which affects the eastern more than the western gyre. Variation in PP in the western gyre is enhanced by localised wind regimes that are uncoupled from MEI.

Acknowledgements

We would like to thank the Turkish Meteorological Office for the providing wind speed data. We also thank the Higher Educational Council of TURKEY for providing E. Agirbas with a grant to visit Plymouth Marine Laboratory-UK. G. Tilstone was supported by the European Space Agency (ESA) project COASTCOLOUR (Contract No. 22807/09/I-AM). All SeaWiFS MLAC and GAC products were kindly provided by the NASA GES DAAC. AVHRR SST Pathfinder data were provided courtesy of NOAA. NERC Earth Observation Data Archive and Analysis Service, UK (NEODAAS) provided computing facilities and data storage.

References

Agirbas, E., Seyhan, K., Kasapoglu, N., Feyzioglu, A.M., Ustundag, E., & Eruz, C. (2010). Recent changes of the Turkish anchovy fishery in the Black Sea with special reference to climate change. *Journal of Environmental Protection and Ecology*, 11 (4), 1495–1503-v11_4_1503

Anadon, R., Danovaro, R., Dippner, J.W., Drinkwater, K.F., Hawkins, S.J., O'Sullivan, G., & Oguz, T. (2005). Marine Board Position, Paper 9.

Behrenfeld, M.J., Randerson, J.T., McClain, C.R., Feldman, G.C., Los, S.O., Tucker, C.J., Falkowski, P.G., Field, C.B.,Frouin, R., Esaias, W.E.,Kolber, D.D., & Pollack, N.H. (2001). Biospheric primary production during an ENSO Transition. *Science,* 29, 2594-2597. https://dx.doi.org/10.1126/science.1055071-v29_2597

Behrenfeld, M.J., O'Malley, R.T., Siegel, D.A., McClain, C.R., Sarmiento, J.L., Feldman, G.C., Milligan, A.J., Falkowski, P.G., Letelier, R.M., & Boss, E.S. (2006). Climate-driven trends in contemporary ocean productivity. *Nature,* 444, 752–755. https://dx.doi.org/10.1038/nature05317-v444_755

Bodeanu, N. (2002). Algal blooms in Romanian Black Sea waters in the last two decades of the 20th century. *Cercatari Marine*, 34, 7–22-v34_22

Bodeanu, N., Andrei, C., Boicenco, L., Popa, L., & Sburlea, A. (2004). A new trend of the phytoplankton structure and dynamics in the Romanian marine waters. *Cercetari Marine*, 35, 77–86-v35_86

Bologa, A.S., Frangopol, P.T., Vedernikov, V.I., Stelmakh, L.V., Yunev, O.A., Yilmaz, A., & Oguz, T. (1999). Distribution of planktonic primary production in the Black Sea. In: Besiktepe, S.T., Unluata, U., Bologa, A.S., (eds) NATO TU-Black Sea Project: environmental degradation of the Black Sea: challenges and remedies. Kluwer Academic Publishers, Dordrecht, pp 131–145.

Bologa, A.S. (1986). Planktonic Primary Productivity of the Black Sea: A Review. *Thalassia Jugoslavica*, 21-22, 1-22-v21_22

Boyce, D.G., Lewis, M.R., & Worm, B. (2010). Global phytoplankton decline over the past century. *Nature*, 466 (7306), 591-596. DOI:10.1038/nature09268-v466_7306_596

Carr, M.E., Friedrichs, M.A.M., Schmeltz, M., Aita, M.N., Antoine, D., Arrigo, K.R., Asanuma, I., Aumont, O., Barber, R., Behrenfeld, M., Bidigare, R., Buitenhuis, E.T., Campbell, J., Ciotti, A., Dierssen, H., Dowell, M., Dunne, J., Esaias, W., Gentili, B., Gregg, W., Groom, S., Hoepffner, N., Ishizaka, J., Kameda, T., Le Quere, C., Lohrenz, S., Marra, J., Melin, F., Moore, K., Morel, A., Reddy, T.E., Ryan, J., Scardi, M., Smyth, T., Turpie, K., Tilstone, G., Waters, K., & Yamanaka, Y. (2006). A comparison of global estimates of marine primary production from ocean color. *Deep-Sea Research II*, 53, 741–770. DOI:10.1016/j.dsr2.2006.01.028-v53_770

Cokacar, T., Oguz, T., & Kubilay, N. (2004). Satellite-detected early summer coccolithophore blooms and their interannual variability in the Black Sea. *Deep-Sea Research I,* 51, 1017-1031. DOI:10.1016/j.dsr.2004.03.007-v51_1031

Danovaro, R., Dell'Anno, A., Fabiano, M., Pusceddu, A., & Tselepides, A. (2001). Deep-sea ecosystem response to climate changes: the eastern Mediterranean case study. *TREE*, 16, 505-510. DOI:10.1016/S0169-5347(01)02215-7-v16_510

Daskalov, G.M. (2002). Over fishing drives a trophic cascade in the Black Sea. *Marine Ecology Progress Series*, 225, 53-63. https://dx.doi.org/10.3354/meps225053-v225_63

Daskalov, G.M. (2003). Long-term changes in fish abundance and environmental indices in the Black Sea. *Marine Ecology Progress Series*, 255, 259-270. https://dx.doi.org/10.3354/meps255259-v225_270

Demidov, A.B. (2008). Seasonal dynamics and estimation of the annual primary production of phytoplankton in the Black Sea. *Oceanology*, 5 (48), 664–678-v5_48_678

Demidov, A.B. (1999). Spatial and temporal variability of chlorophyll 'a' in the Black Sea in the winter-spring period. *Oceanology*, 39, 688–700 (English translation)-v39_700

Doney, S.C. (2006). Plankton in a warmer world, *Nature*, 444, 695-696. https://dx.doi.org/10.1038/444695a-v444_696

Enriquez, C.E., Shapiro, G.I., Souza, A.J., & Zatsepin, A.G. (2005). Hydrodynamic modelling of mesoscale eddies in the Black Sea. *Ocean Dynamics*, 55 (5–6), 476–489. https://dx.doi.org/10.1007/s10236-005-0031-4-v55_5-6_489

Frouin, R., & Pinker, R.T. (1995). Estimating Photosynthetically Active Radiation (PAR) at the earth's surface from satellite-observations. *Remote Sensing of Environment*, 51, 98–107. https://dx.doi.org/10.1016/0034-4257(94)00068-x-v51_107

Gregg, W.W., & Carder, K.L. (1990). A simple spectral solar irradiance model for cloudless maritime atmospheres. *Limnology and Oceanography*, 35, 1657–1675. https://dx.doi.org/10.4319/lo.1990.35.8.1657-v35_1675

Gucu, A.C. (2002). Can overfishing be responsible for the successful establishment of Mnemiopsis leidyi in the Black Sea? Estuarine, *Coastal and Shelf Science*, 54, 439-451. https://dx.doi.org/10.1006/ecss.2000.0657-v54_451

Hansen, J., Sato, M., Ruedy, R., Lo, K., Lea, D.W., & Medina-Elizade, M. (2006). Global temperature change. *PNAS*, 26, 14288-14293. https://dx.doi.org/10.1073/pnas.0606291103-v26_14293

Henson, S.A., Sarmiento, J.L., Dunne, J.P., Bopp, L., Lima, I., Doney, S.C., John, J., & Beaulieu, C. (2010). Detection of anthropogenic climate change in satellite records of ocean chlorophyll and productivity. *Biogeosciences*, 7, 621–640. https://dx.doi.org/10.5194/bg-7-621-2010, 2010-v7_640

Hays, G.C., Richardson, A.J., & Robinson, C. (2005). Climate change and marine plankton. *Trends in Ecology and Evolution*, 20, 337–344. https://dx.doi.org/10.1016/j.tree.2005.03.004-v20_344

Head, E.J.H., & Pepin, P. (2010). Monitoring changes in phytoplankton abundance and composition in the Northwest Atlantic: a comparison of results obtained by continuous plankton recorder sampling and colour satellite imagery, *Journal of Plankton Research*, 32, 1649-1660. https://dx.doi.org/10.1093/plankt/fbq120-v32_1660

IPCC, (2007). Climate Change 2007-The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the IPCC., 996 pp.

Kideys, A.E. (1994). Recent Dramatic Changes in the Black Sea Ecosystem: The Reason for the Sharp Decline in Turkish Anchovy Fisheries. *Journal of Marine Systems*, 5, 171-181. https://dx.doi.org/10.1016/0924-7963(94)90030-2-v5_181

Kideys, A.E., & Romanova, Z. (2001). Distribution of gelatinous macrozooplankton in the southern Black Sea during 1996-1999. *Marine Biology*, 139, 535-547. https://dx.doi.org/10.1007/s002270100602-v139_547

Kideys, A.E. (2002). Fall and Rise of the Black Sea Ecosystem. *Science*, 297, 1482-1484. https://dx.doi.org/10.1126/science.1073002-v297_1484

Kopelevich, O.V., Sheberstov, S.V., Yunev, O., Basturk, O., Finenko, Z.Z., Nikonov, S., & Vedernikov, V.I. (2002). Surface chlorophyll in the Black Sea over 1978–1986 derived from satellite and in situ data. *Journal of Marine Systems*, 36, 145-160. https://dx.doi.org/10.1126/science.1073002-v36_160

Krupatkina, D.K., Yunev, O.A., & Zhorov, S.V. (1990). Primary production, chlorophyll and size structure of the Black Sea phytoplankton in the winter and early spring. *Ekol Morya*, 36, 87–91 (in Russian)-v36_91

Krupatkina, D.K., Finenko, Z.Z., & Shalapyonok, A.A. (1991). Primary production and size-fractionated structure of the Black Sea phytoplankton in the winter-spring period. *Marine Ecology Progress Series*, 73, 25–31-v73_31

Mackey, D.J., Parslow, J.S., Griffith, F.B., Higgins, H.W., & Tilbrook, B. (1997). Phytoplankton productivity and the carbon cycle in the western Equatorial Pacific under El Nino and non-El Nino conditions. *Deep Sea Research II*, 44, 1951-1978. https://dx.doi.org/10.1016/S0967-0645(97)00033-7-v44_1978

Martinez, E., Antoine, D., D'Ortenzio, F., & Gentili, B. (2009). Climate-driven basin-scale decadal oscillations of oceanic phytoplankton. *Science*, 326, 1253–1256. https://dx.doi.org/10.1126/science.1177012-v326_1253

Matthäus, W., & Frank, H. (1992). Characteristics of major Baltic inflows – a statistical analysis. *Continental Shelf Research*, 12, 1375-1400. https://dx.doi.org/10.1016/0278-4343(92)90060-W-v12_1400

Matthäus, W. (2006). The history of investigation of salt water inflow into the Baltic Sea – from the early beginning to the recent results. Marine Science Reports, No. 65, Baltic Sea Research Institute Warnemünde, 81 pp.

McQuatters-Gollop, A., Mee, L.D., Raitsos, D. E., & Shapiro, G.I. (2008). Non-linearities, regime shifts and recovery: The recent influence of climate on Black Sea chlorophyll. *Journal of Marine Systems*, 74, 649-658. https://dx.doi.org/10.1016/j.jmarsys.2008.06.002-v74_658

Mee, L.D. (1992). The Black Sea in crisis: The need for concerted international action. *Ambio*, 21, 278 – 286-v21_278

Mee, L.D. (2006). Reviving dead zones. *Scientific American*, 295 (5), 54–61-v295_5_61

Mikaelyan, A.S., Zatsepin, A.G., & Chasovnikov, V.K. (2013). Long-term changes in nutrient supply of phytoplankton growth in the Black Sea. *Journal of Marine Systems*, 117-118, 53-64. https://dx.doi.org/10.1016/j.jmarsys.2013.02.012-

v117-118_64

Morel, A. (1988). Optical modelling of the upper ocean in relation to its biogenous matter content (Case I waters). *Journal of Geophysical Research-Oceans,* 93, 749-768. https://dx.doi.org/10.1029/JC093iC09p10749-v93_768

Morel, A., & Berthon, J.F. (1989). Surface pigments, algal biomass profiles, and potential production of the euphotic layer-relationships reinvestigated in view of remote-sensing applications. *Limnology and Oceanography*, 34, 1545–1562. https://dx.doi.org/10.4319/lo.1989.34.8.1545-v34_1562

Morel, A. (1991). Light and marine photosynthesis-a spectral model with geochemical and climatological implications. *Progress in Oceanography*, 26, 263–306. https://dx.doi.org/10.1016/0079-6611(91)90004-6-v26_306

Morel, A., Antoine, D., Babin, M., & Dandonneau, Y. (1996). Measured and modelled primary production in the northeast Atlantic (EUMELI JGOFS program): the impact of natural variations in photosynthetic parameters on model predictive skill. *Deep-Sea Research I,* 43, 1273–1304. https://dx.doi.org/10.1016/0967-0637(96)00059-3-v43_1304

Niermann, U., Kideys, A.E., Kovalev, A.V., Melnikov, V., & Belokopytov, V. (1999). Fluctuations of pelagic species of the open Black Sea during 1980–1995 and possible teleconnections. In: Besiktepe ST, Unluata U, Bologa AS (eds) NATO TU-Black Sea Project: environmental degradation of the Black Sea: challenges and remedies. Kluwer Academic Publishers, Dordrecht, pp 147–173.

Oguz, T., Latun, V.S., Latif, M.A., Vladimirov, V.V., Sur, H.I., Markov, A.A., Ozsoy, E., Kotovshchikov, V.V., Eremeev, V.V., & Unluata, U. (1993). Circulation in the surface and intermediate layers of the Black Sea. *Deep-Sea Research I,* 40, 1597-1612. https://dx.doi.org/10.1016/0967-0637(93)90018-X-v40_1612

Oguz, T., Aubrey, D.G., Latun, V.S., Demirov, E., Koveshnikov, L., Sur, H.I., Diaconu, V., Besiktepe, S., Duman, M., Limeburner, L., & Ermeev, V. (1994). Mesoscale circulation and thermohaline structure of the Black Sea observed during HytdroBlack'91.soscale circulation. *Deep-Sea Research I,* 41 (4), 603-628. https://dx.doi.org/10.1016/0967-0637(94)90045-0-v41_4_628

Oguz, T. (2005). Black Sea Ecosystem response to climatic teleconnections. *Oceanography,* 18 (2), 122-133. https://dx.doi.org/10.5670/oceanog.2005.47-v18_2_133

Oguz, T., & Ediger, D. (2006). Comparison of in-situ and satellite-derived chlorophyll pigment concentrations and impact of phytoplankton bloom on the sub-oxic layer structure in the western Black Sea during May-June 2001. *Deep Sea Research Part II: Topical Studies in Oceanography,* 53 (17-19), 1923-1933. https://dx.doi.org/10.1016/j.dsr2.2006.07.001-v53_17-19_1933

Oguz, T., Dippner, J.W., & Kaymaz, Z. (2006). Climatic regulation of the Black Sea hydro-meteorological and ecological properties at interannual-to-decadal time scales. *Journal of Marine Systems,* 60, 235-254. https://dx.doi.org/10.1016/j.jmarsys.2005.11.011-v60_254

Oguz, T., & Gilbert, D. (2007). Abrupt transitions of the top-down controlled Black Sea pelagic ecosystem during 1960–2000: evidence for regime-shifts under strong fishery exploitation and nutrient enrichment modulated by climate-induced variations. *Deep-Sea Research I*, 54, 220–242. https://dx.doi.org/10.1016/j.dsr.2006.09.010-v54_242

Oguz, T., Velikova, V., Cociasu, A., & Korchenko, A. (2008). State of the Environment Report 2001-2006/7, the State of Eutrophication, pp 83-112.

Oguz, T., Akoglu, E., & Salihoglu, B. (2012). Current state of overfishing and its regional differences in the Black Sea. *Ocean and Coastal Managment*, 58, 47-56. https://dx.doi.org/10.1016/j.ocecoaman.2011.12.013-v58_56

Ozsoy, E., & Unluata, U. (1997). Oceanography of the Black Sea. A review of some recent results. *Earth-Science Reviews*, 42, 231–272. https://dx.doi.org/10.1016/S0012-8252(97)81859-4-v42_272

Prodanov, K., Mikhaylov, K., Daskalov, G., Maxim, K., Ozdamar, E., Shlyakhov, V., Chashcin, A., & Arkhipov, A. (1997). Environmental management of fish resources in the Black Sea and their rational exploitation. General Fisheries Council of the Mediterranean Studies and Reviews 68, 1-178.

Rykaczewski, R.R., & Dunne, J.P. (2011). A measured look at ocean chlorophyll trends. *Nature*, 472 (7342), E5-E6. https://dx.doi.org/10.1038/nature09952-v472_7342_E6

Saba, V.S., Friedrichs, M.A.M., Antoine, D., Armstrong, R.A., Asanuma, I., Behrenfeld, M.J., Ciotti, A.M., Dowell, M., Hoepffner, N., Hyde,K.J.W., Ishizaka,J., Kameda,T., Marra, J., Mélin, F., Morel, A., O'Reilly, J., Scardi, M., SmithJr., W.O., Smyth, T.J., Tang, S., Uitz, J., Waters, K., & Westberry, T.K. (2011). An evaluation of ocean color model estimates of marine primary productivity in coastal and pelagic regions across the globe. *Biogeosciences*, 8, 489–503. https://dx.doi.org/10.5194/bg-8-489-2011, 2011-v8_503

Shiganova, T.A. (1998). Invasion of the Black Sea by the ctenophore Mnemiopsis leidyi and recent changes in pelagic community structure. *Fisheries Oceanography,* 7, 305-310. https://dx.doi.org/10.1046/j.1365-2419.1998.00080.x-v7_310

Smyth, T.J., Tilstone, G.H., & Groom, S.B. (2005). Integration of radiative transfer into satellite models of ocean primary production. *Journal of Geophysical Research-Oceans,* 110, (C10). https://dx.doi.org/10.1029/2004JC002784-v110_C10

Sorokin, Yu I. (1983). The Black Sea. In: Ketchum BH (ed) Estuaries and enclosed sea ecosystem of the world, Vol 26. Elsevier, Amsterdam, pp 253–292.

Sorokin, Yu I. (2002). The Black Sea: ecology and oceanography. Biology of Inland Waters. Backhuys, Leiden, the Netherlands. 875 pp.

Tilstone, G.H., Smyth, T.J., Gowen, R.J., Martinez-Vicente, V., & Groom, S.B. (2005). Inherent optical properties of the Irish Sea and their effect on satellite primary production algorithms. *Journal of Plankton Research*, 27, 1127-1148. https://dx.doi.org/10.1093/plankt/fbi075-v27_1148

Tilstone, G.H., Smyth, T.J., Poulton, A., & Hutson, R.

(2009). Measured and remotely sensed estimates of primary production in the Atlantic Ocean from 1998 to 2005. *Deep Sea Research II*, 56, 918-930. https://dx.doi.org/10.1016/j.dsr2.2008.10.034-v56_930

Tolmazin, D. (1985). Changing coastal oceanography of the Black Sea, I: Northwestern shelf. *Progress in Oceanography*, 15, 217-276. https://dx.doi.org/10.1016/0079-6611(85)90038-2-v15_276

Uysal, Z., & Sur, H.I. (1995). Net phytoplankton discriminating patches along the Southern Black Sea Coast in winter 1990. *Oceanoligica Acta*, 18(6), 639-647-v18_6_647

Vedernikov, V.I., Konovalov, B.V., & Koblents-Mishke, O.I. (1980). Peculiarities of primary production and chlorophyll distribution in the Black Sea in autumn 1978. In: Vinogradov ME (ed) The Black Sea pelagial ecosystem. Nauka, Moscow, pp 105–117 (in Russian).

Vedernikov, V.I., Konovalov, B.V., & Koblents-Mishke, O.I. (1983). Seasonal variations of phytoplankton pigments in the near-shore waters of the northeastern Black Sea. In: Sorokin YuI, Vedernikov VI (eds) Seasonal variations of the Black Sea plankton. Nauka, Moscow, pp 66–84 (in Russian).

Vedernikov, V.I., & Demidov, A.B. (1993). Primary production and chlorophyll in the deep regions of the Black Sea. *Oceanology*, 33, 229-235. https://dx.doi.org/10.1134/S0001437008050068-v33_235

Vinogradov, M., Shushkina, E., Mikaelyan, A., & Nezlin, N.P. (1999). Temporal (seasonal and interannual) changes of ecosystem of the openwaters of the Black Sea. In: S.B.e. al (Ed.), Environmental Degradation of the Black Sea: Challenges and Remedies. Kluwer Academic Publishers, pp 109–129.

Yilmaz, A., Tugrul, S., Polat, C., Ediger, D., Coban, Y., & Morkoc, E. (1998). On the Production, Elemental Composition (C, N, P) and Distribution of Photosynthetic Organic Matter in the Southern Black Sea. *Hydrobiologia*, 363, 141-156. https://dx.doi.org/10.1023/A:1003150512182-v363_156

Yilmaz, A., Coban-Yildiz, Y., & Tugrul, S. (2006). Biogeochemical cycling and multilayer production in the Black Sea. *Geophysical Research Abstracts*, Vol 8, 00541-v8_00541

Yunev, O.A. (1989). Spatial distribution of chlorophyll ‘a’ and phaeophetin ‘a’ in the western Black Sea in winter. *Oceanologia*, 29, 480–485 (in Russian)-v29_485

Yunev, O.A., Vedernikov, V.I., Basturk, O., Yilmaz, A., Kideys, A.E., Moncheva, S., & Konovalov, S.K. (2002). Long-term variations of surface chlorophyll a and primary production in the open Black Sea. *Marine Ecology Progress Series*, 230, 11–28. https://dx.doi.org/10.3354/meps230011-v230_28

Yunev, O.A., Moncheva, S., & Carstensen, J. (2005). Long-term variability of vertical chlorophyll a and nitrate profiles in the open Black Sea: eutrophication and climate change. *Marine Ecology Progress Series*, 294, 95–107. https://dx.doi.org/10.3354/meps294095-v294_107

Zaitsev, Y., & Mamaev, V. (1997). Marine biological diversity in the Black Sea: a study of change and decline. GEF Black Sea Environmental Programme. United Nations Publications, New York. 208 pp.

Zatsepin, A.G., Ginzburg, A.I., Kostianoy, A.G., Kremenetskiy, V.V., Krivosheya, V.G., Stanichny, S.V., & Poulain, P-M. (2003). Observations of Black Sea mesoscale eddies and associated horizontal mixing. *Journal of Geophysical Research*, 108 (C8) Art. No. 3246. https://dx.doi.org/10.1029/2002JC001390-v108_C8_3246