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The impact of the 2003 summer heat wave and the 2005 late cold wave on the phytoplankton in the north-eastern English Channel

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Abstract

The phytoplankton composition was investigated at two fixed stations in the north-eastern English Channel from November 1997 to December 2005. The warmest temperatures in European historical records were recorded in August 2003. This event was associated with an exceptional abundance peak of the dinoflagellates *Akashiwo sanguinea* (9600 cells L^{-1}) and *Ceratium fusus*. The lowest February temperatures for the 1998–2005 period were recorded in 2005, coinciding with the absence, for the first time in recent decades, of the spring bloom of *Phaeocystis globosa*. The 'de-eutrophication', mainly the reduction of river nutrient loads, is progressively reducing the magnitude of the *Phaeocystis* blooms. Exceptionally in 2005, the colder temperatures increased water column mixing, favouring the dominance of tychoplanktonic diatoms until early March (pre-bloom period). The delay in spring stratification, lower light availability due to turbidity (resuspended sediment) and organic matter, and competition with tychoplanktonic diatoms contributed to retard the timing of the spring phytoplankton bloom and disadvantage the development of *Phaeocystis*. The summer 2003 European heat wave is expected to have had little influence on total annual primary production, because it occurred at mid-summer, the period of lowest annual phytoplankton abundance. However, the anomalous weather in the second half of winter 2005 did affect the annual primary production. ***To cite this article: F. Gómez, S. Souissi, C. R. Biologies 331 (2008).***

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Résumé

L'impact de la canicule de 2003 et de la vague de froid tardive de 2005 sur le phytoplancton de la Manche orientale. La composition du phytoplancton a été étudiée sur deux stations fixes de la Manche orientale, de novembre 1997 à décembre 2005. Les températures les plus chaudes en Europe ont été enregistrées en août 2003. Cet événement a été associé à une prolifération exceptionnelle des dinoflagellés *Akashiwo sanguinea* (9600 cellules L^{-1}) et *Ceratium fusus*. Les températures les plus froides en février (période 1998–2005) ont été enregistrées en 2005 ; ceci a coïncidé avec l'absence, pour la première fois durant les dernières décennies, de la prolifération du bloom printanier de *Phaeocystis globosa*. La diminution de l'intensité de l'eutrophisation, en particulier la réduction des apports fluviaux en sels nutritifs, a contribué à la réduction progressive de l'intensité des proliférations de *Phaeocystis*. Exceptionnellement, en 2005, les températures les plus froides ont augmenté le mélange de la colonne d'eau,

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favorisant la dominance des diatomées tychoplanctoniques jusqu'au début de mars (période de pré-bloom). La modification de la phénologie de la stratification de la colonne d'eau au début de mars a réduit la disponibilité de la lumière due à la turbidité (resuspension du sédiment) et la matière organique. Le retard de la stratification de la colonne d'eau ainsi que la compétition pour les sels nutritifs avec les diatomées tychoplanctoniques ont contribué à retarder le bloom phytoplanctonique printanier et à défavoriser aussi le développement de *Phaeocystis*. La canicule de 2003 s'est produite pendant la période à faible abondance phytoplanctonique ; par conséquent, elle a eu une faible influence sur la production primaire annuelle. En revanche, les anomalies météorologiques enregistrées au cours de la deuxième moitié de l'hiver 2005 ont affecté la production primaire annuelle. ***Pour citer cet article : F. Gómez, S. Souissi, C. R. Biologies 331 (2008).***

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Keywords: Climate change bio-indicators; 2003 summer European heat wave; Extreme weather; *Phaeocystis*; English Channel

Mots-clés : Bio-indicateurs du changement climatique ; Canicule de 2003 en Europe ; Météorologie extrême ; *Phaeocystis* ; Manche orientale

1. Introduction

There is increasing evidence of global warming with the mean air surface temperature rising by ∼0.6 °C during the twentieth century and recent years ranking amongst the warmest years in the instrumental record of global surface temperature since 1850 [1]. The impact of global climate change on the Earth's ecosystems is the subject of an increasing number of studies. Global warming has been found to correlate with changes in the distribution of organisms and in the timing of seasonal events [2,3]. The North Atlantic isotherms, which play a central role in influencing the distribution of marine species, are more regularly found further north in recent years than at any time since the 1850s [4]. However, extreme climate events can generate a greater impact on human activities and the natural environment than mean climatic changes [5].

The summer of 2003 has probably been the hottest since the year 1500 [6]. The summer 2003 European heat wave resulted in more than 70,000 additional human deaths in Europe, especially in France [7]. The biological consequences of the heat wave have been reported for invertebrates and fish in European rivers [8,9] and the thermal stability and anoxia of lakes [10]. To the best of our knowledge, there have been no reported consequences of the 2003 heat wave for marine ecosystems other than a mucilage outbreak in the coastal Mediterranean Sea [11].

Exceptionally warm sea surface temperatures in the tropical North Atlantic and the most active and destructive hurricane season on record characterized the second half of 2005 [12]. Although the warm events tended to receive more attention, the winter of 2005 also showed unusual weather features in western Europe. December and January 2005 registered above normal temperatures and little snowfall, whereas during February and into March, snow cover reached its maximum extent. In addition, at the beginning of March, a strong cold front swept over the entirety of Europe [13].

To evaluate the effects of climatic variability on marine ecosystems requires time-series monitoring programs. Spring blooms of the prymnesiophyte *Phaeocystis globosa* Scherffel regularly afflict the coastlines of northern France, Belgium, the Netherlands and Great Britain. The duration and magnitude of the blooms have increased due to eutrophication, primarily due to the extensive use of artificial fertilizers, after the middle of the twentieth century with a peak in the 1990s [14,15]. The French national SOMLIT (Service d'Observation en Milieu LITtoral) monitoring program was established off Boulogne-sur-Mer (NE English Channel) in November 1997. A first study based on the analysis of an 8-y time series revealed the recent arrival of two diatoms, *Chaetoceros peruvianus* Brightwell and *Eucampia cornuta* (Cleve) Grunow, considered as bio-indicators of the northwards expansion of sub-tropical species. The sustained warm temperatures in summer–autumn 2005 were associated with an unusual rhizosolenioid diatom assemblage [16]. These changes in phytoplankton composition are expected to have a low impact on total annual primary production because they occur after the spring bloom, and when phytoplankton biomass is low. However, a change in the composition and abundance of the main phytoplankton primary producer is expected to have important consequences. This study describes two features: (1) the absence in 2005 of the proliferation of the main primary producer, *Phaeocystis*, and (2) the response of the phytoplankton to the summer 2003 European heat wave in the NE English Channel.

2. Material and methods

Samples were collected during 158 cruises carried out on board R/V 'Sepia II' from November 1997 to December 2005 off Boulogne-sur-Mer in the north-eastern

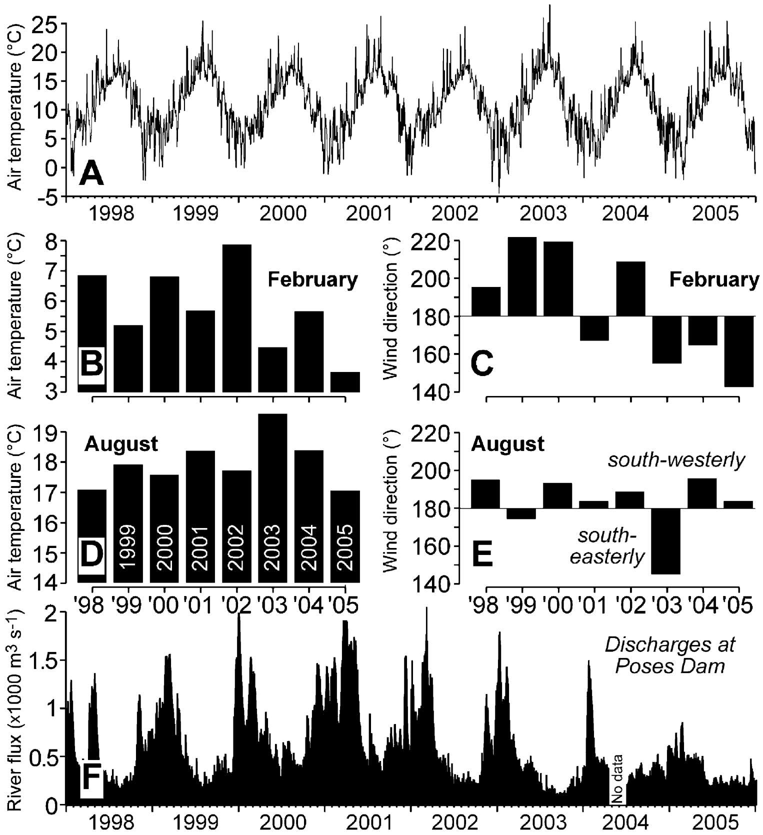

Fig. 1. Temporal distribution (1998–2005) of mean daily air temperature (°C) at Boulogne-sur-Mer (NE English Channel) (A); (B, C) mean daily air temperature (°C) and wind direction (°) with respect to north in February for the 1998–2005 period; (D, E) mean daily air temperature (°C) and wind direction (°) with respect to north for the month of August; (F) Freshwater discharges of the Seine River at Poses Dam. Source: Station Hydrométrique de Poses of DIREN, Île de France, available at GIP Seine-Aval (http://seine-aval.crihan.fr/webGIPSA/).

English Channel at two stations. One station was located 2 km offshore (50°40′75N; 1°31′17E, 21 m depth) and the other station at 8 km offshore (50°40′75N; 1°24′60E, 50 m depth). Continuous weather measurements were provided by the French Meteorological Agency (Météo-France Boulogne-sur-Mer) from a meteorological station located at Boulogne-sur-Mer (50°44N, 01°36E, altitude 73 m). Seawater sampling and phytoplankton analysis are described in Gómez and Souissi [16]. Daily discharges of the Seine River measured at the Poses dam are obtained from the GIP Seine-Aval (http://seine-aval.crihan.fr/).

3. Results

3.1. Extremes temperatures in 2003 and 2005

The analysis of the meteorological data in the period 1998–2005 showed an increase in temperature oscillations since 2003, characterised by colder winters and warmer summers. The coldest mean daily air temperatures were recorded from mid-December to February 2003, with a minimum of −4.56 °C on 8 January 2003. The warmest mean daily air temperature of the 8-y time series occurred from 3–12 August 2003 (Fig. 1A). This heat wave showed two peaks: the first peak on 4–5 August with mean daily air temperature ∼25 °C associated with north-easterly winds (∼75°), and a more intense second peak on 10–11 August with mean daily air temperature ∼28 °C peak associated with south-easterly winds (∼120°). The warmest temperatures were recorded on 11 August with 35 °C. Our sampling region, located near the Straits of Dover, is characterised by strong winds. The summer 2003 European heat wave was correlated with a strong decrease in wind stress and an exceptional incidence of easterly winds in August when compared to other years (Fig. 1D, E).

The coldest month of February in the 8-y time series was recorded in 2005 and was associated with a marked change of the wind direction (Fig. 1B, C). The mean air temperature fell below 0 °C on 3 March, which was the latest subzero temperature in the 8-y time series. In contrast, warm temperatures arrived unusually early in 2005, up to 25.32 °C in early June, and continued to late autumn (Fig. 1A). The warmest years, based on the number of days with mean daily air temperatures higher than 22 °C, were 2003 (8 days) and 2005 (6 days). These data reveal the extreme variability in air temperatures for the years 2003 and 2005 when compared to the other years of the 8-y time series.

The Seine River is the main supplier of freshwater into the English Channel and has a significant contribution to the nutrient load of this area. These nutrient inputs are transported into our sampling stations, mainly the inshore station, through the northward 'coastal flow' [17,18]. The river discharges at the Poses Dam showed a peak in winter, with the exception of 2005. The river discharges showed a minimum in the summer of 2003 (Fig. 1F).

3.2. The summer 2003 European heat wave and the proliferation of dinoflagellates

Within the context of global climate change, warm events typically receive greater attention as they may allow the evaluation of the ecosystem response to future warming scenarios. The exceptionally warm conditions in August 2003 favoured the development of the dinoflagellates *Akashiwo sanguinea* (Hirasaka) G. Hansen *et* Moestrup and *Ceratium fusus* (Ehrenberg) Dujardin. During the 8-y time series, *A. sanguinea* were restricted to sporadic single records in summer and autumn. Exceptionally in late summer 2003, *Akashiwo sanguinea* showed a marked peak of 9600 cells L^{-1} in the surface waters of the neritic station (Fig. 2A–D). *Ceratium fusus* also reached an exceptional abundance after the heat wave, with the highest abundances in the surface offshore waters (320 cells L^{-1}) (Fig. 2E–H). The genus *Ceratium* was also represented by sporadic records of *C. lineatum* (Ehrenberg) Cleve and *C. furca* (Ehrenberg) Claparède *et* Lachmann. Other dinoflagellates such as *Karenia mikimotoi* (Miyake *et* Kominami *ex* Oda) G. Hansen *et* Moestrup were observed after the heat wave, although the abundance was lower than in other years.

3.3. Cold late winter 2005 and the Phaeocystis bloom decline

The blooms of *Phaeocystis globosa* are a recurrent phenomenon in the northern English Channel and the southern North Sea. In our sampling stations the abundance during the blooms ranged from 30–50 × 10^6 cells L^{-1} in onshore waters, whereas in offshore waters (8 km off) the abundance rarely exceeded 20 × 10^6 cells L^{-1}. The blooms began in February and extended until late May or early June, with the highest values usually in April. The highest value (101 × 10^6 cells L^{-1}) was recorded in March 1999. The most relevant feature during this 8-y time series was the absence of the *Phaeocystis* bloom in spring 2005 (Fig. 2I–L). Single cells and a low number of *Phaeocystis* colonies were observed in January–February of 2005. However, in spring 2005 the proliferation of *Phaeocystis* was negligible compared to previous years. A slight proliferation of *Phaeocystis* was observed in October 2005 (Fig. 2J).

As a general trend, the phytoplankton abundance in December–January was very low and the dominant species were tychoplanktonic diatoms such as *Paralia sulcata* (Ehrenberg) Cleve or *Raphoneis amphiceros* (Ehrenberg) Ehrenberg. *Skeletonema* cf. *marinoi* Sarno *et* Zingone and *Asterionellopsis glacialis* (Castracane) Round were usually present, being replaced along the month of February by the spring blooming species: *Phaeocystis* and the diatoms *Guinardia delicatula* (Cleve) Hasle, *Rhizosolenia imbricata* var. *shrubsolei* (Cleve) Schröder, *Guinardia striata* (Stolterfoth) Hasle and *Guinardia flaccida* (Castracane) H. Peragallo. Anomalously in 2005, the tychoplanktonic diatoms dominated until March, and *Skeletonema* reached high abundances from February to the middle of March (up to 116 × 10^3 cells L^{-1}). Microscopy observations revealed a high concentration of particulate matter, probably associated with the suspended sediment due to the increase of water column mixing. These particles, together with organic compounds from the excretion or decomposition of *Skeletonema*, are expected to contribute to the reduction of underwater light availability in late winter 2005 when compared to other years.

4. Discussion

4.1. Thermal stratification in August 2003 and the proliferation of dinoflagellates

The summer of 2003 was characterized by exceptionally warm weather in Europe, with the mean temperature exceeding that of any summer for the previous 500 years [6]. Thermal stratification is a major factor affecting the reduction of water column mixing [30]. In the case of the sampling stations located near the Straits of Dover the winds reach a high magnitude [31]. The winds showed low intensity in August and September 2003. In August 2003 when compared with the same

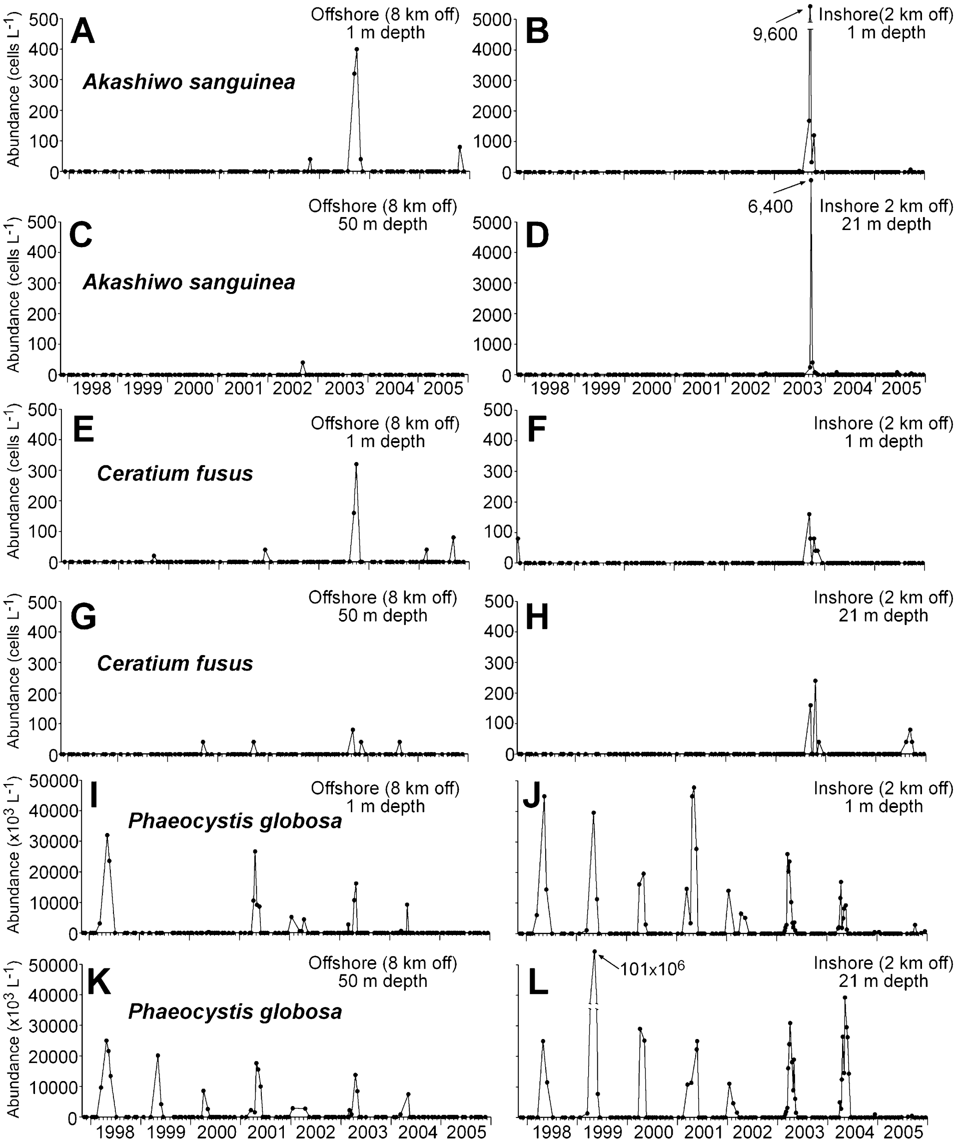

Fig. 2. Temporal distribution of the abundance (cells × L^{-1}) of (A–D) *Akashiwo sanguinea*, (E–H), *Ceratium fusus* and (I–L) *Phaeocystis globosa* off Boulogne-sur-Mer (1998–2005). Left and right panels are for offshore and inshore stations, respectively. Note the change of scale in the figures B and D.

months in other years, the easterlies showed an unusual predominance (Fig. 1C).

In the southern English Channel the magnitude of the winds is markedly lower than on the northern side. The summer stratification favours the proliferation of motile phytoplankton such as the dinoflagellate *Karenia mikimotoi* and coccolithophorids [32]. In June and July 2003 prior to the exceptional August heat wave, temperatures higher than the average values in Europe were also recorded [33]. A *Karenia mikimotoi* bloom was observed in June–July 2003 in the southern English Channel [34]. The heat wave of August 2003 may favour the development of *K. mikimotoi* or other dinoflagellates. However, it can be hypothesised that the previous nutrient depletion may limit an extension of the *Karenia* bloom into August despite the favourable physical conditions.

Global climate change is expected to alter the species composition of local planktonic communities as well increasing the risk of invasion by exotic species [35]. However, the summer 2003 European heat wave favoured the development of two autochthonous species. *Akashiwo sanguinea* is a widespread species described as *Gymnodinium splendens* Lebour in the English Channel off Plymouth [36], and *Ceratium fusus* is also a widespread species known in European waters. The elevated temperatures may favour exotic warm-water species. However, if 'seed populations' of these species have a low abundance, a short event such as a two-week heat wave may be insufficient to trigger proliferations.

4.2. The decline of Phaeocystis spring blooms

The spring blooms of *Phaeocystis* which have been documented since the early phytoplankton studies [19–21], are a recurrent phenomenon in the northern English Channel and North Sea. The magnitude of the blooms in the region has increased since the middle of the twentieth century, with the greater bloom durations in the 1990s [14]. Coastal eutrophication is generally perceived as a shift from diatom towards *Phaeocystis* dominance due to an over-enrichment of nitrogen and phosphorus with respect to silicic acid [15]. In our sampling location, the *Phaeocystis* blooms reached 101×10^6 cells L^{-1} in March 1999. An abundance of 200×10^6 cells L^{-1} has been reported along the Dutch coast in May 1985 [22]. In the last decade the magnitude of the coastal North Sea blooms has decreased. This appears to be associated with the 'de-eutrophication' of the North Sea [14]. In the northern English Channel, the nutrient loads exported by the Seine River as well as other rivers in the region have decreased [23]. The general trend towards 'de-eutrophication' may be primarily responsible for the reduction in the magnitude of the *Phaeocystis* blooms.

This study has focused on the absence in 2005, for the first time, of the *Phaeocystis* spring bloom in the north-eastern English Channel. In the North Sea, Cadée and Hegeman reported that currently *Phaeocystis* cell numbers and bloom durations are decreasing, and in 2002 the spring peak was absent [14]. These authors reported that since 1975 the beginning of the *Phaeocystis* bloom ($>1 \times 10^6$ cells L^{-1}) has changed from ~16 April to ~27 March, coinciding with the progressive increase of spring temperatures. It may be expected that the weather features in February and early March will now have more effects on the development of the *Phaeocystis* bloom than in the past.

Beyond the long-term decrease of the nutrient loads into the northern English Channel, the absence of the *Phaeocystis* bloom may also be associated with unfavourable meteorological conditions in a particular year. It is generally accepted that phytoplankton production in late winter and early spring is limited by light availability, because under the prevailing non-stratified conditions individual algal cells spend most of the time below the euphotic zone. Relatively low temperatures and high wind speeds during winter and early spring promote a late onset of stratification [3,24]. The mean daily air temperature in winter 2005 fell below 0 °C on 3 March, which was the latest occurring subzero temperature in the 8-y time series (Fig. 1A). The usual winter peak of river discharges (nutrient loads) was absent in 2005 (Fig. 1F). In addition to nutrients, the development of the flagellate *Phaeocystis* requires an increase of the stratification and light [25,26]. The anomalous cold conditions in February and early March extended the mixing period, with two effects in underwater light availability: directly through the reduction of irradiance due to cloudiness, and indirectly due to high turbidity from sediment resuspension. The extension of these anomalous weather features until early March favoured the development of *Skeletonema* cf. *marinoi*. This is a common diatom in high turbidity environments such as the Seine Estuary [27] and in 2005 the proliferation even dominated in our sampling stations located 2 and 8 km offshore. The development of *Skeletonema* and other diatoms may increase particle concentration due to the excretion of organic compounds [28] and cell debris. The organic particles in suspension may intercept light more effectively than the inorganic matter [29]. In addition, it can be hypothesized that these diatoms partially consume the winter stock of nutrients required to trigger the *Phaeocystis* spring bloom. It is not easy to establish the key factor(s) that hindered the proliferation of *Phaeocystis*. If global warming is associated with the earlier appearance of the spring phytoplankton bloom, this increases the probability of a cold wave event that may affect the development of the dominant species. Our results show that climate variability during the pre-bloom period (February and early March) was essential for the development of the main primary producer.

4.3. Final remarks

This study describes the response of the phytoplankton community to extreme weather features. The summer 2003 European heat wave occurred in mid-summer that constitutes the normal period for the occurrence of heat waves. In mid-summer, the spring phytoplankton bloom had already declined and the phytoplankton biomass showed the lowest annual values. Any change at that period is expected to have little influence on total annual primary production and carbon flux to higher trophic levels. The same conclusion can be applied for the cold waves. The first half of winter 2003 was the coldest of the 8-y time series. Phytoplankton abundance was low and restricted to tychoplanktonic species in December and January. A cold wave at these months, beyond the increase of the winter nutrient stock, is expected to have little influence on the further development of the spring phytoplankton bloom. In contrast to other regions where diatoms dominate the spring bloom, in the northern English Channel and the southern North Sea diatoms and the flagellate *Phaeocystis* compete with each other. The massive blooms of *Phaeocystis* favoured by the over-enrichment of nitrate and phosphate versus silicic acid (use of artificial fertilizers) are progressively weaker due to the 'de-eutrophication', consequently being more vulnerable to anomalous climatic events. Cold events in the pre-bloom period, February and early March, seem to negatively affect *Phaeocystis* in its competition with the diatoms. This alteration is expected to have important consequences for higher trophic levels that need to be evaluated.

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