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Inter-annual variability in phytoplankton summer blooms in the freshwater tidal reaches of the Schelde estuary (Belgium)

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ABSTRACT

The inter-annual variability in phytoplankton summer blooms in the upper reaches of the Schelde estuary was investigated between 1996 and 2005 by monthly sampling at 10 stations. The large inter-annual variations of the chlorophyll *a* concentration in the freshwater tidal reaches were independent from variations in chlorophyll *a* in the tributary river Schelde. Summer mean chlorophyll *a* concentrations were significantly negatively correlated with flushing rate (Spearman correlation: $r = -0.67$, $p = 0.05$, $n = 9$) but not with temperature, irradiance and suspended particulate matter or dissolved silica (DSi) concentrations. During dry summers, low flushing rates permitted the development of dense phytoplankton populations in the upper part of the estuary, while during wet summers high flushing rates prevented the development of dense phytoplankton blooms. Flushing rate was also found to be important for the phytoplankton community composition. At low flushing rates, the community was dominated by diatoms that developed within the upper estuary. At high flushing rates, chlorophytes imported from the tributary river Schelde became more important in the phytoplankton community. The position of the chlorophyll *a* maximum shifted from the head of the estuary when flushing rates were low, to more downstream when flushing rates were high. Although DSi concentrations tended to be lower during years of high phytoplankton (mainly diatom) biomass, the relation with flushing rate was not significant.

1. Introduction

In estuaries where the tidal wave is not artificially arrested by locks, the tidal wave penetrates further inland than seawater, leading to the existence of a freshwater estuary subjected to tidal activity. The tidal range in the freshwater tidal zone often exceeds the tidal range near the mouth of the estuary. These freshwater tidal reaches of estuaries are rarely included in estuarine studies. In the past, primary production in the freshwater tidal reaches has often been considered to be negligible due to the high turbidity of the water (e.g. Uncles and Stephens, 1993). An increase in chlorophyll *a* concentration can usually be linked to an increase in primary production or to an import of phytoplankton from the rivers. If high chlorophyll *a* concentrations were measured in the freshwater tidal reaches these were ascribed to import from tributary river(s) (e.g. Jackson et al., 1987). The freshwater tidal reaches of estuaries are indeed highly turbid, as the combination of a shallow water column and strong tidal currents results in high sediment transport capacity. Moreover, complex hydrodynamical processes like 'tidal pumping' may result in an accumulation of suspended matter supplied by the rivers (e.g. Wolanski, 1995). Nevertheless, the upper reaches of estuaries are often characterised by massive phytoplankton blooms (e.g. Moon and Dunstan, 1990; Cole et al., 1992; Kies, 1997; Muylaert et al., 2005). Recent studies in the Schelde estuary revealed that net primary production in the freshwater tidal reaches is possible despite the high turbidity of the water. Net primary production in this turbid environment is possible thanks to a shallow water column, which results in a relatively favourable mixing depth to photic depth ratio (Desmit et al., 2005; Muylaert et al., 2005).

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Estimates of annual areal rates of primary production in the freshwater tidal reaches of the Schelde estuary are nearly an order of magnitude higher than in the brackish reaches of the Schelde estuary (Muylaert et al., 2005). The contribution of the freshwater tidal reaches to total primary production of the estuary is therefore significant, despite the fact that these zones occupy a relatively small area. As a consequence, the impact of algal blooms in the freshwater tidal reaches on nutrient fluxes through the estuary is potentially high. Phytoplankton bloom in the freshwater tidal reaches of European estuaries are often dominated by diatoms (Schuchardt and Schirmer, 1991; Muylaert et al., 2000; Gameiro et al., 2004), probably because diatoms are the only phytoplankton group that can survive in systems with a high turbidity and a short water retention time. In the Schelde estuary, the phytoplankton community is dominated by diatoms mainly represented by *Cyclotella* and *Stephanodiscus* (Muylaert et al., 2000). Chlorophytes represent the second phytoplankton community observed in the Schelde estuary. They are observed in summer and are mainly represented by *Scenedesmus* (Muylaert et al., 2000).

These diatom blooms may at times consume most of the DSi (dissolved silica) that is imported by the rivers (Muylaert et al., 2001; Soetaert et al., 2006). This depletion of DSi may have important consequences in coastal waters, which mainly depend on terrestrial sources of Si supplied through estuaries to sustain diatom production.

As a consequence of climate change, estuarine primary production can be expected to undergo changes in the near future (Howarth et al., 2000; Paerl et al., 2006). Climate change may affect water temperature in the estuary, turbidity, irradiance and river discharge: four parameters of fundamental importance for the phytoplankton production. Long-term monitoring data may reveal the influence of inter-annual variations in factors such as discharge or temperature on ecosystem functioning, and may therefore be informative for predicting future responses of climate change on the estuarine ecosystem. Although previous studies have reported long-term trends in primary production or primary producers in estuaries (Adolf et al., 2006; Valdes-Weaver et al., 2006), so far none has focused on the upper, freshwater tidal reaches. In this study, we describe the inter-annual variability in chlorophyll *a* concentration of the phytoplankton summer blooms in the upper Schelde estuary for the period 1996–2005 and relate it to variation in water temperature, irradiance, water retention time, DSi and suspended particulate matter (SPM) concentrations.

2. Materials and methods

2.1. Study site

The Schelde river has a length of 190 Km from Gouy (France) to Ghent (Belgium). The Schelde river is not influenced by the tide due to the presence of sluices in the city of Ghent. The Schelde river is considered as an important river with a high cross section (171 m^2 in average) and depth (4.8 m in average) (Scaldit Report, 2004).

The Schelde estuary is a macrotidal estuary in Western Europe that is shared between Belgium and The Netherlands (Fig. 1). In contrast to many other European estuaries, where the tidal wave is arrested by locks near the freshwater–seawater interface, the Schelde estuary is characterised by an extensive freshwater tidal zone with a length of about 60 Km (from upstream of Antwerpen to Gent). As the Schelde catchment is densely populated, nutrient inputs are high and concentrations of inorganic nutrients N and P are never limiting for phytoplankton (e.g. Baeyens et al., 1998). DSi limitation may occur during short periods in summer when discharge is low and primary production is high (Muylaert et al., 2001; Carbonnel, personal communication).

2.2. Sampling and analyses

The freshwater tidal reaches of the Schelde estuary were sampled monthly at 10 stations from 1996 to 2005 (Fig. 1). The surface water was sampled from a boat placed in the middle of the channel of the estuary using a bucket. Temperature was measured in situ with a YSI 650 Multi-parameter Display Systems multimeter equipped with a YSI 600R sensor. Suspended particulate matter (SPM) concentration was estimated by weighing the particulate matter collected on a GF/F filter. DSi analysis was conducted on an ICP (Inductively Coupled Plasma) IRIS spectrophotometer. A known water volume was filtered onto a GF/F filter for phytoplanktonic pigment analyses by HPLC. The filters were dried between blotting paper to remove excess water, wrapped in aluminium foiled and stored at $-80\,^{\circ}C$ to avoid pigments degradation. Pigments were then extracted and analysed by HPLC according to the method of Wright et al. (1991). From 1996 to 1999, only chlorophyll *a* and *b* concentrations were measured by HPLC, other pigments concentrations were not assessed. During the year 2000, however, no phytoplankton pigment samples were collected. In 2001, chlorophyll *a* concentration was determined by spectrophotometry instead of HPLC. Spectrophotometrical chlorophyll *a* measurements are known to over-estimate chlorophyll *a* concentration as they also include degradation pigments and chlorophyll *b* (Arar and Collins, 1997). A regression based on 305 simultaneous chlorophyll *a* measurements made by HPLC and spectrophotometry in 2002, 2003 and 2004 was used to correct the spectrophotometrical data collected in 2001.

For microscopical analyses, samples were fixed with Lugol's solution in the field, and post-fixed for long-term preservation with formalin in the lab (final concentration 4%). No samples for microscopical analysis were available for the period before 2002. In each sample, 100 phytoplankton 'units' (cells, coenobia or colonies) were enumerated and identified using an inverted microscope.

2.3. Data analyses

Only data on summer blooms (June–September) in the freshwater reaches of the estuary (upstream from the confluence of the Rupel) were used in this study. Chlorophyll *a* concentration was used as a proxy for the intensity of the summer bloom in the freshwater reaches. Because chlorophyll *a* data collected during the same summer season are not fully independent (e.g. if chlorophyll *a* concentration is high in June, it is likely to be high in July as well), data from a single summer were reduced to a volume weighted single average chlorophyll *a* value. This reduced a dataset of 339 entries to only nine values, one for each summer. As the volume of the upper estuary increases strongly in the downstream direction, the average chlorophyll value was weighted by the volume of each compartment in which the sample was collected. The freshwater tidal reaches of the Schelde (total volume 43×10^6 m^3) was divided into equal compartments, one compartment for each sampling station. The volume of each compartment was calculated using a third order polynomial regression using the width and depth as explained in Muylaert et al. (2005). The cross surface area was calculated by integrating the resulting equation between depth at mid-tide and maximum depth. The average volume of each compartment was then calculated by multiplying length and cross surface area. This weighted mean summer chlorophyll *a* concentration was related to temperature, irradiance, retention time, DSi and SPM concentrations. For temperature, DSi and SPM, weighted mean summer values were calculated using the same method as for chlorophyll *a*. The extinction coefficient (Kd in m^{-1}) was calculated from SPM concentration measured in the upper Schelde estuary. The solar irradiance was measured daily by the Belgian KMI (Royal Meteorological Institute) at Brussels and data were averaged over

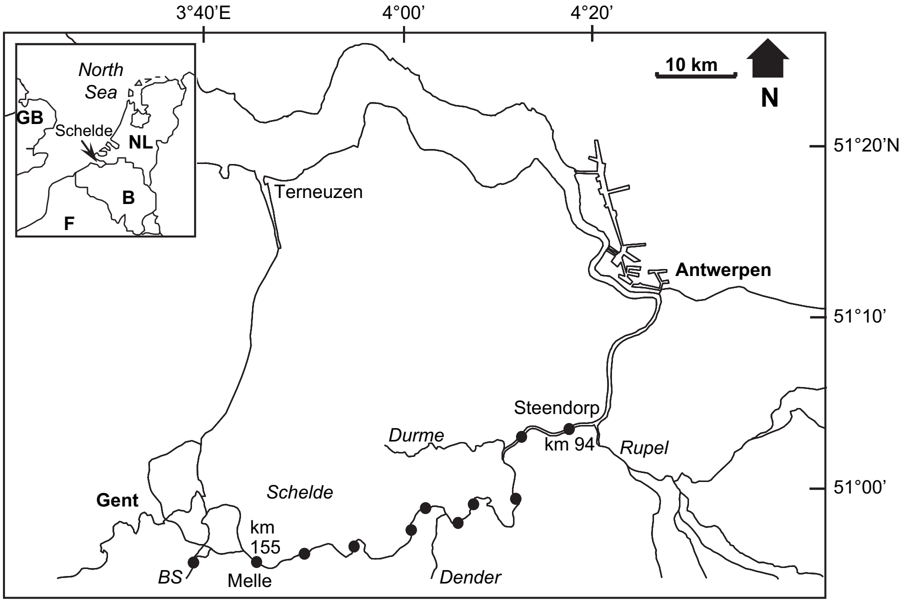

Fig. 1. Schelde estuary with sampling stations (black dots) in the river Schelde (BS) and in the freshwater reaches of the Schelde estuary between Steendorp and Melle respectively at 94 and 155 Km from the mouth of the estuary.

the summer period. The flushing rate was estimated as Q/V (day^{-1}), where Q is the mean summer discharge in the freshwater reaches of the estuary ($\mathrm{m}^3\,\mathrm{day}^{-1}$) and V is the average volume of the freshwater tidal reaches (m^3). Discharge was measured daily by the Flemish AWZ ('Administratie Waterwegen en Zeewezen'). Spearman correlation coefficients were used to relate weighted mean summer chlorophyll *a* to other parameters.

3. Results

Spatio-temporal variation in chlorophyll *a* concentration in the freshwater tidal reaches of the Schelde estuary for the period 1996–2005 is presented in Fig. 2. Each year, chlorophyll *a* concentration in the freshwater tidal reaches was low in winter, increased in spring, reached its maximum in summer and decreased in autumn. In the river Schelde, the major tributary of the freshwater tidal reaches, chlorophyll *a* concentration was maximal in spring and was always much lower than in the freshwater tidal reaches during summer.

Large inter-annual differences in summer chlorophyll *a* concentration were observed for the entire freshwater reaches of the Schelde estuary (Fig. 3). The summer maxima for chlorophyll *a* concentration was lowest in 1996 and highest in 2003. The years 1997, 2003 and 2004 were characterised by above-average weighted mean summer chlorophyll *a* concentration, while 1996, 1998, 1999, 2001, 2002 and 2005 had a lower-than-average weighted mean summer chlorophyll *a* concentration (Fig. 3). In years with relatively low weighted mean summer chlorophyll *a* concentration, the chlorophyll *a* maximum was situated in the downstream part of the freshwater tidal reaches. In years with high weighted mean summer chlorophyll *a* concentration, the chlorophyll *a* maximum was situated closer to the head of the estuary (Fig. 2). The position of the chlorophyll *a* maximum was significantly correlated with the weighted mean summer chlorophyll *a* concentration (Fig. 4, Spearman correlation: $r = 0.75$, $p = 0.02$, $n = 9$). The mean weighted summer chlorophyll *a* concentration was positively related to temperature, irradiance and SPM concentrations and negatively to DSi concentrations and the flushing rate (Fig. 5). Only the negative relation between mean weighted summer chlorophyll *a* concentration and the flushing rate was significant at the *p*-level of 0.05 ($p = 0.049$).

In the present study as well as in previous ones (e.g. Muylaert et al., 2000; Lionard et al., 2005, 2008), the two major phytoplankton groups in the upper Schelde estuary were diatoms (represented by *Cyclotella* and *Stephanodiscus*) and chlorophytes (represented by *Scenedesmus*) (data not shown). As chlorophyll *b* is present in chlorophytes but not in diatoms, the chlorophyll *b*/*a* ratio

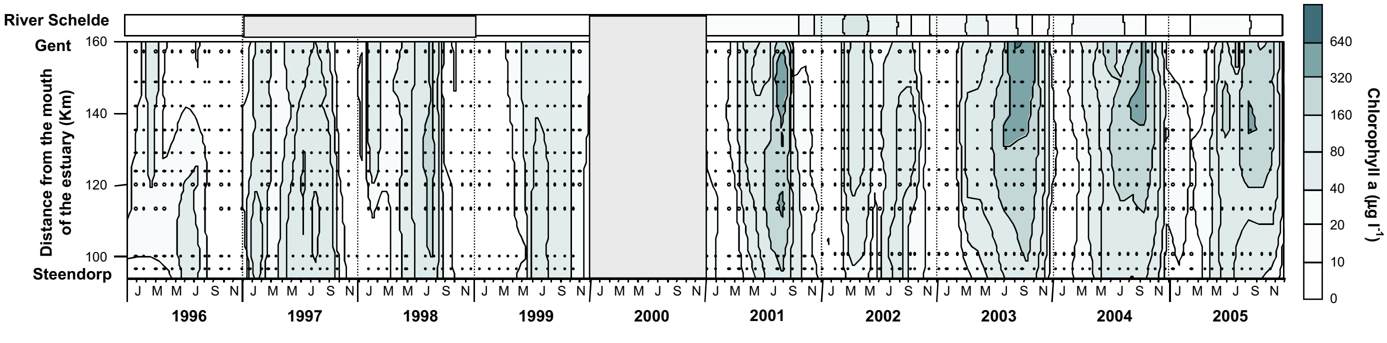

Fig. 2. Chlorophyll *a* concentration in $\mu\mathrm{g\,l}^{-1}$ in the freshwater part of the Schelde estuary between Melle and Steendorp from 1996 to 2005. Black dots represent samples. Chlorophyll *a* measured in the river Schelde at the sampling time in the freshwater estuary is presented. No data are available for 2000 in the freshwater part of the Schelde estuary and for 1997, 1998 and 2000 in the river Schelde.

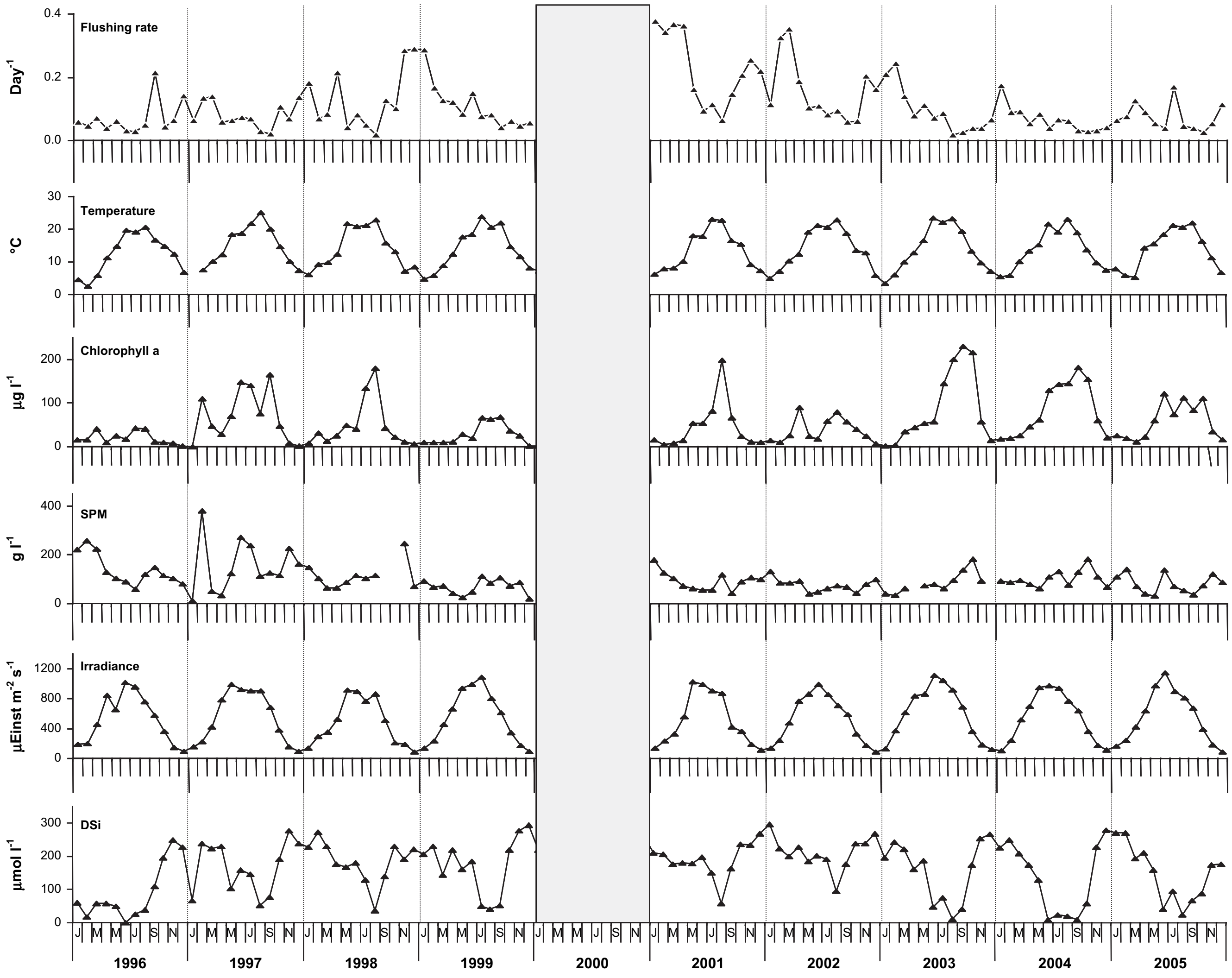

Fig. 3. Monthly average value of the flushing rate (day^{-1}), temperature (°C), chlorophyll *a* (µg l^{-1}), SPM (g l^{-1}), irradiance (µE m^{-2} s^{-1}), dissolved Silica (µmol l^{-1}) from 1996 to 2005. No data are available in 2000.

can be used as an indicator for the relative importance of chlorophytes over diatoms in the phytoplankton community. The chlorophyll *b*/*a* ratio was significantly positively correlated with the flushing rate (Fig. 6; $r = 0.86$, $p = 0.01$, $n = 9$), indicating that chlorophytes became more important relative to diatoms during years with a high water flushing rate.

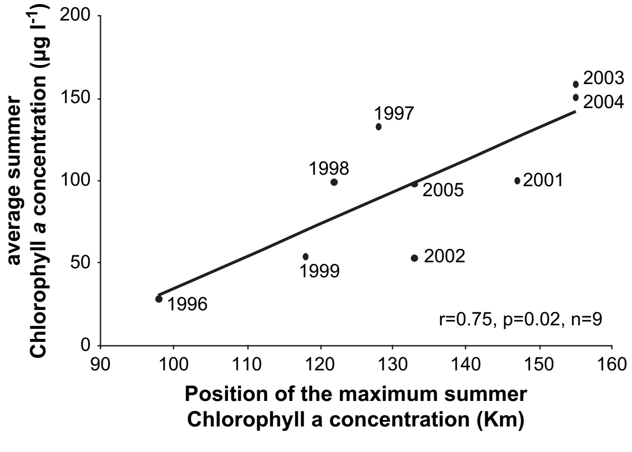

Fig. 4. Correlation between the average summer chlorophyll *a* concentration (µg l^{-1}) measured in the freshwater reaches of the Schelde estuary and the position of the maximum summer chlorophyll *a* concentration from the mouth of the estuary (Km). Spearman correlation: $r = 0.75$, $p = 0.02$, $n = 9$. Data points are labelled with the respective year of sampling.

4. Discussion

During the 9-years of monitoring in the freshwater tidal reaches of the Schelde estuary, large inter-annual variations in summer chlorophyll *a* concentrations were observed. In some years, chlorophyll *a* concentrations rarely exceeded 50 µg l^{-1}, while in other years maxima exceeded 500 µg l^{-1}. These variations were not due to differences in inputs of phytoplankton from the tributary Schelde river, as chlorophyll *a* concentrations in the Schelde river were always much lower than in the freshwater tidal reaches of the Schelde estuary during the summer blooms. Inter-annual variations in summer blooms should therefore be due to differences in phytoplankton production within the freshwater tidal reaches of the Schelde estuary.

In order to elucidate what factors might regulate this inter-annual variability in summer bloom intensity, the mean summer weighted chlorophyll *a* concentration was related to several parameters that are known to influence phytoplankton primary production. Of all parameters investigated, only flushing rate was significantly correlated with the mean summer weighted chlorophyll *a* concentration. The flushing rate is defined as the rate at which liquids that enter a region are removed from it. In the Schelde

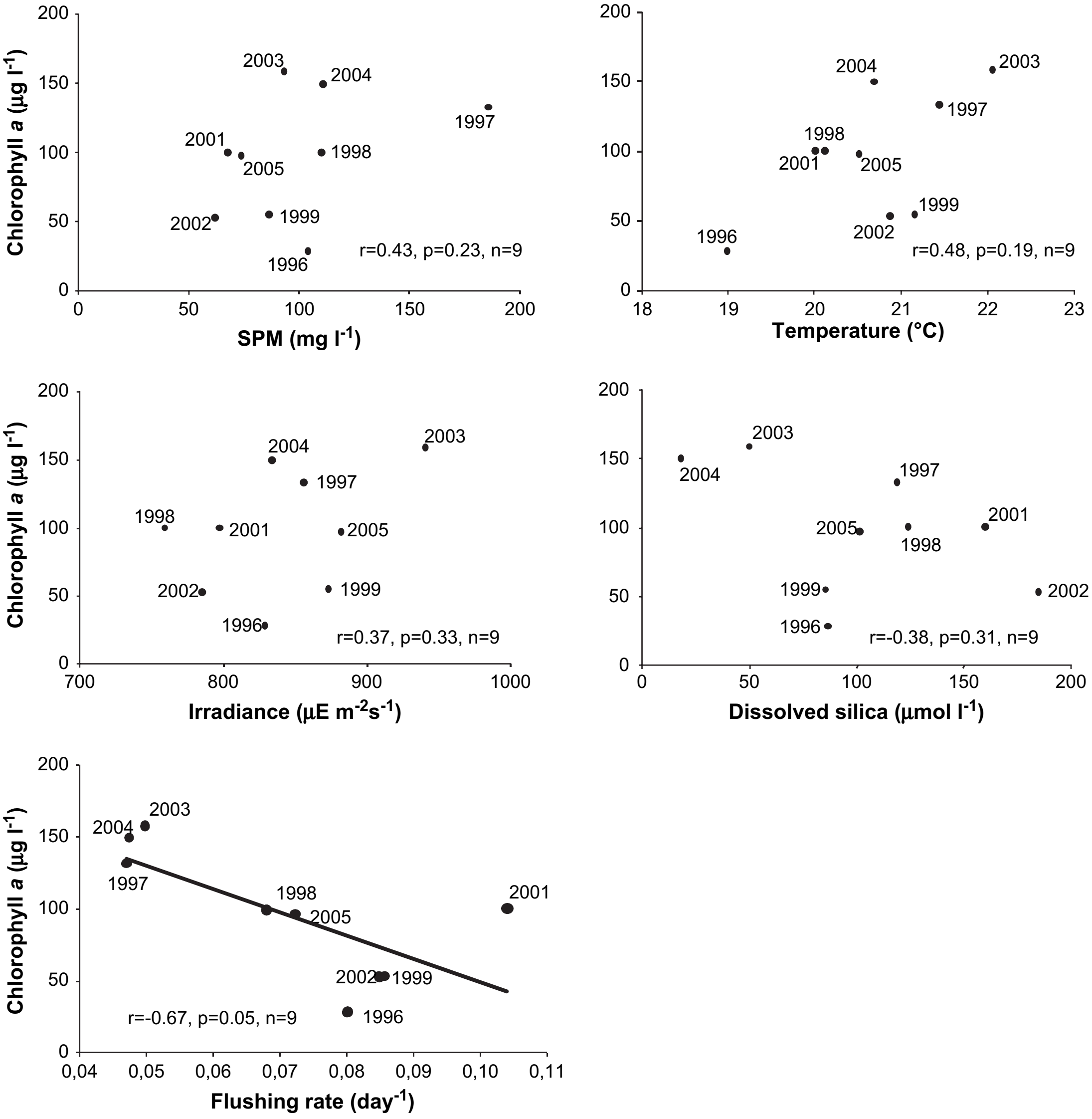

Fig. 5. Correlation between the average summer chlorophyll *a* concentration ($\mu g\, l^{-1}$) and environmental parameters: suspended particulate matter (SPM) ($mg\, l^{-1}$), irradiance ($\mu E\, m^{-2}\, s^{-1}$), temperature (°C), dissolved silica ($\mu mol\, l^{-1}$) and flushing rate (day^{-1}). Spearman correlations results are indicated for each correlation. Trend line is presented only when the correlation is significant. Data points are labelled with the respective year of sampling.

estuary, the flushing rate varied by a factor 2 from year to year: from 0.05 to 0.1 day^{-1}. Phytoplankton blooms were more intense during summers with low discharge and low flushing rate. Flushing rate is an important parameter determining phytoplankton development in lotic systems like estuaries and rivers (Reynolds, 2000). It is especially important when phytoplankton growth rates are low, as it is the case in the freshwater tidal Schelde estuary, where the high turbidity results in strongly light-limited growth rates (Desmit et al., 2005; Muylaert et al., 2005). Therefore, it is not surprising to find that inter-annual variations in discharge result in interannual variations in summer bloom intensity. The discharge, define as the amount of water flowing through the estuary, has been shown to be an important factor regulating the seasonal development of phytoplankton in the Schelde estuary (Muylaert et al., 2005; Arndt et al., 2007). In a previous study, punctual increases in discharge during summer were shown to result in washout of phytoplankton from the freshwater tidal reaches of the Schelde estuary (Muylaert et al., 2001). The present study permits going further by linking the inter-annual variation in summer Chlorophyll *a* concentration with the flushing rate. In studies in other estuaries, inter-annual differences in phytoplankton biomass have also been found to be related to discharge (e.g. Tamar estuary, Jackson et al., 1987, and Tagus estuary, Gameiro et al., 2004). However, in those studies, a positive correlation between discharge and phytoplankton biomass was observed. In sub-estuaries of Chesapeake Bay (Malone et al., 1988;

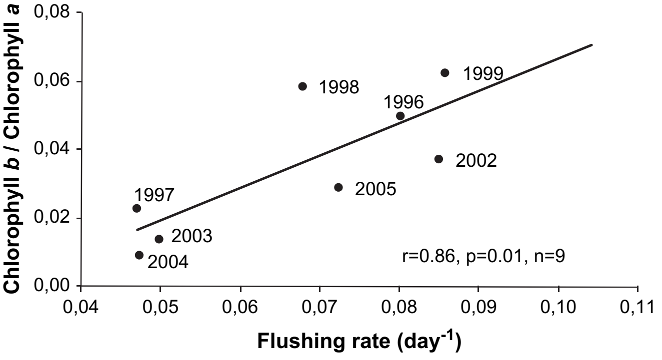

Fig. 6. Correlation between the chlorophyll *b* on chlorophyll *a* ratio in summer and the average summer flushing rate (day^{-1}). Spearman correlation coefficient: $r = 0.86$, $p = 0.01$, $n = 9$.

Harding, 1994; Adolf et al., 2006) and in the Neuse river estuary (Mallin et al., 1993), increases in discharge were associated with nutrient inputs that resulted in more intense phytoplankton blooms. Control of phytoplankton bloom intensity by nutrients is much more unlikely in the upper Schelde estuary, which receives very high N and P inputs from human activities in the catchment (Baeyens et al., 1998; Van Damme et al., 2005).

Two other observations point to a strong influence of discharge on phytoplankton summer blooms in the upper Schelde estuary. First, when the mean weighted summer chlorophyll *a* concentration was low, chlorophytes were an important component in the phytoplankton community of the upper estuary. Chlorophytes are dominant in the tributary Schelde river and decline in abundance upon import into the estuary, where they are replaced by diatoms (Muylaert et al., 2000, 2001). The disappearance of chlorophytes in the estuary is probably due to an unfavourable light climate in the estuary, which is the result of a high turbidity combined with a deep water column (Lionard et al., 2005). Therefore, the increase in relative abundance of chlorophytes when phytoplankton blooms are less intense is the result of an increased import of chlorophytes from the river (Fig. 6), which is the result of a higher discharge.

Second, the position of the chlorophyll *a* maximum within the freshwater tidal reaches was situated more downstream when blooms were relatively weak and more upstream when blooms were more intense. At the most upstream sites, SPM concentrations are generally lower and the water column is shallower, which results in a more favourable underwater light climate and, hence, higher phytoplankton growth rates (Muylaert et al., 2005). Due to the geomorphology of the upper Schelde estuary with a shallow water column and a width channel a low water volume can easily increased the discharge at these upstream sites. As a consequence, water retention time is very low: only 4.7 days for the estuary upstream of Dendermonde at an average summer discharge of 21.8 $m^3\,s^{-1}$. Our observations of phytoplankton biomass indicate that only at very low discharges the phytoplankton can stay sufficiently long in the most upstream sites of the estuary to take advantage of the favourable growth conditions at these sites, and attain a high biomass in this part of the estuary.

In contrast to N and P, DSi concentrations are within the natural range of concentrations in freshwaters. DSi is an essential nutrient for phytoplankton in the upper Schelde estuary as the phytoplankton community is dominated by diatoms (Muylaert et al., 2000). A previous study conducted by Struyf et al. (2005) demonstrated the importance of the Si freshwater marshes recycling in the availability of DSi for phytoplankton in spring and summer months. However, during summer, DSi concentrations are severely depleted in the upper Schelde estuary (Muylaert et al., 2001; Carbonnel, personal communication). In the present study, the weighted mean summer DSi concentration decreased with increasing weighted mean summer chlorophyll *a* concentration but this relation was not statistically significant.

5. Conclusion

In conclusion, this study demonstrated that the intensity of summer phytoplankton blooms in the upper Schelde estuary can vary strongly from year to year. These variations seem to be mainly the result of variations in river discharge, which influence the rate at which phytoplankton is washed out of the upper estuary. Changes in the climate that affect discharge may therefore probably also affect phytoplankton bloom development in the upper Schelde estuary.

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