RESEARCH PAPER

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

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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 $0.2\,^{0}C$ 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.
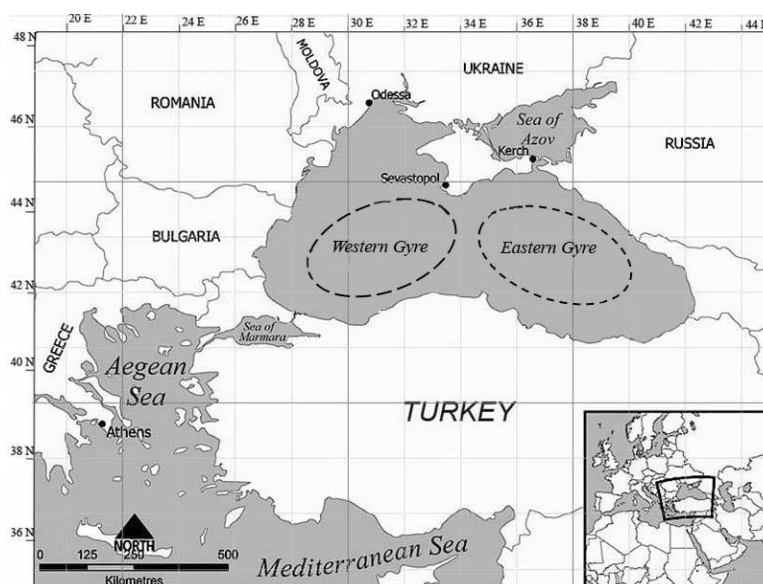

Figure 1. The Black Sea showing the western (41°N 28°E, 45°N 35°E) and eastern Gyres (41°N 35°E, 45°N, 42°E).

SeaWiFS OC4v6

Monthly composite of SeaWiFS level-3 data, with 9 km spatial resolution, from September 1997 to December April 2010, was 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:

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

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
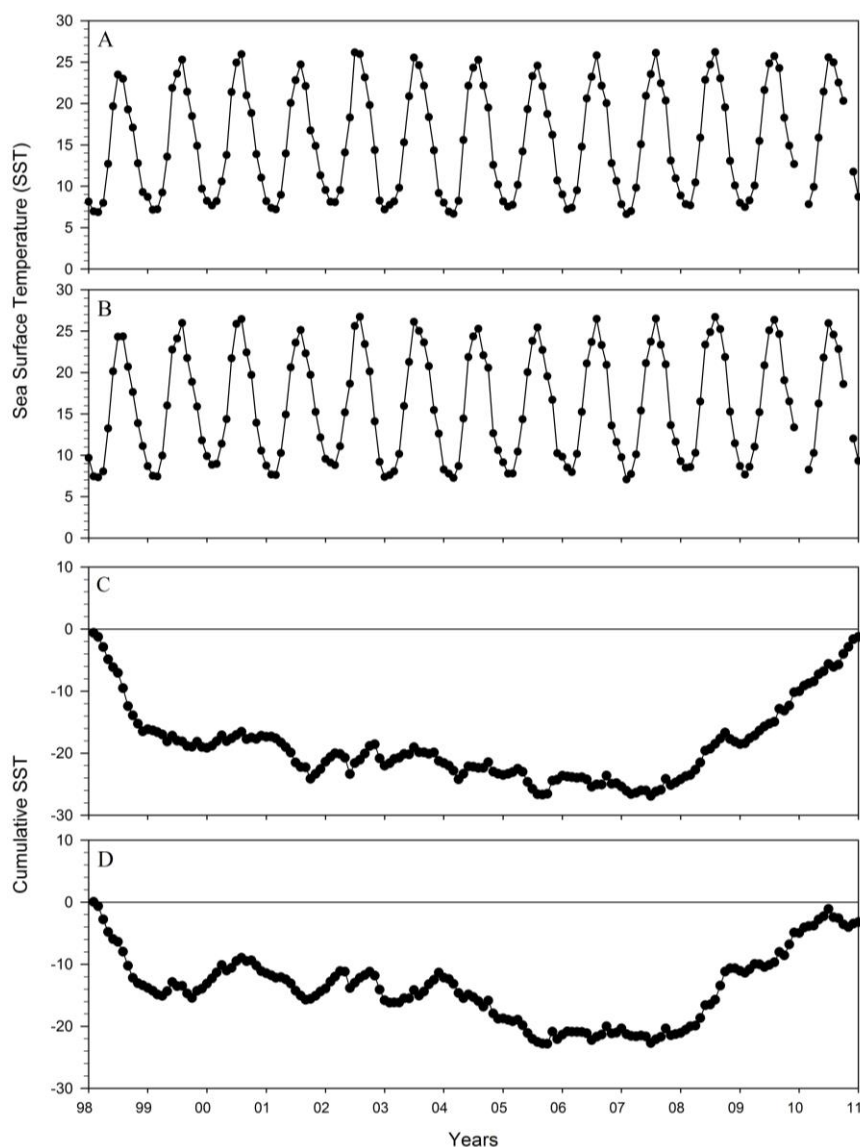
SeaWiFS Chl-a was slightly higher in the

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).

western Gyre (0.78 mg.m^{-3}) compared to the eastern 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
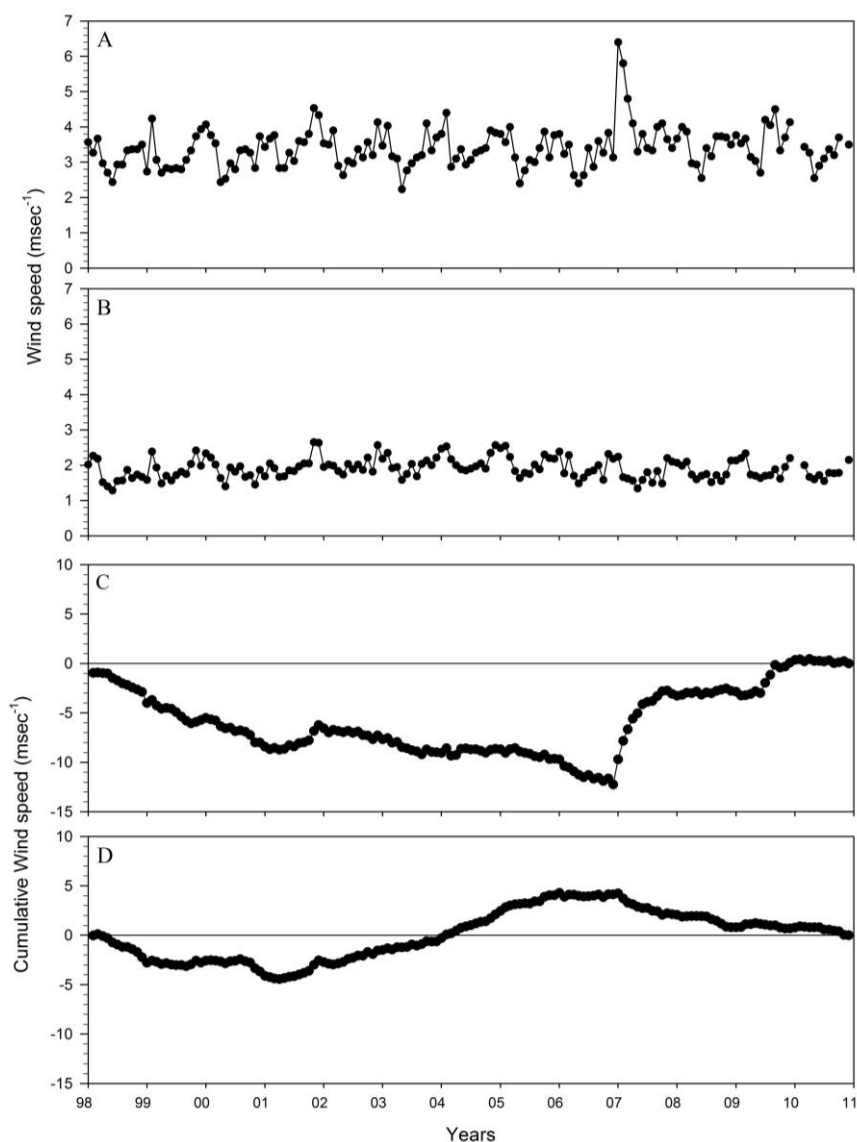
Figure 3. Wind speed data from 1998 to 2011 for the western Gyre (A) and eastern Gyre (B) of the Black Sea and cumulative sum of the anomalies in wind speed for the western (C) and eastern Gyre (D).

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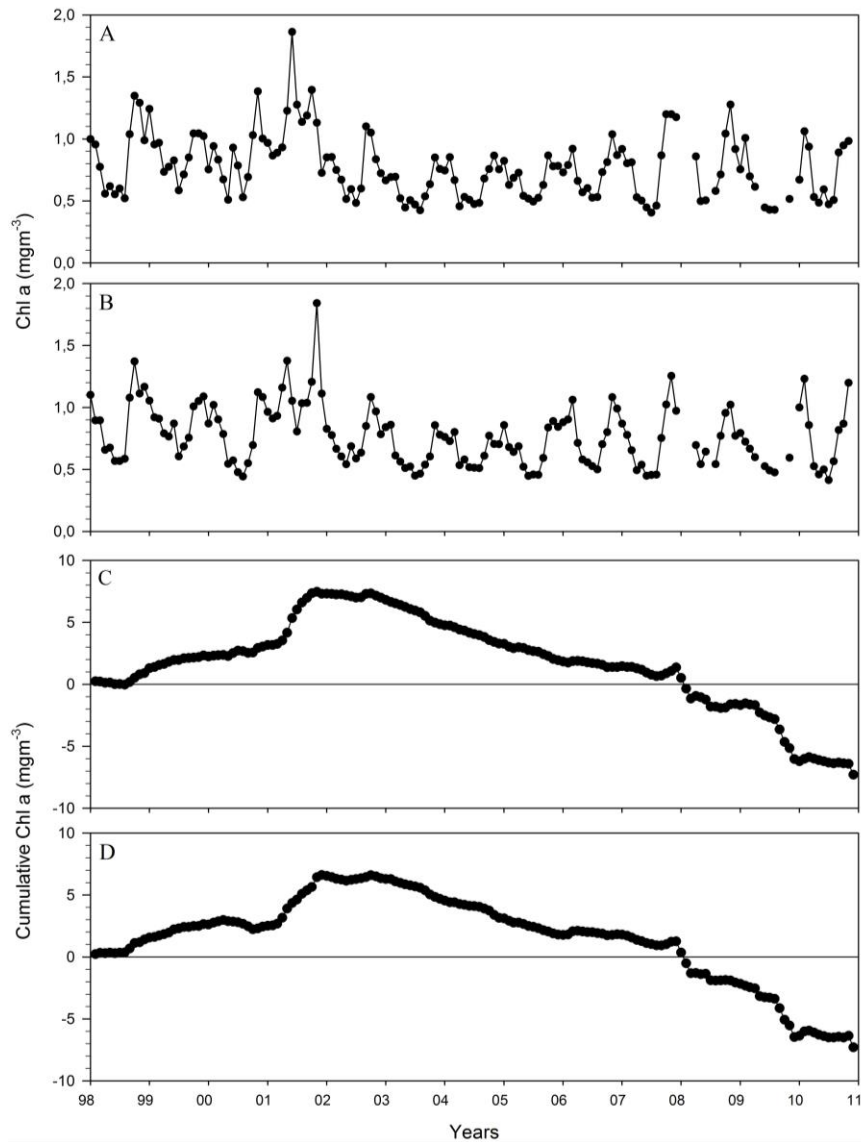
Figure 4. SeaWiFS Chlorophyll-a (Chl-a) from 1998 to 2011 for the western (A) and eastern Gyre (B) of the Black Sea and cumulative sum of the anomalies in Chl-a for the western (C) and eastern Gyre (D).

coast of the Black Sea has been estimated to be 247-1925 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
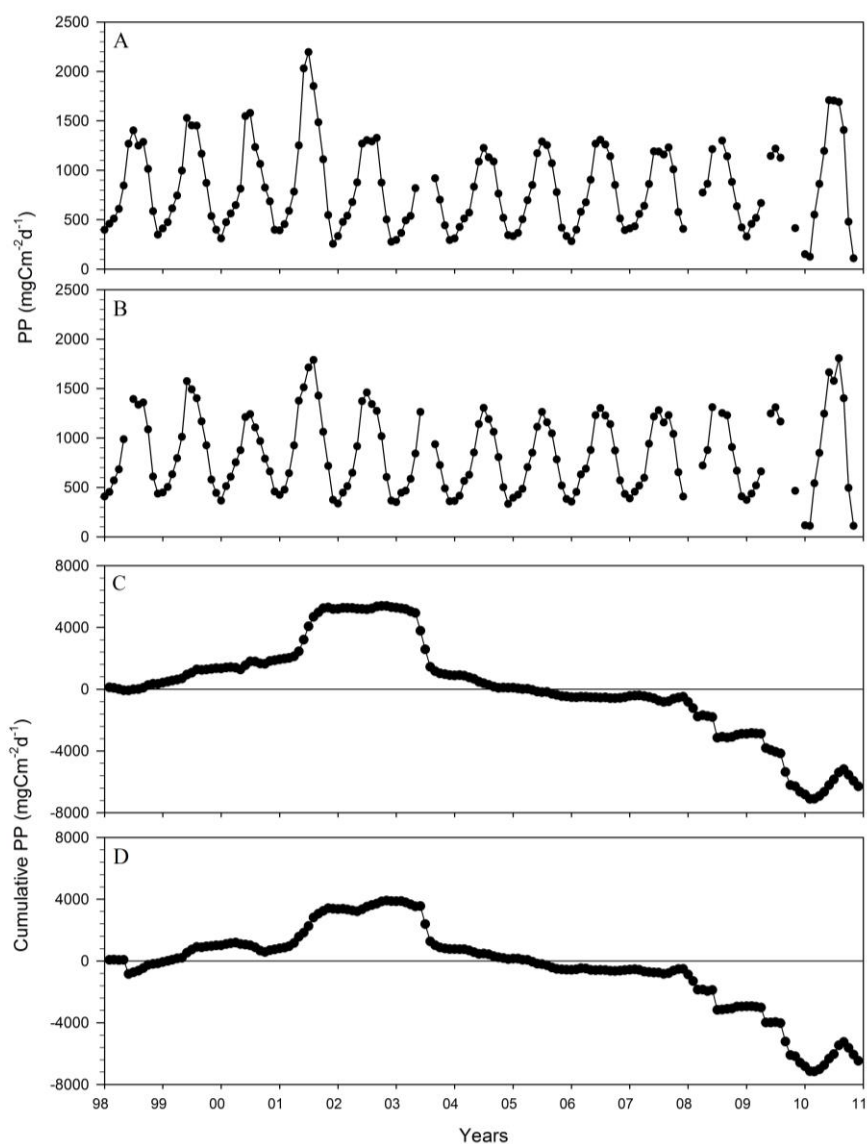
Figure 5. SeaWiFS derived Primary Production (PP) using the Wavelength Resolving Model of Smyth et al (2005) from 1998 to 2011 for the western (A) and eastern Gyre (B) of the Black Sea and cumulative sum of the anomalies in PP for the western (C) and eastern Gyre (D).

be problematic because of the high CDOM 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 determined by the cyclonic boundary Rim current and
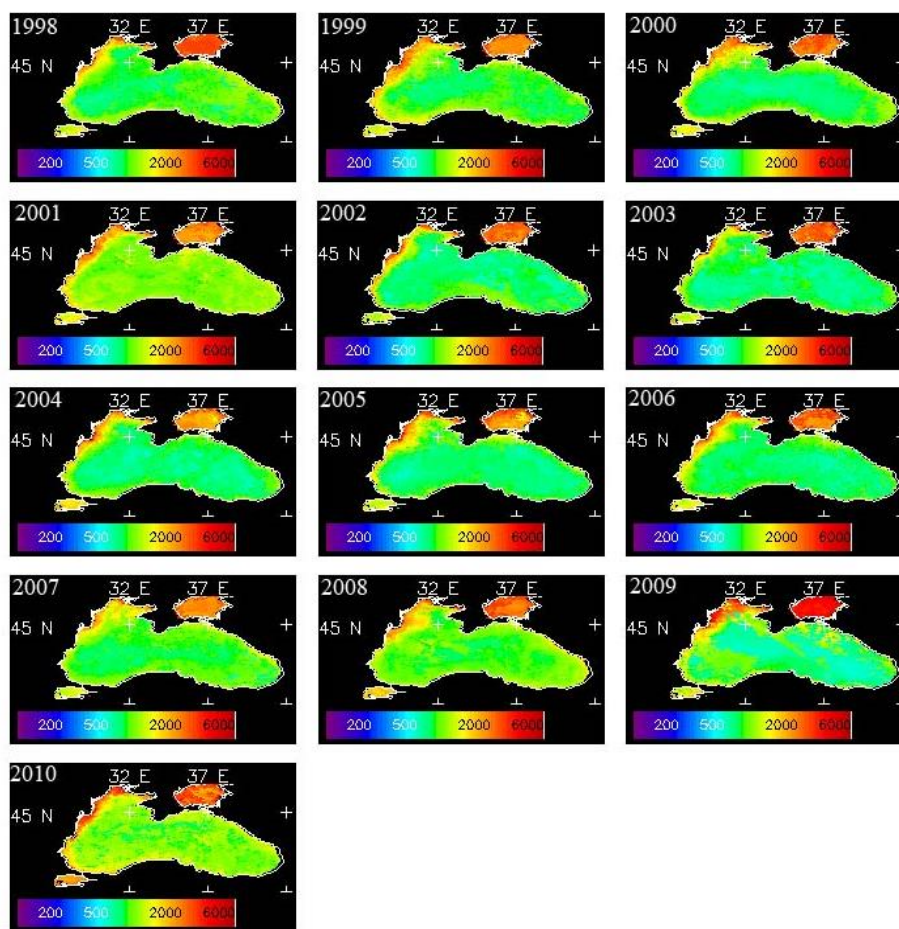
Figure 6. Maps of mean annual primary production (mgCm^{-2}d^{-1}) derived from the Wavelength Resolving Model (WRM) of Smyth et al (2005) from 1998 to 2011 for the Black Sea.

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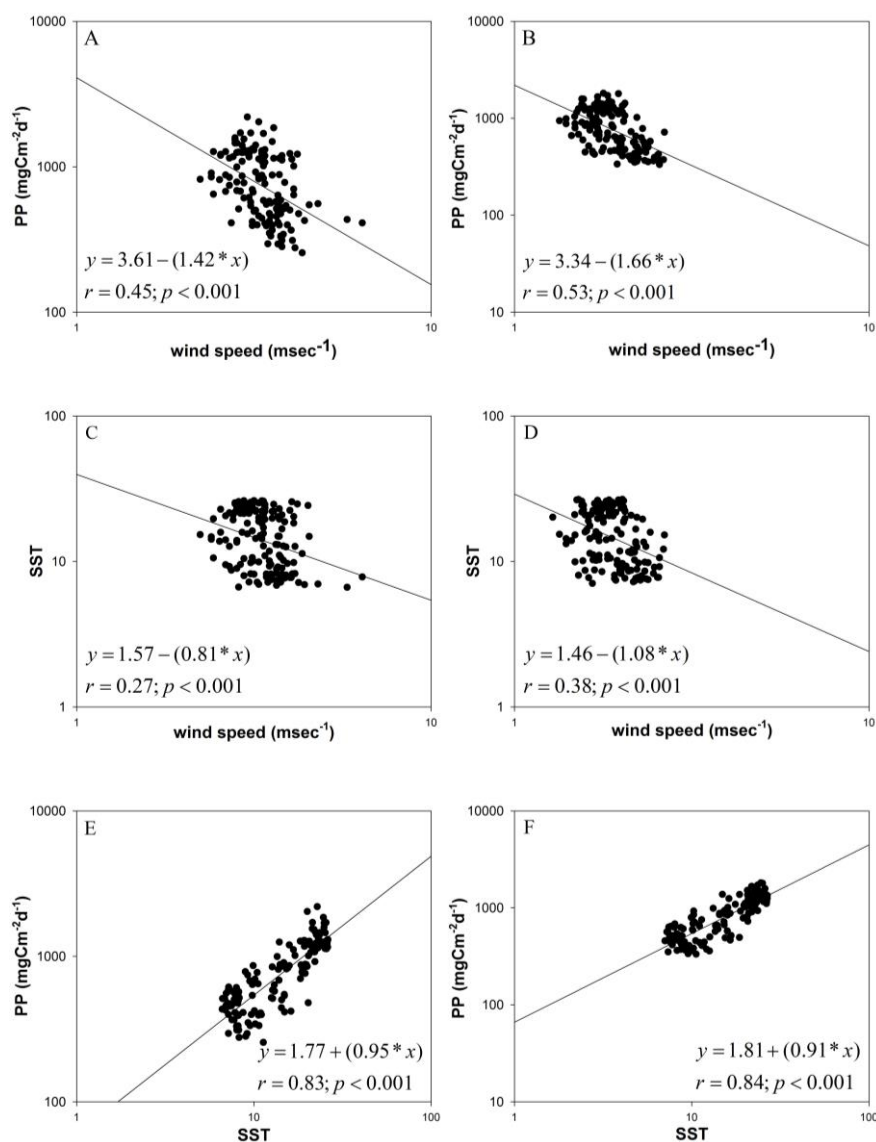
Figure 7. Linear regression between PP and wind speed (A), wind speed and SST (C) and PP and SST (E) for the western Gyre and PP and wind speed (B), wind speed and SST (D) and PP and SST (F) for the eastern Gyre of the Black Sea.

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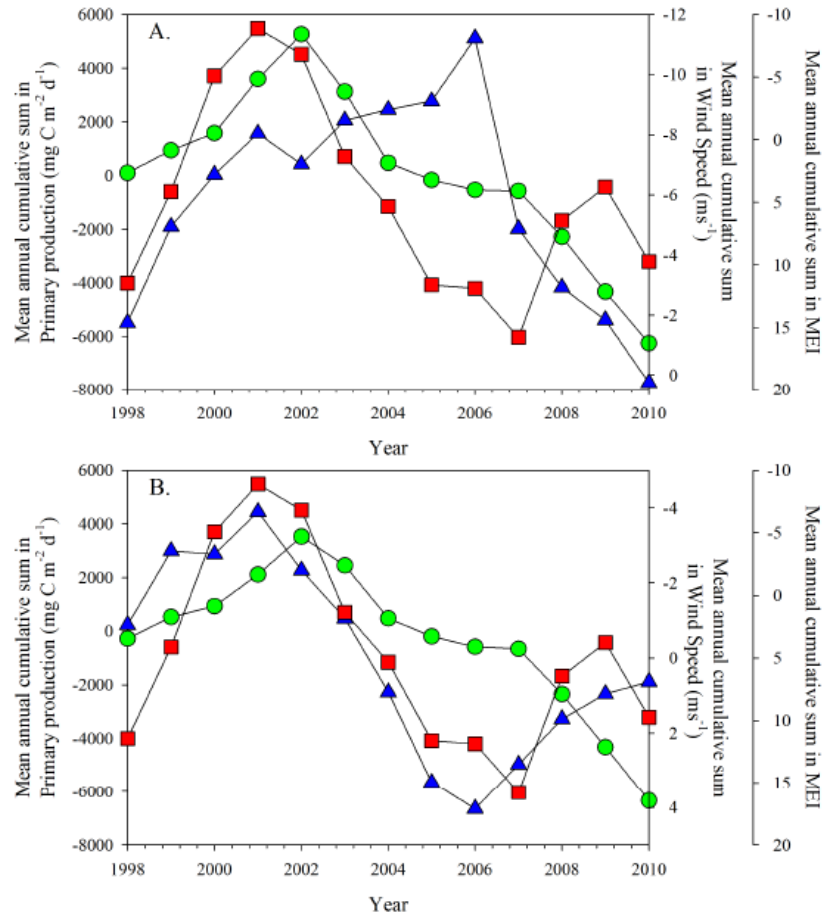
Figure 8. Mean annual cumulative sums in primary production, wind speed and Multivariate ENSO index for the western (A) and eastern (B) Gyres. Primary production is green circles, Multivariate ENSO index is red squares and wind speed is blue triangles (note reversal of range for MEI and wind speed).

(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, then 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

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