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1 **Non-linearities, regime shifts and recovery: The recent influence of climate on Black**  
2 **Sea chlorophyll**

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14

15 **Abstract**

16

17 The Black Sea ecosystem experienced severe eutrophication-related degradation during the  
18 1970s and 1980s. However, in recent years the Black Sea has shown some signs of recovery  
19 which are often attributed to a reduction in nutrient loading. Here, SeaWiFS chlorophyll *a*  
20 (chl *a*), a proxy for phytoplankton biomass, is used to investigate spatio-temporal patterns in  
21 Black Sea phytoplankton dynamics and to explore the potential role of climate in the Black

22 Sea's recovery. Maps of chl *a* anomalies, calculated relative to the 9 year mean, emphasise  
23 temporal variability of phytoplankton biomass in the Black Sea, particularly between the  
24 riverine-influenced Northwest shelf and the open Black Sea. Evolution of phytoplankton  
25 biomass has shown significant spatial variability of the 'system memory' between three  
26 major regions of the Black Sea. With the exception of 2001, chl *a* has generally decreased  
27 during our 9 year time-series. However, the winter of 2000-2001 was anomalously warm  
28 with low wind stress, resulting in reduced vertical mixing of the water column and retention  
29 of nutrients in the photic zone. These conditions were associated with anomalously high  
30 levels of chl *a* throughout much of the open Black Sea during the following spring and  
31 summer. The unusual climatic conditions occurring in 2001 may have triggered a shift in the  
32 Black Sea's chl *a* regime. The long-term significance of this recent shift is still uncertain but  
33 illustrates non-linear response to climate forcing that makes future ecosystem change in the  
34 pelagic Black Sea ecosystem difficult to predict.

35

36 **Key words:** Black Sea, chlorophyll, eutrophication, climate change, system memory, regime  
37 shift

38

## 39 **1. Introduction**

40

41 The pelagic Black Sea ecosystem has undergone significant changes during the last 30 years  
42 including habitat loss (Zaitsev and Mamaev, 1997), collapse of predatory fish stocks  
43 (Daskalov, 2002), wide-spread establishment of the invasive ctenophore *Mnemiopsis leidyi*  
44 (Kideys, 2002), and massive phytoplankton blooms resulting in hypoxia and loss of benthic

45 communities (Cociasu et al., 1996). It is widely accepted that these changes are at least  
46 partially attributable to intense eutrophication, particularly in coastal waters (Mee, 1992;  
47 Mee, 2006; Niermann, 1999; Yunev et al., 2002; Zaitsev and Mamaev, 1997). In recent years,  
48 the Black Sea has shown some signs of improvement such as an increase in the proportion of  
49 diatoms in the phytoplankton community (Bodeanu et al., 2004), a decrease in the number of  
50 monospecific algal blooms (Bodeanu et al., 2004), a decrease in phytoplankton biomass  
51 (Yunev et al., 2002), and decreased area of hypoxia (Mee, 2006). This system recovery  
52 appears to be linked to a reduction in intensive farming practices after the collapse of the  
53 Soviet Union (Mee et al., 2005). However, the role of climate in the Black Sea's recovery is  
54 unclear.

55

56 The aforementioned alterations to the Black Sea's ecosystem are all directly or indirectly  
57 connected to changes that occurred in the phytoplankton community. As phytoplankton  
58 comprise the base of the marine food web, alterations in phytoplankton production and  
59 community composition may have profound consequences for higher trophic levels (Edwards  
60 and Richardson, 2004). Due to their short life cycles and quick response to changes in their  
61 environment phytoplankton are sensitive to ecosystem change (Hays et al., 2005). However,  
62 most of the historical ecological data available regarding plankton in the Black Sea are the  
63 result of near-shore monitoring programmes or occasional research cruises and are therefore  
64 limited in temporal and spatial extent and, consequently, the amount of information the data  
65 can provide. The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) satellite, however,  
66 provides daily remotely-sensed spatially-comprehensive estimates of chlorophyll *a* (chl *a*)  
67 concentration, a proxy for phytoplankton biomass. Although SeaWiFS is not without  
68 limitations (see Oguz and Ediger, 2006 for more information on calibration issues), the

69 comprehensive spatio-temporal nature of this dataset enables the exploration of changes in  
70 and the possible recovery of the pelagic Black Sea system.

71

72 The aims of the work are 1) to investigate variability in recent inter- and intra-annual chl *a*  
73 dynamics in the Black Sea through the use of SeaWiFS satellite data, 2) to explain spatial  
74 patterns in phytoplankton biomass, and 3) to explore the role of climate in the recovery of the  
75 Black Sea.

76

## 77 **2. Materials and methods**

### 78 **2.1 Study area**

79

80 The Black Sea drains a catchment area containing large parts of 12 countries, covering a land  
81 area of 2 million km<sup>2</sup>, and receiving waste water from more than 100 million people (Mee,  
82 1992). The Black Sea is a nearly enclosed body of water, with only a narrow inlet to the  
83 Mediterranean through the Bosphorus Strait. In its northwestern region, the Black Sea has a  
84 wide and biologically active continental shelf while the open sea is permanently anoxic  
85 below 100-150 m (Sorokin, 2002). Hydrographically, the Black Sea is divided into two  
86 distinct regions: the shallow (< 200 m) Northwest Shelf and the deep (> 1000 m) central sea  
87 (Fig. 1). The Northwest Shelf receives most of the nutrient load to the Black Sea through  
88 riverine inputs from the Dniester, Dnieper and Danube rivers and is therefore the region most  
89 severely impacted by eutrophication (Cociasu and Popa, 2005). A large part of the terrestrial  
90 nutrients entering the Black Sea originate in central and western Europe, particularly those  
91 transported by the Danube, which alone is responsible for 75% of total nutrient input to the

92 Black Sea (Mee, 1992; Zaitsev and Mamaev, 1997). A rim current creates a fluid boundary at  
93 the edge of the shelf, separating shallow shelf and deep open waters (Simonov and Altman,  
94 1991). This liquid boundary is intermittently crossed by mesoscale eddies and filaments  
95 providing an efficient exchange mechanism between nutrient-rich shelf waters and the less  
96 productive waters of the central basin (Enriquez et al., 2005; Zaitsepin et al., 2003).

97

98 For the purpose of this study, the Black Sea is separated into three regions: (1) the shallow  
99 Northwest Shelf, (2) the deeper western gyre and (3) the eastern open Black Sea (Fig. 1). The  
100 far eastern open sea, although deep, was excluded from this study due to the complex nature  
101 of the relatively poorly studied Batumi gyre. GIS polygons representing the open and coastal  
102 Black Sea study areas were used to regionally partition each geographically referenced data  
103 set used in the analysis (SeaWiFS chl *a*, wind stress, sea surface temperature (SST)).

104 **[FIGURE 1]**

## 105 **2.2 Data**

106 Wind speed and sea surface temperature (SST) data were obtained from the NCEP/NCAR  
107 Reanalysis Project at the NOAA-CIRES Climate Diagnostics Center (NOAA-CIRES Climate  
108 Diagnostics Center, 2006). Wind speed was converted into wind stress, which is a function of  
109 wind speed, non-dimensional drag coefficient and boundary layer air density (Pickard &  
110 Pond 1978). Wind stress regulates the dynamics of the boundary layer and is connected to the  
111 production of wind-driven surface currents, the generation of surface waves and upper-ocean  
112 mixing (Pond and Pickard, 1978). Therefore, low wind stress contributes to formation of  
113 highly stratified waters. Monthly wind stress and SST anomalies were calculated by  
114 subtracting from each monthly value the corresponding long-term monthly mean of the 100

115 month time-series. Danube river discharge data were obtained from the Global Runoff Data  
116 Centre, a digital worldwide repository of discharge data and associated metadata (Global  
117 Runoff Data Centre, 2005).

118

119 SeaWiFS current reprocessed version (v5.1) data produced by Ocean Biology Processing  
120 Group were acquired from the NASA Ocean Color website (NASA Ocean Biology  
121 Processing Group, 2006). The data were Level 3, 8-day products (9 km x 9 km square  
122 resolution) of the near-surface Chl *a* concentration ( $\text{mg m}^{-3}$ ), estimated using the ocean  
123 Chlorophyll 4 - version 4 (OC4-v4) algorithm (O'Reilly et al., 1998):

$$124 \text{ chl } a = 10^{(0.366-3.067x + 1.930x^2 + 0.649x^3 - 1.532x^4)},$$

125 where  $x = \log_{10}((R_{rs\ 443} > R_{rs\ 490} > R_{rs\ 510})/R_{rs\ 555})$  and  $R_{rs}$  is the satellite  
126 calculated remote sensing reflectance. The first ( $x$ ) equation takes the highest reflectance  
127 value from a waveband at 443, 490, or 510 nm and divides it by the reflectance at 555 nm;  
128 reflectance maximum moves towards higher wavebands as the chl *a* concentration increases.  
129 This  $x$  value then goes into an equation that results from a statistical fit of this empirical  
130 algorithm to a large in situ database. NASA processed these data using a series of radiometric  
131 corrections (e.g., atmospheric) to eliminate the presence of clouds, haze, and water vapour  
132 (Mueller and Austin, 1995). The 8-day products were aggregated into monthly means from  
133 September 1997 through December 2005.

134

135 In order to remove the long-term mean, to emphasize subtle temporal patterns in productivity,  
136 and to allow for the relative comparison of chl *a* dynamics, standardized chl *a* anomalies ( $z$ )  
137 were calculated as:

138

139 
$$z = \frac{(x - \bar{x})}{\sigma}$$

140 where  $\bar{x}$  = the long-term mean and  $\sigma$  = the standard deviation. This was repeated for  
141 each SeaWiFS measurement ( $n=6683$ ) at three temporal scales: 1) the intra-annual (monthly  
142 composite) anomaly was calculated based on the long-term mean of each calendar month  
143 relative to the composite annual mean; 2) the inter-annual chlorophyll anomaly was  
144 calculated from the yearly mean of each complete calendar year available (1998-2005)  
145 relative to the composite annual mean; and 3) the individual monthly chl *a* anomalies were  
146 calculated for each month (September 1997 – December 2005,  $n = 100$ ) relative to the long-  
147 term monthly means.

148

149 Interpolated maps illustrating standardized chl *a* anomalies in the Black Sea were created for  
150 each month using the inverse distance weighting (IDW) method of interpolation on a 9 x 9  
151 km data grid (Caruso and Quarta, 1998) thereby creating a continuous distribution of  
152 chlorophyll concentration across the Black Sea. IDW assumes that interpolated points are  
153 more influenced by nearby data than data that are further away (Caruso and Quarta, 1998),  
154 and like all geostatistical methods, assumes that spatial structures are stable in time for the  
155 duration of the sampling period.

156

157 The Black Sea includes both Case I (open ocean) and Case II (optically complex coastal)  
158 waters (IOCCG, 2000). In Case II waters, chl *a* is difficult to distinguish from particulate  
159 matter and/or yellow substances (dissolved organic matter) and so global chl *a* algorithms



160 (such as OC4-v4) are less reliable (IOCCG, 2000). SeaWiFS has also been found to  
161 overestimate chl *a* concentrations by a factor of 4 in the Black Sea (Oguz and Ediger, 2006).  
162 Nevertheless, the observation of near-coastal chl *a* with remote sensing satellites has been  
163 found to provide important information on potential relationships with climate and nutrient  
164 enrichment in the Black Sea (Barale et al., 2002; Nezlin, 2001).

165

166 Pearson correlation analysis was used to calculate ‘system memory’ effects in each region of  
167 the Black Sea (see ‘Results’ section for more information). Each monthly chl *a* anomaly was  
168 correlated with the anomalies of each of the previous 4 months. Two methods were used to  
169 assess changes in monthly anomalies of each variable. First, the relatively simple and well  
170 known cumulative sums method was applied in order to summarize major changes by  
171 smoothing high frequency variability and highlighting changes in local mean values along the  
172 time-series. Successive positive anomalies produce an increasing slope, while successive  
173 negative anomalies produce a decreasing slope. The occurrence of shifts was then confirmed  
174 and their significance evaluated using an automatic sequential algorithm, which detects  
175 regime shifts by accounting for statistically significant differences between the means in  
176 consecutive segments of a time-series (Rodionov, 2004). This method is based on a regime  
177 shift index (RSI) combined with a sequential *t* test (Rodionov, 2004). Absolute value of RSI  
178 indicates magnitude of shift while its sign indicates change in direction of mean between  
179 regimes. More information on the RSI may be found in (Rodionov, 2004; Rodionov, 2007).  
180 An 18 month minimum regime length was chosen in order to increase the likelihood of  
181 selecting real shifts as opposed to small variations in the mean; however, any shift detected  
182 must be considered in context of the relatively short (100 months) length of the time-series  
183 evaluated here.

184

### 185 **3. Results and discussion**

#### 186 **3.1 Chl *a* anomalies**

187

188 Changes in climate affect productivity in the Black Sea through changes in temperature, wind  
189 patterns, and riverine inputs, but the spatial variation of impact, extent of change to the  
190 pelagic system and the exact mechanisms through which change will occur are not fully  
191 understood. The open and shelf regions of the Black Sea are distinct systems, whose  
192 productivity is regulated by different drivers. Production in the shelf system is linked to both  
193 freshwater inflow and climatic processes (Bodeanu, 2002; Bodeanu et al., 2004) while the  
194 open Black Sea is predominantly influenced by climatic forces, primarily wind and  
195 temperature, aspects of which regulate stratification, upwelling, and pattern and magnitude of  
196 circulation (Mikaelyan, 1995; Sorokin, 2002). Inter- and intra-annual chl *a* concentrations  
197 throughout the Black Sea are patchy, with an obvious difference between the chlorophyll-rich  
198 shelf and comparatively less productive open regions (Fig. 2, 3) (Sorokin, 2002).

199 **[FIGURE 2]**

200 **[FIGURE 3]**

201 The chl *a* seasonal cycle can be used to provide a baseline of ‘typical’ relative chl *a*  
202 conditions in the Black Sea throughout the year (Fig. 3a). It is immediately clear that the  
203 seasonal cycle of chl *a* is not spatially uniform across the Black Sea. The open Black Sea  
204 experiences its chl *a* maximum during autumn and winter with minimum levels found during  
205 the summer months (as first described by Vinogradov et al., 1999). The bloom begins near  
206 the shelf slope in the northwestern region during September and progresses eastward across

207 the open Black Sea, covering the entire basin during October and November. The blooming  
208 cycle in the open Black Sea is primarily a response to the erosion of the seasonal pycnocline  
209 in autumn which replenishes the photic zone with nutrients from the mixed layer  
210 (Vinogradov et al., 1999). The bloom ends as stratification occurs, nutrients are depleted and  
211 grazer biomass increases (Vinogradov et al., 1999). The eastern Black Sea is the last region in  
212 which the phytoplankton bloom disperses in early spring. Unlike the open Black Sea, the  
213 seasonal cycle of the Northwest Shelf undergoes two blooms, an annual pattern typical of  
214 temperate waters (Sorokin, 2002). The spring bloom is dependent upon Danube River flow,  
215 and commences during April and May, the months of maximum Danube discharge, when  
216 nutrient-rich shelf waters are sufficiently warm for phytoplankton growth (Fig. 3a) (Cociasu  
217 and Popa, 2005; Yunev et al., 2007). The decline of the spring bloom on the shelf is most  
218 likely a combination of nutrient depletion and increased zooplankton grazing pressure (Chu et  
219 al., 2005). A late summer/autumn bloom also occurs in shelf waters as zooplankton grazing  
220 pressure is reduced, but is not as intense as the spring bloom. The chl *a* minimum occurs  
221 during autumn and winter in the shelf region, when Danube discharge is lowest and shelf  
222 waters well-mixed and cool.

223

224 Differences between the three regions may be partially described by variability in regional  
225 ‘system memory’, or the persistence of a bloom-sustaining state from one month to the next  
226 (Table 1). Such conditions are reflected in chl *a* anomalies; i.e., a positive chl *a* anomaly  
227 indicates that the conditions conducive to phytoplankton growth are also present. The  
228 relationship (quantified as a correlation) between chl *a* anomalies in consecutive months  
229 provides an indication of the time it takes for environmental conditions (e.g., nutrients,  
230 stratification, horizontal exchanges, etc) to change in a particular region. The system memory  
231 is defined as a length of time over which the correlation remains above a certain level (in our

232 case above  $r^2 = 0.50$ ). Thus, strength of system memory is a function of the rate of change of  
233 flux of chl *a* into and out of a region (through large scale circulation or mesoscale eddies) as  
234 well as local conditions (e.g., weather conditions, nutrients, local mixing) which regulate  
235 phytoplankton growth and death. Strength of system memory is variable between regions; in  
236 other words, the temporal pattern at which bloom conditions develop and the length of time  
237 for which they are sustained is not consistent across the whole Black Sea. Memory is longest  
238 in the western open Black Sea, with a correlation of  $r^2 > 0.50$  at a 4 month lag period. System  
239 memory is considerably shorter in the eastern open Black Sea and Northwest Shelf with  
240 memory in both regions decreasing rapidly after only one month. The shallow shelf is a  
241 physically dynamic system that is strongly influenced by sharp variations in riverine input as  
242 well as short term weather changes and active hydrodynamic processes (Zatsepin et al.,  
243 2003), resulting in limited system memory in that region. The memory of the eastern open  
244 Black Sea is shorter than that of the open western Black Sea. The reasons for the difference  
245 between system memory in the two open regions are not entirely clear but may be attributed  
246 to regional differences in gyres, eddies, and variability in the rim current (Enriquez et al.,  
247 2005; Zatsepin et al., 2003). This variability in system memory indicates that the western  
248 open Black Sea appears to be the most stable region, with bloom events, and the underlying  
249 hydrodynamic conditions that enable them, likely to persist for longer in that region than in  
250 either the shelf or eastern open regions. In this respect, the Western Black Sea acts as a  
251 repository for the surface open sea system where there is a tendency for the overall  
252 circulation to pool water and associated chlorophyll. Further investigation is needed to  
253 determine the relative importance of chl *a* flux and local processes to the system memory of  
254 each region.

255

256 Due to the differences in the shelf and open water systems, the response of the Black Sea to  
257 changes in climate is not spatially homogeneous. A clear example of the decoupled nature of  
258 the two systems occurred in 2001 when an extensive bloom encompassed most of the open  
259 Black Sea from March through November, with chl *a* levels reaching > 2 sd above the long-  
260 term mean (Fig. 2, 3b, 3c). The cause of the 2001 bloom was almost certainly climate-related.  
261 The winter of 2000-2001 was exceptionally warm with very low wind stress in the central  
262 Black Sea. The warm, stable winter resulted in stratification throughout the season and  
263 constrained the formation of the Cold Intermediate Layer (CIL), an intrusion of cold water  
264 between the pycnocline and thermocline at approximate 50-150 m depth (Oguz and Ediger,  
265 2006). The CIL normally traps nutrients below surface waters, locking them out of the photic  
266 zone, until mixing energy caused by winter storms or upwelling returns them to the photic  
267 zone (Yunev et al., 2005). However, in the absence of subduction, nutrients may have  
268 remained in the surface waters, available for uptake by plankton.

269

270 The bloom of 2001 was decoupled from conditions in shelf waters. The shelf, though  
271 quantitatively richer in chl *a* than the open Black Sea, contained anomalously low levels of  
272 chl *a* during most of the year (Fig. 3c). Phytoplankton biomass on the Northwest Shelf is  
273 intimately related to riverine outflow, and Danube discharge is correlated with chl *a* ( $r^2 =$   
274  $0.30$ ,  $p = 0.015$ ,  $n = 64$ ). Danube outflow was uncommonly low during the winter of 2000-01,  
275 causing the front between high chl *a* Danube-influenced and low chl *a* open sea waters to be  
276 close to the coastline (the boundary is clearly observable in Figure 3c, particularly during  
277 February and April). During winter, nutrient-rich waters are usually subducted and during  
278 cold winters, the contribution of nutrient-rich water from the northwestern continental slope  
279 and Northwest Shelf may constitute 60% of the CIL water mass (Stanev et al., 2003). Since  
280 this process did not occur in 2001, the nutrient rich waters stayed on the surface of the shelf

281 where they were later mixed into the open Black Sea. The intrusion of low chl *a* waters from  
282 the open Black Sea and the out-mixing of the nutrient rich shelf waters resulted in  
283 anomalously low chl *a* levels in the shelf region during most of 2001. Concurrently, close  
284 inshore, where blooms were still fed by river discharge, high temperatures and low wind  
285 stress encouraged stratification and resulted in severe hypoxia in bottom waters (Kondratiev  
286 and Lemeshko, 2003).

287

288 The warm, stratified conditions occurring throughout the winter of 2000-2001 lengthened the  
289 phytoplankton growing season and caused alterations to phytoplankton community  
290 composition across the Black Sea (Fig. 4). Dinoflagellates, which are well-suited to stratified  
291 conditions (Margalef, 1978), occurred in very high numbers (91% of biomass) in both open  
292 (Soydemir et al., 2003) and shelf (Bodeanu et al., 2004) waters. Although the chl *a*  
293 concentration in the shelf region was relatively low during most of 2001, nine algal blooms  
294 occurred during summer, with 13 species reaching bloom concentrations, conditions similar  
295 to those seen in shelf waters during the eutrophic 1980s (Bodeanu et al., 2004). Additionally,  
296 there was no coccolithophore bloom in the open Black Sea during the summer of 2001  
297 (Soydemir et al., 2003). This shift in community composition was indirectly visible through  
298 remotely-sensed chl *a*, which shows a distinct spring bloom in the open sea in addition to the  
299 usual high chl *a* level that occurs during late autumn (Fig. 4). The double bloom structure was  
300 previously common in the Black Sea during periods of non-diatom dominance in both open  
301 and shelf waters and is visible in Coastal Zone Color Scanner data from the late 1970s and  
302 early 1980s (Bodeanu et al., 2004; Oguz et al., 2003).

303 [FIGURE 4]

304 Changes in the phytoplankton community such as those observed during 2001 may have  
305 profound consequences for higher trophic levels. It is already known that warming seas are  
306 detrimental to diatoms due to increased stratification and consequent nutrient depletion of  
307 surface waters (Bopp et al., 2005). A shift to a non-diatom dominated phytoplankton  
308 community may result in an increased number of ‘trophic dead-ends’ (Verity and Smetacek,  
309 1996). This was the case during the hot summer of 2001 when blooms of jellyfish and  
310 *Noctiluca scintillans* occurred in shelf waters (Velikova and Mihneva, 2005). Abundance of  
311 *Noctiluca*, a heterotrophic dinoflagellate used as an indicator of water quality in the Black  
312 Sea, had previously been found to be decreasing (daNUbs, 2005) and its resurgence in 2001  
313 has been linked to the unusual climatic conditions (Velikova and Mihneva, 2005).  
314 Additionally, a hypoxic event on the shelf resulting in mass fish mortalities took place in  
315 2001 (Boicenco, personal communication; Kondratiev and Lemeshko, 2003). High numbers  
316 of algal blooms, hypoxic events, faunal mortalities, and a non-diatom dominated  
317 phytoplankton community are all conditions reminiscent of those regularly found in the Black  
318 Sea during the period of peak eutrophication in the 1970s and 1980s. Such trophic changes  
319 and their related consequences may become increasingly common if they are also a symptom  
320 of a warming climate, and could have serious impacts for higher trophic levels, including  
321 commercially important fish species.

322

323 The response of phytoplankton production to warming SST is geographically variable on a  
324 global scale: increases in chl *a* have been observed in temperate seas as rising SST extends  
325 the growing season and prolonged periods of stratification reduce light limitation (e.g. North  
326 Sea (McQuatters-Gollop et al., 2007)), but, conversely, warming SST has resulted in  
327 decreased productivity in much of the tropical to mid-latitude World Ocean as stratification  
328 prevents nutrient upwelling (Behrenfeld et al., 2006). In general, the second scenario is true

329 of the open Black Sea; apart from 2001, the open Black Sea experienced a statistically  
330 significant decrease in annual mean (western open:  $r^2 = 0.75$ ,  $p = 0.012$ ; eastern open:  $r^2 =$   
331  $0.89$ ,  $p = 0.001$ ; 2001 excluded) and winter (November-March,  $r^2 = 0.49-0.73$ ,  $p < 0.05$ ) chl *a*  
332 concentrations between 1998 and 2005. During all years except 2001, the open Black Sea  
333 also underwent a bloom cycle similar to that of the nearby oligotrophic Mediterranean  
334 (Bricaud et al., 2002) with an autumn chl *a* peak and summer minimum, but no spring bloom.  
335 However, the winter of 2000-01 was exceptionally warm and stable and the water remained  
336 stratified throughout autumn and winter thereby extending the growing season. That year the  
337 Black Sea responded as a temperate system with a double bloom pattern characteristic of  
338 mid-latitude oceans. The chl *a* anomalies observed after 2001 were nearly the opposite of  
339 those observed before, with most of the Black Sea comparatively low in chl *a* (Fig. 3b).

340

### 341 **3.2 Non-linearities**

342

343 It is now clear that the role played by winter weather in the production of phytoplankton  
344 biomass is non-linear in the Black Sea. It has previously been believed that windy, cold  
345 winters lead to bigger spring/summer blooms due to enhanced vertical mixing and stronger  
346 upwelling and that the effects of eutrophication are magnified during years with severe  
347 winters (such as during the late 1980s and early 1990s) and depressed during warm winters  
348 (Oguz, 2005; Oguz and Gilbert, 2007). The trend toward milder winters in recent years has  
349 also been cited as the reason for the disappearance of the spring bloom in the open Black Sea  
350 (Oguz, 2005). Yet the warmest winter of the last 50 years resulted in an extensive bloom  
351 encompassing nearly the entire Black Sea as well as the return to the previously-observed  
352 double bloom structure. Furthermore, the winter of 2003 was comparatively windy and cool,



353 which, according to the previously postulated relationship between winter weather and  
354 phytoplankton production, should have resulted in higher chl *a*, yet 2003 had the lowest chl *a*  
355 anomaly of the time-series (Fig. 2, 3b).

356

357 The non-linear relationship between winter weather and phytoplankton biomass may be  
358 explained by the degree of subduction of water below the photic zone, most noticeably in the  
359 CIL. During years when subduction occurs, nutrient rich water is stored below the photic  
360 zone where nutrients remain unavailable throughout spring and summer; however, the  
361 disappearance or severe erosion of the CIL in 2001 kept nutrients available in surface waters,  
362 resulting in high levels of chl *a*. The degree of subduction of nutrient rich water depends on  
363 the regeneration of the CIL, which in turn depends on the severity of winter weather,  
364 particularly from January through March when CIL replenishment is at its strongest (Sorokin,  
365 2002). For formation of the CIL to be prevented it may be necessary for SST to be warmer  
366 than some ‘threshold’ temperature during those key months; in other words, the warming of  
367 the open Black Sea may indeed result in decreased chl *a*, but only if winter temperature  
368 remains below a certain threshold level and nutrients are subducted and stored below the  
369 photic zone. The gradual erosion of the CIL due to warmer winters has already been  
370 documented (Oguz et al., 2003) and the lack of its formation as observed during 2001 could  
371 become a regular feature as warm winters become more common.

372

### 373 **3.3 Regime shifts**

374

375 The anomalous climatic conditions that occurred during 2001 may have triggered a shift in  
376 the Black Sea chl *a* regime (Fig. 5). A distinct switch to a predominantly negative chl *a*  
377 anomaly post-2001 is clearly observable in the open Black Sea and, to a lesser extent, on the  
378 shelf (Fig. 2, 3b). A clear downward trend in the chl *a* anomaly beginning in January 2002  
379 was observed for the open Black Sea and in March 2002 for the Northwest Shelf (Fig. 5). A  
380 second, positive trend also began in shelf waters in October 2004. These three shifts are all  
381 statistically significant (open region: January 2002 (RSI: -0.67;  $p < 0.01$ ); shelf region: March  
382 2002 (RSI: -0.88;  $p < 0.01$ ), October 2004 (RSI: 0.66;  $p < 0.01$ )) (Fig. 5). None of these shifts  
383 corresponded with a shift in wind stress but the October 2004 shift in the Northwest Shelf  
384 region coincided with a shift in SST (RSI: 0.10,  $p < 0.05$ ). The lack of direct relationship  
385 between climate and chlorophyll is a factor of the synergistic and interactive impacts of  
386 climate on phytoplankton biomass. Thresholds and non-linearities make it difficult to model  
387 the climate-chl *a* relationship and accurately predict the consequences of changes in climate.

388 **[FIGURE 5]**

389 Due to the limited length of the SeaWiFS dataset, it is difficult to assess the full significance  
390 of these shifts on the Black Sea ecosystem. As more data, particularly those from other  
391 ecological time-series, become available, an increasingly thorough examination of the  
392 importance of the detected shifts can be made. If the shifts in chl *a* coincide with changes in  
393 other trophic levels, they may be part of an ecological regime shift, a stepwise alteration in  
394 the composition and productivity of the whole ecosystem at a regional scale that reflects  
395 major hydrographic change (Beaugrand, 2004). Oguz and Gilbert (2007) recently suggested  
396 that since 1995 the open Black Sea has undergone a period of decreasing chlorophyll as a  
397 result of warming SST and decreased nutrient loading. The shift in open Black Sea  
398 chlorophyll identified here may therefore be a stepwise change occurring as part of this shift  
399 in phytoplankton biomass. Alternately, the shifts in chlorophyll described here could be

400 caused by natural variability or might be part of an oscillatory cycle. Regardless of their  
401 cause, these changes in the chl *a* regime cannot be underestimated. Non-linear responses in  
402 biological communities have been found to amplify subtle environmental changes; in other  
403 words, environmental shifts may be detectable in the phytoplankton before they are  
404 detectable in the environmental variables themselves (Taylor et al., 2002).

405

#### 406 **4. Conclusions**

407

408 The relationship between climate and chl *a* in the Black Sea is complex; however it is highly  
409 likely that climate has played a significant role in the recovery of the Black Sea. A decreasing  
410 trend in chl *a* and primary production has been observed world wide as SST increases  
411 (Behrenfeld et al., 2006), suggesting that reduced phytoplankton biomass in the Black Sea  
412 ecosystem is not solely a factor of diminished nutrient loading. The Black Sea nutrient  
413 regime is also dependent on degree of nutrient subduction, a function of CIL formation and  
414 winter temperature; however, the relationship between chl *a* and these aspects of climate  
415 appears to be non-linear, with a possible temperature threshold constraining subduction. A  
416 further non-linearity was evidenced in a shift in the chlorophyll regime which coincided with  
417 the anomalous climatic conditions occurring in 2001. Although the significance of the chl *a*  
418 shift has yet to be determined, it may be a precursor of further ecosystem change. These  
419 unpredictable responses to climatic variability emphasize the uncertain future the Black Sea  
420 faces as our climate changes.

421

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427

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- 568
- 569

570 **Figure legends**

571 Figure 1. Black Sea regions used in this study. The line surrounding the open Black Sea is  
572 also the 200m isobath.

573 Figure 2. Time-series of chlorophyll (standardized) and climatic anomalies in the open and  
574 Northwest Shelf of the Black Sea. Shaded areas highlight season of CIL formation  
575 and nutrient subduction.

576 Figure 3. Standardized anomaly maps illustrating (a) the mean seasonal intra-annual chl *a*  
577 cycle, standardized across the year; (b) inter-annual chl *a*, standardized across all  
578 years; and (c) a detail of 2001, an exceptionally productive year in the Black Sea,  
579 standardized to the 9 year mean of each calendar month.

580 Figure 4. Seasonal chl *a* cycles for the Northwest Shelf 1997-2005 (▲), the open Black Sea  
581 during 2001 (○), and the open Black Sea excluding 2001 (●). The 2001 seasonal cycle  
582 for the open Black Sea resembles that of the Northwest Shelf with a spring and an  
583 autumn bloom.

584 Figure 5. Shifts in chl *a* anomaly revealed by (a) cumulative sums method and (b, c)  
585 automatic sequential algorithm. (a) A major shift in the Black Sea's chl *a* regime  
586 occurred after 2001 (Northwest Shelf (○), Open Black Sea (●)). (b) Statistically  
587 significant shifts were identified in the shelf region in March 2002 and October 2004  
588 and (c) in the open region (western and eastern open regions combined for brevity) in  
589 January 2002.

590

591

Table 1: Correlation matrix illustrating variability in chlorophyll system memory length between Black Sea regions. Bold values denote significant relationships ( $p < 0.05$ ).

	Northwest Shelf						Western Open Black Sea						Eastern Open Black Sea					
	month 0	month 1	month 2	month 3	month 4	month 5	month 0	month 1	month 2	month 3	month 4	month 5	month 0	month 1	month 2	month 3	month 4	month 5
month 0		<b>0.56</b>	<b>0.35</b>	<b>0.38</b>	<b>0.38</b>	<b>0.37</b>		<b>0.75</b>	<b>0.67</b>	<b>0.60</b>	<b>0.52</b>	<b>0.44</b>		<b>0.56</b>	<b>0.29</b>	<b>0.27</b>	<b>0.21</b>	0.15
month 1	<b>0.56</b>		<b>0.55</b>	<b>0.35</b>	<b>0.38</b>	<b>0.39</b>	<b>0.75</b>		<b>0.75</b>	<b>0.67</b>	<b>0.60</b>	<b>0.52</b>	<b>0.56</b>		<b>0.55</b>	<b>0.29</b>	<b>0.27</b>	<b>0.21</b>
month 2	<b>0.35</b>	<b>0.55</b>		<b>0.55</b>	<b>0.35</b>	<b>0.39</b>	<b>0.67</b>	<b>0.75</b>		<b>0.76</b>	<b>0.67</b>	<b>0.60</b>	<b>0.29</b>	<b>0.55</b>		<b>0.56</b>	<b>0.28</b>	<b>0.26</b>
month 3	<b>0.38</b>	<b>0.35</b>	<b>0.55</b>		<b>0.55</b>	<b>0.35</b>	<b>0.60</b>	<b>0.67</b>	<b>0.76</b>		<b>0.76</b>	<b>0.67</b>	<b>0.27</b>	<b>0.29</b>	<b>0.56</b>		<b>0.56</b>	<b>0.28</b>
month 4	<b>0.38</b>	<b>0.38</b>	<b>0.35</b>	<b>0.55</b>		<b>0.55</b>	<b>0.52</b>	<b>0.60</b>	<b>0.67</b>	<b>0.76</b>		<b>0.77</b>	<b>0.21</b>	<b>0.27</b>	<b>0.28</b>	<b>0.56</b>		<b>0.56</b>
month 5	<b>0.37</b>	<b>0.39</b>	<b>0.39</b>	<b>0.35</b>	<b>0.55</b>		<b>0.44</b>	<b>0.52</b>	<b>0.60</b>	<b>0.67</b>	<b>0.77</b>		0.15	<b>0.21</b>	<b>0.26</b>	<b>0.28</b>	<b>0.56</b>	



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The Editor, Journal of Marine Systems  
Dear Sir/Madam

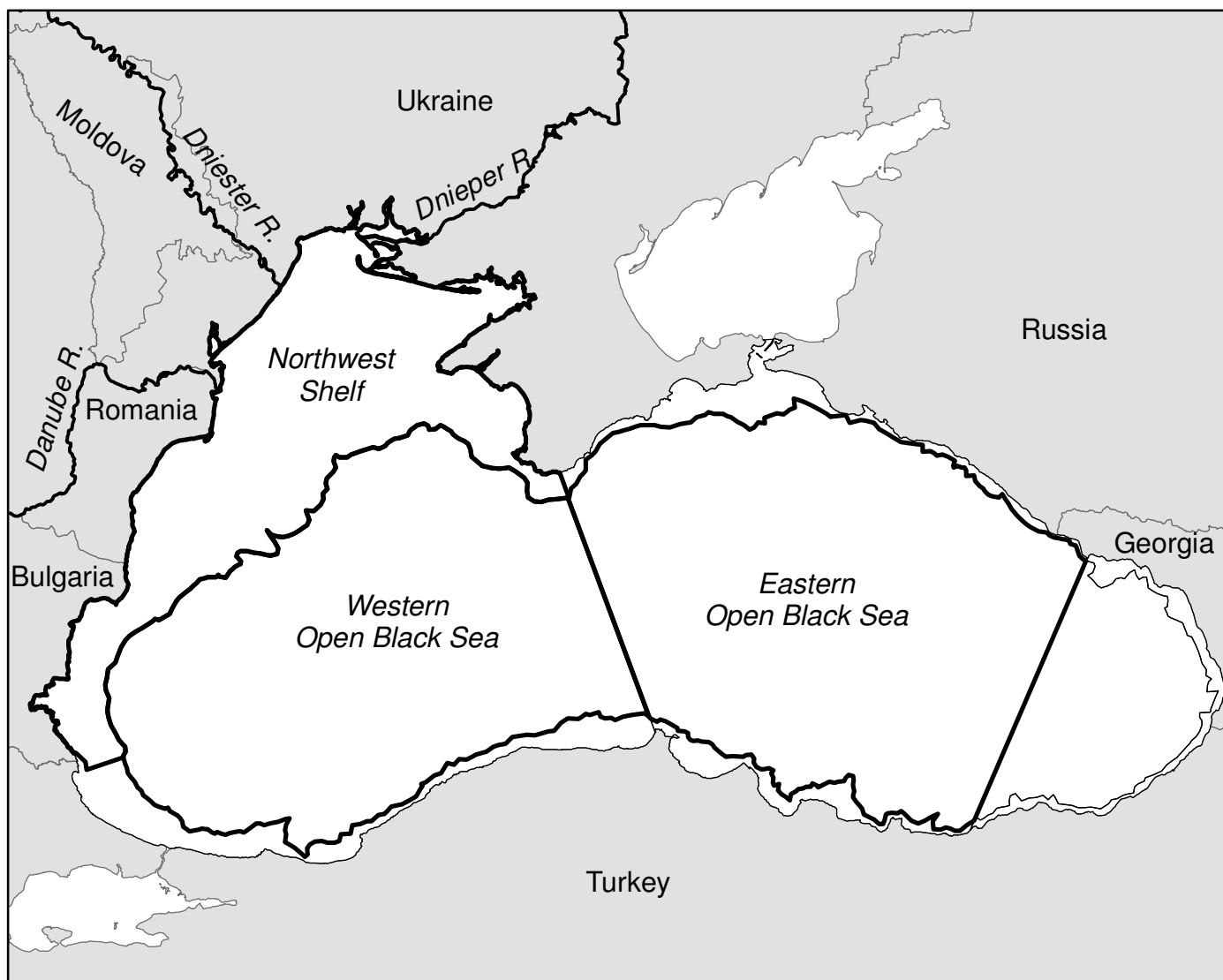
The Black Sea ecosystem experienced severe eutrophication-related degradation during the 1970s and 1980s. However, in recent years the Black Sea has shown some signs of recovery which are often attributed to a reduction in nutrient loading. Here, SeaWiFS chlorophyll *a* (chl *a*), a proxy for phytoplankton biomass, is used to investigate spatio-temporal patterns in Black Sea phytoplankton dynamics and to explore the potential role of climate in the Black Sea's recovery. Maps of chl *a* anomalies, calculated relative to the 9 year mean, emphasise temporal variability of phytoplankton biomass in the Black Sea, particularly between the riverine-influenced Northwest shelf and the open Black Sea. Evolution of phytoplankton biomass has shown significant spatial variability of the 'system memory' between three major regions of the Black Sea. With the exception of 2001, chl *a* has generally decreased during our 9 year time-series. However, the winter of 2000-2001 was anomalously warm with low wind stress, resulting in reduced vertical mixing of the water column and retention of nutrients in the photic zone. These conditions were associated with anomalously high levels of chl *a* throughout much of the open Black Sea during the following spring and summer. The unusual climatic conditions occurring in 2001 may have triggered a shift in the Black Sea's chl *a* regime. The long-term significance of this recent shift is still uncertain but illustrates non-linear response to climate forcing that makes future ecosystem change in the pelagic Black Sea ecosystem difficult to predict.

The attached article, entitled "Non-linearities, regime shifts and recovery: The recent influence of climate on Black Sea chlorophyll", contains original, unpublished data and results and is of immediate interest to oceanographers and marine biologists/ecologists. Climate researchers and environmentalists interested in the role of plants in the marine ecosystem would also find our findings particularly pertinent as well as researchers interested in anthropogenic impacts on the marine ecosystem. We hope that you will consider this manuscript for publication in Journal of Marine Systems.

Yours Sincerely,  
Abigail McQuatters-Gollop (corresponding author), Laurence D. Mee, Dionysios E. Raitsos, Georgy I. Shapiro

Figure 1

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**Figure 2**

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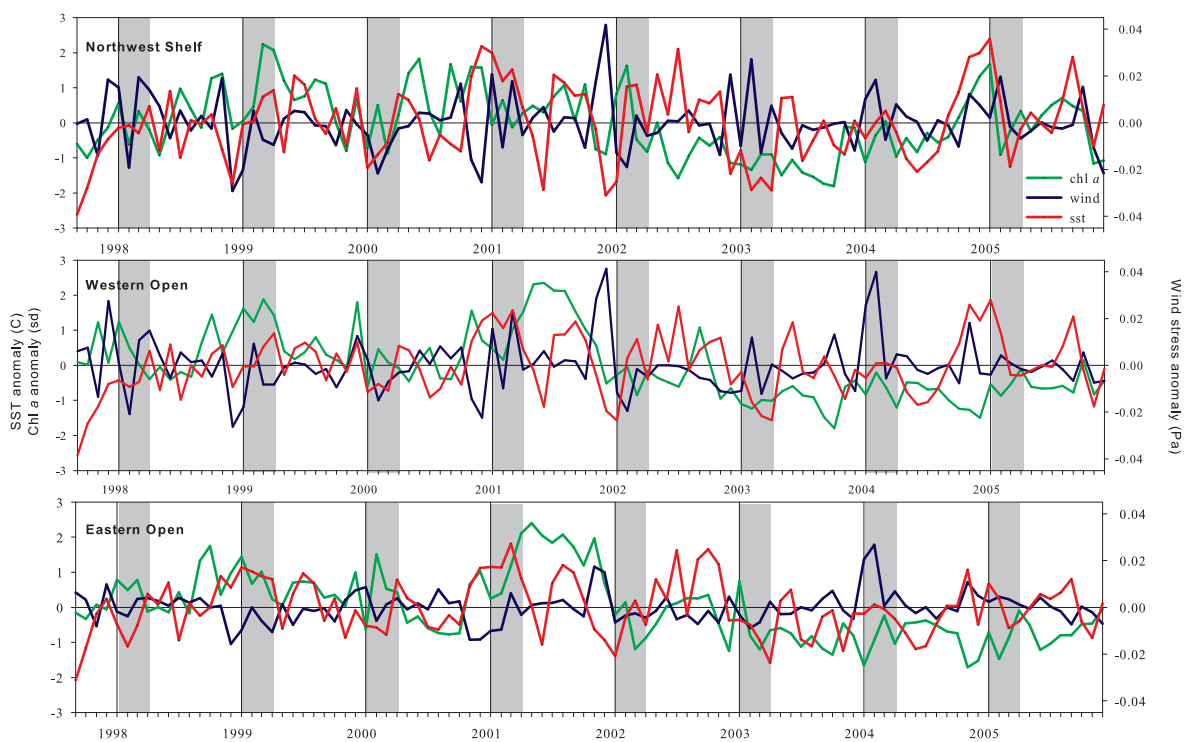
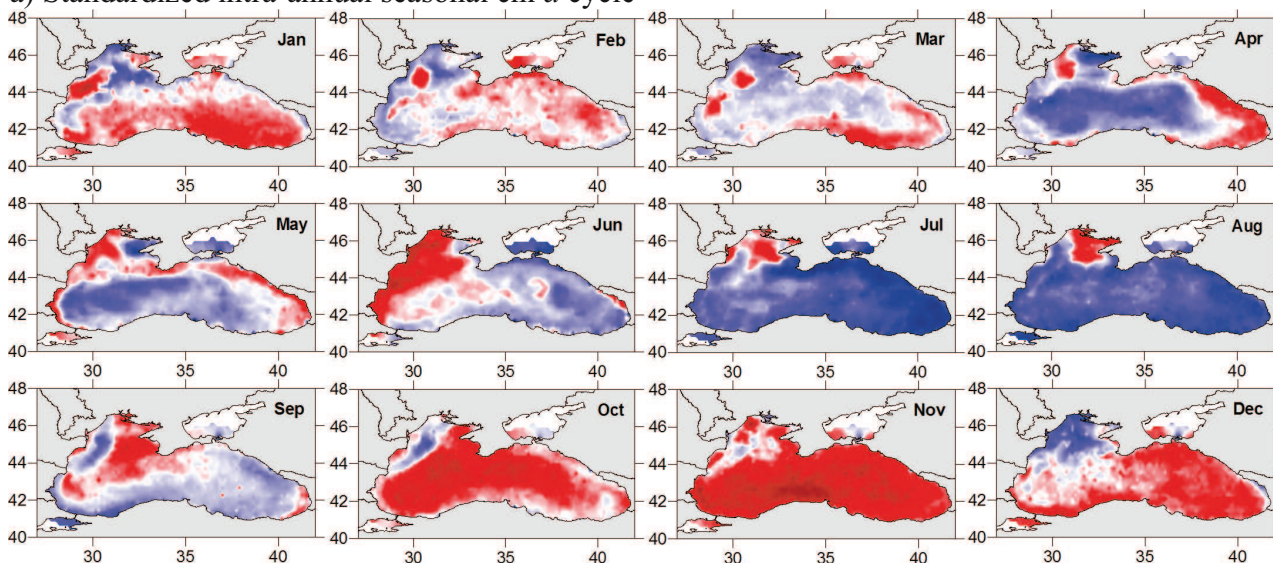


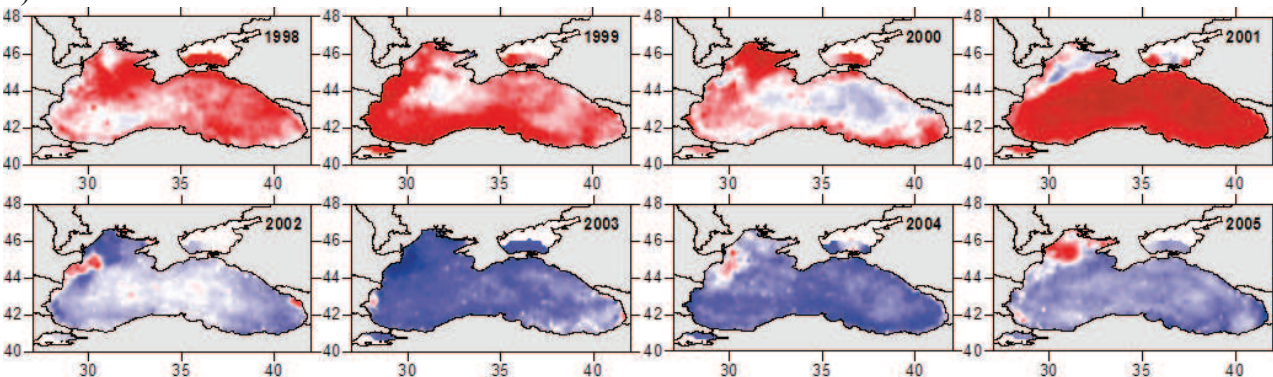
Figure 3

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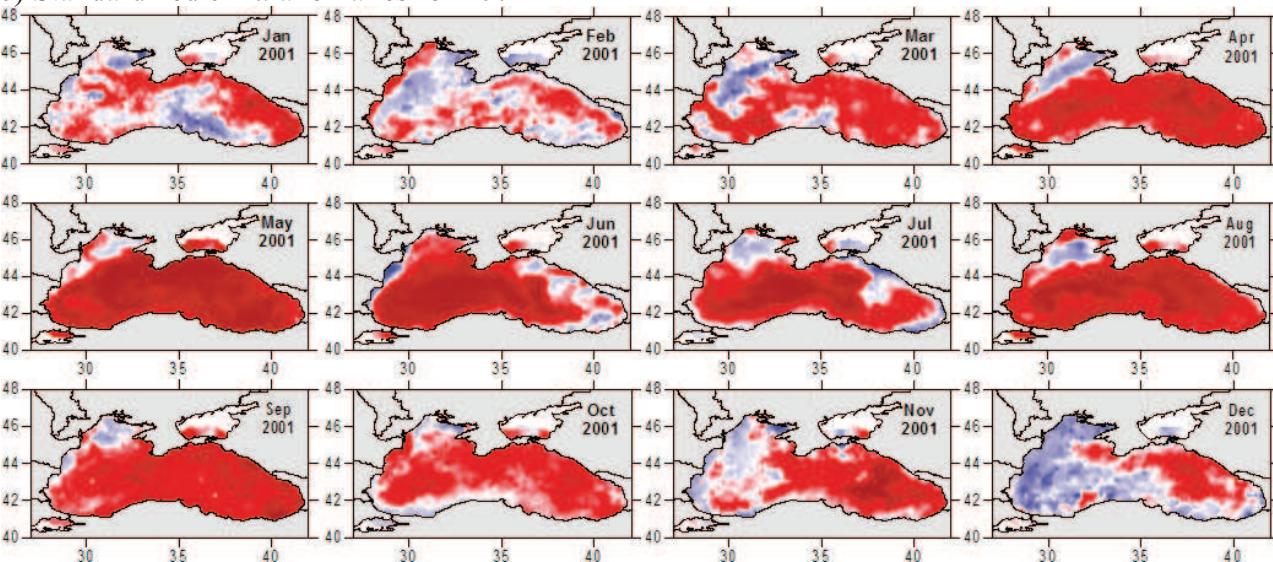
a) Standardized intra-annual seasonal chl *a* cycle



b) Standardized inter-annual chl *a* anomalies



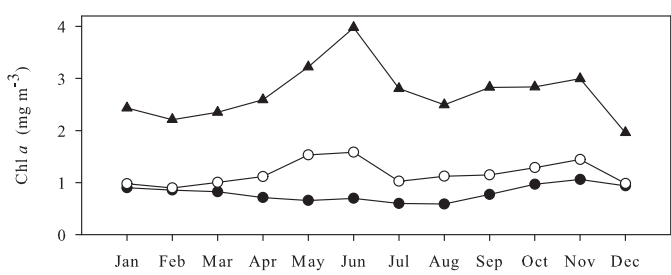
c) Standardized chl *a* anomalies for 2001



Standard deviations from mean

Figure 4

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**Figure 5**

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