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**Succession of primary producers and micrograzers in a coastal ecosystem dominated by *Phaeocystis globosa* blooms**

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Keywords:	Phaeocystis globosa, diatoms, micrograzer community, eastern English Channel



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2 1 **Succession of primary producers and micrograzers in a coastal ecosystem**  
3  
4 2 **dominated by *Phaeocystis globosa* blooms**

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26 13 **Keywords:** *Phaeocystis globosa*, diatoms, micrograzer community, eastern English Channel.  
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**Abstract:**

The community structures and succession of phytoplankton, protozooplankton and copepods were studied from February 2007 to July 2009 in a coastal area of the eastern English Channel subject to *Phaeocystis globosa* blooms. While diatom blooms preceded *P. globosa* blooms each year, the community structure and stock of heterotrophic protists appeared to be related to the dominant *P. globosa* life cycle stages. In 2007 the dominance of large colonies ( $>100\ \mu\text{m}$ ,  $375\ \mu\text{g C L}^{-1}$ ) which resulted in a high biomass of healthy free cells ( $163\ \mu\text{g C L}^{-1}$ ) accompanied high spirotrich ciliate stocks (up to  $58\ \mu\text{g C L}^{-1}$ ) and high abundances of the copepods *Acartia clausi* and *Temora longicornis* (up to  $11\ \text{ind L}^{-1}$ ). In 2008, the bloom which lasted a shorter period of time, was dominated by large colonies ( $328\ \mu\text{g C L}^{-1}$ ), and fewer free cells ( $131\ \mu\text{g C L}^{-1}$ ). This corresponded with a lower abundance of grazers, with stocks of heterotrophic protists and copepods 1.6 times and 2.2 times lower, respectively. In 2009, the *P. globosa* bloom was again dominated by large colonies and  $<100\ \mu\text{m}$  diatoms. This corresponded to a dominance of heterotrophic dinoflagellates among the protists (62% of the total heterotrophic protist biomass) and *Acartia clausi* (55% of the copepod abundance). Overall, heterotrophic dinoflagellates appeared to be likely the most important group of phytoplankton grazers.

**INTRODUCTION**

In the North Sea and in the eastern English Channel, gelatinous colonies of *Phaeocystis globosa* Scherffel, 1900 (Prymnesiophyceae) several mm in size (Rousseau et al., 2007) commonly dominate the phytoplankton community during spring, following the decline of an earlier diatom bloom (e.g., Lancelot et al., 1998). *P. globosa*, a species of ephemeral occurrence alternates between a colonial stage in the earlier phase and solitary cells during the decline of the bloom (Rousseau et al., 2007). In the colonial form, *P. globosa* can represent over 90% of phytoplankton biomass (Lancelot, 1995; Lamy et al., 2009), and be responsible for the massive load of organic matter into the ambient water, often resulting in foam accumulation along the shoreline (Van Boekel et al., 1992).

Generally speaking, phytoplankton blooms occur as a result of growth greatly exceeding mortality, often through escaping control by grazers (Strom 2002; Irigoien et al., 2005). In the particular case of *P. globosa*, experimental and modelling studies suggest that in early stages of the bloom, solitary cells are well-grazed by the microzooplankton but control ceases when colonies start to form (Verity, 2000). Culture experiments have shown that the smaller forms of *P. globosa*, free

1  
2 46 cells of 4-8  $\mu\text{m}$ , can support the growth and reproduction of protists, but not copepods (Tang et al.,  
3  
4 47 2001). Furthermore, field studies of microzooplankton grazing during blooms of *Phaeocystis* have  
5  
6 48 indicated high grazing rates (e.g., Stelfox-Widdicombe et al., 2004). Thus, existing evidence  
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8 49 supports a view that microzooplankton grazing could potentially impact *Phaeocystis* blooms. In  
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10 50 contrast, several field studies focusing on mesozooplankton impact on *P. globosa* have reported  
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12 51 grazing rates that vary from negligible, suggesting the unsuitability of *P. globosa* for many species  
13  
14 52 of mesozooplankton (Hansen et al., 1993; Gasparini et al., 2000), to highly variable (Seuront and  
15  
16 53 Vincent, 2008). These discrepancies may be attributable to the effects of colony size on  
17  
18 54 susceptibility to copepod grazing (e.g., Verity, 2000) and/or copepods switching to heterotrophic  
19  
20 55 food (Hansen and Van Boekel, 1991; Nejstgaard et al., 2001). Overall, despite the existence of  
21  
22 56 numerous studies dealing with *P. globosa* blooms, the identities and relative importance of the  
23  
24 57 major groups of grazers remains obscure. In a model simulation study, Verity (2000) postulated that  
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26 58 transitions between life cycle stages of *P. globosa* may potentially be important to interactions  
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28 59 between phytoplankton, micro- and mesozooplankton and that these interactions may depend on  
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30 60 the match or mis-match of phytoplankton and grazer communities.

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32 61 Here we attempt to clarify whether succession of the phytoplankton community corresponded to  
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34 62 changes in the grazer community, especially with regard to heterotrophic protists. Our study covered  
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36 63 3 years of the critical period of phytoplankton growth and senescence in a coastal system (eastern  
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38 64 English Channel) over a period of 2.5 years. Such an approach permits the identification of "regular  
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40 65 and recurrent patterns from occasional and exceptional events" (Ribera d'Alcala et al., 2004). We  
41  
42 66 hypothesized that although the bloom is dominated by a single species, *P. globosa*, phytoplankton  
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44 67 community composition preceding and following the bloom is likely to be variable, as well as the  
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46 68 intensity of the bloom, and in particular the magnitude and the timing of *P. globosa* life stages  
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48 69 (flagellated cells, colonies, and free colonial cells). Because of their known potential as *P. globosa*  
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50 70 grazers and because of the scarcity of studies in particular in the eastern English Channel, our study  
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52 71 focused on the effects of phytoplankton variability on heterotrophic protists (ciliates and  
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54 72 dinoflagellates) as well as including copepods, consumers of both phytoplankton and heterotrophic  
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56 73 protists.

## 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 **METHOD**

### 76 **Study site and Sampling**

1  
2 77 Water samples were collected at the coastal station (50° 40' 75 N, 1° 31' 17E, 20-25 m water depth)  
3  
4 78 of the SOMLIT network (Service d'Observation du Milieu Littoral) in the eastern English Channel  
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6 79 (Strait of Dover, Fig. 1). The eastern English Channel is characterized by its tidal range, between 3  
7  
8 80 and 9 m, and a residual circulation parallel to the coast, where the continental inputs are restricted to  
9  
10 81 the coastal area and transported from south-west to north-east. This so-called 'coastal flow'  
11  
12 82 (Brylinski et al., 1991) is separated from offshore waters by a tidally maintained frontal area  
13  
14 83 (Brylinski and Lagadeuc, 1990). Sampling was always carried out at high tide. Sampling was  
15  
16 84 conducted on 52 dates over the study period (22, 14, and 16 samples in 2007, 2008 and 2009,  
17  
18 85 respectively). Sampling frequency was planned to be weekly, during the period of growth and  
19  
20 86 senescence of the spring bloom and about every 2 weeks for the rest of the year. Actual sampling  
21  
22 87 frequency varied with weather conditions in the channel and thus, varied from a minimum of less  
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24 88 than a week (3 days) to a maximum of 57 days (overall mean and median frequency of 17 days and  
25  
26 89 14 days, respectively). Sub-surface sampling (2-3 m water depth) was conducted for phytoplankton  
27  
28 90 and microzooplankton, and vertical hauls for mesozooplankton.  
29

### 29 92 **Physico-chemical parameters and Chlorophyll-*a* (Chl-*a*)**

30 93 Seawater temperature (T, °C) and salinity (S) were measured using a conductivity– temperature–  
31  
32 94 depth profiling system (CTD Seabird SBE 25). Inorganic nutrients concentrations were determined  
33  
34 95 from 100 mL samples with an Alliance Integral Futura Autoanalyser II for nitrate (NO<sub>3</sub><sup>-</sup>), nitrite  
35  
36 96 (NO<sub>2</sub><sup>-</sup>), silicate [(SiO<sub>4</sub>)<sup>4-</sup>] and phosphate (PO<sub>4</sub><sup>3-</sup>; Strickland and Parsons, 1972; Aminot and Kerouel,  
37  
38 97 2004). Chlorophyll-*a* (Chl-*a*) concentrations were measured on 90% (v/v) acetone extracted  
39  
40 98 particulate material isolated by filtration on GF/F glass-fibre filters (Whatman). Concentrations were  
41  
42 99 determined by fluorescence using a 10-AU Turner Designs<sup>®</sup> fluorometer (Lorenzen, 1966).  
43  
44 100 Particulate organic carbon (POC) was analyzed by filtering (<150 mm Hg) duplicate 50 to 200 mL  
45  
46 101 seawater samples through pre-combusted (4 to 5 h at 480°C) glass fibre filters (Whatman GF/F, 25  
47  
48 102 mm). Analysis was performed on a NA2100 Frisons CHN analyzer after drying filters at 60°C for  
49  
50 103 24 h and exposure to HCl 1 N vapors for 5 h.  
51

### 52 105 **Sample Analysis**

53 106 Phytoplankton: For microphytoplankton floristic analysis, samples were fixed with Lugol-  
54  
55 107 glutaraldehyde solution (1% v/v; Breton et al., 2006) and examined using an inverted microscope  
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57 108 (Nikon Eclipse TE2000-S) after sedimentation in 5-25 mL Hydrobios chambers. Diatom carbon  
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60

1  
2 109 biomass was calculated on the basis of cell concentration and specific biometry using the size-  
3  
4 110 dependent relationship recommended by Menden-Deuer and Lessard (2000). Carbon biomass of the  
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6 111 *Phaeocystis globosa* colonies was calculated from biovolume measurements at x100 or x200  
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8 112 magnification, as previously described by Breton et al. (2006). The microphytoplankton was further  
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10 113 divided in two size groups: (i) Phytoplankton smaller than 100  $\mu\text{m}$  (small colonies of *P. globosa*,  
11  
12 114 and diatoms) and (ii) phytoplankton larger than 100  $\mu\text{m}$  (large colonies of *P. globosa* and large  
13  
14 115 diatoms). To enumerate nanophytoplankton ( $< 20 \mu\text{m}$ ) 5 to 10 mL samples were preserved using  
15  
16 116 borax buffered formaldehyde (1% v/v). Samples were filtered onto black Nuclepore filters, (pore  
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18 117 size: 0.8  $\mu\text{m}$ ) and stained with DAPI (Porter and Feig, 1980) within 5 h of sampling and stored at –  
19  
20 118 20°C until counting. Cells were enumerated using a Leica FW4000 epifluorescence microscope at  
21  
22 119 x1000. To distinguish between phototrophic and heterotrophic cells, autofluorescence (chlorophyll)  
23  
24 120 was determined under blue light excitation (BP 450-480 nm). Free colonial and flagellated  
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26 121 *Phaeocystis* cells are easily distinguished based on their morphology. Colonial cells are in the size  
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28 122 range of 4.5– 8  $\mu\text{m}$ , have an anterior longitudinal groove and lack filamentous appendages.  
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30 123 Flagellated cells have a rounded shape, and are smaller than colonial cells, with a diameter of 3–5  
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32 124  $\mu\text{m}$  (reviewed in Rousseau et al. 2007). Phototrophic nanoplankton consisted almost exclusively of  
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34 125 free *P. globosa* cells and cryptophytes (see results) and will be designated from now-on in the text  
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36 126 as phototrophic nanoflagellates (PNF).

37  
38 127 Nano-sized diatoms were counted along with microphytoplankton as described above. For each  
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40 128 sample, at least 30 fields and at least 250 phototrophic nanoflagellates (PNF) were counted on each  
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42 129 filter. To estimate PNF biomass, biovolume was calculated based on the linear dimensions (length  
43  
44 130 and width) of cells using an image analyser with a camera mounted on the microscope. Biovolume  
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46 131 was then converted to biomass according to Menden-Deuer and Lessard (2000).

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48 132 Heterotrophic protists: For heterotrophic protist enumeration, duplicate samples (250 mL) were  
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50 133 placed in opaque glass bottles. One 250 mL sample was fixed with acid Lugol's solution (2% v/v)  
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52 134 for quantitative counts, and the other with borax buffered formaldehyde (1% v/v) for determination  
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54 135 of the trophic type of the ciliates, heterotroph or mixotroph, based on the presence or absence of  
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56 136 sequestered chloroplasts. The samples were then stored at 4°C in the dark until analysis (most often  
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58 137 within the following week and maximally 3 weeks later). Samples were further sedimented in 50 or  
59  
60 138 100 mL Hydrobios chambers for at least 24 h before enumeration using an Nikon Eclipse TE2000-S  
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62 139 inverted microscope at 200x or 400x magnification. Lugol's fixed samples were enumerated and  
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64 140 sized with phase contrast. The formaldehyde-fixed samples were examined using blue light



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2 141 excitation (DM 500 nm dichromic mirror, BP 450 to 480 nm excitation filter, BA 515 nm barrier  
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4 142 filter and a 100 W mercury burner) to detect chlorophyll autofluorescence and to distinguish  
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6 143 plastidic from non-plastidic ciliates. Ciliates were identified wherever possible to genus or species  
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8 144 level following Kofoed and Campbell (1929) for tintinnid ciliates, the Planktonic Ciliate Project  
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10 145 (<http://www.liv.ac.uk/ciliate/intro.htm>), University of Liverpool, 2002, for spirotrich and other  
11  
12 146 ciliates, and following Schiller (1931-1937), Gomez and Souissi (2007) and Maar et al. (2002) for  
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14 147 heterotrophic dinoflagellates. Ciliates were further divided into 3 size groups (<20, 20-40, >40  $\mu\text{m}$ )  
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16 148 and dinoflagellates in 5 size groups (<10, 10-20, 20-40, 40-60, >60  $\mu\text{m}$ ). Linear dimensions (length  
17  
18 149 and diameter) were measured at x400 magnification using an image analyser with a camera mounted  
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20 150 on the microscope. Biovolumes of cells were calculated assuming the nearest geometrical shape; for  
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22 151 this a minimum of 10 cells (for rare tintinnids) and a maximum of 300 cells (for the most abundant  
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24 152 *Strombidium* and *Strobilidium*) were measured. Biovolumes were converted to carbon biomass  
25  
26 153 using a conversion factor of 190 fg C  $\mu\text{m}^{-3}$  for ciliates (Putt and Stoecker, 1989) and 0,760 x  
27  
28 154 volume<sup>0.819</sup> pg C  $\mu\text{m}^{-3}$  (Stoecker et al., 1994) for dinoflagellates.

27 155 Mesozooplankton: Zooplankton samples for quantitative analysis were collected by means of  
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29 156 vertical or sub-vertical hauls from the bottom to the surface, using a 200  $\mu\text{m}$  mesh size WP2 net  
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31 157 (UNESCO, 1968). The volume filtered was measured with a TSK flow-meter, mounted on the  
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33 158 mouth of the net (0.25  $\text{m}^2$  mouth area). The filtered volume varied between 1  $\text{m}^3$  and 7  $\text{m}^3$ . The  
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35 159 choice of mesh size, while preventing a quantitative study of copepod nauplii, was made as  
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37 160 compromise between sampling small metazoa and limiting and/or delaying the clogging of the net in  
38  
39 161 this eutrophic and turbid coastal area. Thus the lower values of filtered volume correspond to rapid  
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41 162 clogging of the net by tripton or phytoplankton (e.g. *Phaeocystis globosa*). After each haul, the  
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43 163 sample was preserved in a 5% buffered-formaldehyde seawater solution until laboratory analysis.

43 164 In the laboratory, all specimens were identified and counted in subsamples (1/10 to 1/30) of  
44  
45 165 the whole sample. Zooplankton species were determined under a binocular microscope following  
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47 166 Rose (1933) for the copepods and the Plankton identification Leaflets (ICES, 1939-2001) for the  
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49 167 other groups which were determined at different level (Phylum, Class, Order or Species). In order to  
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51 168 facilitate comparison with phytoplankton and microzooplankton, for total copepods and for the 2  
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53 169 dominant key species for the area, *Acartia clausi* and *Temora longicornis* biomass was also  
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55 170 estimated. Individual species-specific biomass for copepods was determined by measuring dry  
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57 171 weights and converted into carbon units assuming a 40% carbon content (Gorsky et al., 1988). A  
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59 172 minimum of 400 copepods were used to calculate conversion factors (401, 1153 and 545 copepods  
60



for *Temora longicornis*, *Acartia clausi* and other copepods). The averages of carbon per individual copepod were  $3.56 \pm 1.73$ ,  $1.59 \pm 0.41$  and  $2.34 \pm 2.63 \mu\text{g C copepod}^{-1}$  for *Temora longicornis*, *Acartia clausi*, and other copepods, respectively. These empirical conversion factors determined from our samples were then used to convert abundance into biomass data.

## Data analysis

To portray temporal patterns of different phytoplankton and heterotrophic compartments considered in this study the method of cumulated function (Ibanez et al., 1993) was used. This method can be applied to portray trends in data series with missing values and does not require special conditions. The calculation consists of subtracting a reference value (here for a biomass parameter we used the annual mean of the series) from the data; the resulting residuals are then successively added, forming a cumulative function. Successive positive residuals produce an increasing slope indicating higher values than the overall mean, whereas successive negative residuals produce a decreasing slope indicating values lower than the overall mean. A succession of values similar to the mean show no slope.

$$S_p = \sum_{t=1}^p x_t - p_k \quad (1)$$

$S_p$  = consecutive terms of the cumulative sums

$x_t$  = value for each sampling date (t)

$p_k$  = annual mean

Spearman correlations were calculated using series of cumulative sums ( $S_p$ ). These correlations have an informative rather than an absolute value since the terms of cumulative sums are autocorrelated. For this reason correlations can be relevant only if the correlation coefficient ( $r$ ) is highly significant ( $p = 0.01$  so 1%) for the degrees of freedom considered.

Log-log plots of total phytoplankton, diatoms, colonies and free *P. globosa* cells were used to investigate linkages with grazers, in particular ciliates and dinoflagellates (Irigoien et al. 2005).

## RESULTS

### Environmental parameters

1  
2 201 Salinity ranged from 33 to 35 and the seawater temperature from 4.6°C to 18.2°C (Fig. 2a).  
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4 202 Concentrations of inorganic nutrients exhibited typical seasonal patterns for this temperate coastal  
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6 203 area: Highest concentrations were recorded at the end of winter before the onset of the  
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8 204 phytoplankton bloom reaching 37.23  $\mu\text{M}$  for  $\text{NO}_3^- + \text{NO}_2^-$ , 15.05  $\mu\text{M}$  for  $(\text{SiO}_4)^{4-}$ , 0.77  $\mu\text{M}$  for  $\text{PO}_4^{3-}$   
9  
10 205 in 2007 (Table I); nutrient concentrations always dropped dramatically at the end of spring. A  
11  
12 206 decrease in the maximum value of inorganic nutrients was observed from 2007 to 2009 and this was  
13  
14 207 more pronounced for  $\text{NO}_3^- + \text{NO}_2^-$  concentrations (Table I). POC ranged from 114 to 1675  $\mu\text{g C L}^{-1}$   
15  
16 208 in 2007 and from around 100 to 600  $\mu\text{g C L}^{-1}$  in 2008 and 2009 (Table I)

### 16 209 **Phytoplankton**

17  
18 210 Chlorophyll *a* (chl *a*) concentrations ranged from 0.8 to 20.3  $\mu\text{g Chl a L}^{-1}$  (Table I) with minima  
19  
20 211 during autumn/winter (October - February) and maxima in late spring (April-May, Fig. 2b). The  
21  
22 212 peak value of chl *a* concentration observed during spring coincided with the *P. globosa* bloom,  
23  
24 213 except in 2009 when the chl *a* maximum was due to diatoms and occurred before the peak of the  
25  
26 214 phytoplankton biomass (Fig. 2b). Total phytoplankton biomass ranged from 2 to 638  $\mu\text{g C L}^{-1}$ , with  
27  
28 215 a maximum in spring and a minimum in autumn/winter (from October to February-Table II; Fig 2b).  
29  
30 216 Based on our data a highly significant empirical relationship between POC:chl and  
31  
32 217 Cphytoplankton:Chl was calculated ( $\text{COP}=92.0 + 47.6 [\text{Chl a}]$ , and  $\text{Cphytoplankton}=29.4 +$   
33  
34 218  $23.6[\text{Chl a}]$ ,  $r^2=0.425$  and  $r^2=0.552$  with  $p<0.0001$  respectively, figures not shown).

35  
36 219 *Phaeocystis globosa* blooms are ephemeral and at our study site occurred from late March to  
37  
38 220 early May and lasted about one month each year (37, 27 and 29 days in 2007, 2008 and 2009,  
39  
40 221 respectively, Fig. 3b,c). During the blooms, *P. globosa* represented up to 93% of the  
41  
42 222 microphytoplankton and up to 100% of the nanophytoplankton biomass and large colonies (>100  
43  
44 223  $\mu\text{m}$ ) constituted most (56 to 93%) of the *P. globosa* biomass. With regard to inter-annual  
45  
46 224 differences, from 2007 to 2009 maximum biomass values increased for *P. globosa* colonies (from  
47  
48 225 316 to 392  $\mu\text{g C L}^{-1}$ ) and free colonial cells (from 62 to 153  $\mu\text{g C L}^{-1}$ ) while flagellated cells  
49  
50 226 decreased slightly (from 66 to 50  $\mu\text{g C L}^{-1}$ ; Fig. 3c).

51  
52 227 Diatoms were always present with mean biomass values of 92% of total phytoplankton  
53  
54 228 biomass over the study period. Diatom biomass ranged from 2 to 345  $\mu\text{g C L}^{-1}$  (Table II). The mean  
55  
56 229 of diatom biomass during the spring bloom (from March to May) was lowest in 2009 and highest in  
57  
58 230 2007 (Table III). The diatom 20-100  $\mu\text{m}$  size class was the most important for all years and showed  
59  
60 231 the highest biomass mean during the spring bloom in 2008 (Table III).

1  
2 232 We distinguished 3 distinct assemblages of diatoms. The first group, composed of cells  
3  
4 233 between 20-120  $\mu\text{m}$  and characterized by *Pseudonitzschia* spp., and *Chaetoceros* spp., was present  
5  
6 234 during *P. globosa* blooms and persisted during the post-bloom period until August. In 2009 the  
7  
8 235 *Pseudonitzschia* spp. group also dominated the phytoplankton during the pre-bloom period (209  $\mu\text{g}$   
9  
10 236  $\text{C L}^{-1}$  in early March; Fig. 3a). The second group, characterized by diatoms forming colonies ( $> 100$   
11  
12 237  $\mu\text{m}$ ) such as *Skeletonema costatum* 5-20  $\mu\text{m}$  length, *Brockmaniella brockmanii* and *Ditylum*  
13  
14 238 *brightwelli* 20-120  $\mu\text{m}$  length, marked the early spring period. The third group appeared from the  
15  
16 239 end of summer to winter, composed of large fine-walled diatoms such as *Guinardia* spp.,  
17  
18 240 *Rhizosolenia* spp. and *Chaetoceros* spp.

### 18 241 **Heterotrophic protists (ciliates and dinoflagellates)**

19  
20 242 The biomass of heterotrophic protists over the study period showed low values during autumn-  
21  
22 243 winter (0.6 to 20.0  $\mu\text{g C L}^{-1}$ ) and higher values during spring-summer (2.8 to 61.1  $\mu\text{g C L}^{-1}$ ). The  
23  
24 244 overall biomass of protists during the spring bloom was similar in 2007 and 2009 and greater than  
25  
26 245 that recorded for 2008 (Table III). Despite these differences, some common features were observed  
27  
28 246 every year: a) heterotrophic dinoflagellate biomass exceeded that of ciliates, except in spring 2007  
29  
30 247 (Fig. 4a), b) ciliates were almost equally divided between heterotrophs and mixotrophs (Fig. 4b).

31  
32 248 Ciliate abundance and biomass over the study period ranged from 0.5 to 19.5  $10^3$  cells  $\text{L}^{-1}$   
33  
34 249 and from 0.4 to 58.1  $\mu\text{g C L}^{-1}$ , respectively (Table II). High abundance and biomass were recorded  
35  
36 250 in May 2007 and 2009, while in 2008 ciliate abundance and biomass were relatively low ( $< 5.2$   $10^3$   
37  
38 251 cells  $\text{L}^{-1}$  and  $< 10$   $\mu\text{g C L}^{-1}$ , Fig. 4a). The taxonomic composition of the ciliate community was  
39  
40 252 largely invariant over the 2.5 years and was dominated (86% of abundance) by Spirotrichs of the  
41  
42 253 genera *Strombidium*, *Strobilidium*, *Leegardiella*, *Tontonia* and the haptorid *Myrionecta rubra*.  
43  
44 254 Among heterotrophic aloricate ciliates, *Strombidium lynni*, *Leegardiella sol*, and *Strobilidium*  
45  
46 255 *spiralis* were present in all samples. Scuticociliates were occasionally present during the study in  
47  
48 256 particular after wind events in 2007 and 2008 (mean  $< 1$   $\mu\text{g C L}^{-1}$ ). Tintinnids were insignificant  
49  
50 257 during the whole study and will not be further considered (max. 0.33  $\mu\text{g C L}^{-1}$ ; mean 0.02  $\mu\text{g C L}^{-1}$ ).  
51  
52 258 Carnivorous ciliates, the suctorians (*Acineta* sp. and *Podophyra* sp.) were present in low numbers  
53  
54 259 (up to 80 cells  $\text{L}^{-1}$ ). The mixotrophic community was essentially composed by *Laboea strobila*,  
55  
56 260 *Tontonia* spp, *Strombidium acutum* and *S. capitatum*. *Myrionecta rubra* was also present in large  
57  
58 261 numbers and biomass (up to 4.32  $10^3$  cells  $\text{L}^{-1}$ , 8.02  $\mu\text{g C L}^{-1}$ ) during different seasons, without a  
59  
60 262 marked seasonality (Fig. 4b). The biomass of heterotrophs and mixotrophs was in a similar range  
61  
62 263 (from 0.1-34.3 and 0.1-24.6  $\mu\text{g C L}^{-1}$ , respectively) to that of heterotrophs representing 55% and

1  
2 264 mixotrophs + *M. rubra* representing 45% of the mean ciliate biomass over the study period (Fig. 4b,  
3  
4 265 Table II). The alternation of heterotrophs/mixotrophs was particularly noticeable in 2008 when  
5  
6 266 outside of the period of dinoflagellate dominance, mixotrophic ciliates + *M. rubra* represented up to  
7  
8 267 62% of the ciliate biomass and 28% of the biomass of heterotrophic protists (Fig. 4b). The 20-40  $\mu\text{m}$   
9  
10 268 size class ( $11.5 \pm 3.7 \cdot 10^3 \mu\text{m}^3$ ) was the modal size-class for heterotrophs while mixotrophs were  
11  
12 269 dominated by the  $>40 \mu\text{m}$  size class ( $88.6 \pm 35.4 \cdot 10^3 \mu\text{m}^3$ ). However, it should be noted that in  
13  
14 270 spring 2009, *Tontonia* spp. alone represented 74.1% of the ciliate biomass and 51.9% of the ciliate  
15  
16 271 abundance.

16 272 Dinoflagellate biomass ranged from 0.2 to 51.9  $\mu\text{g C L}^{-1}$  (Table II; Fig. 4a) and increased  
17  
18 273 from 2007 to 2009 (Table III) with the increase of the ratio of dinoflagellate to ciliate biomass  
19  
20 274 average during the spring bloom (from March to May), 0.3, 1.5 and 2.1 in 2007, 2008, 2009,  
21  
22 275 respectively, cf. Table III). The dinoflagellate community was composed almost exclusively of  
23  
24 276 heterotrophic species. The most abundant species (84% of abundance and 86% of biomass) were the  
25  
26 277 athecate forms such as *Gyrodinium spirale*, *Spatulodinium pseudonociluca*, *Gymnodinium* spp.  
27  
28 278 while thecate dinoflagellates were dominated by *Protopteridinium* spp. and *Prorocentrum micans*.  
29  
30 279 Dinoflagellates were particularly abundant during the pre-bloom period and at the end of the  
31  
32 280 *Phaeocystis globosa* bloom, when they accounted from 72.8 to 93.5% and up to 86.3% of the  
33  
34 281 heterotrophic protist biomass respectively; they were also abundant during the summer (52.7 to  
35  
36 282 81.1% of the biomass). In 2007 the assemblage of  $<20$  ( $1.9 \pm 1.0 \cdot 10^3 \mu\text{m}^3$ , *Protopteridinium* spp.)  
37  
38 283 and 20-40  $\mu\text{m}$  ( $15.1 \pm 7.3 \cdot 10^3 \mu\text{m}^3$ , *G. spirale*) size groups dominated the dinoflagellate community  
39  
40 284 (48% and 44% of dinoflagellate abundance respectively). In 2008 the larger size-class of 20-40  $\mu\text{m}$   
41  
42 285 was dominant yet still composed of *Gyrodinium spirale* and *Protopteridinium* spp. accounting from  
43  
44 286 19 to 94% with a mean of 51% of the dinoflagellate biomass. In 2009, the  $>40 \mu\text{m}$  size class was  
45  
46 287 dominant with the highest biomass (18 to 87% with mean of 46%).  
47  
48 288

### 46 289 **Mesozooplankton**

48 290 The abundance of mesozooplankton ranged from 0.6 to 13.9 ind.  $\text{L}^{-1}$  and was dominated by  
49  
50 291 copepods (0.03 to 10.9 ind.  $\text{L}^{-1}$ ) equal to  $68.4\% \pm 22.4$  of total abundance (Table II, Fig. 4c).  
51  
52 292 Copepod biomass ranged from 0.07 to 27.3  $\mu\text{g C L}^{-1}$  (mean  $6.4 \pm 6.6 \mu\text{g C L}^{-1}$ , Table II). The dominant  
53  
54 293 copepod species were *Acartia clausi* and *Temora longicornis*, which accounted for  $44.4 \pm 18.8\%$  and  
55  
56 294  $23.3 \pm 15.7\%$  of copepod abundance and  $31.4 \pm 15.4\%$  and  $33.2 \pm 18.7\%$  of copepod biomass,  
57  
58 295 respectively. Yet, we observed a change in relative abundances of these species during the spring  
59  
60

1  
2 296 bloom (from March to May). The *Acartia* to *Temora* ratio of average biomass values increased from  
3  
4 297 0.25 in 2007 to 1.9 in 2009 (Table III, Fig. 4c). *Paracalanus parvus* and *Centropages hamatus* were  
5  
6 298 also present in lower abundances and accounted for  $7.0 \pm 5.4$  and  $13.6 \pm 13.3\%$  of total copepod  
7  
8 299 abundance, respectively.

9 300 Pluteus and larvae of the urchin *Echinocardium cordatum* were present each year in spring during  
10  
11 301 less than 1 week and occurred between the two maxima of copepods (Fig. 4). Their highest  
12  
13 302 abundance was observed in May 2007 when they reached up to  $11.3 \text{ ind. L}^{-1}$  (up to 82% of  
14  
15 303 zooplankton abundance) and they were absent during the rest of the year. Appendicularians  
16 304 (*Oikopleura dioica*) feeding essentially on picoplankton, were also observed in low numbers (0 to  
17  
18 305  $2.9 \text{ ind. L}^{-1}$ , mean  $15.3 \pm 11.8\%$  of the mesozooplankton abundance).  
19

### 20 306 21 22 307 **Temporal Trends based on cumulative sums**

23 308 The cumulative sums show temporal trends in terms of differences from overall averages, temporal  
24  
25 309 variations not easily seen in figures such as Figures 3 and 4. We focused on the temporal trends of  
26  
27 310 the three major types of consumers (ciliates, dinoflagellates and copepods) and autotrophs (Fig. 5a-  
28  
29 311 i).

30 312 In 2007 the ciliate biomass was strongly related with all phytoplankton compartments (Fig  
31  
32 313 5a-c, diatoms  $r = 0.88$ , *P. globosa* colonies  $r = 0.97$  and free cells  $r = 0.93$ ,  $n = 21$ ,  $p < 0.0001$ ). In  
33  
34 314 2008, no significant relation was observed with the phytoplankton and the ciliate cumulated sums  
35  
36 315 values remained close to the average annual biomass (more or less parallel to the x-axis, Fig. 5a-c).  
37  
38 316 In 2009, the ciliates related again with *P. globosa* colonies and free cells with a strong anomaly at  
39  
40 317 the end of April (Fig. 5a-b) which corresponds to a highest ciliate biomass recorded in 2009 (Fig.  
41 318 5a).  
42

43 319 Dinoflagellates showed a remarkable co-variation with total phytoplankton biomass during  
44  
45 320 the whole study ( $r = 0.51$ ,  $n = 51$ ,  $p < 0.0002$ ; c.f. Fig. 5 d, e, f). Noteworthy is the fact that positive  
46  
47 321 slopes in phytoplankton cumulative function were in general observed before those of  
48 322 dinoflagellates, except for *P. globosa* colonies and free cells in March 2007 (Fig. 5d-f). Overall,  
49  
50 323 dinoflagellates appeared to be tightly linked to bulk phytoplankton stocks as well as stocks of  
51  
52 324 *Phaeocystis* free cells, colonies as well as diatoms, despite changes in the composition of the diatom  
53  
54 325 assemblages.

55 326 Copepod biomass was also related tightly with the phytoplankton biomass overall ( $r = 0.70$ ,  
56  
57 327  $n = 51$ ,  $p < 0.0001$ ). However, in contrast to dinoflagellates there were some marked anomalies with  
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1  
2 328 regard to temporal trends of *Phaeocystis* colonies and diatoms (Fig. 5g-i). In 2008, copepod  
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4 329 cumulated sums remained close to the annual average but with a slight increase corresponding to the  
5  
6 330 bloom of *P. globosa* colonies in May (Fig. 5h). Considering heterotrophic protists as prey, *Temora*  
7  
8 331 *longicornis* were related to ciliate biomass ( $r = 0.42$ ,  $n = 51$ ,  $p < 0.002$ ; data not shown) and *Acartia*  
9 332 *clausi* to heterotrophic dinoflagellate biomass ( $r = 0.35$ ,  $n = 51$ ,  $p < 0.012$ ; data not shown).  
10

### 11 333 12 13 334 General Relationships

14 335 The plots of log transformed data of biomass of major phytoplankton groups and their potential  
15  
16 336 predators indicated curvilinear relationships. The biomass of total protists increased linearly with  
17  
18 337 total phytoplankton and levels around  $70 \mu\text{g C L}^{-1}$  (Fig. 6a). The same type of relationship was  
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20 338 observed with ciliates vs PNF and dinoflagellates vs diatoms levelling around 50 and  $30 \mu\text{g C L}^{-1}$ ,  
21  
22 339 respectively (Fig. 6b,c). The calculated regressions for the linear part of the relations, showed a  
23  
24 340 stronger relation for total phytoplankton vs protists, followed by PNF vs ciliates and dinoflagellates  
25 341 vs diatoms (Fig. 6, a,b,c). The relationship between dinoflagellates and *P. globosa* colonies  
26  
27 342 suggested a curvilinear relationship, with dinoflagellate biomass decreasing for biomass higher than  
28  
29 343  $1 \mu\text{g C L}^{-1}$  (Fig. 6d). The log-log plots of copepod biomass and auto- and heterotrophic protists did  
30  
31 344 not show any significant relationship.  
32 345

### 33 34 346 DISCUSSION

35  
36 347 To our knowledge, this is the first study exploring a 2.5 years data of both primary producers and  
37  
38 348 grazers in a system characterized by blooms of *Phaeocystis*. The primary aim of this study was to  
39 349 determine whether variations of the phytoplankton community corresponded with changes in the  
40  
41 350 grazer community, especially with regard to heterotrophic protists. During our study, we observed  
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43 351 phytoplankton successions typical of the eastern English Channel and in the Southern Bight of the  
44  
45 352 North Sea with diatom blooms preceding *Phaeocystis* blooms (e.g., Breton et al., 2000; Rousseau et  
46 353 al., 2002; Seuront and Vincent, 2008; Guiselin, 2010). The phenomenon is generally ascribed as a  
47  
48 354 succession in high nutrient coastal waters following silicate limitation of diatom production (e.g.,  
49  
50 355 Rousseau et al., 2000) or alternatively, due to light limitation of diatoms (Peperzak et al., 1998).  
51

52 356 We found considerable variability in the *Phaeocystis* bloom as well as the diatom  
53  
54 357 assemblages preceding and following the bloom, similar to previous studies in the same area. For  
55 358 example, Gomez and Souissi (2008), based on sampling at approximately monthly intervals from  
56  
57 359 1998 to 2005, reported declines of the *P. globosa* spring bloom in offshore but not inshore waters  
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59  
60

1  
2 360 and shifts in diatom assemblages (Gomez and Souissi, 2007). During our study, the *P. globosa*  
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4 361 concentrations were close to values of the 1998 *P. globosa* bloom (Gomez and Souissi, 2008; Table  
5  
6 362 II). We encountered variability in bloom duration, composition in terms of colony sizes and relative  
7  
8 363 importance of non-colonial cells, as well as changes in the diatom assemblages, in particular the  
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10 364 diatom group of *Pseudonitzschia* spp. present usually during and after the bloom (Rousseau et al.,  
11  
12 365 2002; Guiselin, 2010), appeared before the *P. globosa* bloom in 2009. Moreover change in the  
13  
14 366 dynamics of *P. globosa* life stages was also observed from 2007 to 2009: increases of maximum  
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16 367 biomass of free cells (Fig. 3c), fewer small colonies (20-100  $\mu\text{m}$ ) and a slight increase of large  
17  
18 368 colonies (Fig. 3b).

19  
20 370 Along with variability in the phytoplankton, we found marked changes among the grazer  
21  
22 371 communities, in terms of both compositional shifts and changes in abundance. In the heterotrophic  
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24 372 protist community, the most obvious difference was a shift from a dominance of spirotrich ciliates in  
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26 373 2007 to dinoflagellates, largely *Gyrodinium spirale*, dominating the protist community in 2008 and  
27  
28 374 2009. The ciliate community was, overall, similar in abundance and composition to those found in  
29  
30 375 other systems subject to *Phaeocystis* blooms. For example, Verity et al. (1993) reported ciliate  
31  
32 376 abundances during the spring bloom in the North Atlantic of 1.9 - 17.2 cells  $\text{mL}^{-1}$ . The composition  
33  
34 377 of ciliates was comparable to that found in the Kattegat (Levinsen and Nielsen, 2002) and the  
35  
36 378 proportion of mixotrophic species + *M. rubra* we found (45% of the ciliate biomass) similar to the  
37  
38 379 values recorded for the North Sea (28% and 53% of the ciliate biomass nearshore and offshore  
39  
40 380 respectively; Stelfox-Widdicombe et al., 2004). The relatively low ciliate abundances found in 2008  
41  
42 381 and 2009 compared to 2007 correspond with lower concentrations of free cells of *Phaeocystis* (Fig.  
43  
44 382 3c; Fig. 4a), known to support ciliate growth (Tang et al., 2001) as well as lower concentrations of  
45  
46 383 copepods (Fig. 4c), the major predators of ciliates (e.g., Stoecker and Capuzzo, 1990; Christaki and  
47  
48 384 Van Wambeke, 1995; reviewed by Calbet and Saiz 2005).

49  
50 385 Perhaps the most remarkable finding of our study is with regard to heterotrophic  
51  
52 386 dinoflagellates, largely the species putatively identified as *Gyrodinium spirale*. Abundance trends of  
53  
54 387 heterotrophic dinoflagellates closely tracked those of diatoms as well as colonies of *Phaeocystis*  
55  
56 388 (Fig. 5e,f). The biomass of heterotrophic dinoflagellates, in carbon units, was consistently about  
57  
58 389 10% of autotrophic biomass (see Fig. 3 and Fig. 4a) and they may have been the major consumers of  
59  
60 390 phytoplankton. Heterotrophic dinoflagellates, typically display low growth efficiencies and require  
61  
62 391 relatively high prey concentrations, relative to ciliate microzooplankton (Hansen, 1992; Strom and  
63  
64 392 Morello, 1998). However, they are capable of rapid growth given sufficient prey. In laboratory  
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66 393



1  
2 392 experiments, *Protoperidinium* species feeding on diatoms have daily division rates ranging from 0.5  
3  
4 393 - 2 per day (Menden-Deuer et al., 2005) and *Gyrodinium spirale*, feeding on other dinoflagellates,  
5  
6 394 divides about once per day rate in the presence of phytoplankton prey concentrations typical of our  
7  
8 395 study site, above  $100 \mu\text{g L}^{-1}$ , with gross growth efficiencies ranging from about 10 to 20 % (Kim  
9  
10 396 and Jeong, 2004). Employing these growth parameters, rough estimates suggest then a possibly  
11 397 major role for heterotrophic dinoflagellate as phytoplankton grazers at our study site. While  
12  
13 398 heterotrophic dinoflagellates are known to be important grazers of diatoms (Sherr & Sherr 2007),  
14  
15 399 our data suggests a significant role as consumers of *Phaeocystis* as well.

16 400 Copepods dominated the mesozooplankton assemblage (68.4%, Table II) with the usual copepod  
17  
18 401 species found in the eastern English Channel and in the North Sea (Breton 2000, Rousseau et al.  
19  
20 402 2000, Brylinski 1986). Abundances of copepods ( $0.03 - 10.9 \text{ ind. L}^{-1}$ , Table II) were similar to those  
21  
22 403 previously recorded for the study site, November 1995 to July 1997 (Breton 2000). In our samples,  
23  
24 404 *Acartia clausi* and *Temora longicornis* were the most abundant species found during this study  
25 405 (Table II). Brylinski (2009) reported that *T. longicornis* habitually dominate copepod abundance  
26  
27 406 during the spring and *A. clausi* during the summer.

28  
29 407 During our study period, *T. longicornis* showed a decrease from 2007 to 2009 that  
30  
31 408 corresponded with the decrease of *P. globosa* bloom duration, fewer large *Phaeocystis* colonies ( $>$   
32 409  $100 \mu\text{m}$ ) and lower ciliate biomass (Table III). It is tempting to relate the decrease in *Temora*  
33  
34 410 *longicornis* to declines in ciliate biomass ( $r=0.42$ ; cf. Results), as this species is thought to feed  
35  
36 411 selectively on ciliates and discriminate against both *Phaeocystis* (Hansen and Van Boekel, 1991;  
37  
38 412 Hansen et al., 1993) as well as dinoflagellates (Vincent and Hartmann, 2001). The species which  
39  
40 413 replaced *Temora longicornis*, *Acartia clausi*, while known to ingest ciliates (Gismervik and  
41 414 Andersen, 1997), apparently does not selectively prey on them in natural populations (Tiselius,  
42  
43 415 1989). The correlation between *A. clausi* and dinoflagellate biomass can be attributed to *A. clausi*  
44  
45 416 preference for dinoflagellates over phytoplankton (Vargas and Gonzalez, 2004; Leising et al., 2005  
46  
47 417 a,b). With regard to the impact of copepod grazing on the communities of heterotrophic protists and  
48 418 phytoplankton, some rough estimates can be made based on maximal reported clearance rates,  $40$   
49  
50 419  $\text{mL d}^{-1} \text{ Temora}^{-1}$  (Tiselius, 1989) and  $30 \text{ mL d}^{-1} \text{ Acartia}^{-1}$ , (Gismervik and Andersen, 1997) and our  
51  
52 420 peak copepod abundances (Fig. 4c). Such calculations suggest a weak control, clearing at most  
53  
54 421 about 15% of the water column per day in 2008 and 2009 in the *Acartia* dominated years compared  
55 422 to 2007 in which peak populations of *Temora* may have been capable of clearing about 50% of the  
56  
57 423 water column per day. Nauplii of the 2 dominant copepod species were not quantitatively sampled  
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59  
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1  
2 424 in this work, we can speculate that nauplii maxima usually occur a few weeks before adult maxima  
3  
4 425 and they can eventually have an important grazing impact in phytoplankton; since in cultures they  
5  
6 426 can feed on the same range of prey as the adults (e.g. *Isochrysis galbana* of about 12  $\mu\text{m}$  and  
7  
8 427 *Rhodomonas marina* 5-7  $\mu\text{m}$ ) (S. Souissi, Wimereux Marine Station, personal communication).  
9  
10 428

11 429 The log-log plots displayed curvilinear relationships between phytoplankton and predator. Irigoien  
12  
13 430 et al. (2005) using a large scale data set, observed the same type of relationship, observing a plateau  
14  
15 431 of microzooplankton biomass with increasing phytoplankton biomass at around 50  $\text{mg C m}^{-3}$ ; which  
16  
17 432 they attributed to the presence of unfavourable prey and/or predation by mesozooplankton. In our  
18  
19 433 study microzooplankton also levelled at around this same value range (70  $\text{mg C m}^{-3}$  Fig 6a). In the  
20  
21 434 plots of ciliates vs PNF and dinoflagellates vs diatoms, protistan biomass levelled at lower levels  
22  
23 435 (Fig. 6b, c; 50 and 30  $\text{mg C m}^{-3}$ , respectively) suggesting predation of copepods on  
24  
25 436 microzooplankton which may have favoured further phytoplankton accumulation. The log-log  
26  
27 437 relation between dinoflagellates and *P. globosa* colonies (Fig. 6d) indicated that while small  
28  
29 438 colonies (representative of low biomass) may be suitable prey for dinoflagellates, larger colonies  
30  
31 439 (representative of high biomasses) are more difficult to consume. Given that large colonies are  
32  
33 440 unsuitable for copepods, this could intensify predation on dinoflagellates (Fig. 6d). The cumulated  
34  
35 441 sum analysis showed some significant temporal relationships between copepods and phytoplankton  
36  
37 442 and between copepods and heterotrophic protists. While phytoplankton and protists have similar  
38  
39 443 growth rates, the absence of log-log relation between copepods and protists (autotrophic and  
40  
41 444 heterotrophic) can be attributed to the time lags between the appearance of prey and the predator (of  
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43 445 the order of days to weeks).  
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46  
47 447 The more than two year's sampling allowed assessment of the variability found in a "regular  
48  
49 448 and recurrent event", the phytoplankton blooms of the eastern English Channel. We found  
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51 449 differences in the phytoplankton blooms as well differences in the grazer assemblages, notably a  
52  
53 450 marked variability from one year to the other in abundances of ciliate microzooplankton and the  
54  
55 451 identity of the dominant copepod species. In contrast, heterotrophic dinoflagellates appear to be a  
56  
57 452 relatively consistent assemblage in terms of both their aggregate biomass compared to  
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59 453 phytoplankton, and their species composition. Heterotrophic dinoflagellates likely represent the  
60  
61 454 primary consumers of phytoplankton, but there is also indication that they suffer enhanced predation

1  
2 455 pressure by copepods particularly when large *Phaeocystis* colonies dominate the phytoplankton  
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4 456 assemblages.

5 457  
6  
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17  
18 464 work.  
19  
20 465

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### 39 631 **Table and Figure legends**

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41 632  
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43 633 Table I: Environmental parameters from February 2007 to July 2009 in the eastern English Channel  
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45 634 [min – max]. Numbers in parenthesis indicate the number of samples per year.

46 635  
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48 636 Table II: Autotrophic and heterotrophic abundance and biomass ([min – max]; mean ± sd), and % of  
49  
50 637 total protist biomass and total metazoan abundance, from February 2007 to July 2009 in the eastern  
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52 638 English Channel.

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54 639  
55 640 Table III: Averages of biological stocks (biomass or abundance) during the spring bloom periods  
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57 641 (from March to May) for 2007, 2008 and 2009 in the eastern English Channel.

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8 645 Figure 1: Location of the SOMLIT station (●)

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11 647 Figure 2: Temporal variation of (a) temperature ( $^{\circ}\text{C}$ ) and salinity; (b) chlorophyll *a* ( $\mu\text{g Chl}a \text{ L}^{-1}$ )  
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13 648 and phytoplankton biomass ( $\mu\text{g C L}^{-1}$ ) at SOMLIT station (eastern English Channel) from February  
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15 649 2007 to July 2009.

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18 651 Figure 3: Temporal variation of autotrophic biomass ( $\mu\text{g C L}^{-1}$ ) at SOMLIT station (eastern English  
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20 652 Channel) from February 2007 to July 2009 a) diatoms 20-100 and  $>100 \mu\text{m}$ , (b) *Phaeocystis globosa*  
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22 653 colonies 20-100 and  $>100 \mu\text{m}$ ; (c) *P. globosa* colonial free cells, *P. globosa* flagellated cells and  
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24 654 other phototrophic nanophytoplankton (other PNF).

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27 656 Figure 4: Temporal variation of heterotrophic protist and copepod biomass ( $\mu\text{g C L}^{-1}$ ) at SOMLIT  
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29 657 station (eastern English Channel) from February 2007 to July 2009 (a) ciliates and dinoflagellates  
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31 658 (b) *Myrionecta rubra*, mixotrophic and heterotrophic ciliates (c) total copepod, dominant copepod  
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33 659 species *Temora longicornis* and *Acartia clausi* abundances.

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36 661 Figure 5: Temporal trends of heterotroph and autotroph biomass ( $\mu\text{g C L}^{-1}$ ) as cumulative sums. (a  
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38 662 to c) ciliates and phytoplankton, (d to f) heterotrophic dinoflagellates and phytoplankton and (g to i)  
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40 663 copepods and phytoplankton.

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43 665 Figure 6: Plots of log transformed data of biomass of major phytoplankton groups and their potential  
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45 666 protozoan predators. The dotted line in panels a, b and c indicates the 1:1 line. (a,b and c), Bold lines  
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47 667 represent regressions for the linear part of the relation (grey rhombus), and the fine lines represent  
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49 668 the polynomial model (grey and empty rhombus fitted with *R* software (<http://www.r-project.org/>)  
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51 669 (d) the full line represent the polynomial model given above the figure.

671 Table I

	2007	2008	2009
Seawater temperature (°C)	[7.9 – 18.2]	[7.7 – 18.1]	[4.6 – 18.6]
Salinity	[32.7 – 34.4]	[33.5 – 34.5]	[33.4 – 34.6]
NO <sub>3</sub> <sup>-</sup> + NO <sub>2</sub> <sup>-</sup> (μM)	[0.10 - 37.23]	[0.13 - 23.56]	[0.09 - 14.07]
(SiO <sub>4</sub> ) <sup>4-</sup> (μM)	[0.84 - 15.05]	[0.65 - 15.05]	[0.53 - 6.32]
PO <sub>4</sub> <sup>3-</sup> (μM)	[0.03 - 0.77]	[0.05 - 0.71]	[0.08 - 0.54]
Chlorophyll a (μg L <sup>-1</sup> )	[0.8 – 20.3]	[2.1 – 15.7]	[2.4 – 14.5]
POC (μM)	[114 - 1675]	[115 – 603]	[122 – 631]

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673 Table II

Autotrophic and Heterotrophic Protists		Abundance ( $10^3$ cells $L^{-1}$ )	Biomass ( $\mu g$ C $L^{-1}$ )	% biomass of microplankton	% biomass of nanoplankton
Total phytoplankton		[18 – 35341] 5280 $\pm$ 6479	[2.2 – 637.7] 177 $\pm$ 155	[40.0 – 97.1] 79.7 $\pm$ 14.5 %	[2.9 – 60.0] 20.3 $\pm$ 14.5 %
Diatom		[18 – 2382] 483 $\pm$ 504	[2.2 – 345.3] 109 $\pm$ 88	[6.7 – 100] 84.4 $\pm$ 27.9 %	[0.21 – 100] 18.8 $\pm$ 19.7 %
<i>Phaeocystis globosa</i>		[0 – 35079] 4785 $\pm$ 6458	[0 – 607.2] 66 $\pm$ 124	[0.00 – 93.3] 15.6 $\pm$ 27.9 %	[0.00 – 99.8] 73.6 $\pm$ 23.0 %
Total	heterotrophic protist	[0.9 – 37.3] 8.8 $\pm$ 6.7	[0.6 – 61.1] 17.5 $\pm$ 15.0	[74.4 – 99.2] 88.6 $\pm$ 7.3 %	[0.8 – 25.6] 11.4 $\pm$ 7.3 %
Ciliate		[0.5 – 19.5] 3.4 $\pm$ 3.6	[0.4 – 58.1] 8.7 $\pm$ 11.7	[5.9 – 98.3] 52.1 $\pm$ 26.9 %	[4.3 – 69.4] 26.6 $\pm$ 15.5 %
Dinoflagellate		[0.3 – 32.4] 5.3 $\pm$ 5.4	[0.2 – 51.9] 8.8 $\pm$ 9.9	[1.7 – 94.1] 47.9 $\pm$ 26.9 %	[30.6 – 95.7] 73.4 $\pm$ 15.5 %
Copepods		Abundance (ind $L^{-1}$ )	Biomass ( $\mu g$ C $L^{-1}$ )	% abundance of mesozooplankton	
<i>Temora longicornis</i>		[0.01 – 4.8] 0.8 $\pm$ 1.1	[0.02 – 17.1] 2.7 $\pm$ 3.8	[0.3 - 46.4] 16.3 $\pm$ 12.2%	
<i>Acartia clausi</i>		[0.01 – 4.6] 1.2 $\pm$ 1.3	[0.02 – 7.3] 1.9 $\pm$ 2.0	[0.7 - 59.2] 29.7 $\pm$ 16.7%	
Copepods		[0.03 – 10.9] 2.6 $\pm$ 2.6	[0.07 – 27.3] 6.4 $\pm$ 6.6	[1.6 - 95.4] 68.4 $\pm$ 22.4 %	

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675 Table III

	2007	2008	2009
Autotrophic and heterotrophic protist biomass ( $\mu\text{g C L}^{-1}$ )			
Total diatoms	139.5	127.3	115.7
Diatoms 20 – 100 $\mu\text{m}$	69.8	80.4	65.7
Diatoms > 100 $\mu\text{m}$	63.9	46.2	45.7
<i>Phaeocystis globosa</i>	158.0	180.5	117.2
Free cells	47.3	47.3	47.9
Colonies	110.6	133.2	69.3
Colonies > 100 $\mu\text{m}$	108.7	132.5	68.6
Heterotrophic protists	26.7	7.7	30.1
Mixotrophic ciliates	9.1	1.8	4.8
Heterotrophic ciliates	11.9	1.3	4.8
Dinoflagellates	5.7	4.6	20.5
Copepod biomass ( $\mu\text{g C L}^{-1}$ )			
Total Copepods	10.0	5.6	6.1
<i>Acartia clausi</i>	1.5	1.8	3.1
<i>Temora longicornis</i>	5.9	2.5	1.6

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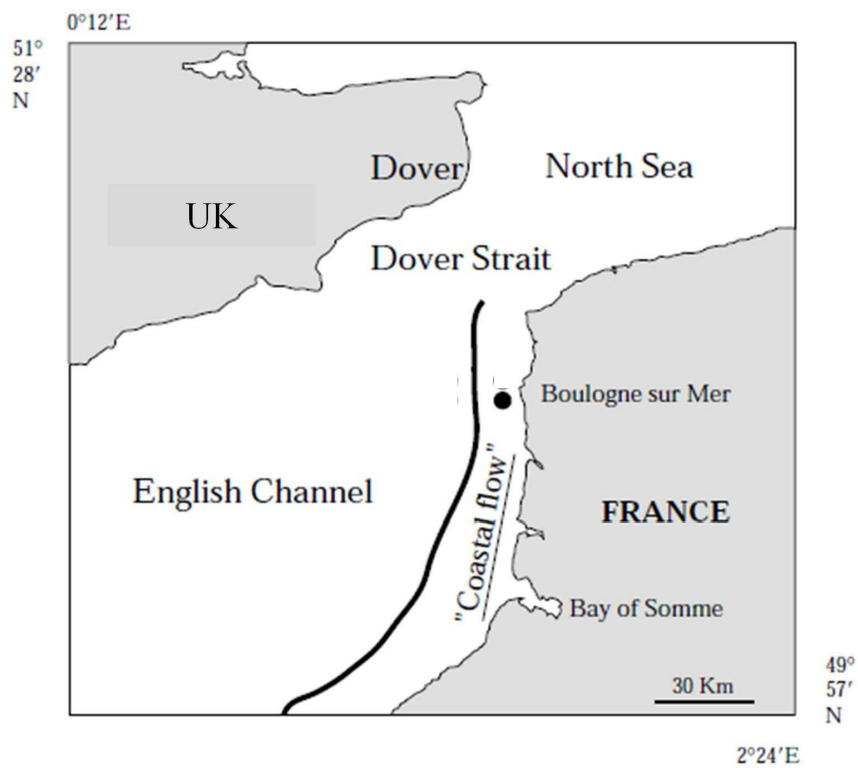


Fig. 1

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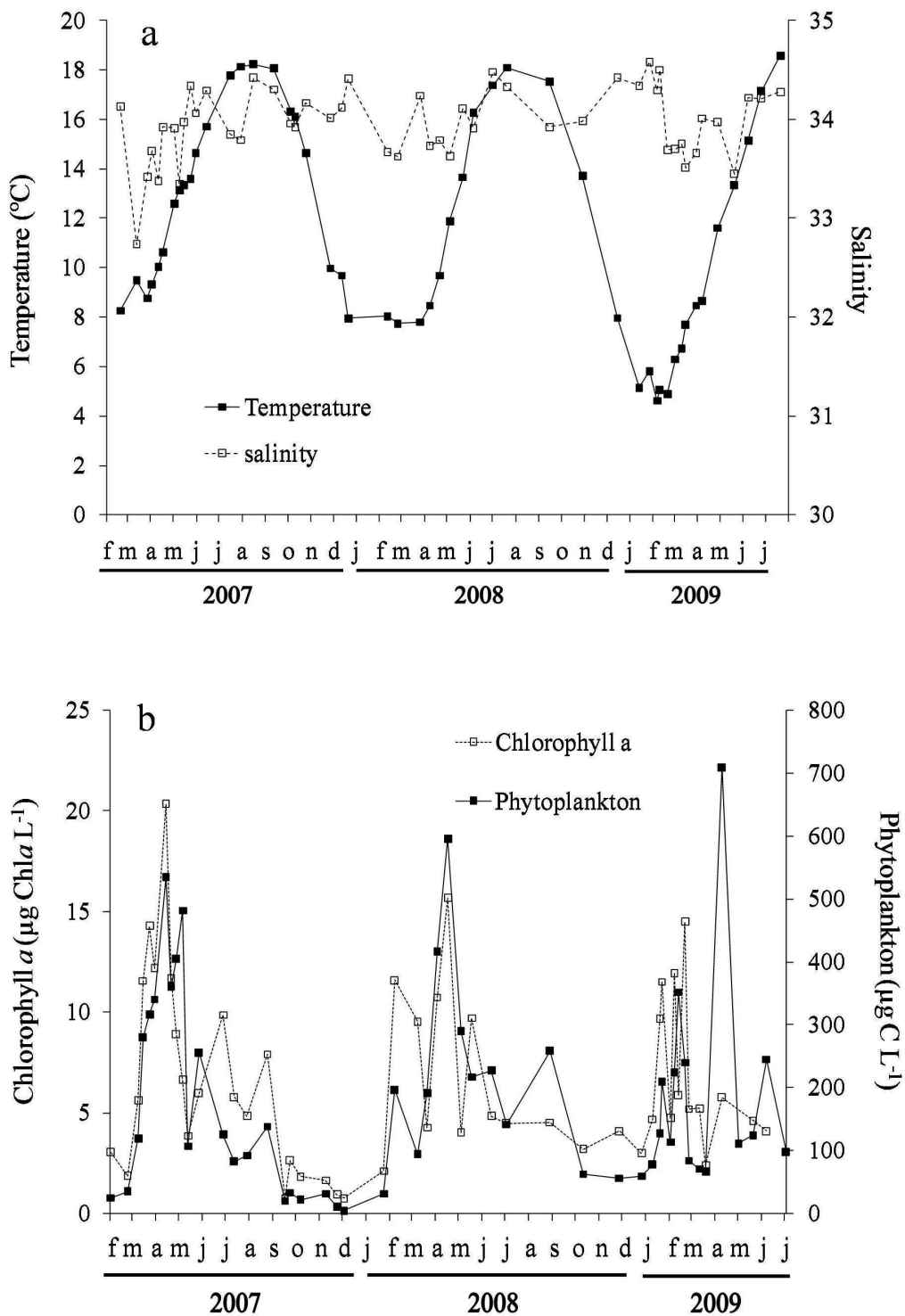


Fig. 2



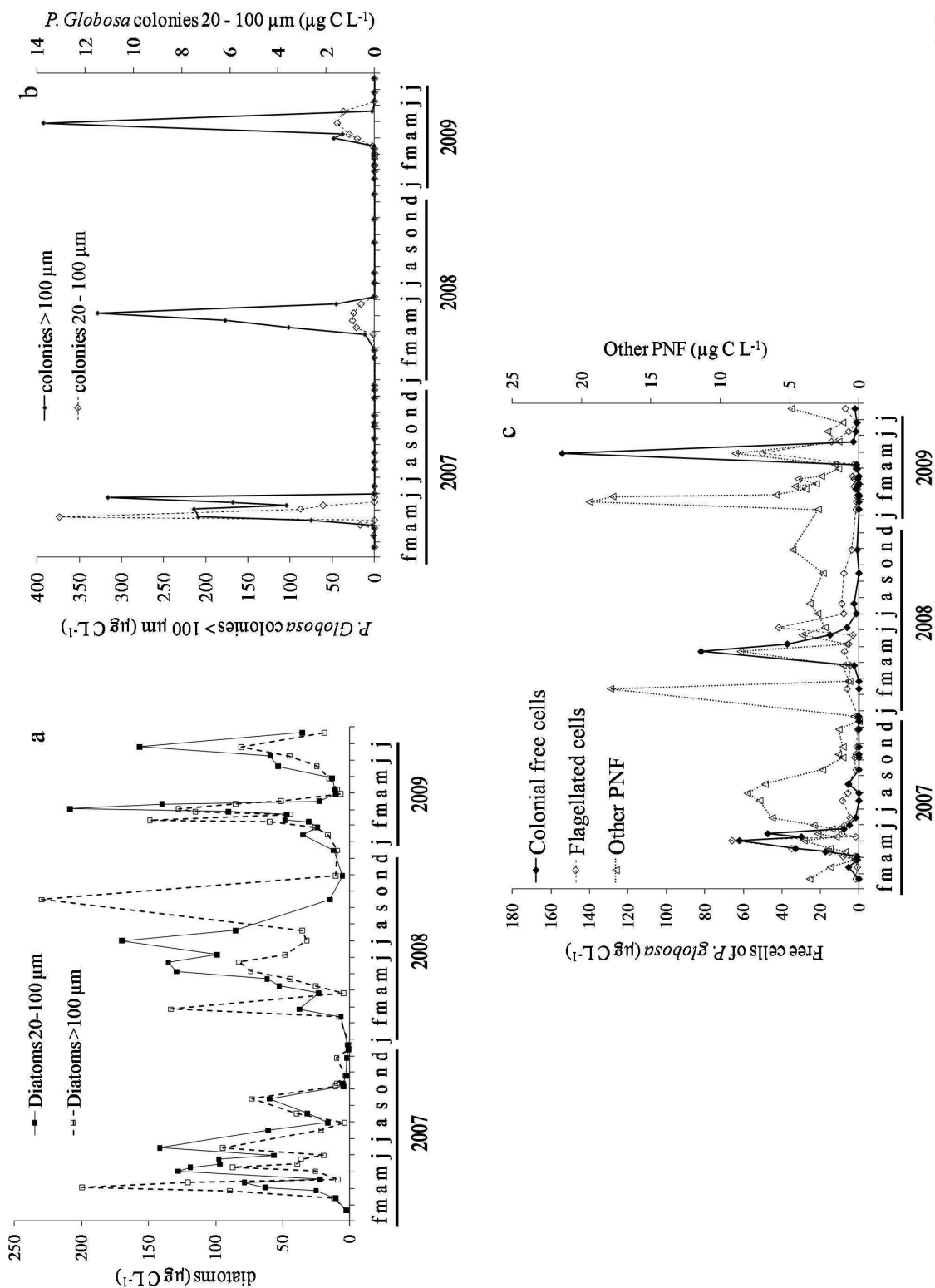


Fig. 3

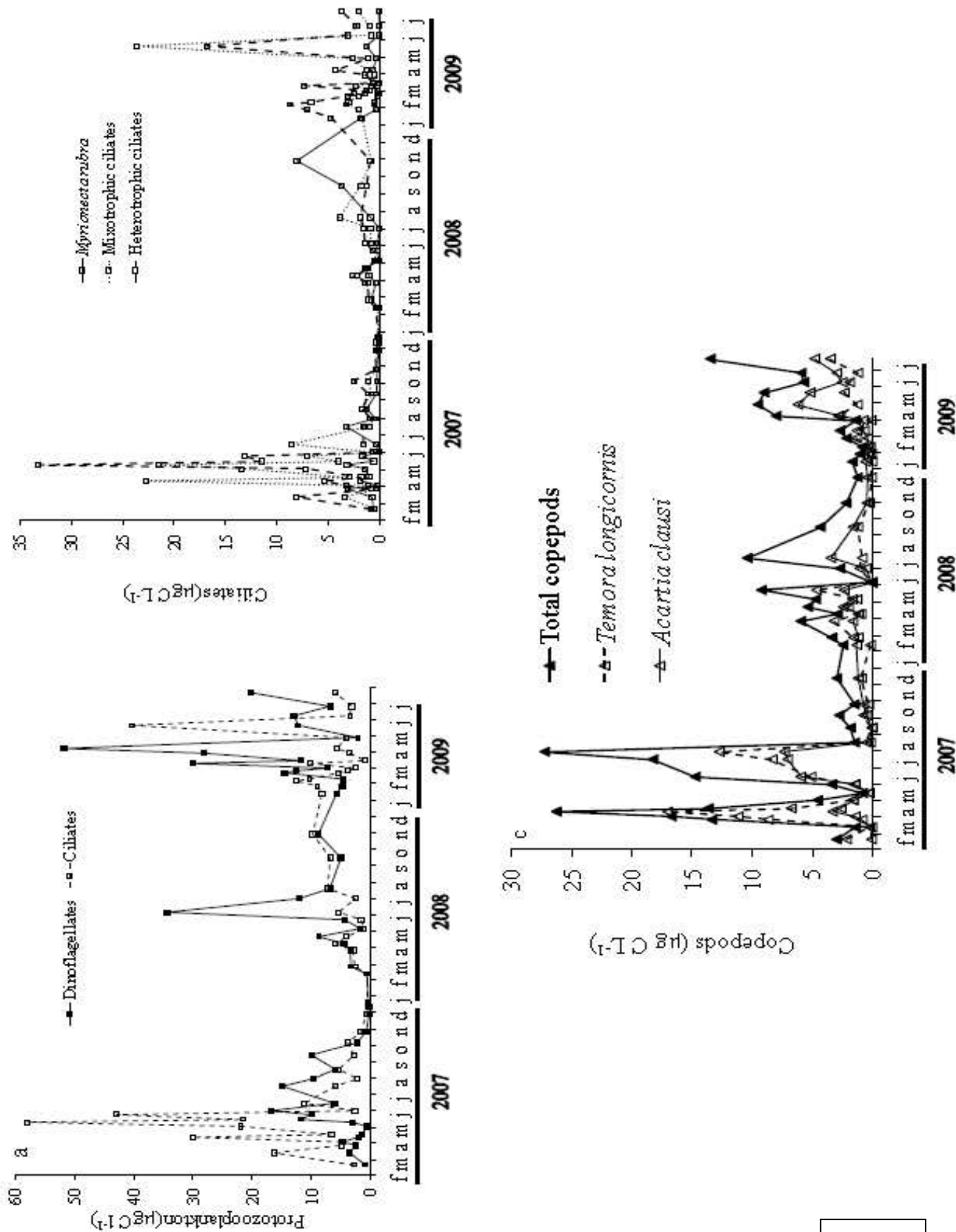


Fig. 4

Autotroph cumulative deviations

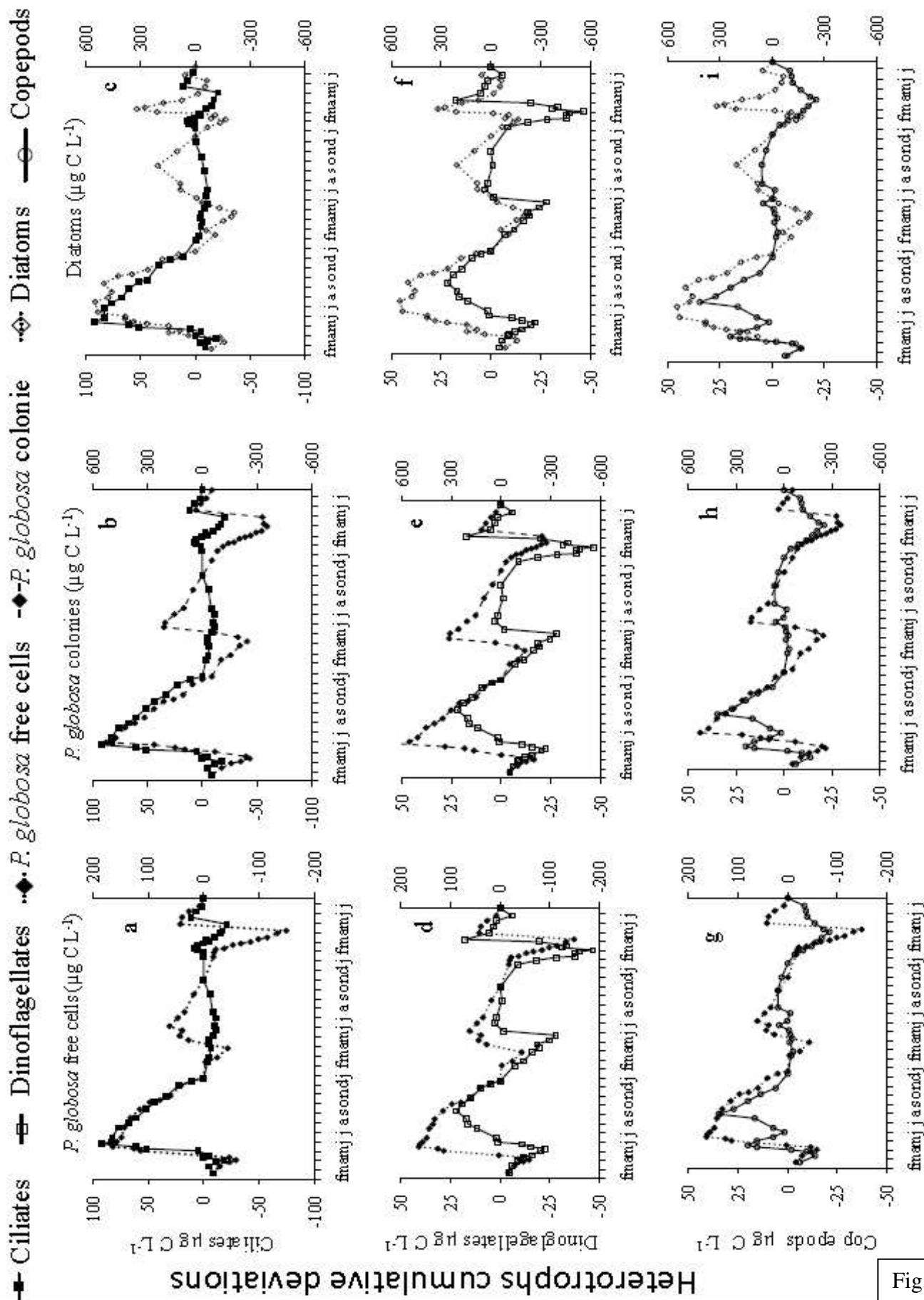


Fig. 5

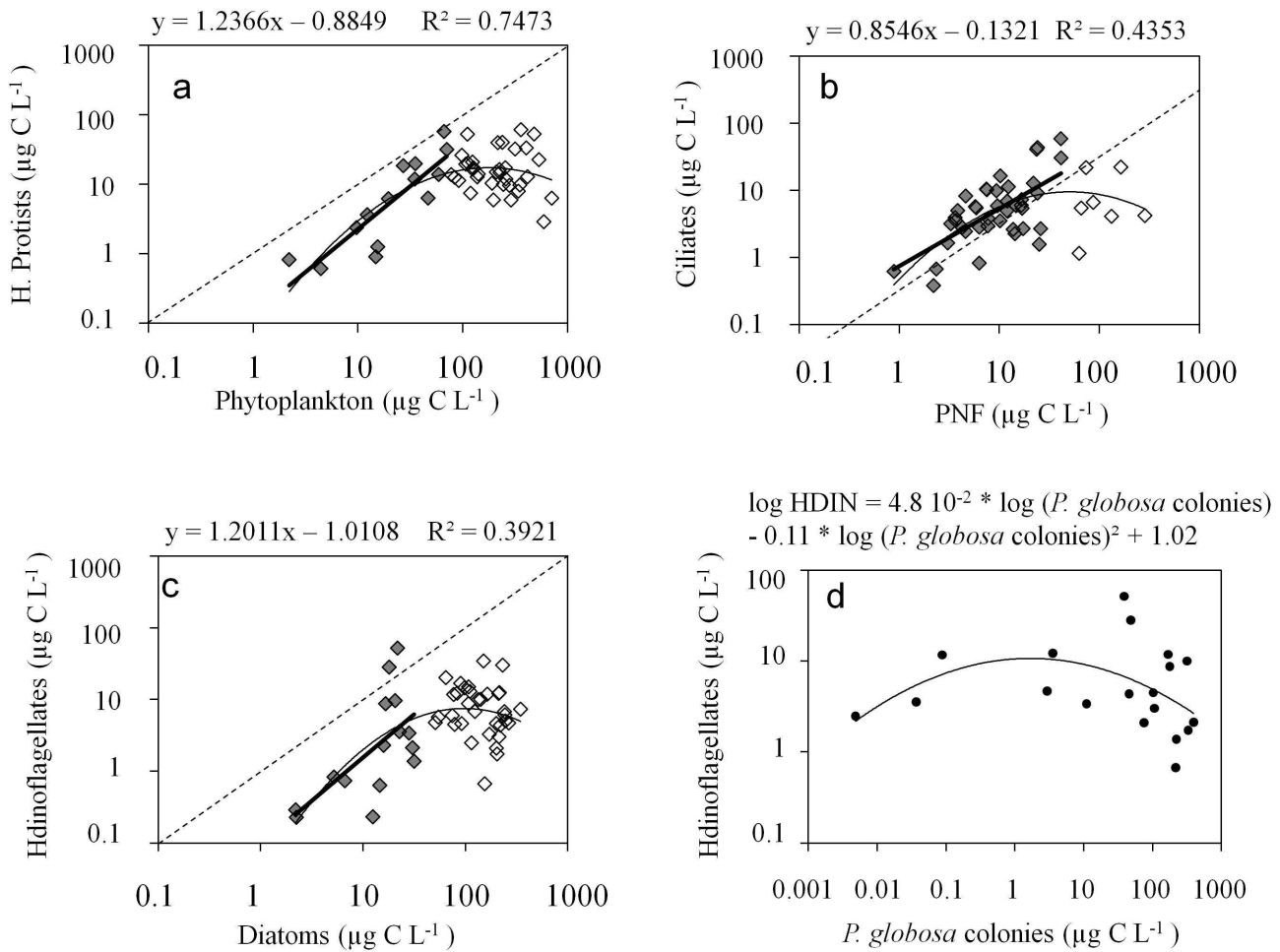


Fig. 6