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1 Influence of **ocean - lagoon** exchanges on spatio-temporal variations of
2 phytoplankton assemblage in an Atlantic **Lagoon** ecosystem
3 (Oualidia, Morocco)

4
5 Laila Somoue^a, Herve Demarcq^b, Ahmed Makaoui^a, **Karim Hilmi^a**, Omar Ettahiri^a,
6 Abdelouahed Ben Mhamed^a, Aziz Agouzouk^a, Tarik Baibai^a, Jamila Larissi^a, Said
7 Charib^a, Abdelkrim Kalmouni^a, Mohamed Laabir^{c*}

8
9 ^a *Institut National de Recherche Halieutique (INRH), Bd Sidi Abderrahmane, Ain Diab*
10 *Casablanca, Morocco*

11 ^b *MARBEC, IRD, IFREMER, CNRS, Montpellier University, Sète, France*

12 ^{c*} *MARBEC, Montpellier University, IRD, IFREMER, CNRS, Place Eugène Bataillon,*
13 *Montpellier, France*

14
15

Corresponding author mohamed.laabir@umontpellier.fr (**M. Laabir**)

16
17 **ABSTRACT**

18 The Oualidia **Lagoon** is a semi enclosed marine ecosystem connected to the Atlantic Ocean
19 of Morocco and exposed to human activities, mainly agriculture and oyster farming. The
20 present study aims to characterize the spatio-temporal variation of the phytoplankton
21 assemblage and to highlight the effect of **the main** environmental parameters on this
22 important planktonic component evolving in a vulnerable anthropized ecosystem. For this
23 purpose, a field survey was carried out during four seasons in 2011 to determine the biotic
24 (phytoplankton, chlorophyll a) and abiotic (temperature, salinity and nutrients) **variables**
25 during low and high tide periods. Results highlight an established spatial variation of
26 physico-chemical parameters especially at low tide, **with contrasted environmental conditions**
27 **between the upstream and downstream zones**. The phytoplankton diversity and abundance
28 were characterized by a pronounced seasonal pattern. The Oualidia **Lagoon** is a nutrient rich
29 ecosystem, especially in its upstream part. **We also** showed that both planktonic diversity and

30 abundance were maximum in autumn and summer. The phytoplankton richness is governed
31 by two main factors: the seasonality of nutrient enrichment and the regular supply of Atlantic
32 seawater. Nitrate and ammonium were the main environmental abiotic factors determining
33 the development of phytoplankton populations. The dynamic of phytoplankton in the
34 Oualidia Lagoon is highly influenced by marine waters incoming from the Atlantic Ocean
35 especially during the upwelling season. Finally, potential harmful algal species belonging to
36 different genera such as *Pseudo-nitzschia*, *Alexandrium*, *Prorocentrum*, *Dinophysis*,
37 *Ostreopsis*, *Karenia*, *Coolia*, *Gonyaulax*, *Gymnodinium*, *Dictyocha* and *Chattonella* were
38 encountered showing a potential in this ecosystem to develop noxious blooms.

39

40 **Key words:** Oualidia Lagoon, Phytoplankton, Environmental factors, African Atlantic coast,
41 Ocean - Lagoon exchange

42

43 HIGHLIGHTS

- 44 - The spatio-temporal variation of phytoplankton assemblage (biodiversity and
45 abundance) was driven by environmental constraints from both land and sea
- 46 - The taxonomic richness was dominated by typical marine species
- 47 - The inventoried taxa were dominated by diatoms and dinoflagellates when
48 considering both species number and density
- 49 - Potential Harmful Algal Blooms species, belonging to different genera such as
50 *Pseudo-nitzschia*, *Alexandrium*, *Prorocentrum*, *Dinophysis*, *Ostreopsis*, *Karenia*,
51 *Coolia*, *Gonyaulax*, *Gymnodinium*, *Dictyocha* and *Chattonella* were encountered
- 52 - The warm season (August and October) showed the highest values of phytoplankton
53 species diversity and densities particularly upstream

54

55 1. Introduction

56 Coastal Lagoons are among the most productive marine ecosystems, however they remain
57 fragile and are often exposed to multiple natural and anthropogenic constraints (Kjerfve,
58 1994). Lagoons are highly productive areas that are located in the transitional areas at the
59 land-ocean boundary (Perez-Ruzafa et al., 2012). These areas have become important
60 because they provide the key to understanding the general dynamics of the seas they are

61 connected with. Their existence and their influence on the coastal zones have become a
62 fundamental study topic in many disciplines (Basset et al., 2012). A better knowledge of the
63 functioning of these ecosystems is required to ensure their sustainable management (Rharbi et
64 al., 2001; Rosa et al., 2019). The Oualidia Lagoon, located on the Atlantic coast of Morocco
65 (Africa), was registered as a RAMSAR site (International convention of wetlands
66 conservation) since 2005 (Maanan et al., 2014) because of its great ecological and socio-
67 economic importance. It holds an increasing touristic activity and it is one of the most
68 important Moroccan zones for oyster farming since 1950 (Rharbi et al., 2001). Other socio-
69 economic activities in this area includes intensive agriculture, livestock, fishing, and salt
70 mining. Local residents exploit mussels (*Perna perna* and *Mytilus galloprovincialis*) fixed on
71 the rocks and reef flats and collect clams (*Ruditapes decussatus*) (Maanan et al., 2014; Jayed
72 et al., 2015). Phytoplankton community in coastal Lagoons are a major component of the
73 food web structure and functioning and supply the major source of organic carbon (Gaikwad
74 et al., 2004). Phytoplankton sensitivity to environmental changes and the fluctuation of its
75 specific composition are precious indicators of alterations of the whole ecosystem (Devassy
76 and Goss, 1988). Phytoplankton species diversity is sensitive to environmental parameters, a
77 slight modification in the state of the environment could modify this diversity (Ghsoh et al.,
78 2012). As an example, nutrients supply, driven either from land or from the ocean through
79 tidal influence have been shown to influence the phytoplankton activity, and consequently the
80 functioning of communities in Lagoons (Sylaios and Theocharis, 2002).

81 To our knowledge, studies on phytoplankton in African Atlantic coastal ecosystems are rare.
82 The only study on qualitative and quantitative distribution of phytoplankton in Oualidia
83 Lagoon was carried out from January to December 1997 by Bennouna et al. (2000). They
84 showed that diatoms were the dominant organisms at most times (70 to 98% of the
85 phytoplankton population). However, the performed studies in Oualidia focused mainly on
86 Harmful Algal Blooms (HABs) species (Bennouna, 1999; 2000, 2002) and were carried out
87 in a limited number of stations. Taleb et al. (2002) showed that maximum Paralytic Shellfish
88 Poisoning (PSP) toxin level recorded in mussel from Oualidia Lagoon during the November
89 1994 was up to 2500 $\mu\text{g Eq STX.100 g}^{-1}$ of shellfish meat which is much higher than the
90 regulatory international threshold of 80 $\mu\text{g Eq STX 100 g}^{-1}$ of shellfish meat. Both the
91 dinoflagellates *Alexandrium minutum* and *Gymnodinium catenatum* were suspected to be the
92 causative species but without formal identification. Bennouna et al. (2002) reported the
93 occurrence of the dinoflagellate *Lingulodinium polyedrum* causing red tides along the

94 Moroccan Atlantic coast including Oualidia Lagoon in July 1999. More recently, Daghor et
95 al. (2018) reported an intense bloom of the dinoflagellate *Karenia sp.* the Oualidia Lagoon
96 with concentrations up to 1.04×10^7 cells L⁻¹. Here we conducted a field study covering for
97 the first time the entire Lagoon from downstream to upstream during four seasons in 2011
98 with three main objectives : 1) to highlight the diversity of microphytoplankton species of the
99 Oualidia Lagoon on a seasonal basis, 2) to investigate the effect of environmental factors on
100 the spatio-temporal variation of phytoplankton communities and 3) to highlight the influence
101 of ocean - Lagoon exchange on spatio-temporal variations of phytoplankton assemblage in
102 this African Atlantic Lagoon ecosystem.

103

104 2. Material and Methods

105 2.1 Study area

106 The Oualidia Lagoon located 76 km south of El Jadida and 67 km north of Safi (Fig. 1) is one
107 of the most important coastal ecosystems on the Moroccan Atlantic coast. This Lagoon is 7
108 km long and 0.5 km wide, with a total area of 3.5 km² (Hilmi et al., 2005; 2009 ; Maanan et
109 al., 2014) and widely connected with the Ocean through a major inlet (150 m wide and 2 m
110 deep) and a secondary pass active in open sea during the highest tides (Mejjad et al., 2016;
111 Maanan et al., 2014). The Lagoon is composed of a network of very narrow dendritic
112 channels, connected to a main channel of 6.5 km long and 2 m depth in average with a
113 maximum of 5 m during high tides (Bidet and Carruesco, 1982). The intertidal zone (75% of
114 the Lagoon surface) is predominantly sandy with rare slicks. The upper part of the Lagoon
115 (0.6 km²) is composed of salt marshes. The Oualidia climate is arid to semi-arid, maximum
116 temperatures of up to 40°C in summer were recorded when an Eastern warm wind (Chergui)
117 blows. However, generally, the mean daily atmospheric temperature varies between 21°C and
118 22°C in summer and between 14°C and 15°C in winter (Bennouna et al., 2002). The low and
119 seasonal rainfalls account for 1% of the fresh water entering the Lagoon and the rest is
120 coming from groundwater. The annual cumulative rainfall in 2011 are 442.3 mm (maximum
121 of 331.9 mm during January-June 2011 and 110.4mm during July-December; data from
122 National Meteorological Services). The annual hygrometric deficit was 650 mm. The
123 predominant wind directions are WSW to NW during the wet season and NNE to NE during
124 the dry season (Zourarah, 2002; Zourarah et al, 2007; Mejjad et al., 2016). The hydrological
125 regime of the Lagoon is tightly associated with the tidal rhythm (Orbi et al., 2008; Hilmi et

126 al., 2005, 2009). A high nutrient input is favored by rising tides in the Lagoon, which
127 increases organic production and improves aquaculture yields (Maanan et al., 2014). Makaoui
128 et al. (2005) reported that the Lagoon is more influenced by the oceanic input of nutrients
129 particularly the case of PO₄ in reason of upwelling events. Mejjad et al. (2016) suggested that
130 seasonal and diurnal nutrient variability in the Oualidia Lagoon results from the influence of
131 the water continental inputs, precipitation and evaporation regimes as well as oceanic-Lagoon
132 exchanges. There are no river discharging into the Lagoon, but several authors have
133 mentioned the existence of underground freshwater seepage probably in the first part of the
134 Lagoon and upstream (Carruesco, 1989; Hilmi et al., 2005, 2009; Rharbi et al., 2001).
135 Several authors (Hilmi et al., 2005; 2009, Koutitonsky et al., 2006; 2012) have studied the
136 tidal regime and the water circulation in the Oualidia Lagoon. They concluded that this
137 marine system is governed by the semi-diurnal tide (M2 tide) which dominates in the Atlantic
138 Ocean. The tide's amplitude reaches around 3 m at the entrance of the Lagoon during the
139 spring tides, and around 0.8 m during the neap tides. Due to the complex topography and the
140 small depths observed upstream of the Lagoon, tides are asymmetric in nature and the
141 amplitude of M2 tide is decreasing due to the friction on the bottom. On average, the
142 maximum and minimum depths in the Lagoon are 5 m and 1.5 m, respectively (Bennouna et
143 al., 2002). A maximum of 77% or 52% of the channel volume is flushed during one spring or
144 neap tide, respectively (Hilmi *et al.*, 2005). Carruesco (1989) estimated a renewal of 89% or
145 72% of the Lagoon waters during one spring or neap tidal cycle, respectively. Using 2D
146 hydrodynamic model, Hilmi *et al.* (2005) found that tidally averaged renewal time for the
147 whole Lagoon was 7 days, while the local renewal time at the upstream end of the Lagoon is
148 25 days. Oyster farming is the most widespread aquaculture activity in the Oualidia Lagoon.
149 The average annual production of oysters is estimated to be 250 tons (Rharbi, 2000).

150

151 2.2. Sampling and measurements

152 Six stations along Oualidia Lagoon were sampled monthly from downstream to upstream
153 during representative months of the four seasons of 2011: winter (February), spring (May),
154 summer (August) and fall (October) (Fig. 1). Water sampling was performed using an
155 hydrobiological bottle at subsurface (-0.5 m depth). The maximum depths of the stations
156 ranged between 0.5 to 3.5m at low tide and 2 to 6.5m at high tide.

157 2.2.1 Abiotic factors

158 Temperature, salinity and nutrients (nitrate, ammonium and phosphates) were measured in all
159 stations during low and high tides. Temperature and salinity were determined using a probe
160 WTW LF195. 500 ml of seawater was filtered (0.45 μm) and conserved at $-20\text{ }^{\circ}\text{C}$ until the
161 analyses of nutrients performed spectrophotometrically according to the method of Aminot
162 and Kerouel (2004).

163

164 2.2.2. Biotic factors

165 Chlorophyll *a* (Chl-*a*) measurements were performed from 500 ml seawater samples filtered
166 throughout 47 μm Whatman GF/F filter during low and high tides. Chl-*a* was extracted from
167 filters immersed in 10 ml 90 % acetone for 24 h in the dark at $-4\text{ }^{\circ}\text{C}$ (Strickland and Parsons,
168 1972, Linder,1974), and analyzed using a fluorometer 10-AU (Turner Design).

169 Determinations of phytoplankton species and abundances were made from 100 ml of sea
170 water fixed using Lugol's iodine. Phytoplankton counts were done for samples of only high
171 tides. Phytoplankton counts were carried out according to the Utermöhl (1958) method and
172 the determination of the different taxa was made by inverted light microscopy (Nikon) with
173 appropriate identification keys (Trégouboff and Rose, 1957; Nezan and Piclet, 1996; Tomas,
174 1997; Botes, 2003). Phytoplankton abundance was expressed in cells L^{-1} . The frequency of
175 taxa, expressed in%, was calculated using formula :

176 $F = (\mu_i / \mu_T) * 100$ (μ_i = number of samples in which species is present and μ_T = total number
177 of samples).

178

179 2.3 Data analyses

180 Each station was characterized by a specific assemblage of microphytoplankton described by
181 its species richness (RS) index (number of species recorded), total density (D), Shannon
182 diversity H index (Shannon and Weaver, 1949).

183 Species diversity (H) was calculated using Shannon's formula:

$$184 H = \sum_{i=1}^S n_i/N * \log_2 n_i/N$$

185 Where, S = specific richness (number of species); n_i = abundance of species *i* and N = total
186 abundance of all species.

187 PCA and Co-inertia analysis were performed with the ADE4 package in the R software (Dray
188 and Dufour, 2007) to evaluate the associations between species composition and
189 environmental variables. A redundancy analysis (RDA) as developed by Van Den
190 Wollenberg (1977) was carried out in place of the co-inertia analysis and have given very
191 similar results. The considered taxa were diatoms and dinoflagellates with percentage of
192 occurrence $\geq 40\%$. The abbreviated names of species are given in table 2. Only data related to
193 high tide sampling were considered for the environmental parameters, since phytoplankton
194 was only taken at high tide period. The abundances were transformed into $\log(X + 1)$ to
195 minimize differences in numbers.

196

197 **3. Results**

198 *3.1. Abiotic factors and chlorophyll a*

199 *3.1.1. Temperature and salinity*

200 In May (spring) and October (autumn), the temperature did not undergo diurnal variations
201 both upstream and downstream and temperature ranged between 20 and 22.5 °C at low tides
202 (LT) and high tides (HT). In August (summer season) at HT, upwelling marine waters cool
203 the Lagoon waters with the lowest registered temperature (15.5 °C), while at LT the
204 temperature ranged between 20 °C and 24 °C, at downstream and upstream, respectively. In
205 February (winter), marine inputs tend to warm the Lagoon waters and temperature increased
206 from 15 °C to 18 °C (Fig. 2a, b and Appendix 1). The Lagoon is highly influenced by marine
207 waters (salinity of 35) at HT, with salinity exceeding 35 at all stations (a maximum of 36.5)
208 except at station 6 (located upstream) where an average salinity of 30 was recorded. In
209 contrast, at LT, the Lagoon waters were characterized by a salinity increasing from 23 at
210 upstream to 36 at downstream of the Lagoon (Fig. 2).

211

212 *3.1.2. Nutrients*

213 The Oualidia Lagoon was characterized by relatively high nutrient concentrations, generally
214 at LT, with values increasing upstream (Fig. 3). Nitrate (NO₃) showed the highest
215 concentration in August and October (up to 30 μM and 20 μM, respectively) at HT (Fig. 3b).
216 At LT, February and May were characterized by the highest concentrations with values of up

217 to 30 and 40 μM respectively at station 6 upstream (Fig.3a). Phosphates (PO_4) ranged
218 between 1.3 and 4 μM at HT (in February, May and August) and between 0.8 and 2.5 μM at
219 LT (in August and May, Fig. 3c and d). October was globally the least rich month in PO_4 ,
220 especially at HT ($< 1\mu\text{M}$) and February at LT (Fig. 3d). Temporal variation in ammonia
221 (NH_4) concentration was observed with high levels (up to 30 μM) in August and October at
222 HT (Fig. 3f). NH_4 concentrations remain low in February and May ($< 3\mu\text{M}$) during HT (Fig.
223 3f). At LT, the highest levels of NH_4 (17-24 μM , maximum in May) were recorded (Fig. 3e),
224 whereas all other concentrations were lower than 6 μM during all other seasons.

225

226 3.1.3. Chlorophyll a

227 The highest chlorophyll a (Chl-a) concentrations during the survey were observed in August
228 with maximal values of 6 $\mu\text{g L}^{-1}$ at LT and 3.89 $\mu\text{g L}^{-1}$ at HT. During this period, Ch-a at all
229 stations, was $> 4\mu\text{g L}^{-1}$ at LT and $< 4\mu\text{g L}^{-1}$ at HT. For the other seasons, Chl-a
230 concentrations were $< 2.1\mu\text{g L}^{-1}$ (Fig. 4). The maximum Ch-a for each period was observed
231 in LT when compared to HT.

232

233 3.2 Microphytoplankton

234 3.2.1. Taxonomic composition

235 The phytoplankton of the Oualidia Lagoon covers six groups and 114 taxa. Diatoms and
236 Dinoflagellates were the most represented in term of species, with 68 and 40 taxa,
237 respectively. In contrast, Silicoflagellates, Euglenophytes and Raphidophytes were poorly
238 represented (Table 1). Diatom species dominated the microphytoplankton in all stations and
239 seasons (Fig. 5), with a relative abundance exceeding 80 %. However, Dinoflagellates
240 accounted for 50 % of microphytoplankton in St2 in May and St6 in August and were
241 represented mainly by *Scrippsiella sp.* and *Peridinium quadridentatum*.

242

243 3.2.2. Specific richness and specific diversity

244 The number of taxa recorded per station varied between 13 and 42. October and particularly
245 August showed the highest numbers of taxa (generally ≥ 32) in contrast with February and

246 May (13-33 taxa) situations (Fig. 6a). The highest specific richness was observed upstream,
247 at station 5 (27-40 taxa). The Shannon (H) index values of phytoplankton were generally > 3
248 during all periods. In summer, microphytoplankton was more diversified (H > 4), mainly
249 downstream (maximum of 4.7) compared to upstream (3.3). The lowest diversity (2.5) was
250 observed at Station 5 in May, due to the important proliferation of the diatom *Nitzschia spp*
251 (Fig. 6b).

252

253 3.2.3. Distribution of microphytoplankton densities

254 The distribution of phytoplankton abundance was very heterogeneous along the Lagoon. The
255 highest densities (Fig. 7) were observed in October (2.20×10^4 cells L⁻¹ and 4.46×10^4 cells L⁻¹)
256 and August (1.42×10^4 to 3.09×10^4 cells L⁻¹), with a peak in St6 (6.92×10^4 cells L⁻¹) due to the
257 proliferation of several diatom species (*Thalassiosira spp.*, *Surirella sp.*, *Chaetoceros spp.*)
258 and the dinoflagellate *Peridinium quadridentatum*. Low densities were recorded in February
259 and May (0.4×10^4 cells L⁻¹ and 1.95×10^4 cells L⁻¹).

260

261 3.3. Effects of the environmental factors

262 The links between species composition and environmental variables was established using a
263 co-inertia analysis. The necessary preliminary step was to perform a centered PCA (Principal
264 Component Analysis) in order to evaluate the spatiotemporal distribution of taxa
265 independently of the environmental variables (Fig. 8). The analyzed matrix includes
266 observations from all stations as summarized in Table 2. The abundances were transformed
267 into log (X + 1) to account for the data distribution skewness and make them closer to a
268 normal distribution. The first two axes of the factorial plane F1 X F2 represented 41% of the
269 total inertia for the PCA. The PCA revealed important differences in species associations
270 (Fig. 8a) between seasons and few differences between stations (Fig. 8b). The species are
271 well scattered in the F1 x F2 factorial plane. Two main groups of taxa have emerged: Group I
272 mostly associated to August and October periods and was represented mainly by marine
273 species frequently encountered in Atlantic coastal waters. Some of them are considered to be
274 upwelling indicators (*Chaetoceros*, *Pseudo-nitzschia*, *Thalassiosira*, *Leptocylindrus danicus*
275 and *Gymnodinium* : Elghrib et al., 2012). Group II was mainly associated with February and
276 May periods (Fig. 8a), and was mainly represented by brackish or freshwater species

277 belonging to *Surirella*, *Paralia* and *Navicula* genera, frequently observed in this Lagoon. The
278 equivalent PCA was performed on the environmental variables only (plot not shown) and
279 indicated that the environmental parameters (72% of the variability accounted for the first
280 two axis) were contrasted between seasons, driven by an axis of variable salinity (46%) and
281 Temperature axis (26%) with nutrients evenly balanced between both.

282 The co-inertia analysis revealed the seasonal effect of environmental factors of the species
283 associations (Fig. 9). The first axis F1 was described by NO₃ and mainly NH₄. There was a
284 clear separation between the salinity and nutrients particularly NO₃ and NH₄. Temperature
285 contributed significantly to the formation of the F2 axis. It was opposite to the nutrient
286 especially to the PO₄ (Fig. 9a). A separation between the different periods was also clearly
287 visible. The stations of each period, with few exceptions, formed a single group (Fig. 9c).
288 August and October periods are highly diversified and correspond to an important
289 development of many phytoplankton taxa resulting from a NO₃ and NH₄ supply from the sea.
290 In these two periods, the close relationship between environmental factors and taxa is
291 generally well marked (Fig. 9c). August was characterized by low temperatures ranging
292 between 15 °C and 17 °C and high levels of nutrients mainly NO₃ (from 9 to 11 µM with a
293 maximum of 33.3 µM at station 6). This upstream station was characterized by highly
294 contrasted environmental and biological parameters including low salinities (29.5), high
295 temperature (22.8 °C) and high levels of nitrogen nutrients (32-33.3 µM). In August (Fig. 9b)
296 several taxa (Group II) such as *Navicula*, *Diploneis*, *Pleurosigma* and *Surirella* were
297 dominant whereas their abundance in the other periods were generally low; which suggest
298 their preference for cold waters and the availability of nitrogen nutrients mainly NO₃.
299 October was characterized by high temperatures (20 °C to 21.2°C), very low levels of PO₄
300 (<1 µM) and high levels of nitrogen mainly in NH₄ (31 µM). This month was marked by the
301 proliferation of dinoflagellates taxa (Fig. 9b) such as *Scrippsiella* (700 cell L⁻¹),
302 *Protopteridinium* (800 cells L⁻¹), and harmful or potentially toxic taxa such as *Pseudo-*
303 *nitzschia* (9700 cells L⁻¹), *Prorocentrum* (900 cells L⁻¹), and *Dinophysis* species (400 cells L⁻
304 ¹) including *Dinophysis caudata*; *Dinophysis acuminata* and *Dinophysis fortii*. February and
305 May were characterized by low levels of NH₄ (0.4-8 µM) but an important level in
306 phosphates (1.4- 3.7 µM), compared to August and October (PO₄ : 0.4- 2 µM). At February
307 and May, phytoplankton richness was low (Fig. 9b) where a few taxa (Group III) such as
308 *Diplopsalis*, *Thalassionema nitzschoides* and *Alexandrium* showed relative high abundance.

309

310 4. Discussion

311 Data showed that Oualidia Lagoon is characterized by important tidal variations of the
312 environmental parameters in all sampled stations and across seasons, with consequences on
313 the dynamic of phytoplankton assemblages. Tidal differences in temperature were highly
314 marked in February and August. In the summer months, the seasonal upwelling of the
315 Atlantic coast cools the Lagoon waters and water fill the entire Lagoon at high tides. The
316 salinity at HT was similar to that prevailing in the open Atlantic Ocean, with decreasing
317 values from downstream to upstream (St1 to St6). At LT, the decreasing gradient of the
318 salinity from St1 to St6 was more pronounced. The permanent occurrence of freshwater
319 resurgences (Rharbi et al., 2003; Hilmi et al., 2009) in the Lagoon influences the distribution
320 of salinity, mainly upstream where desalination reached its maximum (22.9). Nutrient
321 concentrations, particularly nitrates, increased from downstream to upstream. At LT, the
322 present study confirmed the results of several authors (Mejjad et al., 2016; Rharbi et al.,
323 2003) who indicated the presence of an increasing gradient downstream-upstream in nutrients
324 and a decreasing gradient for salinity. This is due to the hydrodynamic characteristics of the
325 Lagoon (Mejjad et al., 2016; Hilmi *et al.*, 2005, 2009) as the marine influence is marked
326 downstream because of the change to Lagoon-oceanic connection (Fig. 1). The stations
327 located upstream were more influenced by the continental enrichment together with
328 freshwater resurgences likely rich in nutrients in this part of the Lagoon. This enhances the
329 development and the richness of phytoplankton upstream. The upstream zone is enriched in
330 nitrogen due to agricultural activities and even downstream area is enriched through tidal
331 currents (Rharbi et al., 2003; Bennouna, 1999). These authors suggested that Chl-a
332 concentration increased upstream and this is confirmed by our observation mainly at LT for
333 chlorophyll recorded values. Tidal currents were shown to be higher downstream of the
334 Oualidia Lagoon (Hilmi et al., 2005, 2009; Koutitonsky et al., 2006). Thus, the considerable
335 reduction in the hydrodynamic intensity in the upstream area could favor not only the
336 phytoplankton development as shown in our study but also the benthic fauna as suggested by
337 other authors (Bidet and Carruesco, 1982; Elasri et al., 2015, 2017). Kamara et al. (2008)
338 pointed out that the upstream part of the Lagoon was a stable area and was therefore suitable
339 for Clams growth.

340 In terms of seasonal variability, the waters of the Lagoon were rich in nitrates and ammonium
341 during all seasons of 2011. The higher concentrations occurred generally at LT, especially in
342 spring (May), where NO_3 and NH_4 were at $\text{LT} > 35\mu\text{M}$ and $20\mu\text{M}$, respectively. They did not

343 exceed 9 μM at HT. The registered high concentrations of NO_3 at LT are in favor of
344 anthropogenic origin due mainly to agriculture, freshwater resurgence and urban discharges.
345 High levels of PO_4 are observed at HT, particularly in February, with a maximum of $3\mu\text{M}$,
346 reflecting the significant oceanic input of PO_4 during this season, and probably NH_4 during
347 August and October. These conclusions are corroborated with the study of Makaoui et al.,
348 (2005) who reported that the Lagoon is more influenced by the oceanic input of nutrients
349 particularly PO_4 in reason of upwelling events. Mejjad et al. (2016) suggested that seasonal
350 and diurnal nutrient variability in the Oualidia Lagoon results from the influence of the water
351 continental inputs, precipitation and evaporation regimes as well as oceanic-lagoon
352 exchanges.

353 The observed variability in nutrients concentrations have direct effect on the development of
354 phytoplankton with high Chl-a concentrations observed in August (values of $3.89 \mu\text{g.l}^{-1}$ at HT
355 and $6.52 \mu\text{g.l}^{-1}$ at LT). Interestingly the values of Chl-a are high despite moderate
356 microphytoplankton concentrations in Oualidia. This could be explained by the potential
357 contribution of other groups as pico and nano-phytoplankton. Further studies have to focus on
358 the distribution and abundance of these groups, their contribution to the total chlorophyll
359 biomass and to quantify potential relationships linking their temporal changes to
360 environmental factors. Our results corroborated those of Garcia Olivia et al. (2018) who
361 suggested that the functioning of the coastal lagoons and their biological assemblages are
362 strongly determined by the environmental conditions of each Lagoon and by the connectivity
363 that these environments maintain with the adjacent sea. At the same time, the hydrodynamic
364 behavior of coastal lagoons plays a crucial role in their functioning, not only in terms of
365 water quality conditions, but also in terms of environmental range for species inhabiting the
366 Lagoons, species connectivity, and fishing capacities (Pérez-Ruzafa et al., 2012; 2018,
367 Gamito et al., 2005). Our results show that most of the environmental variables including
368 nutrients are influenced by hydrodynamic and tidal rhythm in the Oualidia Lagoon.

369 Studies on phytoplankton diversity and dynamic in Oualidia are rare; the obtained data
370 characterizing the spatio-temporal variations of abundance and diversity of
371 microphytoplankton would help us to better understand the functioning of this human
372 impacted ecosystem but also may contribute to sustainable management of the aquacultural
373 resources as the reared mollusk *Crassostrea gigas*. Our results suggest that in terms of
374 phytoplankton, the Lagoon of Oualidia is a highly diversified ecosystem, well structured and
375 balanced in phytoplankton populations during all the periods and particularly in August. The

376 Shannon index values ranged between 3 and 4.69 bits suggesting the influence of oceanic
377 waters on the phytoplankton populations of the Lagoon. Ghosh et al. (2012) suggested that
378 high diversity indices reflect a healthy ecosystem when the opposite is a sign of degraded
379 environment. Our data corroborated those of Bennouna (1999; 2000) who showed that the
380 diversity indices of phytoplankton in Oualidia were high (3 to 4.5 bits) and approached those
381 observed in oceanic environment. The phytoplankton of Oualidia Lagoon was represented by
382 five groups, with diatoms and dinoflagellates being the most dominant taxa when considering
383 both species number and density. During our survey, diatoms dominated upstream and
384 downstream during the different seasons, with the exception of St2 in May and St6 in August
385 which showed an important development of two dinoflagellate species *Scrippsiella sp.* and *P.*
386 *quadridentatum*. These results corroborated those of Elghrib et al. (2012) and Demarcq and
387 Somoue (2015) who showed that diatoms are dominating in Moroccan Atlantic coastal
388 waters. Bennouna, (1999; 2000) reported that the Oualidia Lagoon was characterized by the
389 dominance of diatoms almost 10 years ago. Other studies showed that diatoms and
390 dinoflagellates dominate the phytoplankton in Moroccan Atlantic coastal ecosystems such as
391 Dakhla Bay (Saad et al. 2013), Moulay Bouselham Lagoon (Loumrhari et al., 2009) and
392 Cintra Bay (unpublished data) but also in Moroccan Mediterranean marine ecosystems (the
393 coastal waters M'diq Bay or Oued Laou : Rijal leblad et al., 2013 and the Nador Lagoon : El
394 Madani et al., 2011) but also in the Tunisian Mediterranean lagoons of Bizerte (Armi et al.,
395 2010) and the Cullera Estany spanish Lagoon (Pachès et al., 2014). Badylakande and Philips,
396 (2004) reported that the relatively high level of diatoms dominance in lagoons may in part be
397 attributable to tidal mixing energy and tidal water in flux. Diatoms are often more dependent
398 on and tolerant of environments characterized by strong vertical mixing energy, while the
399 turbulence of the water column at these sites may have a negative impact on the relative
400 success of dinoflagellates (Margalef et al. 1979; Smayda and Reynolds 2001). At the species
401 level, another feature of tidally mixed regions of the Lagoon is the presence of phytoplankton
402 taxa considered oceanic or neritic such as *Thalassionema nitzschioides* and *Skeletonema*
403 *costatum*. Overall, there was a general tendency for dinoflagellates to bloom during the warm
404 season, while the dominant diatoms bloomed over a broader temperature range (Badylakande
405 and Philips, 2004).

406 Phytoplankton in the Oualidia Lagoon was represented by 114 taxa, mainly dominated by
407 marine species, such as *Leptocylindrus danicus*, *Leptocylindrus minimus*, *Pseuonitzschia*
408 *delicatissima*, *Pseudo-nitzschia seriata*, *Thalassiosira*, *Chaetoceros*, *Dinophysis*,

409 *Protopteridinium*. Brackish or freshwater taxa were faintly encountered such as *Bacillaria*
410 *paxillifera*, *Epithemia*, *Euglena*. We also noted the presence of benthic species such as
411 *Amphora*, *Cocconeis*, *Licmophora*, *Nitzschia* indicated a mixing of the water column with a
412 sediment resuspension from the bottom favored by the hydrodynamic regime and the shallow
413 depth of the lagoon (Bennouna et al., 2000; Rharbi, 2000). Our results suggest that the
414 oceanic waters substantially influence the Oualidia lagoon. The present study highlights the
415 influence of the tidal currents in the Oualidia Lagoon on phytoplankton composition with
416 marine species entering at HT periods from the Atlantic Ocean.

417 In general, our results corroborated those obtained in macrotidal Atlantic Lagoons and
418 differed from those of Mediterranean ecosystems. In terms of seasonality, Rosa et al. (2019)
419 showed in their study on Ria Formosa lagoon (southwestern Iberia) that this Lagoon acted as
420 a source of material during Spring and Summer seasons, which contributed to increase the
421 biological productivity of the coastal ocean. Upwelling events that occurred more evidently
422 during the Autumn survey drove an import amount of nutrients into the Lagoon, enhancing
423 its biological productivity. Glé et al. (2008) showed that nutrient levels in Arcachon Bay (a
424 mesotidal coastal lagoon of 174 km² on the southwest Atlantic coast of France) seem to play
425 an important role in the control of phytoplankton primary production rates during the
426 productive period and explain their spatial, seasonal and inter-annual variability. Bennouna et
427 al., (2000) revealed that phytoplankton development in the Oualidia Lagoon, begins in May
428 and is marked by two peaks: in June (maximum 11.9×10^4 cells L⁻¹) and July (7.6×10^4 cells L⁻¹).
429 In August, phytoplankton concentrations are again low (0.25×10^4 to 0.71×10^4 cells L⁻¹),
430 then increase and fluctuate to give an autumnal peak in October and November. In Moulay
431 Bouselham Lagoon (located in Northern Moroccan Atlantic Ocean), Loumrhari et al., (2009)
432 emphasized that a maximum phytoplankton abundance was recorded from March to
433 September with a maximum of 3.6×10^4 cells L⁻¹. The minimum phytoplankton abundance
434 was recorded in February (9×10^3 cells L⁻¹). In the Nador Lagoon (Moroccan Mediterranean),
435 El Madani et al, (2011) have listed 311 phytoplankton species belonging to seven groups with
436 133 diatoms and 169 dinoflagellates species. The maximum phytoplankton abundance was
437 found in August due to the bloom of *Nitzschia longissima* (1.7×10^7 cells L⁻¹ at station located
438 in the N-W Beninsar area). The minimum abundance was recorded in November. In the
439 Tunisian North Lagoon of Bizerte, Armi et al., (2010) reported the importance of
440 environmental factors and nutrient inputs in structuring the biomass of phytoplankton
441 communities. According to Kjerfve (1986; 1994) and Umgiesser et al. (2014), coastal lagoons

442 can be subdivided into choked, restricted, and leaky systems based on the degree of water
443 exchange between lagoon and ocean. This exchange greatly influences the variability of
444 abiotic factors, thus controlling the abundance and composition of phytoplankton populations
445 and consequently the upper trophic levels in the lagoons. Oualidia Lagoon is considered to be
446 a leaky system (Hilmi et al., 2009), and is subject to a very significant oceanic influence.

447 In our study, the highest phytoplankton species diversity (> 4 bits) and density ($> 400 \times 10^2$
448 cells L^{-1}) were found in summer and autumn in the entire lagoon, particularly at St5 and St6.
449 This was due to the higher nutrient concentrations ($> 30 \mu M$) measured in the stations located
450 upstream and confirmed by the regularly high values of Chl-a recorded at all stations in
451 summer at LT. This zone was also exceptionally exposed to the sediment suspension rich in
452 organic matter, caused by the dredging of the sediment trap set up upstream in February
453 2011. This event could be responsible of the high levels of ammonium and nitrate measured
454 during May 2011, which could stimulate the phytoplankton development observed in August
455 and October 2011. Also, the nutrients input originating from continental shelf together with
456 freshwater resurgences and from Atlantic waters related to upwelling characterizing this
457 region mainly in summer and persisting in autumn (Makaoui et al., 2005) are probably
458 responsible of the observed enrichment of the Oualidia Lagoon waters. In contrast, Winter
459 (February) and Spring (May) periods showed the lowest values of species diversity and
460 phytoplankton cell abundances. Our results corroborated those of Rharbi (2000; 2001) who
461 reported that the Oualidia Lagoon is under the influence of the upwelling, causing a drop in
462 temperature together with high nutrient concentrations enhancing phytoplankton development
463 during spring and summer. Our results showed that nutrients seem to be the main
464 environmental abiotic factors determining the development of several phytoplankton
465 populations. In Oualidia, the phytoplankton diversity seems to be favored by a wide range of
466 temperature and salinity related to intense water exchanges with the Atlantic Ocean.
467 Phytoplankton showed a rapid response to modified nutrient levels through changes in
468 biomass and composition (Reynolds, 2006). Our field results show that nitrogenous
469 compounds (NO_3 and NH_4) could be responsible for the growth of many taxa such as
470 *Thalassiosira*, *Scrippsiella*, *Chaetoceros*, *Prorocentrum*, *Proto-peridinium* and *Surirella*
471 mainly in August and October, although they are less represented in space and during all
472 periods. Potential toxic or harmful species (Lassus et al. 2016; Moestrup et al. 2009), which
473 appear in the 'harmful algal bloom' list of the Intergovernmental Oceanographic Commission
474 of UNESCO, belonging to different genera such as *Pseudo-nitzschia*, *Alexandrium*,

475 *Prorocentrum*, *Dinophysis*, *Ostreopsis*, *Karenia*, *Coolia*, *Gonyaulax*, *Gymnodinium*,
476 *Dictyocha* and *Chattonella* were present in Oualidia, particularly in October. Even if their
477 concentrations were relatively low (unpublished data), they are subject to regular monitoring
478 program as Oualidia Lagoon holds important oyster farming and recreational activities.
479 Consequently, the ecology, the biology and the toxicity of these HABs species have to be
480 investigated.

481

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489

References

- Aminot, A., Kerouel R., 2004. Hydrologie des écosystèmes marins. Paramètres et analyses.
Ed. Ifremer.
- Armi, Z., Trabelsi, E., Turki, S., Bejaoui, B., Ben Maiz, N., 2010. Seasonal phytoplankton
responses to environmental factors in a shallow Mediterranean lagoon. J. Mar. Sci. Tech.
15, 417–426. <https://doi.org/10.1007/s00773-010-0093-y>
- Badylakande, S., and Philips, J., 2004. Spatial and temporal patterns of phytoplankton
composition in a subtropical coastal lagoon, the Indian River Lagoon, Florida, USA . J.
Plankton. Res. 26, 1229–1247.
- Basset, A., Barbone, E., Elliott, M., Li, B.-L., Jorgensen, S. E., Lucena-Moya, P., Pardo, I.,
Mouillot, D., 2012. A unifying approach to understanding transitional waters:
Fundamental properties emerging from ecotone ecosystems. Est. Coast. Shelf. Sci. 132, 5–
16. Doi: 10.1016/j.ecss.2012.04.012.

- Bennouna, A., 1999. Etude du phytoplancton du complexe lagunaire Oualidia-Sidi Moussa. Thèse de 3ème Cycle, Université Chouaib Doukkali, Faculté des Sciences. El Jadida. Maroc.
- Bennouna, A., Assobhei, O., Berland, B., 2000. Étude des populations phytoplanctoniques de la lagune de Oualidia (Maroc), dinoflagellés potentiellement nuisibles. *Mar. Life*. 10 (1-2), 3-18.
- Bennouna, A., Berland, B., AlAttar, J. Assobhei, O., 2002. Eau colorée à *Lingulodinium polyedrum* (Stein) Dodge dans une zone aquacole du littoral du Doukkala (Atlantique marocain). *Oceanol. Acta*. 25, 159-170.
- Bidet, J.C., Carruesco, C., 1982. Etude sédimentologique de la lagune de Oualidia (Maroc). *Oceanol. Acta*. 29-37.
- Botes, L. 2003. Phytoplankton Identification Catalogue Saldanha Bay, South Africa, April 2001. Globallast. Monograph. Series. N° 7. IMO, London.
- Carruesco, Ch., 1989. Genèse et évolution à l'holocène de trois lagunes de la façade atlantique : Moulay Bousselham, Oualidia (Maroc) et Arcachon (France). Thèse Doctorat d'Etat, Université de Bordeaux I. France.
- Daghor, L., Hssaida, T., Chaira, K., Bouthir, F., Fraikech, M., El Bouhmadi, K., 2018. The first occurrence of Red Tide caused by *Karenia sp.* in the Atlantic Moroccan Coast (Oualidia Lagoon). *J. Env. Sc. Eng. B7*, 224-229. Doi:10.17265/2162-5263/2018.06.003
- Demarcq, H., Somoue, L., 2015. Phytoplankton and primary productivity off Northwest Africa. In: Valdés, L. and Déniz-González, I. (eds). *Oceanographic and biological features in the Canary Current Large Marine Ecosystem*. IOC-UNESCO, Paris. IOC Technical Series. 115, 161-174. <http://www.unesco.org/new/en/ioc/ts115>.
- Devassy, V.P., Goss, J.I., 1988. Phytoplankton community structure and succession in tropical estuarine complex (Central West Cost of India). *Est. Costal. Shelf. Sci.* 27, 671-685.
- Dray, S., Dufour, A.B., 2007. The Ade4 Package: Implementing the Duality Diagram for Ecologists. *J. Stat. Software*. 22 (1), 1–20. <https://doi.org/10.18637/jss.v022.i04>.
- El Asri, F., Zidane, H., Maanan, M., Tamsouri, M., Errhif A., 2015. Taxonomic diversity and structure of the molluscan fauna in Oualidia Lagoon (Moroccan Atlantic coast). *Env. Monit. Assessment*. 187, 1-10. [http://doi: 10.1007/s10661-015-4752-7](http://doi:10.1007/s10661-015-4752-7)
- El Asri, F., Zidane, H., Errhif, A., Tamsouri, M., Maanan, M., Malouli Idrissi, M., Martin, D. 2017. Polychaete diversity and assemblage structure in the Oualidia Lagoon, Moroccan

- Atlantic coast. J. Mar. Biol. Assoc. U. K. 98(6), 1337-1346. <http://doi:10.1017/S0025315417000388>
- Elghrib, H., Somoue, L., Elkhiaati, N., Berraho, A., Makaoui, A., Bourhim, N., Salah, S., Ettahiri, O., 2012. Phytoplankton distribution in the upwelling areas of the Moroccan Atlantic coast localized between 32°30'N and 24°N. *Comptes. Rendus. Biol.* 335, 541–554. <http://doi:10.1016/j.crv.2012.07.002>.
- Elmadani, F., Chiaar, A., Chafi, A., 2011. Phytoplankton composition and abundance assessment In the Nador lagoon (Mediterranean coast of Morocco). *Acta. Bot.Croat.*70(2), 269–288. DOI:10.2478/v10184-010-0016-3.
- Gaikwad, S.R., Tarot S.R., Chavan, T.P., 2004. Diversity of Phytoplankton and zooplankton with respect to pollution status of river Tapi in North Maharastra region, *J. Curr. Sci.* 5, 749-754.
- Gamito, S.; Gilabert, S.; Marcos, C.; Pérez-Ruzafa, A. 2005. Effects of Changing Environmental Conditions on Lagoon Ecology. In *Coastal Lagoons: Ecosystem Processes and Modeling for Sustainable Use and Development*; Gönenc, I.E., Wolflin, J.P., Eds.; CRC Press: Boca Ratón, FL, USA, pp. 193–229.
- Ghosh, S., Barinova, S., Prakash Keshri, J., 2012. Diversity and seasonal variation of phytoplankton community in the Santragachi lake, West Bengal, India . *Q Science. Connect.* 2012,3. <https://doi.org/10.5339/connect>.
- Glé, C., Del Amo, Y., Sautour, B., Laborde, P., Chardy, P. 2008. Variability of nutrients and phytoplankton primary production in a shallow macrotidal coastal ecosystem (Arcachon Bay, France). *Estuar. Coast. Shelf. Sci.* 76, 642-656. doi:10.1016/j.ecss.2007.07.043
- Hilmi, K., Orbi, A., Lakhdar Idrissi, J., Sarf, F., 2005. Etude courantologique de la lagune de Oualidia (Maroc) en automne. *Bull. Inst. Sci., sect. Sci. Vie.* 26-27, 67-71.
- Hilmi, K., Orbi, A., Lakhdar Idrissi, J., 2009. Hydrodynamisme de la lagune de Oualidia (Maroc) durant l'été et l'automne 2005. *Bull. Inst. Sci., sect. Sci. Vie.* 31, 29-34.
- Jayed, M., Benbrahim, S., Bakkas, S., Ramdani, M., Flower, R., 2015. Accumulation of Organochlorines in the European Clam (*Ruditapes decussatus*) and Sediment of the Oualidia Lagoon (Morocco). *Bul. Env. Cont. Toxicol.* 94, 614–621. <http://doi:10.1007/s00128-015-1517-5>
- Pachés, M., Romero, I., Martínez-Guijarro, R., M. Martí, C., Ferrer, J., 2014. Changes in phytoplankton composition in a Mediterranean coastal lagoon in the Cullera Estany (Comunitat Valenciana, Spain). *Water. Env. J.* 28, 135–144. <http://doi:10.1111/WEJ.12020>.

- Pérez-Ruzafa, A.; De Pascalis, F.; Ghezzi, M.; Quispe-Becerra, J.I.; Hernández-García, R.; Muñoz, I.; Marcos, C. 2018. Connectivity between coastal lagoons and sea: Asymmetrical effects on assemblages' and populations' structure. *Estuar. Coast. Shelf. Sci.* 1-16. doi:10.1016/j.ecss.2018.02.031.
- Pérez-Ruzafa, A.; Marcos, C., 2012. Fisheries in coastal lagoons: An assumed but poorly researched aspect of the ecology and functioning of coastal lagoons. *Estuar. Coast. Shelf Sci.* 110, 15–31. doi:10.1016/j.ecss.2012.05.025.
- Kamara, A., Rharbi, N., Ramdani, M., Berraho, A., 2008. Recherches préliminaires au développement de l'élevage de la palourde européenne (*Ruditapes decussatus*) sur les côtes marocaines et au repeuplement des sites surexploités. *Bul. Soc. Zool. Fran.* 133 (1-3), 193-202.
- Kjerfve, B., 1994. Coastal lagoon processes. Amsterdam. Elsevier Sciences.
- Kjerfve, B., 1986. Comparative oceanography of coastal lagoons, in *Estuarine Variability*, edited by D. A. Wolfe, pp. 63–81, Academic Press, New York.
- Koutitonsky, V. G., Zyserman, J., and Zourarah, B., 2012. Étude par modèle mathématique de l'impact de l'ouverture de la digue amont et de l'enlèvement ou redistribution des sédiments de la sablière sur le comportement hydro-sédimentaire de la lagune de Oualidia. Mission 2 : Modélisation hydro-sédimentaire de l'état actuel et des scénarios d'aménagement. Direction des Ports et du Domaine Public Maritime, Ministère de l'Équipement et du Transport, Royaume du Maroc, 303 p. + Annexes.
- Koutitonsky, V.G., Orbi, A., Ouabi, M., Ibrahim I., 2006. L'étude du comportement hydro-sédimentaire du système lagunaire Oualidia par la modélisation mathématique, Volet 1: synthèse des données et simulation de la réfraction des houles. Direction des Ports et du Domaine Public Maritime, Ministère de l'Équipement et du Transport. Royaume du Maroc. 150 pp.
- Maanan, M., Ruiz-Fernández, A. C., Maanan, M., Fattal, P., Zourarah, B., Sahabi, M., 2014. A long-term record of land use change impacts on sediment in Oualidia lagoon, Morocco. *Inter. J. Sed. Res.* 29(1), 1–10. [http://doi.org/10.1016/S1001-6279\(14\)60017-2](http://doi.org/10.1016/S1001-6279(14)60017-2)
- Makaoui, A., Orbi, A., Hilmi, K., Zizah, S., Larissi, J., Talbi M., 2005. L'upwelling de la côte atlantique du Maroc entre 1994 et 1998. *Comp. Rend. Geo.* 337, 1518-1524.
- Mejjad, N., Laissaoui, A., El-Hammoumi, O., Benmansour, M., Benbrahim, S., Bounouira, H., Benkdad, A., Bouthir, F.Z., Fekri, A., Bounakhla, M., 2016. Sediment geochronology and geochemical behavior of major and rare earth elements in the Oualidia Lagoon in the

<https://www.researchgate.net/publication/292338975>.

- Margalef R., 1968. *Perspectives in ecological theory*, Univ. Chicago Press, Chicago, 111 p.
- Margalef, R., Estrada, M., Blasco, D. 1979. Functional morphology of organisms involved in red tides, as adapted to decaying turbulence. In: Taylor, D.L., Seliger, H.H. (Eds.), *Toxic Dinoflagellate Blooms*. Elsevier/North-Holland, New York, pp. 89–94.
- Moestrup, Ø., Akselmann-Cardella, R.; Churro, C.; Fraga, S.; Hoppenrath, M.; Iwataki, M.; Larsen, J.; Lundholm, N.; Zingone, A. (Eds) .2009 onwards. IOC-UNESCO Taxonomic Reference List of Harmful Micro Algae. Accessed at <http://www.marinespecies.org/habon> on 2020-09-21. doi:10.14284/362
- Nezan, E., Piclet, G., 1996. *Guide pratique à l'usage des analystes du phytoplancton*. Ed. Alain Bargain. IFREMER.
- Orbi, A., Hilmi, K., Lakhdar Idrissi, J., Zizah, S. 2008. Lagoon ecosystem study through two cases: Oualidia (Atlantic) and Nador (Mediterranean) – Morocco. In: Gönenç I. E., Vadineau A., Wollflin J.P. & Russo R.C. (eds): *Sustainable Use and Development of Watersheds*. Springer Eds, Serie C. 289-298.
- Lassus, P., Chomérat, N., Hess, P. & Nézan, E. (2016). *Toxic and harmful microalgae of the World Ocean. Micro-algues toxiques et nuisibles de l'Océan Mondial*. IOC Manuals and guides, 68 (Bilingual English/French). pp. 1-523, 54 pls. Denmark: International Society for the Study of Harmful Algae/ Intergovernmental Oceanographic Commission of UNESCO.
- Linder. A., 1974. A proposal for the use of standardized methods for chlorophyll determinations in ecological and ecophysiological investigations. *Physiol. Plant.* 32, 154-156.
- Loumrhari., A., Akallal., R., Mouradi., Ah., Mouradi, Az. 2009. Succession de la population phytoplanctonique en fonction des paramètres physicochimiques (sites Mehdiya et Moulay Bouselham). *Afrique Science* 05 (3), 128–148. ISSN 1813-548X
- Reynolds, C., 2006. In *The Ecology of Phytoplankton*. Cambridge University Press, UK, pp. 535.
- Rharbi, N., Ramdani, M., Berraho, A., 2003. Elaboration d'une stratégie d'élevage de l'huître *Crassostrea gigas* dans la lagune de Oualidia (Maroc) sur la base de l'étude des relations trophiques. *Bul. Soc. Zool. Fran.* 128(1-2), 53-70.

- Rharbi, N., Ramdani, M., Berraho, A., Lakhdar Idrissi, J., 2001. Caractéristiques hydrologiques et écologiques de la lagune de Oualidia, milieu paralique de la côte atlantique marocaine. *Mar. Life*. 11, 3-9.
- Rharbi, N., 2000. Importance des paramètres hydrologiques et phytoplanctoniques sur la croissance de l'huître *Crassostrea gigas* en élevage dans la lagune de Oualidia. Thèse d'État. Faculté des Sciences Ben Msik, Casablanca, Maroc.
- Rijal Leblad, B., Lundholm, N., Goux, D., Veron, B., Sagou, R., Taleb, H., Nhhala, H., Er-Raioui, H., 2013. *Pseudo-nitzschia Peragallo* (Bacillariophyceae) diversity and domoic acid accumulation in tuberculate cockles and sweet clams in M'diq Bay, Morocco. *Acta. Bot. Croatia*. 72 (1), 35–47.
- Rosa, A., Cardeira, S., Pereira, C., Rosa, M., Madureira, M., Rita, F., Jacob, J., Cravo, A., 2019. Temporal variability of the mass exchanges between the main inlet of Ria Formosa lagoon (southwestern Iberia) and the Atlantic Ocean. *Estuar. Coast. Shelf. Sc.* 228, 106349. doi.org/10.1016/j.ecss.2019.106349
- Saad, Z., Orbi, A., Abouabdellah, R., Saad, A., Oudra, B., 2013. Impact of economic development on the dynamics of phytoplankton and physic-chemical quality of Dakhla Bay (South of Morocco). *South. Asian. J. Exp. Biol.* 3 (5), 274-287. http://www.sajeb.org
- Sabatie, M.R., Shafee, M.S., 1982. Etude préliminaire du rôle de quelques paramètres écologiques de Oualidia. Acte et colloque I.A.V. Hassan II. Rabat, pp 75-90.
- Shannon, C.E., Weaver, W., 1949. The mathematical theory of communication. University of Illinois Press, Urbana.
- Smayda, T.J., Reynolds, C.S. 2001. Community assembly in marine phytoplankton: application of recent models to harmful dinoflagellate blooms. *J. Plankton Res.* 23, 447–461
- Strickland, J.D.H., Parsons, T.R., 1972. A practical handbook of seawater analysis. *J. Fish. Res. Board Can.* 167, 1–310.
- Sylaios, G., Theocharis, V. 2002. Hydrology and nutrient enrichment at two coastal lagoon systems in northern Greece. *Water Resour. Manag.* 16(3), 171–196. https://doi.org/10.1023/A:1020278003138.
- Taleb, H., Valeb, P., Blaghen, M., 2003. Spatial and temporal evolution of PSP toxins along the Atlantic shore of Morocco. *Toxicon*. 41, 199–205.
- Tomas, C. R., 1997. Identifying Marine Phytoplankton. Florida Marine Research Institute. Academic Press.

- Tregoubof, G., Rose, M., 1957. Manuel de planctonologie méditerranéenne tome I et II. CNRS. Paris 1.
- Umgiesser, G.; Ferrarin, C.; Cucco, A.; De Pascalis, F.; Bellafiore, D.; Ghezzi, M.; Bajo, M. 2014. Comparative hydrodynamics of 10 Mediterranean lagoons by means of numerical modeling. *J. Geophys. Res. Oceans*.119, 2212–2226, doi:10.1002/2013JC009512.
- Utermohl, H., 1958. Zur vervollkommung der quantitativen phytoplankton methodik, Mitteilung Internationale Vereinigung Fuer Theoretische unde Amgewandte. *Limnology* 9, 1-38.
- Zourarah, B., 2002. Les processus côtiers actuels et leur impact sur l’environnement littoral des Doukkala (côte atlantique marocaine) : Approche hydrodynamique, Morphologique, Sédimentologique et Géochimique. Thèse de Doctorat d’état, Université Chouaïb Doukkali, El Jadida, Maroc.
- Zourarah, B., Maanan, M., Carruesco, C., Aajjane, A., Mehdi, K., Conceição Freitas, M., 2007. Fifty-year sedimentary record of heavy metal pollution in the lagoon of Oualidia (Moroccan Atlantic coast). *Est. Coast. Shelf. Sc.* 72, 359–369. DOI: 10.1016/j.ecss.2006.11.007.
- Van Den Wollenberg, A L., 1977. “Redundancy Analysis an Alternative for Canonical Correlation Analysis.” *Psychometrika* 42 (2), 207–19. <https://doi.org/10.1007/BF02294050>.

Figures legend

Fig. 1. Sampled stations from downstream to upstream of the Oualidia Lagoon (Atlantic coast, Morocco). Parks (1, 3, 5, 7 and 8) and Past indicate the oyster farming zones and the Ocean/lagoon connection, respectively.

Fig. 2. Spatio-temporal variations of temperature (°C) and salinity at low tide (a and c) and high tide (b and d) periods in the sampled stations of Oualidia Lagoon, upstream and downstream for station 1 and 6.

Fig. 3. Spatio-temporal variations of phosphate, nitrate and ammonium concentrations (μM) at low tide (a,c and e) and high tide (b, d and f) in the sampled stations of Oualidia Lagoon.

Fig. 4. Spatio-temporal variation of chlorophyll *a* concentrations ($\mu\text{g L}^{-1}$) measured at low (a) and high tide (b) in the sampled stations of Oualidia Lagoon.

Fig. 5. Spatio-temporal variation of percentages (%) in term of abundance of different phytoplankton groups in Oualidia lagoon.

Fig. 6. Spatio-temporal variations in species richness (a) and specific diversity (b: Shannon index)

Fig. 7. Spatio-temporal variations of total phytoplankton densities (cells L⁻¹) in Oualidia Lagoon.

Fig. 8. Spatio-temporal projection of phytoplankton communities obtained by performing a central principal component analysis (PCA). (a: Species association; b and d: Projection of stations and c: Projection of seasons)

Fig. 9. Co-inertia analysis performed with environmental factor matrix and phytoplankton matrix. (a: Relationship between environmental variables (a), Species and stations in different seasons respectively (b and c); Contribution of axes: d). (NB: ▲ indicates potentially toxic species)

Table 1. Inventory and percentage frequency of taxa encountered at the Oualidia lagoon

Table 2. The codes assigned to the hydrological and phytoplankton communities for the Co inertia and PCA analyses.

Appendix 1: Table a. Spatio-temporal variation of the temperature (a1) and salinity (a2) at high (HT) and low tides (LT). Table b. Spatio-temporal variation of the concentrations in μM of nitrate (b1), Phosphate (b2) and ammonium (b3) at high (HT) and low tides (LT)

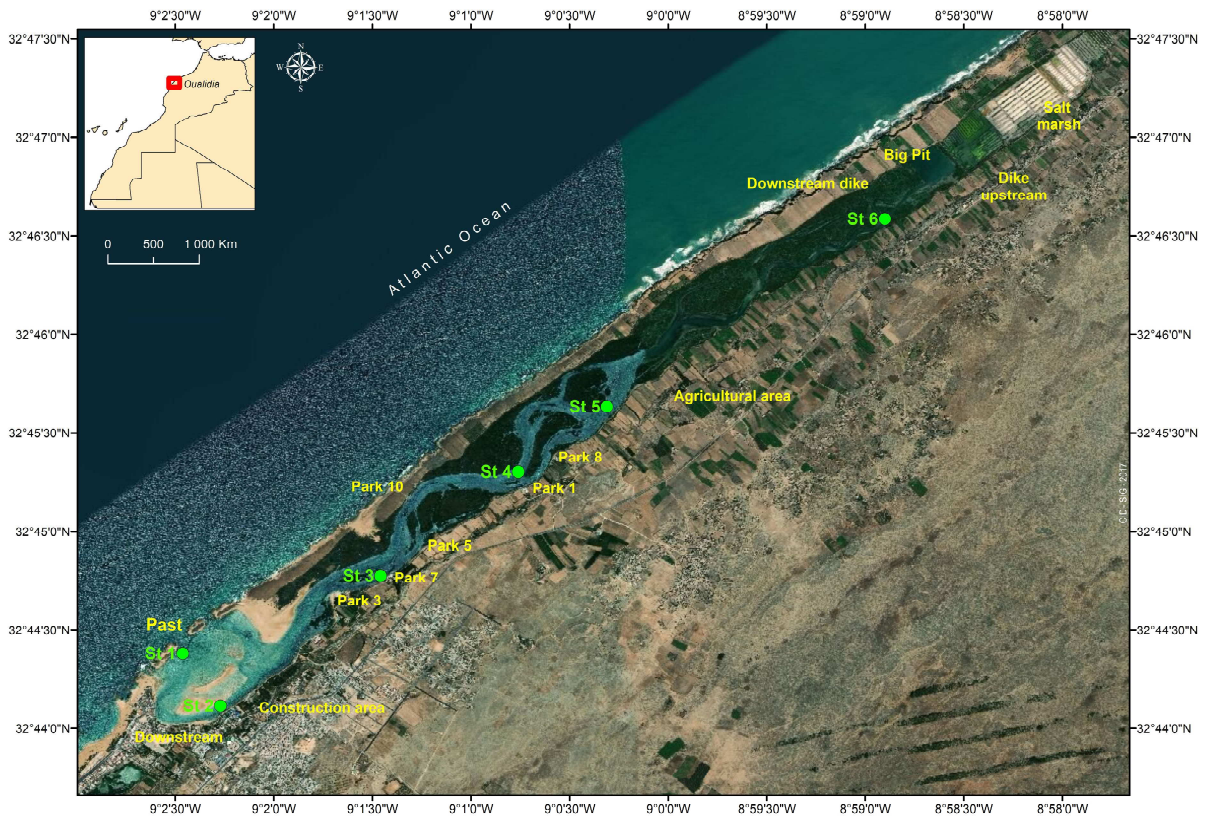


Fig. 1

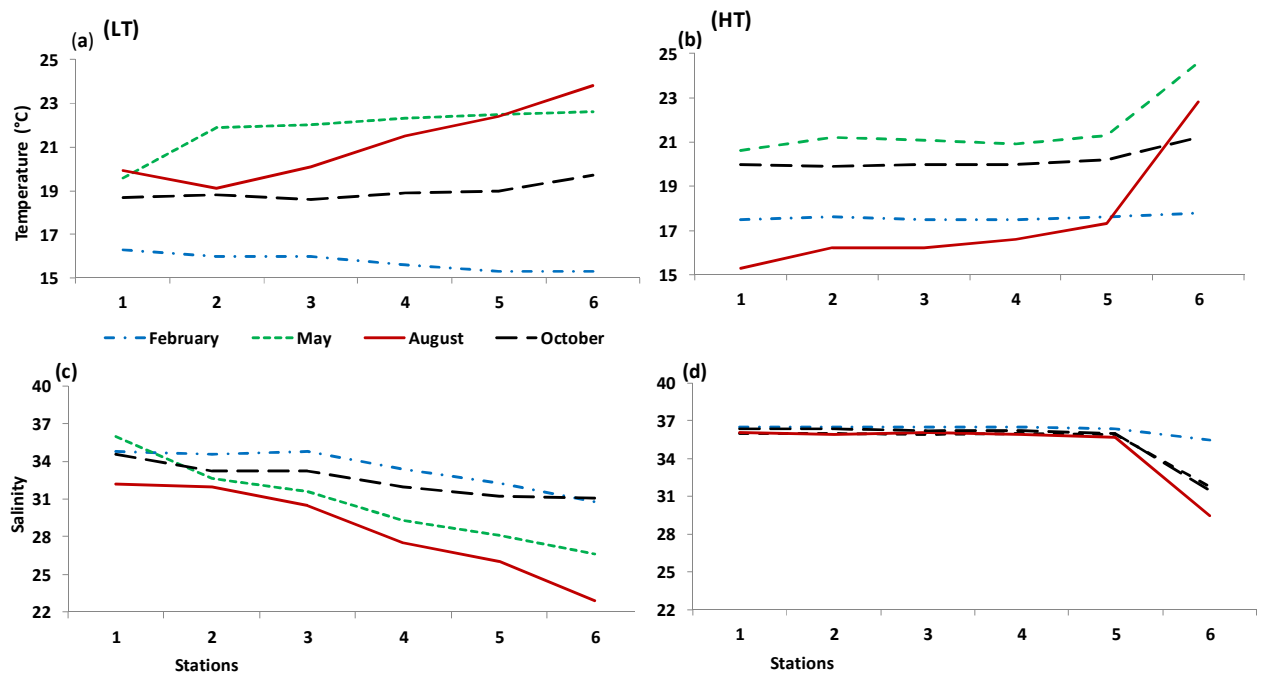


Fig. 2

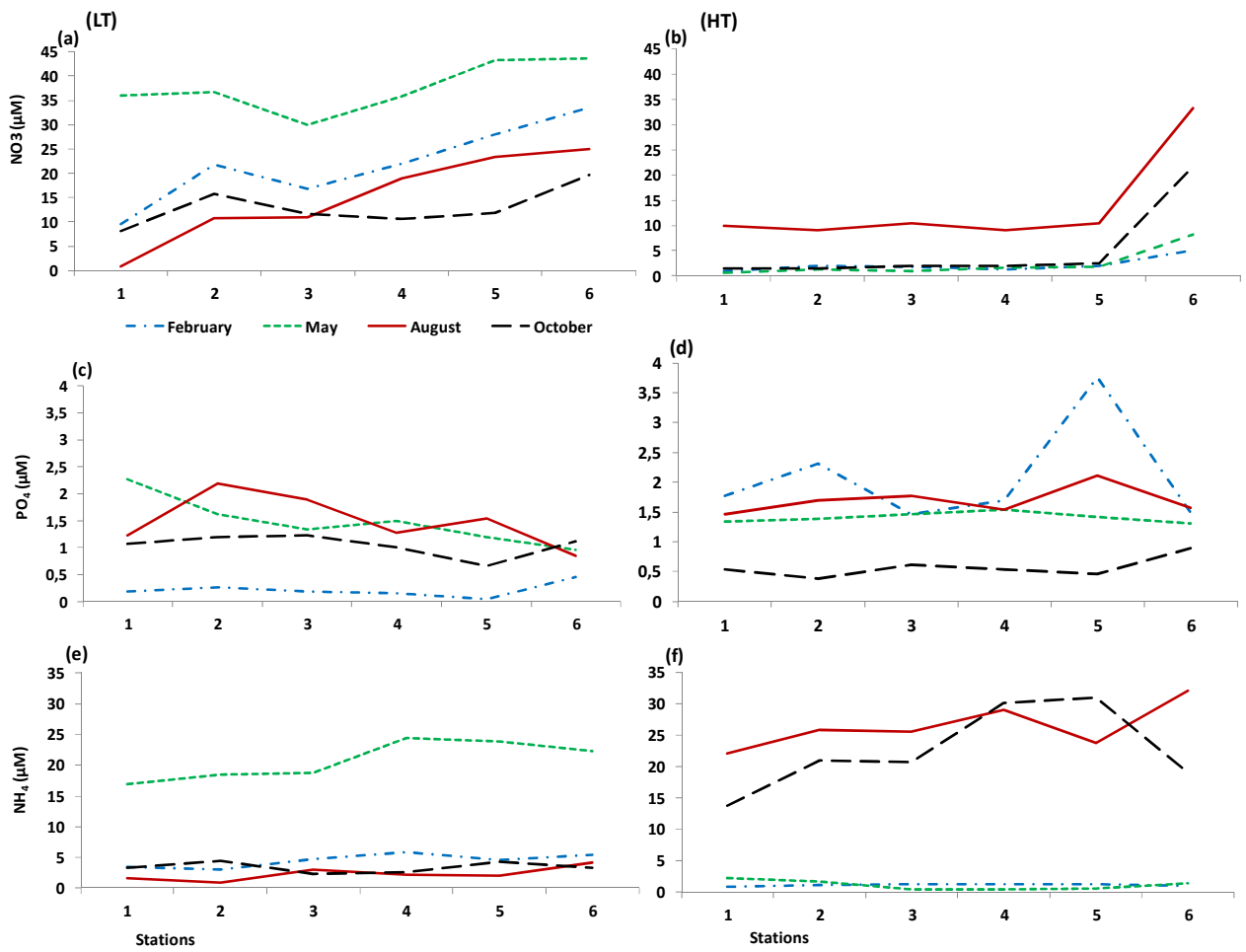


Fig. 3

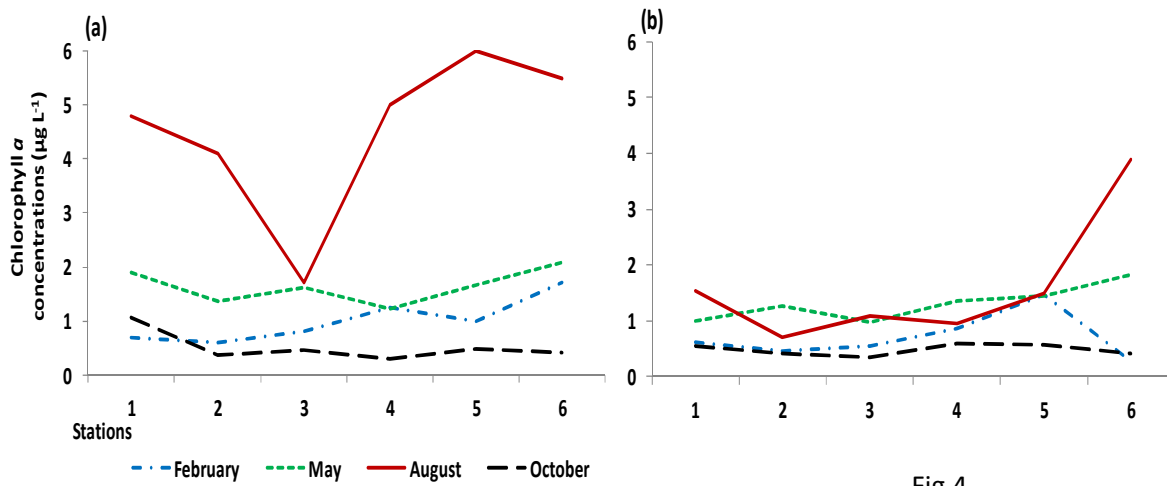


Fig.4

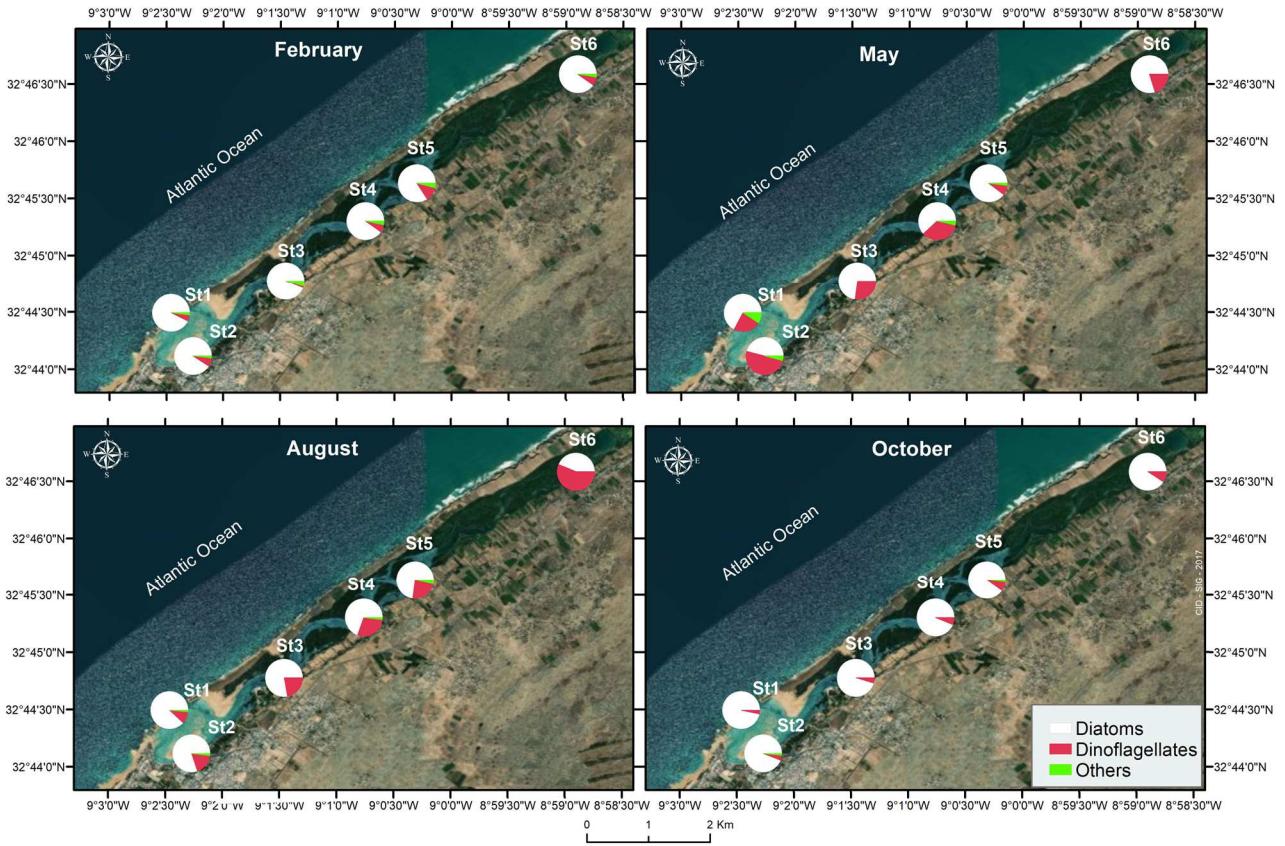


Fig.5

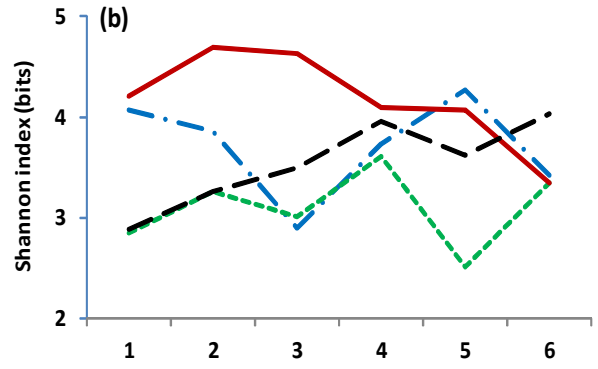
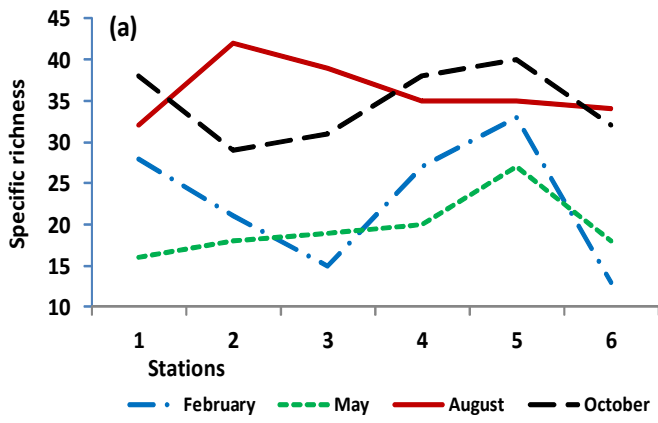


Fig.6

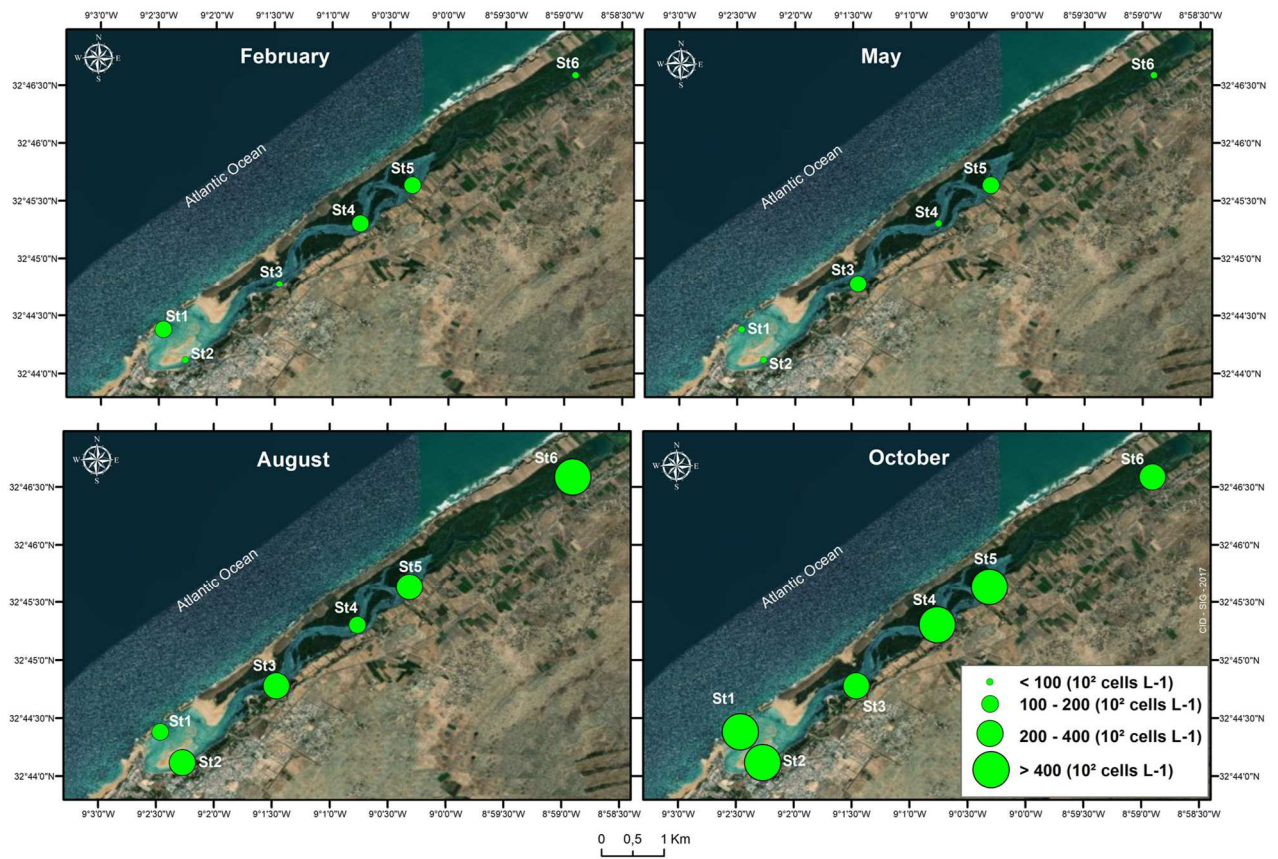


Fig.7

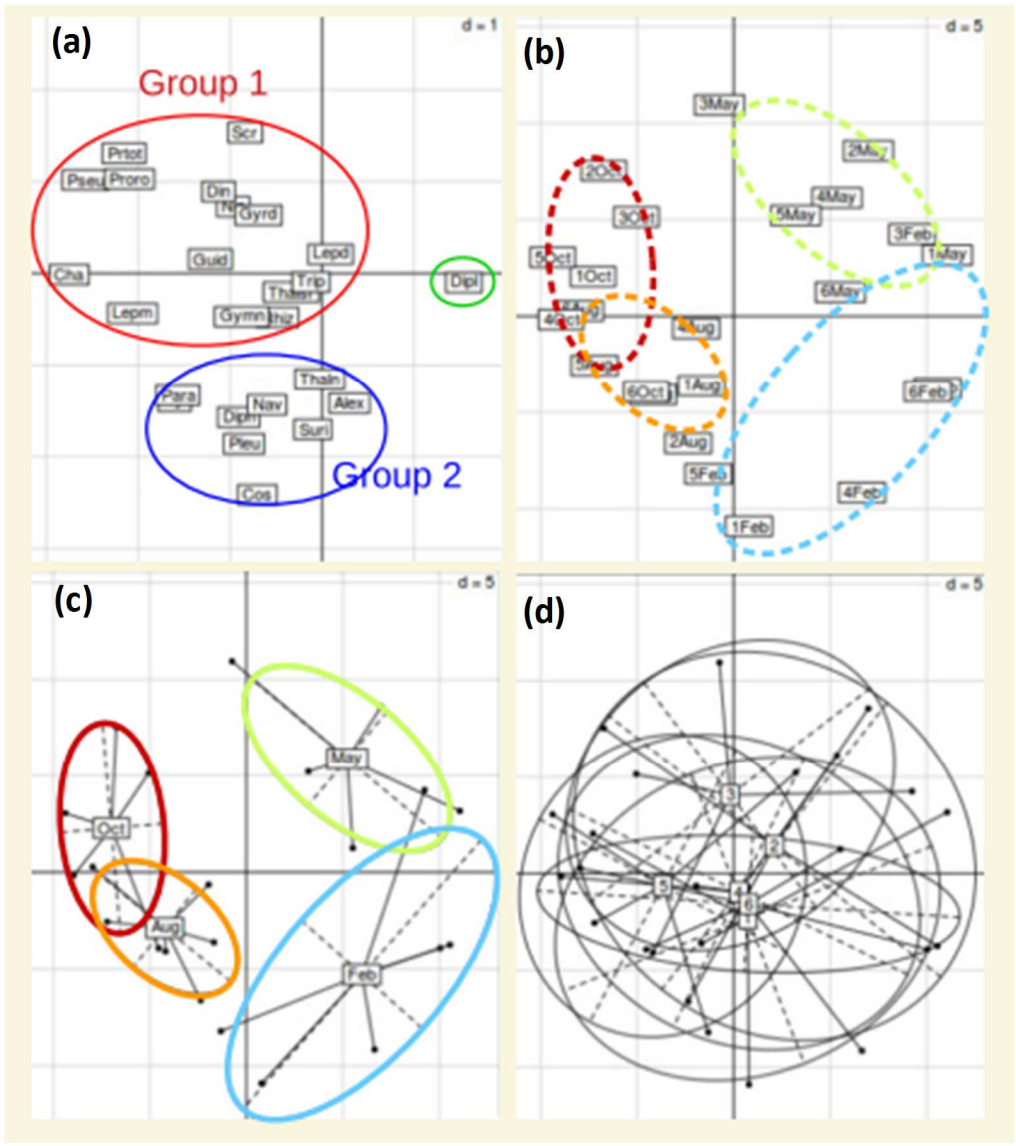


Fig.8

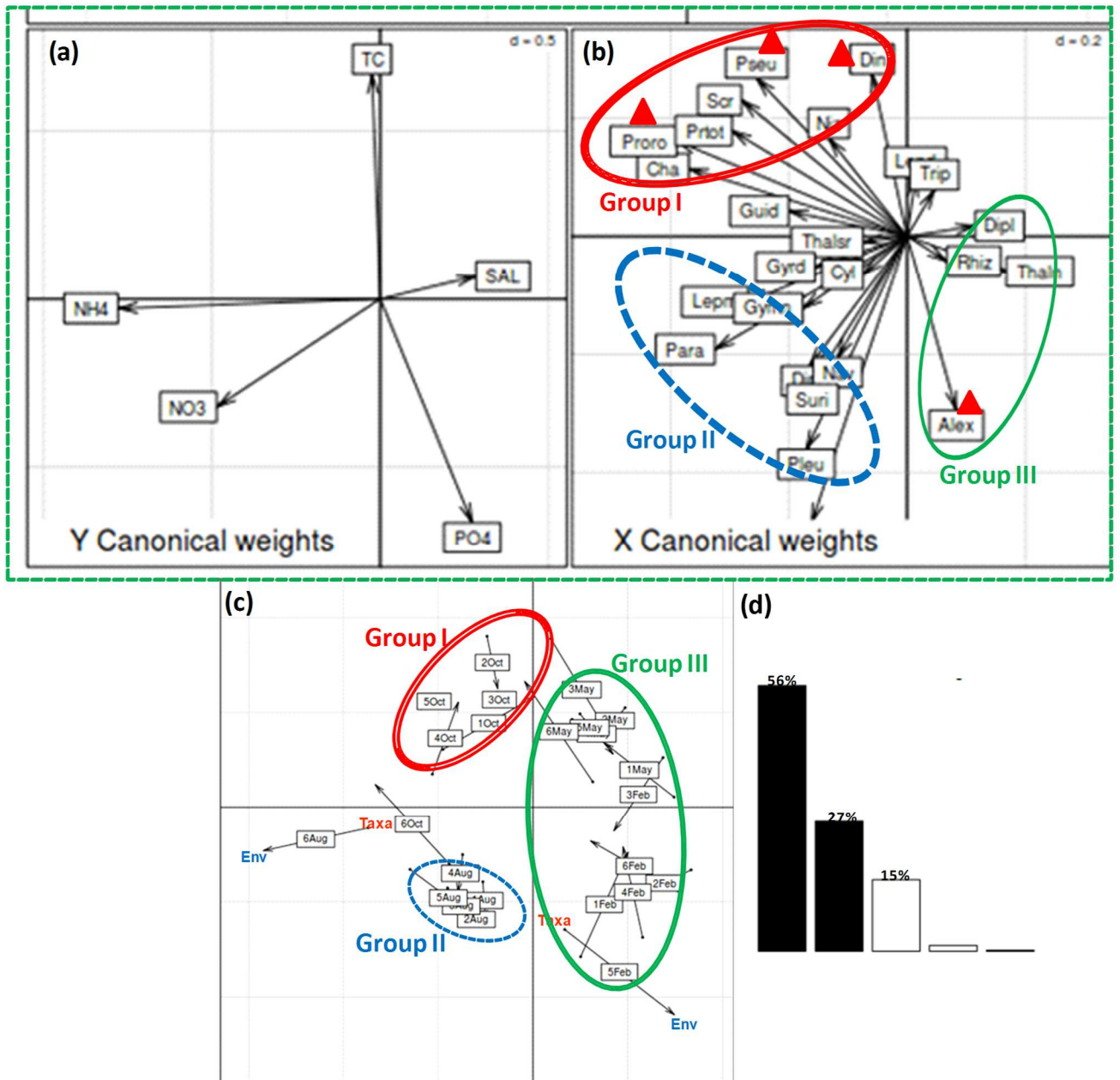


Fig.9

Table 1

Diatoms (% Frequency taxa)	February	May	August	October
<i>Asteromphalus</i> Ehrenberg. 1844	0.0	0.0	33.3	0.0
<i>Adoneis</i> Andrews & Rivera. 1987	16.7	0.0	0.0	0.0
<i>Actinocyclus</i> Ehrenberg. 1837	16.7	0.0	33.3	0.0
<i>Amphora</i> Ehrenberg ex Kützing. 1844	16.7	0.0	83.3	50.0
<i>Bacillaria paxillifera</i> (Müller) Marsson 1901	0.0	0.0	16.7	0.0
<i>Bellerochea</i> Van Heurck. 1885	0.0	16.7	33.3	16.7
<i>Chaetoceros</i> Ehrenberg. 1844	33.3	50.0	83.3	100.0
<i>Cocconeis</i> Ehrenberg. 1836	16.7	0.0	0.0	16.7
<i>Coscinodiscus</i> Ehrenberg. 1839	83.3	0.0	100.0	50.0
<i>Cyclotella</i> (Kützing) Brébisson. 1838	0.0	0.0	66.7	50.0
<i>Cerataulina pelagica</i> (Cleve) Hendey 1937	0.0	0.0	0.0	16.7
<i>Cylindrotheca closterium</i> (Ehrenberg) Reimann & Lewin 1964	66.7	0.0	50.0	100.0
<i>Dactyliosolen</i> Castracane. 1886	0.0	16.7	33.3	33.3
<i>Detonula</i> Schütt ex De Toni. 1894	0.0	0.0	16.7	16.7
<i>Diploneis bombus</i> (Ehrenberg) Ehrenberg 1853	83.3	33.3	100.0	50.0
<i>Diploneis crabro</i> (Ehrenberg) Ehrenberg 1854	0.0	0.0	33.3	33.3
<i>Diploneis</i> spp	100.0	16.7	83.3	100.0
<i>Diatomée</i> sp	16.7	16.7	16.7	0.0
<i>Ditylum brightwellii</i> (West) Grunow in Van Heurck 1885	16.7	0.0	0.0	0.0
<i>Entomoneis</i> Ehrenberg. 1845	0.0	33.3	33.3	33.3
<i>Fragilaria</i> Lyngbye. 1819	66.7	16.7	66.7	16.7
<i>Eucampia</i> Ehrenberg. 1839	0.0	0.0	0.0	33.3
<i>Epithemia</i> Kützing. 1844	0.0	0.0	50.0	33.3
<i>Grammatophora</i> Ehrenberg. 1840	0.0	50.0	50.0	83.3
<i>Guinardia flaccida</i> (Castracane) Peragallo 1892	0.0	0.0	33.3	0.0
<i>Guinardia striata</i> (Stolterfoth) Hasle. 1996	16.7	0.0	33.3	50.0
<i>Guinardia</i> sp1	16.7	0.0	33.3	16.7
<i>Guinardia</i> sp2	0.0	33.3	16.7	16.7
<i>Gyrosigma</i> Hassall. 1845	16.7	0.0	50.0	83.3
<i>Hemiaulus proteus</i> Heiberg. 1863	33.3	0.0	33.3	33.3
<i>Helicotheca tamesis</i> (Shrubsole) Ricard. 1987	16.7	0.0	50.0	16.7
<i>Lauderia annulata</i> Cleve. 1873	16.7	0.0	50.0	50.0
<i>Leptocylindrus danicus</i> Cleve. 1889	66.7	66.7	66.7	83.3
<i>Leptocylindrus minimus</i> Gran 1915	83.3	33.3	100.0	100.0
<i>Leptocylindrus mediterraneus</i> (Peragallo) Hasle 1975	16.7	0.0	0.0	16.7

<i>Licmophora</i> Agardh. 1827	16.7	16.7	16.7	33.3
<i>Lyrella</i> Karayeva. 1978	33.3	0.0	0.0	0.0
<i>Mastogloia</i> Thwaites in Smith. 1856	16.7	0.0	0.0	16.7
<i>Melosira</i> Agardh. 1824	16.7	0.0	66.7	83.3
<i>Navicula</i> Bory de Saint-Vincent. 1822	83.3	83.3	100.0	83.3
<i>Nitzschia</i> Hassall. 1845	83.3	100.0	100.0	100.0
<i>Odontella</i> Agardh. 1832	33.3	16.7	50.0	0.0
<i>Paralia</i> Heiberg. 1863	33.3	16.7	100.0	66.7
<i>Pleurosigma</i> Smith. 1852	50.0	16.7	100.0	33.3
<i>Proboscia alata</i> (Brightwell) Sundström. 1986	33.3	33.3	66.7	50.0
<i>Pseudo-nitzschia delicatissima</i> (Cleve) Heiden. 1928	16.7	50.0	33.3	100.0
<i>Pseudo-nitzschia seriata</i> (Cleve) Peragallo. 1899	0.0	16.7	16.7	83.3
<i>Pseudonitzschia</i> sp	16.7	0.0	16.7	0.0
<i>Rhizosolenia styliformis</i> Brightwell. 1858	0.0	0.0	0.0	16.7
<i>Neocalyptrella robusta</i> (Norman ex Ralfs) Hernández-Becerril & Meave del Castillo. 1997	16.7	0.0	0.0	0.0
<i>Rhaphoneis</i> Ehrenberg. 1844	0.0	16.7	16.7	16.7
<i>Rhizosolenia imbricata</i> Brightwell. 1858	33.3	0.0	0.0	0.0
<i>Rhizosolenia</i> sp	16.7	0.0	0.0	0.0
<i>Rhizosolenia setigera</i> f. <i>pungens</i> (Cleve-Euler) Brunel. 1962	0.0	0.0	0.0	16.7
<i>Rhopalodia</i> Müller. 1895	0.0	0.0	33.3	16.7
<i>Rhabdonema</i> Kützing. 1844	0.0	0.0	16.7	0.0
<i>Synedra</i> Ehrenberg. 1830	0.0	0.0	16.7	83.3
<i>Scoliopleura</i> Grunow. 1860	33.3	16.7	0.0	0.0
<i>Skeletonema costatum</i> (Greville) Cleve. 1873	0.0	0.0	0.0	33.3
<i>Stephanopyxis palmeriana</i> (Greville) Grunow. 1884	0.0	0.0	16.7	33.3
<i>Striatella</i> Agardh. 1832	33.3	0.0	16.7	0.0
<i>Surirella</i> Turpin. 1828	100.0	66.7	100.0	66.7
<i>Thalassionema pseudonitzschioides</i> (Schuette & Schrader) Hasle in Hasle & Syvertsen. 1996	16.7	0.0	33.3	0.0
<i>Thalassionema nitzschioides</i> (Grunow) Mereschkowsky. 1902	50.0	50.0	0.0	33.3
<i>Thalassionema frauenfeldii</i> (Grunow) Tempère & Peragallo. 1910	50.0	0.0	0.0	0.0
<i>Thalassiosira</i> Cleve. 1873	100.0	100.0	100.0	100.0
<i>Trigonium</i> Cleve. 1867	16.7	0.0	16.7	16.7
<i>Triceratium</i> Ehrenberg. 1839	16.7	0.0	0.0	0.0
Dinoflagellates (% Frequency taxa)	February	May	August	October
<i>Alexandrium</i> Halim. 1960	50.0	33.3	66.7	16.7

<i>Tripos fusus</i> (Ehrenberg) Gómez. 2013	0.0	0.0	0.0	33.3
<i>Tripos furca</i> (Ehrenberg) Gómez. 2013	33.3	16.7	16.7	16.7
<i>Tripos macroceros</i> (Ehrenberg) Gómez. 2013	16.7	0.0	0.0	16.7
<i>Cochlodinium</i> Schütt. 1896	0.0	0.0	33.3	0.0
<i>Coolia monotis</i> Meunier. 1919	0.0	16.7	16.7	0.0
<i>Dinophysis acuminata</i> Claparède & Lachmann. 1859	0.0	16.7	0.0	50.0
<i>Dinophysis caudata</i> Saville-Kent. 1881	0.0	0.0	0.0	16.7
<i>Dinophysis fortii</i> Pavillard. 1923	0.0	0.0	0.0	16.7
<i>Dinophysis</i> sp	0.0	0.0	0.0	16.7
<i>Diplosalis</i> Bergh. 1881	50.0	83.3	33.3	16.7
<i>Gonyaulax</i> Diesing. 1866	50.0	0.0	33.3	0.0
<i>Dinoflagellé</i> sp	0.0	0.0	16.7	0.0
<i>Gymnodinium</i> Stein. 1878	66.7	100.0	100.0	83.3
<i>Akashiwo sanguinea</i> (Hirasaka) Hansen & Moestrup. 2000	16.7	0.0	16.7	0.0
<i>Gyrodinium</i> Kofoid & Swezy. 1921	0.0	16.7	83.3	33.3
<i>Gyrodinium fusus</i> (Meunier) Akselman. 1985	0.0	33.3	16.7	0.0
<i>Gyrodinium spirale</i> (Bergh) Kofoid & Swezy. 1921	0.0	16.7	33.3	0.0
<i>Heterocapsa</i> Stein. 1883	0.0	33.3	16.7	33.3
<i>Hermesinum</i> Zacharias. 1906	0.0	0.0	16.7	0.0
<i>Peridiniella</i> Kofoid & Michener. 1911	16.7	16.7	0.0	0.0
<i>Peridinium quadridentatum</i> (Stein) Hansen. 1995	0.0	0.0	16.7	16.7
<i>Polykrikos</i> Bütschli. 1873	0.0	16.7	16.7	16.7
<i>Prorocentrum</i> sp	0.0	16.7	16.7	0.0
<i>Prorocentrum gracile</i> Schütt. 1895	0.0	16.7	33.3	0.0
<i>Prorocentrum lima</i> (Ehrenberg) Stein. 1878	0.0	16.7	0.0	0.0
<i>Prorocentrum micans</i> Ehrenberg. 1834	0.0	50.0	100.0	100.0
<i>Prorocentrum triestinum</i> Schiller. 1918	0.0	0.0	0.0	16.7
<i>Protoperidinium depressum</i> (Bailey. 1854) Balech. 1974	16.7	0.0	0.0	16.7
<i>Protoperidinium diabolium</i> (Cleve. 1900) Balech. 1974	0.0	0.0	16.7	50.0
<i>Protoperidinium conicum</i> (Gran. 1900) Balech. 1974	0.0	0.0	0.0	33.3
<i>Protoperidinium</i> spp	16.7	66.7	50.0	66.7
<i>Pronoctiluca</i> Fabre-Domergue. 1889	0.0	16.7	50.0	33.3
<i>Pyrophacus</i> Stein. 1883	0.0	16.7	0.0	33.3
<i>Karenia</i> Hansen & Moestrup. 2000	0.0	0.0	16.7	0.0
<i>Katodinium</i> Fott. 1957	0.0	0.0	0.0	16.7
<i>Scrippsiella</i> Balech Loeblich III. 1965	16.7	100.0	83.3	83.3
<i>Oxytoxum</i> Stein. 1883	0.0	33.3	16.7	0.0
<i>Ostreopsis</i> Schmidt. 1901	0.0	33.3	33.3	50.0

<i>Torodinium</i> Kofoid & Swezey. 1921	0.0	0.0	16.7	0.0
Others groups (% Frequency taxa)	February	May	August	October
Raphidophyceae				
<i>Chattonella</i> Biecheler. 1936	50.0	33.3	33.3	33.3
Euglenophyceae				
<i>Euglena</i> Ehrenberg. 1830	83.3	50.0	33.3	16.7
Coccolithophoridae				
<i>Coccolithus</i> Schwarz. 1894	16.7	33.3	33.3	50.0
Silicoflagellates				
<i>Octactis octonaria</i> (Ehrenberg) Hovasse. 1946	16.7	0.0	33.3	33.3
<i>Dictyocha</i> sp	33.3	33.3	0.0	0.0
<i>Dictyocha fibula</i> Ehrenberg. 1839	0.0	0.0	0.0	16.7

Table 2

Hydrological variables	Codes
Temperature	TC
Salinity	SAL
Phosphates	PO ₄
Nitrates	NO ₃
Ammonium	NH ₄
Taxa	Codes
<i>Chaetoceros</i>	Cha
<i>Coscinodiscus</i>	Cos
<i>Cylindrotheca</i>	
<i>closterium</i>	Cyl
<i>Diploneis</i>	Dipn
<i>Guinardia</i>	Guid
<i>Leptocylindrus</i>	
<i>danicus</i>	Lepd
<i>Leptocylindrus</i>	
<i>minimus</i>	Lepm
<i>Navicula</i>	Nav
<i>Nitzschia</i>	Niz

<i>Paralia</i>	Para
<i>Pleurosigma</i>	Pleu
<i>Pseudonitzschia</i>	Pseu
<i>Rhizosolenia</i>	Rhiz
<i>Surirella</i>	Suri
<i>Thalassionema</i>	Thaln
<i>Thalassiosira</i>	Thalsr
<i>Alexandrium</i>	Alex
<i>Dinophysis</i>	Din
<i>Diplopsalis</i>	Dipl
<i>Gymnodinium</i>	Gymn
<i>Gyrodinium</i>	Gyrd
<i>Prorocentrum</i>	Proro
<i>Protoperidinium</i>	Prtot