Prediction of nuisance foam events and *Phaeocystis globosa* blooms in Dutch coastal waters, with fuzzy logic.

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Abstract

Phaeocystis globosa is a nuisance algal species because of the foam on beaches that is associated with its blooms. Models of *Phaeocystis* have considered its bloom dynamics, but not the actual foam formation. The process of foam formation is poorly understood which limits the suitability of traditional deterministic model approaches. We therefore applied fuzzy logic to simulate observed *Phaeocystis* bloom dynamics in coastal waters of the North Sea and foam formation on adjacent beaches. *Phaeocystis* bloom initiation is estimated to occur when the mean mixed layer daily irradiance exceeds circa 25 to 35 μmol photons.m^{-2}.s^{-1}. Differences in peak bloom intensity between monitoring stations were correlated to nutrient availability. Bloom termination did not coincide with nutrient depletion. Foam events occurred during and following *Phaeocystis* blooms, when the wind direction was landward. Over the period 1999-2007 80% of observed foam events were correctly predicted by the model. However, there were many false positives. The fuzzy logic approach proved very helpful in screening and adjusting hypotheses on the dynamics of *Phaeocystis* and associated foam events. The resulting model can be used to communicate current understanding of foam formation, enhances the predictability of these events, and provides a basis for more detailed modelling efforts.

Keywords: *Phaeocystis*, phytoplankton, modelling, fuzzy logic, eutrophication, algal blooms, Netherlands, North Sea, latitude: 52.5, longitude: 4.5

1 Introduction

Harmful algal blooms cause severe economic and ecological damage in both marine and freshwater systems worldwide (Hallegraef, 1993; Anderson et al., 2002; Paerl and Huisman, 2008). The marine haptophyte *Phaeocystis globosa* is commonly regarded as a nuisance algal species for several reasons. The species is associated to mass foam accumulations on beaches, which are a nuisance to beach recreation (Lancelot, 1995; Peperzak, 2002). Furthermore, its high biomass accumulation is associated with occasional shellfish mortality (Peperzak and Poelman, 2008), its production of dimethyl-sulphide precursors may promote acid rain (Liss et al., 1994) and *Phaeocystis* blooms have been reported to cause floating slicks on the water, to clog nets and produce bad odour. Blooms of *Phaeocystis* have been observed to increase in both size and frequency in Dutch coastal waters until the 1990s (Bätje and Michaelis, 1986; Cadée and Hegeman, 1986), presumably due to eutrophication.

Understanding of the human impact on harmful algal blooms and vice versa is needed for mitigating measures. Prediction of blooms would enable damage reduction by for example moving shellfish stocks or by nutrient reduction measures. Models can serve both the goal of improved understanding and of prediction based on that understanding. Both freshwater and marine studies often use deterministic models consisting of ordinary and/or partial differential equations. This deductive model approach aims to include all relevant processes as sufficiently accurate as possible to achieve a high predictability of algal bloom formation (e.g. Moll and Radach, 2003 and references therein). Several studies have applied this model approach to *Phaeocystis* (e.g. Lancelot et al., 1997; Los et al., 2008). However, the formation of nuisance foam associated to *Phaeocystis* blooms has to our knowledge not yet been described by deterministic models. The process of foam formation and its relation to *Phaeocystis* and other factors involved are poorly understood, which hampers the formulation of deterministic models.

A disadvantage of many deterministic models is their technical complexity, which often makes model responses and uncertainties difficult to interpret and hampers easy validation in other areas. Furthermore usually only those processes that are sufficiently well understood can be adequately captured in a deterministic model. Moreover, even dedicated deterministic models cannot guarantee high predictability, if algal species are characterized by chaotic dynamics (Huisman et al., 2006; Benincà et al., 2008). Neural networks are an example of the opposite modelling approach (inductive modelling), where an output variable (e.g. algal blooms) is related to a set of input variables by mere correlation (e.g. Recknagel, 1997). This approach allows for the development of models for phenomena that are not yet understood well and may contribute to increasing insight in the underlying processes. However, as the nature of the correlations in these models is not explicit, the models are usually very site specific and cannot be used to predict how the system will respond to changing conditions due to for example climate change or mitigating measures.

Fuzzy logic is an intermediate modelling approach. In fuzzy logic the structure of the model is based on understanding (i.e. deductive) and the relations within the model are quantified partly on expert knowledge and partly on correlations in observed data (inductive). This approach was succesfully applied to algal blooms by Ibelings et al. (2003). They translated expert knowledge on vertical migration by the freshwater cyanobacterium *Microcystis* in relation to water column stability and solar irradiance into a fuzzy logic model. During the HABES-project (Harmful Algal Blooms Expert System) the fuzzy logic approach was succesfully applied to harmful algal blooms in marine waters. Fuzzy logic models were developed for five harmful algal species in seven pilot areas across Europe. An overview of the results for all pilot studies of the HABES project is given by Blauw et al. (2006). Detailed descriptions of studies in specific areas are given by Laanemets et al. (2006), Lilover et al. (2006), Estrada et al. (2008) and Raine et al. (this issue). This paper describes the results for the pilot study on *Phaeocystis globosa* in Dutch coastal waters in the North Sea. The aim of the study is to quantify and improve the understanding of *Phaeocystis* blooms and associated foam events in Dutch coastal waters using fuzzy logic. We aim at a model that can be used for real-time predictions, so only variables that are available in real-time can be used as input to the model.

2 Material and Methods

2.1 Description of fuzzy logic

The concept of 'fuzzy logic' was introduced by Zadeh (1965) as an extension of Boolean logic to enable modelling of uncertainty. Fuzzy logic introduces a concept of partial truth-values, that lie in between "completely true" and "completely false". The central concept of fuzzy logic is the *membership function*, which numerically represents the degree to which an element belongs to a set. In a classical set, a sharp or unambiguous distinction exists between the members and non-members of a set, while in a fuzzy set, the distinction between members and non-members is gradual. An element can be a member of a set to a certain degree and be at the same time a member of a different set to a certain degree. The degree to which a member is an element of a set is called the membership degree (Figure 1). Similar to traditional logic, in fuzzy logic membership values can be combined through operations on fuzzy sets, such as union, intersection and complement.

Fuzzy logic is often used for reasoning in knowledge-based systems, such as expert systems. The knowledge is typically represented in terms of if-then rules. An example is: if A and B then C. The if-part of the rule is called the premise and the then-part the consequent. The truth value of the rule's premise describes to what degree the rule applies in a given situation. The so-called fuzzy inference mechanism is used to determine the consequent fuzzy set based on the truth value of the premise (this is often called the degree of fulfillment). Consequent fuzzy sets of individual rules are then combined (aggregated) into a single fuzzy set. In most practical applications, the resulting fuzzy set is converted (defuzzified) into a real (crisp) value. Both Boolean logic and fuzzy logic are based on rules, representing knowledge expressed in a natural (non-mathematical) language.

2.2 Set-up of conceptual model based on literature study

2.2.1 Bloom initiation and colony formation

A first step in the development of our fuzzy logic model consists of gathering information on the conditions that promote *Phaeocystis* blooms and foam formation. *Phaeocystis* can grow as single cells and in large gelatinous colonies comprising thousands of cells. The colonial cells are embedded in a mucilagenous matrix of polysaccharides, which is widely held responsible for

foam formation (Lancelot, 1995). *Phaeocystis* blooms in the Marsdiep area, a tidal inlet between the Wadden Sea and Dutch coastal waters, often occur in spring following a diatom bloom (Cadée and Hegeman, 2002). Rousseau et al. (2007) reviewed possible triggers for colonial bloom formation, including light (Kornmann, 1955; Peperzak et al., 1998)), the availability of solid substrate (such as diatoms) as nuclei for colony formation, and diatom exudate (Boalch, 1987). Peperzak (1993) measured the transition from flagellated single cells of *Phaeocystis* into colonial and immotile cells as a function of light conditions in the laboratory. He found that at daily irradiance levels below ~100 Wh.m^{-2}.d^{-1} only flagellated cells were present. At higher irradiance levels the percentage of colony cells increased with irradiance. This is relevant for *Phaeocystis* bloom dynamics as the growth rate of colonial cells is considerably higher than the growth rate of single cells (Veldhuis et al., 2005). Peperzak et al. (1998) subsequently showed that the spring bloom of *Phaeocystis* in the North Sea is triggered when the underwater light intensity exceeds this daily threshold of ~100 Wh.m^{-2}.d^{-1} (= 1.65 mol photons.m^{-2}.d^{-1}) at 15 ºC. Assuming a 12-hour light period in spring, this threshold corresponds to an instantaneous light intensity of ~38 µmol photons.m^{-2}.s^{-1} on average. This matches nicely with laboratory experiments by Jahnke (1989), which indicate that *Phaeocystis* could achieve high growth rates of more than 1 division per day when the instantaneous light intensity exceeded circa 36 µmol.m^{-2}s^{-1}. Lancelot et al. (1998) give an overview of production-irradiance parameters for *Phaeocystis* in the North Sea, including the parameter I_k which characterizes the irradiance at which the production-irradiance curve starts to saturate. They found I_k for colonial *Phaeocystis* in the southern North Sea to range between 91 and 180 µmol.m^{-2}.s^{-1}. This corresponds with the I_k of 180 µmol.m^{-2}.s^{-1} found by Jahnke (1989).
Nutrients may also affect bloom initiation and colony formation of *Phaeocystis*. Riegman et al. (1992) found that colony formation occurred under nitrate limitation. Under phosphate limitation colonies were only formed when phosphate concentrations were as high as 1.2 µM and there was no ammonium available. Cariou et al. (1994) found that colony formation was hampered at phosphate concentrations below 0.3 µM. Concentrations of circa 1 µM phosphate appeared favorable for colony formation. They also found that large colonies had a tendency to float.

2.2.2 Bloom development

The intensity, duration, and termination of *Phaeocystis* blooms have been attributed to nutrient availability by many authors. Cadée and Hegeman (2002) found an increasing trend during the late 1970s of both the intensity and duration of *Phaeocystis* blooms in the Marsdiep, which seemed associated with eutrophication. Since 1980 bloom duration has remained high, with maximum bloom duration in the period 1988 to 1991. Veldhuis et al. (1986) suggested that the end of *Phaeocystis* blooms in Dutch coastal waters is induced by phosphate limitation (in 1984 below 0.08 µM P). In coastal stations with replenishment of nutrients by freshwater runoff the bloom intensity was higher, the growth period was longer and the timing of the peak was later than in the more offshore stations. Besides competition for nutrients other causes for bloom termination could be sedimentation, light deficiency, grazing by zooplankton and viral attacks. However, it is possible that sedimentation, grazing or viral attacks are especially effective on the flagellated unicellular life stage of *Phaeocystis* or when the colonies have lost vitality due to deficiency of light or nutrients (Brussaard et al. 2005).

Peperzak (2002) reviewed information on temperature and salinity effects on *Phaeocystis* growth rate reported in the literature. From this review the general conclusion emerged that optimal salinity for *Phaeocystis* is about 29, although it grows well over a wide range of salinities (20 –

35). However, at a salinity below 15 the *Phaeocystis* cells will die. Although colonial cells have been observed at temperatures ranging between -1 to 16 °C, laboratory experiments have revealed a range from 3 to 24 °C, with maximum growth rate at 16 °C (Peperzak, 2002).

2.2.3 Foam formation

Foam formation on beaches is generally assumed to be related to *Phaeocystis* blooms in nearby coastal waters (e.g. Lancelot, 1995; Bätje and Michaelis, 1989). Hamm and Rousseau (2003) studied foam at sea during the decline of a *Phaeocystis* bloom. They found that *Phaeocystis*-derived organic matter degraded while floating or in suspension. In surface slicks covering the water during the *Phaeocystis* bloom, *Phaeocystis* colonies were a major component. Near the sediment no traces of *Phaeocystis* were found. Peperzak (2002) found a good correlation between the averaged timing of *Phaeocystis* blooms and of foam events. Foam events occurred two weeks after *Phaeocystis* blooms had occurred. He also found that foam did not occur on all beaches at the same time. In the Netherlands *Phaeocystis* blooms are commonly defined as occasions with more than 1 million cells.L^{-1} (e.g. Cadée and Hegeman, 1986, 2002; Peperzak, 2002). In this study we will use the same definition of *Phaeocystis* blooms. Peperzak's results suggest that foam formation can be predicted if the bloom period of *Phaeocystis* can be predicted.

2.2.4 Conceptual model set-up

Based on the information from literature described above we expect that foam formation on coastal beaches (the final aim of the model) is controlled by the presence and intensity of *Phaeocystis* blooms. We expect that the onset of *Phaeocystis* blooms is controlled by light availability, that the intensity and duration of *Phaeocystis* blooms are strongly affected by nutrient availability, and that bloom termination is triggered by phosphate depletion. Furthermore, the suitable period and areas for *Phaeocystis* blooms are limited by temperature and salinity constraints. In addition, we hypothesize that wind conditions play a role in foam formation as well, to transport the accumulated *Phaeocystis* mucilage and deposit its foam on the beaches.

2.3 Description of study area

Our study area is the so-called Noordwijk transect. This transect runs perpendicular to the Dutch coast into the North Sea. It starts at the town of Noordwijk, where foam observations have been made with video cameras. Monitoring stations at 2, 10 20 and 70 kilometers from the shore are regularly monitored for water quality and phytoplankton composition (Figure 2). Coastal waters in this area are heavily influenced by the outflow of the Rhine river, creating a highly dynamic environment. On average, the Rhine plume flows northwards along the coast, as a result of the Coriolis effect, prevailing south-westerly winds, and general North Sea circulation. However, depending on weather conditions the Rhine plume may temporarily be transported further offshore or southwards (Lacroix et al., 2004). Stratification regularly occurs in the Dutch coastal zone. The stratification is intermittent and mainly caused by variations in mixing by tides and wind (Simpson et al., 1993). Due to the high impact of river runoff, nutrient concentrations in Dutch coastal waters are high, with median winter concentrations ranging from 63 μM DIN and 1.4 μM DIP at station Noordwijk-2 to 8 μM DIN and 0.5 μM DIP at station Noordwijk-70. The seafloor topography of Dutch coastal waters is gently sloping, circa 20 m deep with sandy sediments. In shallow near-shore waters, sediments get easily resuspended at high wind speeds and strong tidal currents leading to strongly fluctuating turbidity.

2.4 Data sources

2.4.1 Routine monitoring data

The routine monitoring programme of Dutch coastal waters is operated by the Dutch Ministry of Transport, Public Works and Water Management. The monitoring locations are shown in Figure 2. The monitoring programme includes amon others phytoplankton species composition, salinity, water temperature, chlorophyll-a, suspended matter, nitrate, ammonium, ortho-phosphate, dissolved silicate and light extinction. Most parameters are determined in surface samples. Vertical profiles at selected monitoring stations are measured for salinity, temperature, fluorescence and oxygen. The monitoring is performed monthly in winter and circa biweekly during the rest of the year. Most of the data can be downloaded from www.waterbase.nl.

2.4.2 ARGUS video cameras

The ARGUS video system (Aarninkhof et al., 2003) has been operational since 1998 at two locations along the Dutch coastal zone: Noordwijk and Egmond. The ARGUS video system has originally been developed by Oregon State University for monitoring of the dynamics of sandbanks. It comprises video images of the coastal zone taken every hour from a high building on the shoreline. Foam events can be clearly recognised on these images. Images of the ARGUS camera are available in real-time from the website: http://argus-data.wldelft.nl/argus.

2.4.3 Smartbuoy

The Smartbuoy has been deployed at station Noordwijk 10 from March 2000 untill September 2001. Measured parameters include: salinity, water temperature, fluorescence, optical backscatter and the light extinction coefficient. More about the Smartbuoy and its results can be found at: www.cefas.co.uk/data/marine-monitoring/uk-netherlands-collaborative-monitoring-programme-.aspx

2.4.4 Meteorological data

Meteorological data have been recorded by the Royal Netherlands Meteorological Institute (KNMI) at monitoring station ‘de Kooy’. The data include daily observations of wind speed, wind direction and solar irradiance. Part of the data can be downloaded from: www.knmi.nl.

2.5 Data analysis method

The relations in the conceptual model have been quantified through analysis of available data. The analysis focussed on the effects: 1) of light on bloom initiation 2) of nutrients on bloom intensity, 3) of phosphate depletion on bloom termination and 4) of wind conditions and bloom intensity on foam formation.

2.5.1 Bloom initiation

Based on our literature study, we hypothesized that the start of *Phaeocystis* blooms in Dutch coastal waters is triggered by the underwater light climate. We therefore estimated the underwater light climate from available observations. The vertical light gradient can be described by Lambert-Beer's law (Huisman and Weissing, 1994):

$$I_z = I_0 e^{-K_d Z} \qquad \text{(eq.1)}$$

where I_Z is the irradiance (in μmol photons.m^{-2}.s^{-1}; measured in the PAR range from 400 to 700 nm) at depth z (in m), I_0 is the irradiance at the water surface, and K_d is the light extinction coefficient (in m^{-1}). The depth-averaged irradiance within the mixed layer can be calculated from eq.1 as:

$$I_M = \frac{1}{z_M} \int_0^{z_M} I_Z dz = I_0 \left(1 - e^{-K_d z_M}\right) / (K_d z_M) \qquad \text{(eq.2)}$$

where z_M is the depth of the mixed layer. As the product, $K_d\, z_M$, of the light extinction coefficient and mixed-layer depth along the Noordwijk transect is approximately 0.5×20=10 at station Noordwijk-10 and 0.25×30=7.5 at station Noordwijk-70, the term $\exp(-K_d z_M)$ approaches zero. The depth-averaged irradiance may therefore be approximated as:

$$I_M = I_0 / (K_d z_M) \qquad \text{(eq.3)}$$

Daily measurements of total solar irradiance (J.cm^{-2}.d^{-1}) were recorded by the Royal Netherlands Meteorological Institute. The total solar irradiance covers the entire solar spectrum, including infrared light not available for phytoplankton photosynthesis. This was corrected by calculating the solar irradiance within the waveband of Photosynthetically Active Radiation (PAR) from 400 to 700 nm, using a correction factor of 0.45 as the PAR waveband comprises approximately 45% of the total solar irradiance (Kirk, 1994). Subsequently the solar irradiance within the PAR range was converted from J.cm^{-2}.d^{-1} to μmol.m^{-2}.s^{-1}, assuming 2.77×10^{18} photons per Joule (Kirk, 1994), to arrive at the surface irradiance I_0.

For most years, daily measurements of light extinction and mixed-layer depth are not available. In the years 2000 and 2001, continuous measurements of light extinction and salinity at station Noordwijk-10 are available from the Smartbuoy. When salinity is used as a proxy for stratification, changes in mixed-layer depth through stratification can be taken into account for these years. The observed vertical salinity profiles from the routine monitoring programme at station Noordwijk-10 showed that the salinity near the seafloor generally ranges between 29.5 and 32. Under stratified conditions, the surface salinity is about 1 or more units lower. Comparison of the Smartbuoy recordings with the vertical salinity profiles of the routine monitoring programme showed that reduced salinity in the Smartbuoy recordings coincided with vertical salinity differences larger than 1 (data not shown). Therefore, as a first approximation, we assume that if the salinity in the surface is reduced below circa 28, the water column is likely to be stratified. The total depth of the water column at station Noordwijk-10 is about 20 m. According to the vertical profiles of salinity in the DONAR dataset observed in spring of the years 2000 – 2002, the mixed-layer depth during stratified conditions ranged roughly between 4.5

and 8 meters (data not shown). Assuming entrainment of the *Phaeocystis* colonies in the surface-mixed layer, this means that the depth-averaged irradiance for *Phaeocystis* increased with a factor 2.5 to 3.6 (20/8 to 20/4.5) during stratified conditions. In this way, time series of intermittent stratification and associated changes in the depth-averaged daily irradiance at station Noordwijk-10 could be estimated from the Smartbuoy data for the spring periods of 2000 and 2001, so that the bloom development of *Phaeocystis* can be related to the underwater light climate.

For the other years no Smartbuoy data are available. The temporal resolution of the routine monitoring data for station Noordwijk-10 is insufficient to give information on intermittent stratification, which has a major impact on the underwater light climate at this station. Haline stratification does not take place at station Noordwijk-70, because it has less freshwater input. Also the extinction coefficient shows less variability at this station. The underwater light climate of this station has been approximated, by assuming a constant mixed-layer depth equal to the total water depth and a constant light extinction coefficient equal to the long-term average. The resulting estimate of daily irradiance for the years 1990 – 2002 has been used to estimate a threshold irradiance level for *Phaeocystis* bloom formation.

2.5.2 Bloom development

Ideally, the temporal resolution of the monitoring data during the spring period was biweekly, but often at the beginning of the bloom the resolution was still around one sample per 3 – 5 weeks. This low temporal resolution did not allow for detailed analysis of interannual variability in bloom intensity or bloom duration. Instead we compared the median over 1990 – 2002 of the annual peak *Phaeocystis* concentrations and winter nutient concentrations and salinity for all monitoring stations indicated with circles in Figure 2. Also we compared time series of ortho-phosphate concentrations and *Phaeocystis* at station Noordwijk 10 to see if bloom termination coincided with ortho-phosphate concentrations getting depleted.

2.5.3 Foam formation

The video images from 1999 - 2007 have been inspected to assess whether or not foam was visible on the beach. The images were visually classified into 4 classes: 1: no foam, 2: little foam, 3: foam, 4: much foam. Often foam was present only part of the day. For each day the image with most foam has been used to classify the foam presence for that day. Examples of each class of foam intensity are shown in Figure 3.

3 Results

3.1 Data analysis

3.1.1 Bloom initiation

Temporal variation in surface salinity measured by the Smartbuoy indicated that station Noordwijk-10 displays intermittent stratification. This is visualized in Figure 4. Black lines show the depth-averaged irradiance assuming that the water column is not stratified but homogeneously mixed. The two grey lines show the depth-averaged irradiance assuming stratification with a mixed-layer depth of 4.5 and 8 m, respectively. Divergence of the black and grey lines indicate the timing of the stratification events based on observed low surface salinities (Figure 4). Clearly, these stratification events have a strong impact on the depth-averaged irradiance in the mixed layers, favoring suitable light conditions for phytoplankton growth. During presumed stratified periods, chlorophyll fluorescence first decreases and increases sharply afterwards (Figure 4a,b). This chlorophyll signal captures the stratification response of the entire phytoplankton community, which may include *Phaeocystis* but also many other phytoplankton species. Unfortunately, we have only limited data on phytoplankton community composition. The year 2000 showed only one observation of *Phaeocystis* above 1 million cells.L^{-1} in spring (Figure 4c). In 2001, *Phaeocystis* concentrations increased during the first stratification event, decreased thereafter, and then increased again midway during the second stratification event (Figure 4d). This pattern resembled the fluorescence pattern (compare Figures 4b and 4d).

To estimate the light requirements for *Phaeocystis* blooms, we calculated the weekly mean values of the depth-averaged irradiance during the period before bloom development. In the years 1990-2000, *Phaeocystis* blooms (above 1 million cells.L^{-1}) developed at station Noordwijk-70 when the weekly mean value of the depth-averaged irradiance exceeded 25 μmol photons.m^{-2}.s^{-1} in the period before bloom development (Figure 5).

3.1.2 Bloom intensity

We hypothesized that bloom intensity would be strongly related to nutrient availability. We investigated this hypothesis by comparison of the annual peak abundance of *Phaeocystis* and the annual winter nutrient concentrations at 23 monitoring stations in the North Sea. The median value of the annual peak abundance of *Phaeocystis* was positively correlated with the median value of the winter DIP concentration, the winter DIN concentration, the winter N/P ratio and the freshwater fraction (Figure 6).

3.1.3 End of Phaeocystis bloom

The end of *Phaeocystis* blooms does not coincide with phosphate depletion at station Noordwijk-10 (Figure 7). Figure 7 shows the time series of ortho-phosphate and *Phaeocystis* measured at this station during the years 1990 to 2000. The data are synchronized relative to the day when the phosphate concentrations were first observed below 0.2 µM. The *Phaeocystis* blooms generally started about 20 to 25 days before the ortho-phosphate concentrations dropped below 0.2 µM and lasted until about 30 days after the phosphate concentration had been depleted (Figure 7).

3.1.4 Foam formation

Foam events at Noordwijk beach only occur on days when the wind direction is landward (below 30 degrees and above 215 degrees) and wind speed is above circa 3.5 m.s^{-1} (Figure 8). Days with ‘much foam’ (class 4) only occur at wind speeds above circa 6 m.s^{-1}.

The timing of foam events and *Phaeocystis* blooms in the Dutch coastal zone for the years 1999 -

2008 are presented in Figure 9. It can be seen that foam events mostly occur when *Phaeocystis* is abundant. In 2002 there was no *Phaeocystis* bloom in spring and also no foam was observed. The data suggest a time delay of about two weeks between the peak abundance of *Phaeocystis* and foam events (Figure 9). The years 1999, 2001, 2003 and 2007 stand out for their extensive foam events. During the same four years the peak *Phaeocystis* concentrations at station Noordwijk-2 greatly exceeded 10 million cells.L^{-1} (Figure 10).

3.2 Model calibration and validation

3.2.1 Generic model

Based on the results of the data analysis the conceptual model has been adapted and the relations in the model have been quantified. The updated conceptual model is shown in Figure 11.

The relations in the model have been classified as follows:

- The *Phaeocystis* bloom starts when the weekly mean of the depth-averaged irradiance exceeds 25 to 40 µmol.m^{-2}.s^{-1}.
- *Phaeocystis* blooms can occur only if the salinity ranges between 20 and 35, and temperature between 3 – 24 °C.
- Blooms have an average duration of 40 days. The foam period ends 2 weeks after bloom termination.
- The peak bloom intensity can exceed 10 million cells L^{-1} when the winter DIN concentration exceeds 13 µM and the winter DIP concentration exceeds 0.45 µM (Figure 6).
- Nuisance foam on a beach can occur during a bloom period of *Phaeocystis*, when the maximum bloom intensity in nearshore waters is above 10 million cells.L^{-1}, the wind speed is above 3 to 4 m.s^{-1}, and wind direction is landward.

3.2.2 Site-specific model for Noordwijk beach

The generic model has been validated with foam data at Noordwijk beach during the years 1999 – 2007. Along the coast near Noordwijk wind is landward when the wind direction is below 25 to 75 degrees or above 175 to 210 degrees. For most years, detailed time series of mixed-layer depth and extinction coefficient were lacking. To apply the generic model for Noordwijk, we therefore assumed that the water column is completely mixed (mixed-layer depth is 20 m) and approximated the extinction coefficient by its long-term average of 0.5 m^{-1}.

Sensitivity analyses with this model showed that bloom initiation was best simulated with an irradiance threshold of 25 to 35 µmol photons.m^{-2}.s^{-1}. The model predictions of the bloom period and foam events for the years 1999 to 2008 are shown in Figure 9. In total, for the period 1991 – 2007, 9 of the 10 observed intense blooms (>10 million cells.L^{-1}) at station Noordwijk-2 were correctly predicted, while 15 of the 18 observed intense blooms were correctly predicted at station Noordwijk-10 (Table 1). There was only one bloom event, at station Noordwijk-10, where a bloom was observed while no bloom was predicted. Yet, in many cases where the model predicted an intense bloom, these intense blooms were not observed.

The model performance for foam events shows that 30 of the 44 observed foam events were correctly predicted (Table 2). In 8 cases foam was observed, but not predicted. Yet, in 90% of the cases where the model predicted foam formation, no foam was actually observed.

Thus, almost all observed intense blooms and most observed foam events were predicted by the model. However, the model produces a large number of false positive predictions.

4 Discussion

4.1 Bloom initiation

Our starting hypothesis was that blooms would start when the mean mixed layer irradiance exceeds 19 - 36 μmol.m^{-2}.s^{-1}. Assuming that the mixed-layer depth at station Noordwijk-70 equals the total water depth, our time series data indicate that *Phaeocystis* blooms at this station started at daily irradiance levels ranging somewhere from 25 to 40 μmol.m^{-2}.s^{-1}. Temperatures measured during the onset of the bloom varied between 6 and 11 °C. At this temperature range, the growth rate of *Phaeocystis* varies by a factor two (Peperzak, 2002). This could explain the large range in estimated irradiance thresholds for bloom initiation.

Our study aims to predict foam formation on beaches due to *Phaeocystis*. Therefore, it is important to predict *Phaeocystis* blooms in nearshore waters like station Noordwijk- 2. At these nearshore stations, variability in light extinction and mixed-layer depth is much larger than at more remote stations such as Noordwijk-70. In our study area, this variability is strongly influenced by the river plume of the Rhine, causing intermittent haline stratification. In addition, the relatively small water depth at station Noordwijk-2 results in a strong influence of sedimentation and resuspension processes on the underwater light climate. However, sensitivity tests with various set-ups of the fuzzy logic model (not shown) indicated that the model predictions were not improved by taking into account wind speed and / or neap tides as factors involved in bloom initiation. Only in the year 2001, when the Smartbuoy data indicate a strong influence of stratification during neap tides (Figure 4), bloom initiation is better predicted when the tidal phase is taken into account in the model.

4.2 Bloom intensity

Peak bloom intensity of *Phaeocystis* at different stations in the North Sea was clearly correlated with the winter nutrient concentrations (Figure 6). It is interesting to compare these data with the theoretical maximum *Phaeocystis* abundance, which can be calculated if we assume that all dissolved inorganic nutrients available in winter are taken up by *Phaeocystis*. This calculation requires an estimate of the nutrient contents of *Phaeocystis* cells. Van Boekel et al. (1992) estimated the phosphorus content of *Phaeocystis* cells at 0.045 pmol.cell^{-1}. Jahnke (1989) did experiments to determine C:N:P ratios of *Phaeocystis* under different growth conditions and reported the carbon content of cells. With this information the phosphorus content of *Phaeocystis* cells can be estimated as 0.375 pmol.cell^{-1} under P sufficient conditions, 0.236 pmol.cell^{-1} under P deficient conditions at 4 °C, and 0.053 pmol.cell^{-1} under P deficient conditions ranging from 10 to

18 °C. The water temperature during *Phaeocystis* blooms at station Noordwijk 10 km is circa 10 °C. Hence, the estimate based on Jahnke's experiment under P deficient conditions is in the same order of magnitude as the estimate by van Boekel et al. (1992). We therefore used a P content of 0.045 pmol.cell^{-1} to calculate the theoretical maximum *Phaeocystis* abundance as function of the dissolved inorganic phosphorus concentration. The resulting line is plotted in Figure 6a. The line roughly follows the upper contour of the data points. In two locations the observed peak bloom intensity is higher than the theoretical maximum. These are the stations Dantziggat and Marsdiep, both in the Wadden Sea. Possibly internal phosphorus loading from the sediment in summer, which seems a plausible scenario for the Wadden Sea, serves as an additional phosphorus source that explains why peak intensities are higher than can be expected from winter concentrations of DIP in this area. All in all, the theoretical maximum seems to provide a reasonably good estimate of the maximum peak abundance that can be reached in *Phaeocystis* blooms.

Based on the results by Jahnke (1989) the N content (in pmol.cell^{-1}) of *Phaeocystis* cells can be estimated as 4.5 under P sufficient conditions, 3.9 under P limited conditions at 4 °C and 5.4 under P deficient conditions at 10 to 18 °C. Unfortunately, no estimates are available for N deficient conditions. Based on the upper contour of the data points in Figure 7b the N-content of *Phaeocystis* cells can be estimated as circa 1.3 pmol.cell^{-1}. This is considerably lower than the estimates by Jahnke (1989). However, it seems likely that the N content of the cells would decrease under N deficient conditions. The fact that we find a lower N-content than has been observed for N sufficient *Phaeocystis* cells in the laboratory suggests that nitrogen limitation does play a role in our study area.

4.3 Bloom duration

The termination of *Phaeocystis* blooms along the Noordwijk transect did not coincide with phosphate depletion. It could be that *Phaeocystis* prolongs its bloom by efficient utilization of internally stored phosphorus. In addition *Phaeocystis* can use dissolved organic phosphorus to continue growth when dissolved inorganic phosphorus gets depleted (Veldhuis et al., 1991). Figure 7 may even suggest that the start of the bloom could coincide with ortho-phosphate concentrations dropping below 0.3 µM. This seems to contradict with the results by Cariou et al (1994) which suggest that colony formation is hampered below this same ortho-phosphate threshold. However, the coincidence between phosphate depletion and bloom initiation could also be explained by fast growth of colonial *Phaeocystis* cells quickly taking up ortho-phosphate and thereby rapidly depleting ortho-phosphate concentrations in the water.

A comparison of bloom duration at different stations in Dutch marine waters, similar to the analysis of bloom intensity in section 4.2, was hampered by low and variable sampling frequency at the different stations. However, the large variability in bloom duration at different locations suggests that the availability of nutrients might play a role. For example the bloom duration at the station Marsdiep on the edge of the Wadden Sea lagoon is in the order of 10 to 20 weeks, along the Noordwijk transect it is in the order of 3 to 10 weeks and at station L4 near Plymouth it is in the order of 2 to 3 weeks (Purdie et al., 2004).

4.4 Foam

Foam is often not observed when suitable conditions for foam formation are predicted. The vast majority of the observed foam events (circa 85%) occurred during the four years with exceptionally intense *Phaeocystis* blooms: 1999, 2001, 2003 and 2007. In contrast to these observations, our model predicts equally intense *Phaeocystis* blooms every year. In order to reduce the number of false positive predictions we need to better understand the underlying reasons for this large interannual variability of bloom intensity.

4.5 Fuzzy logic

Fuzzy logic is designed to deal with uncertainty on threshold levels. From the perspective of communication of model uncertainties it is good that the model outcome reflects the range of thresholds found in the data analysis. On the other hand, when the model is applied with crisp thresholds the model performance is similar to the model with fuzzy thresholds. So from that perspective the fuzzy thresholds do not form a major improvement compared to a Boolean rule-based model. The main uncertainties that we were faced with in this study concerned uncertainty in the observed phenomena to be modelled such as bloom termination, summer blooms and interannual variability in bloom intenstiy. Due to the low sampling frequency it was not possible to get a reliable estimate of interannual variability in bloom intensity and bloom duration from the available data. Also in some years, for unknown reasons, there was no or hardly any spring *Phaeocystis* bloom and there was a summer *Phaeocystis* bloom instead. Since we do not know what is the reason for this variability we cannot model them with any model, be it a simple fuzzy logic model or a comprehensive 3D physical-biological coupled model such as GEM (Blauw et al., 2009; Los et al., 2008). Moreover, recent model studies suggest that interannual variability in species composition is an inherent feature of plankton communities, generated by the natural complexity of interactions between large numbers of different species (Dakos et al., 2009).

The present model is a zero-dimensional model, so it does not include spatial patterns of blooms and foam. Fuzzy logic models can be developed as two dimensional models, provided that the input data are available as maps, for example from other models.

5 Conclusions

This study showed that a simple model, such as a fuzzy logic model can be a valuable method to quantify and extend the present understanding of harmful algal blooms. During the model implementation a few hypotheses of *Phaeocystis* bloom dynamics have been screened and quantified. The hypothesis that foam events are associated with *Phaeocystis* was supported by our 9 years dataset of daily foam observations. More precisely, we showed that years with more than 10 million cells.L^{-1} in near-shore waters showed considerably more frequent and intense foam events than years with lower *Phaeocystis* abundance. The maximum bloom intensity increases with nutrient availability. For blooms to exceed 10 million cells.L^{-1}, winter nutrient concentrations of circa 13 µM DIN and 0.45 µM DIP would be required. *Phaeocystis* blooms seem to start when the weekly mean of the depth-averaged irradiance exceeds a threshold of circa 25 to 40 µmol.m^{-2}.s^{-1}. The trigger for *Phaeocystis* bloom termination could not be found in this study. It did not coincide with phosphate depletion. Suitable conditions for foam events can be predicted rather well from wind conditions and *Phaeocystis* bloom presence. However, often when suitable conditions for foam formation occur, no foam is observed. It will be an important task for future studies to improve the predictability of foam events through reduction of the number of false positives.

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Figure captions

Figure 1: Illustration of a fuzzy logic membership function for water temperature. a) Crisp classification of water temperature, b) fuzzy classification of water temperature.

Figure 2: Location of the monitoring stations in Dutch coastal waters. Crosses represent historic stations, circles represent operational stations. The three labeled stations are mentioned in the text.

Figure 3: Examples of foam intensity classes obtained from ARGUS video images: a) no foam (class 1), b) little foam or only part of the day foam (class 2), c) foam (class 3), and d) much foam (class 4).

Figure 4: Time series obtained from the Smartbuoy at station Noordwijk-10. a,b) Chlorophyll fluorescence (symbols) in (a) spring 2000, and (b) spring 2001. c,d) *Phaeocystis* abundance (symbols) in (c) spring 2000, and (d) spring 2001. The three lines in each panel represent the depth-averaged irradiance, assuming well-mixed conditions (black line), stratified conditions with a mixed-layer depth of 8 m (thick grey line), and stratified conditions with a mixed-layer depth of 4.5 meter (thin grey line).

Figure 5: Spring observations of *Phaeocystis* at station Noordwijk-70 in the years 1990 – 2002, plotted against the highest weekly mean value of the depth-averaged irradiance in the preceding month.

Figure 6: Median value of the annual peak abundance of *Phaeocystis* during the years 1990 – 2000, for 23 monitoring stations in the North Sea, plotted against a) median winter concentrations of dissolved inorganic phosphorus (DIP), b) median winter concentrations of dissolved inorganic nitrogen (DIN), c) median N/P ratio during winter, and d) mean annual freshwater fraction. The lines indicate the theoretical maximum biomass assuming that all winter nutrients are converted to *Phaeocystis* biomass. The theoretical maximum biomass in (a) assumes a P-content of 0.045 pmol.cell^{-1} (van Boekel et al., 1992). The theoretical maximum biomass in (b) is estimated by drawing a line along the upper contour of the data points, which yields a N-content 1.3 pmol.cell^{-1}.

Figure 7: Time series of (a) dissolved inorganic phosphorus (DIP) and (b) *Phaeocystis* abundance, observed in the years 1990 - 2000 at station Noordwijk-10. The time series are synchronized relative to the first day that phosphate concentrations were observed below 0.2 µM.

Figure 8: Foam intensity at Noordwijk beach as a function of (a) wind speed and (b) wind direction. Foam intensity is classified as ‘no foam’ (class 1), ‘little foam’ (class 2), ‘foam’ (class 3), and ‘much foam’ (class 4).

Figure 9: Model predictions (lines) and observations (symbols) of *Phaeocystis* blooms and foam formation. a,c) *Phaeocystis* observations at stations Noordwijk-2 (squares) and Noordwijk-10 (circles). c,d) Foam intensity at Noordwijk beach (lines represent model predictions; crosses represent observations).

Figure 10: The number of foam events per year versus the annual maximum *Phaeocystis* abundance. Open circles show foam events of class 3 (foam) and class 4 (much foam); closed circles show foam events of class 4 only.

Figure 11: Structure of the fuzzy logic model for *Phaeocystis* blooms and foam formation.

Table 1: Comparison of the number of observations with intense *Phaeocystis* blooms (> 10 million cells.L^{-1}) against model predictions, for stations Noordwijk-2 and Noordwijk-10. The model predictions are based on the membership function of the model variable bloom development. 'Bloom' means a membership of 1, 'Likely bloom' means a membership between 0.5 and 1, 'Possible bloom' means a membership between 0 and 0.5, and 'No bloom' means a membership of 0.

	Simulated	Observed	
		Bloom	No bloom
Noordwijk 2	Bloom	9	21
	Likely bloom	1	3
	Possible bloom	0	5
	No bloom	0	121
Noordwijk 10	Bloom	15	46
	Likely bloom	2	4
	Possible bloom	0	5
	No bloom	1	179

Table 2: Comparison of the number of observations with foam on Noordwijk beach against the model predictions of foam formation. The model predictions are based on the membership function of the model variable foam formation. ‘Foam’ means a membership of 1, ‘Likely foam’ means a membership between 0.5 and 1, ‘Possible foam’ means a membership between 0 and 0.5 and ‘No foam’ means a membership of 0.

Simulated	Observed		
	Foam	Bit foam	no foam
Foam	30	30	248
likely foam	5	20	90
possible foam	1	17	108
no foam	8	54	2558

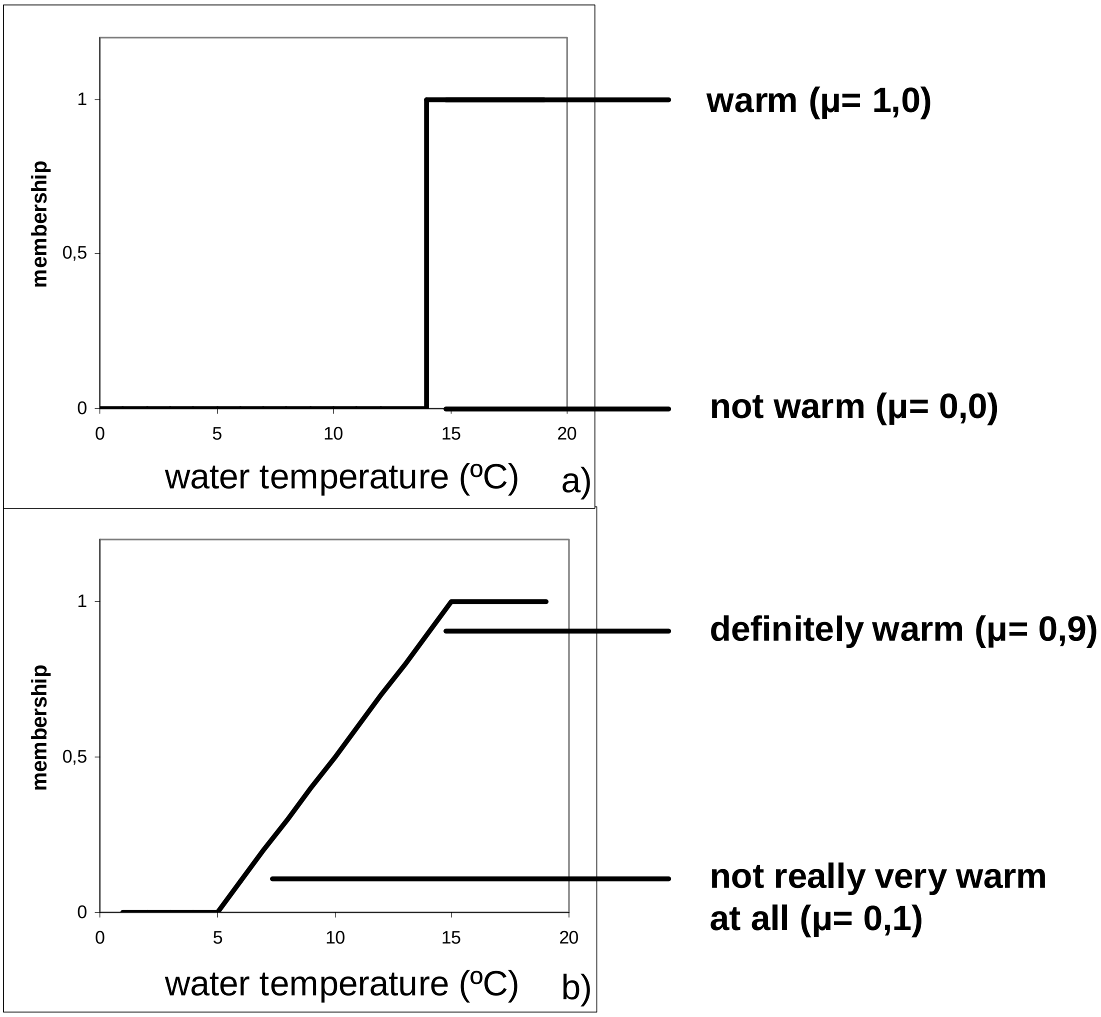
membership
1
0,5
0
0
5
10
15
20
water temperature (ºC)
a)
warm (μ= 1,0)
not warm (μ= 0,0)
membership
1
0,5
0
0
5
10
15
20
water temperature (ºC)
b)
definitely warm (μ= 0,9)
not really very warm
at all (μ= 0,1)

Figure 1

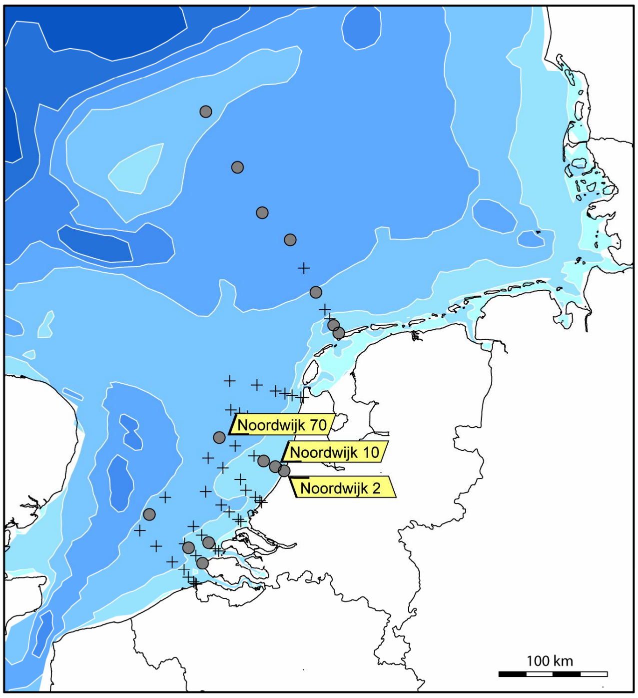

Figure 2


ARGUS2.1 snap Egmond Tue Jun 5 13:00:01 2001 GMT F: 991746001
C: 1 S: 1 Inc: 0 Qual: 80

Figure 3a

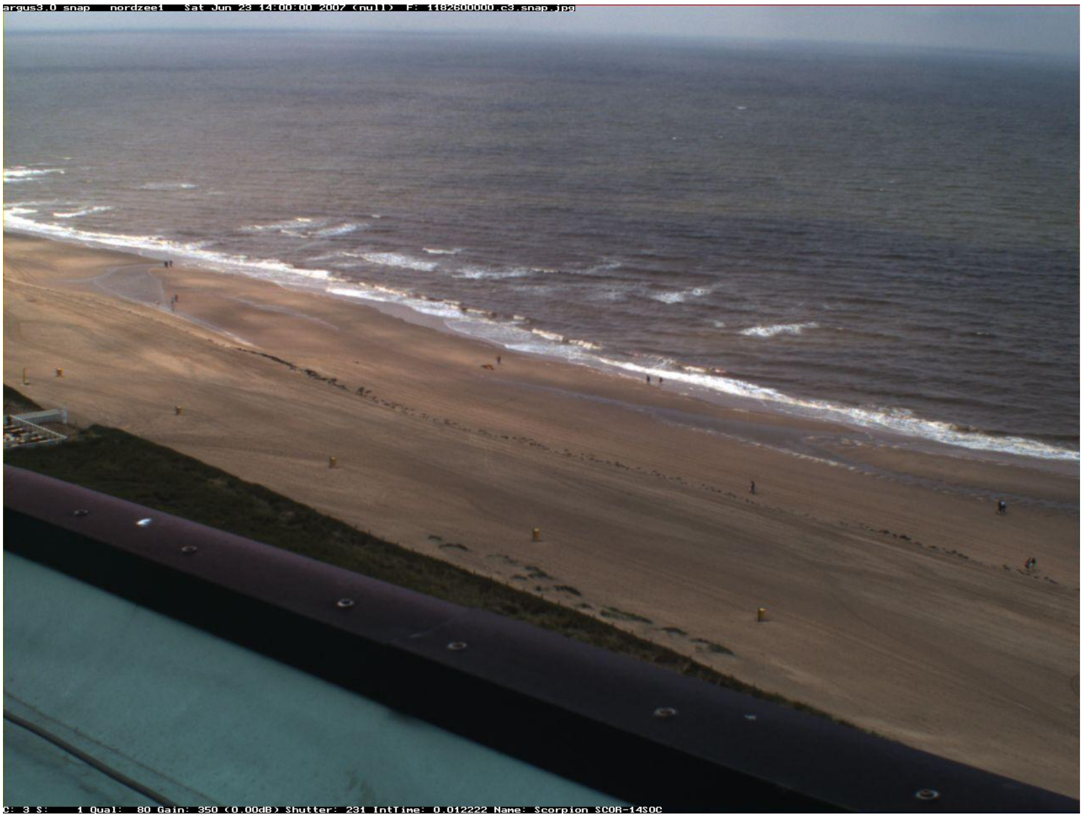
argus3.0 snap   nordzee1   Sat Jun 23 14:00:00 2007 (null) F: 1182600000.c3.snap.jpg
C: 3 S: 1 Qual: 80 Gain: 350 (0.00dB) Shutter: 231 IntTime: 0.012222 Name: Scorpion SCOR-14SOC

Figure 3b


argus3.0 snap   nordzee1   Thu May 10 14:00:00 2007 (null) F: 1178798400.c3.snap.jpg
C: 3 S: 1 Qual: 80 Gain: 350 (0.00dB) Shutter: 232 IntTime: 0.012368 Name: Scorpion SCOR-14SOC

Figure 3c


ARGUS2.1 snap Egmond Sun Jun 3 11:00:00 2001 GMT F: 991566000
C: 1 S: 1 Inc: 0 Qual: 80

Figure 3d

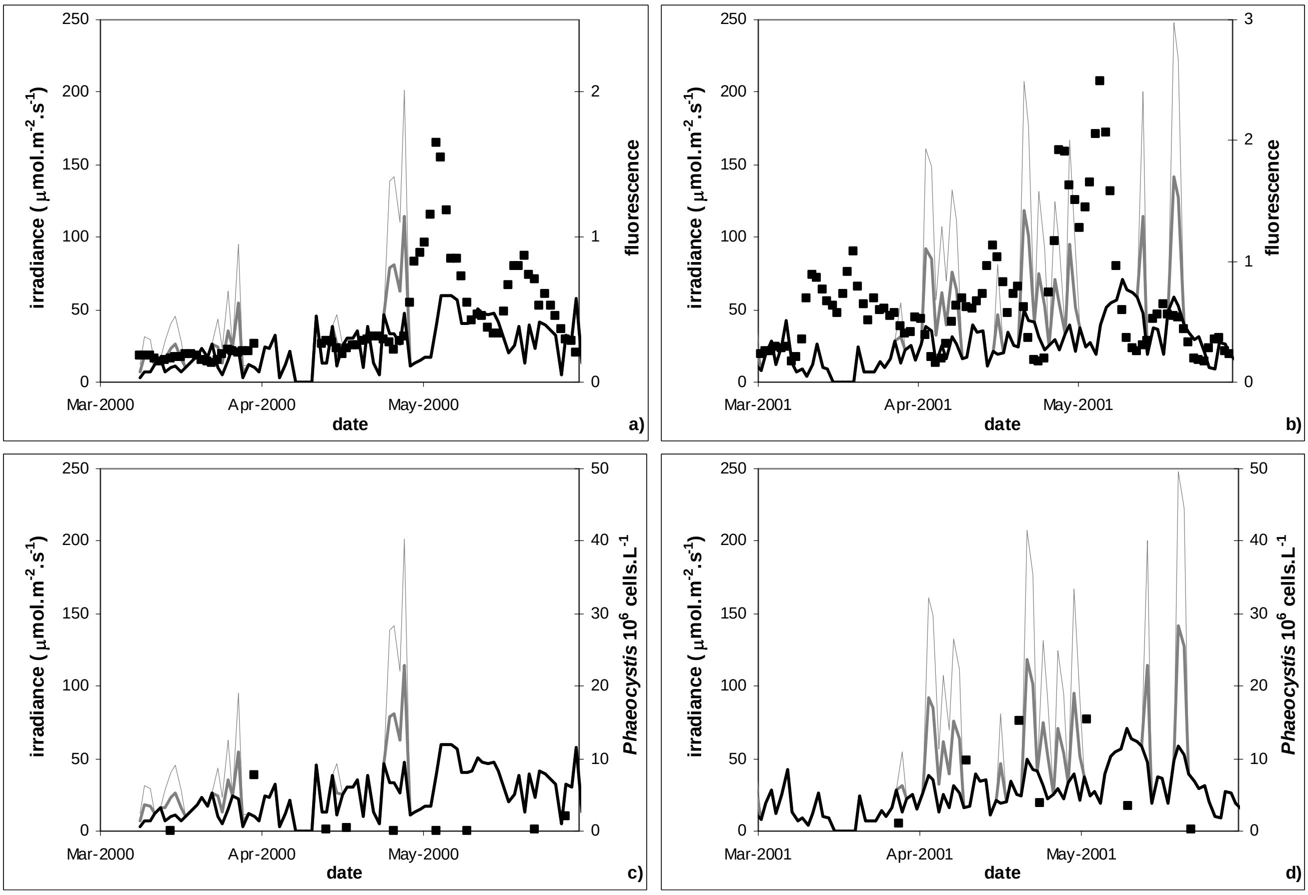
irradiance (μmol.m-2.s-1)
fluorescence
Phaeocystis 10^6 cells.L-1
date
Mar-2000
Apr-2000
May-2000
Mar-2001
Apr-2001
May-2001
0
50
100
150
200
250
1
2
3
10
20
30
40
a)
b)
c)
d)

Figure 4

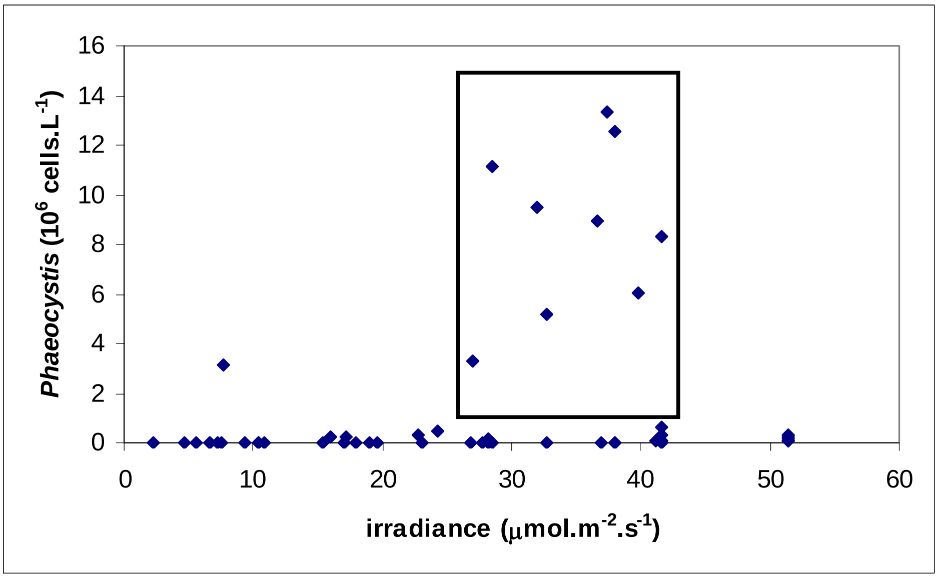
16
14
12
10
8
6
4
2
0
Phaeocystis (10^6 cells.L^{-1})
0
10
20
30
40
50
60
irradiance (μmol.m^{-2}.s^{-1})

Figure 5

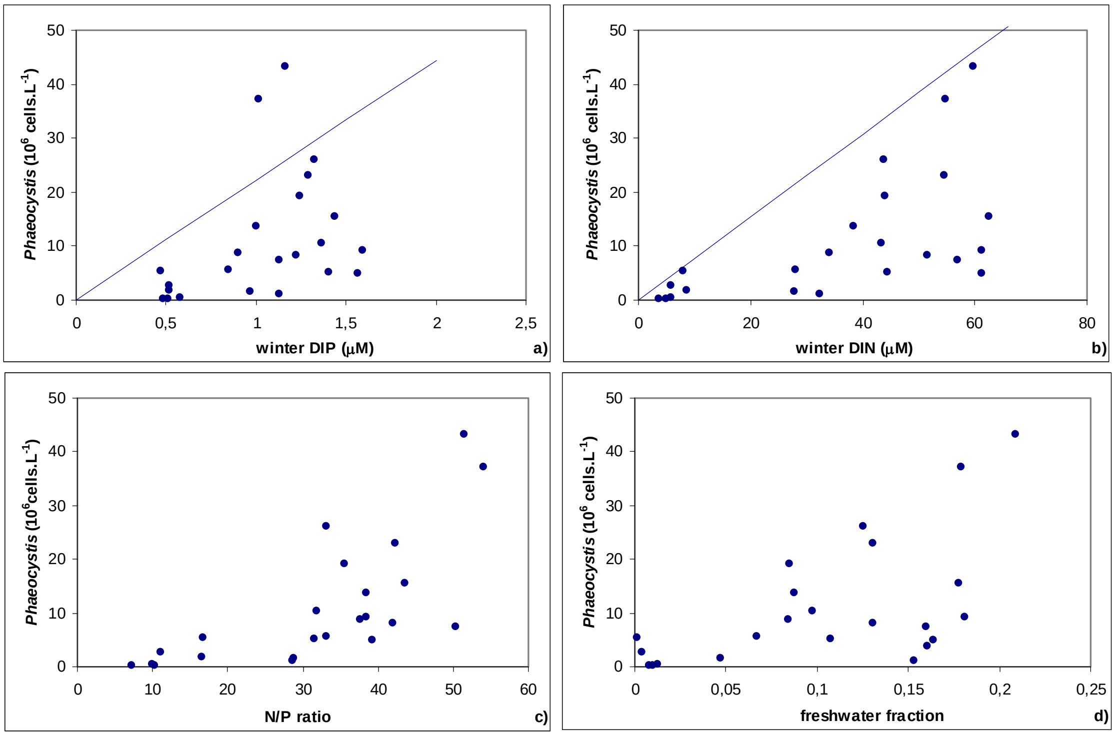
Phaeocystis (10^6 cells.L^-1)
winter DIP (µM)
0
0,5
1
1,5
2
2,5
0
10
20
30
40
50
a)
Phaeocystis (10^6 cells.L^-1)
winter DIN (µM)
0
20
40
60
80
b)
Phaeocystis (10^6cells.L^-1)
N/P ratio
0
10
20
30
40
50
60
c)
Phaeocystis (10^6 cells.L^-1)
freshwater fraction
0
0,05
0,1
0,15
0,2
0,25
d)

Figure 6

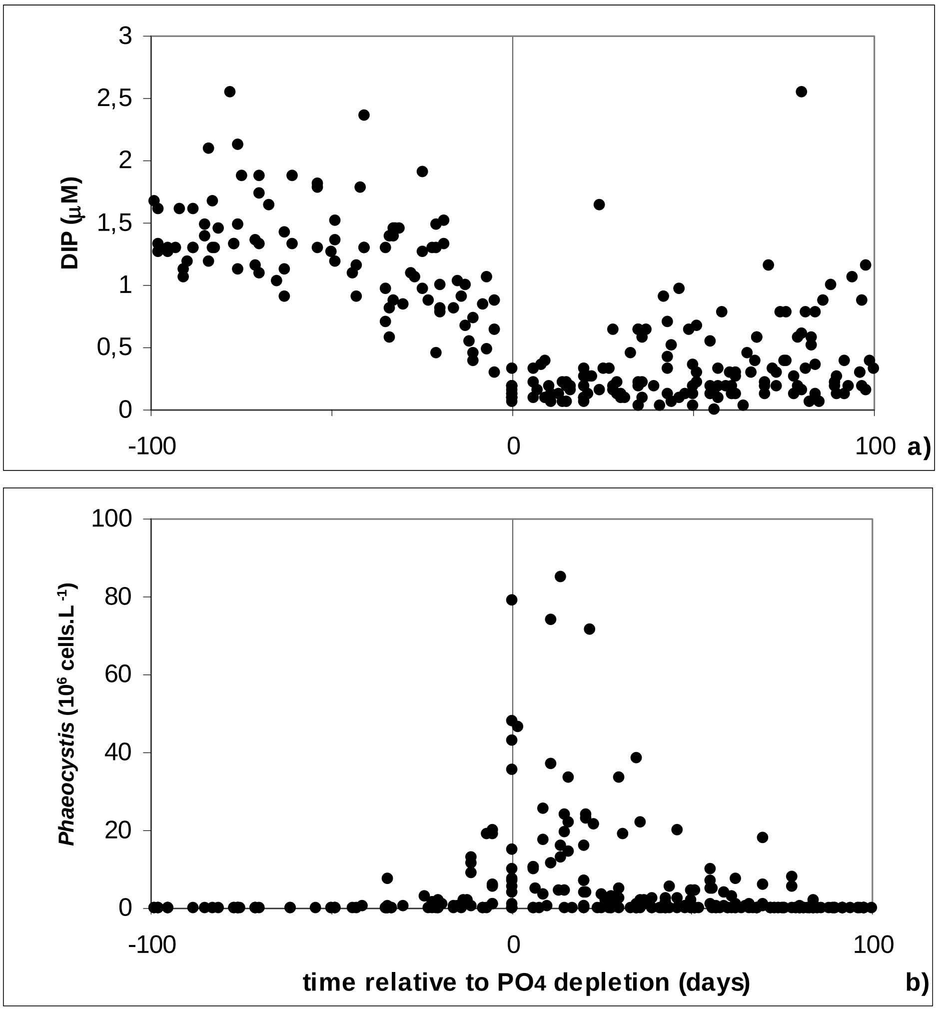
3
2,5
2
1,5
1
0,5
0
DIP (μM)
-100
0
100
a)
100
80
60
40
20
0
Phaeocystis (10^6 cells.L^-1)
-100
0
100
time relative to PO4 depletion (days)
b)

Figure 7

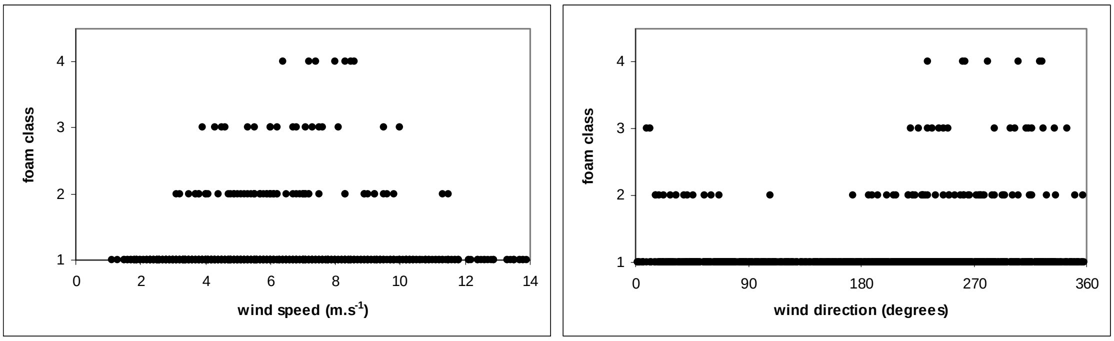
foam class
4
3
2
1
0
2
4
6
8
10
12
14
wind speed (m.s^{-1})
foam class
4
3
2
1
0
90
180
270
360
wind direction (degrees)

Figure 8

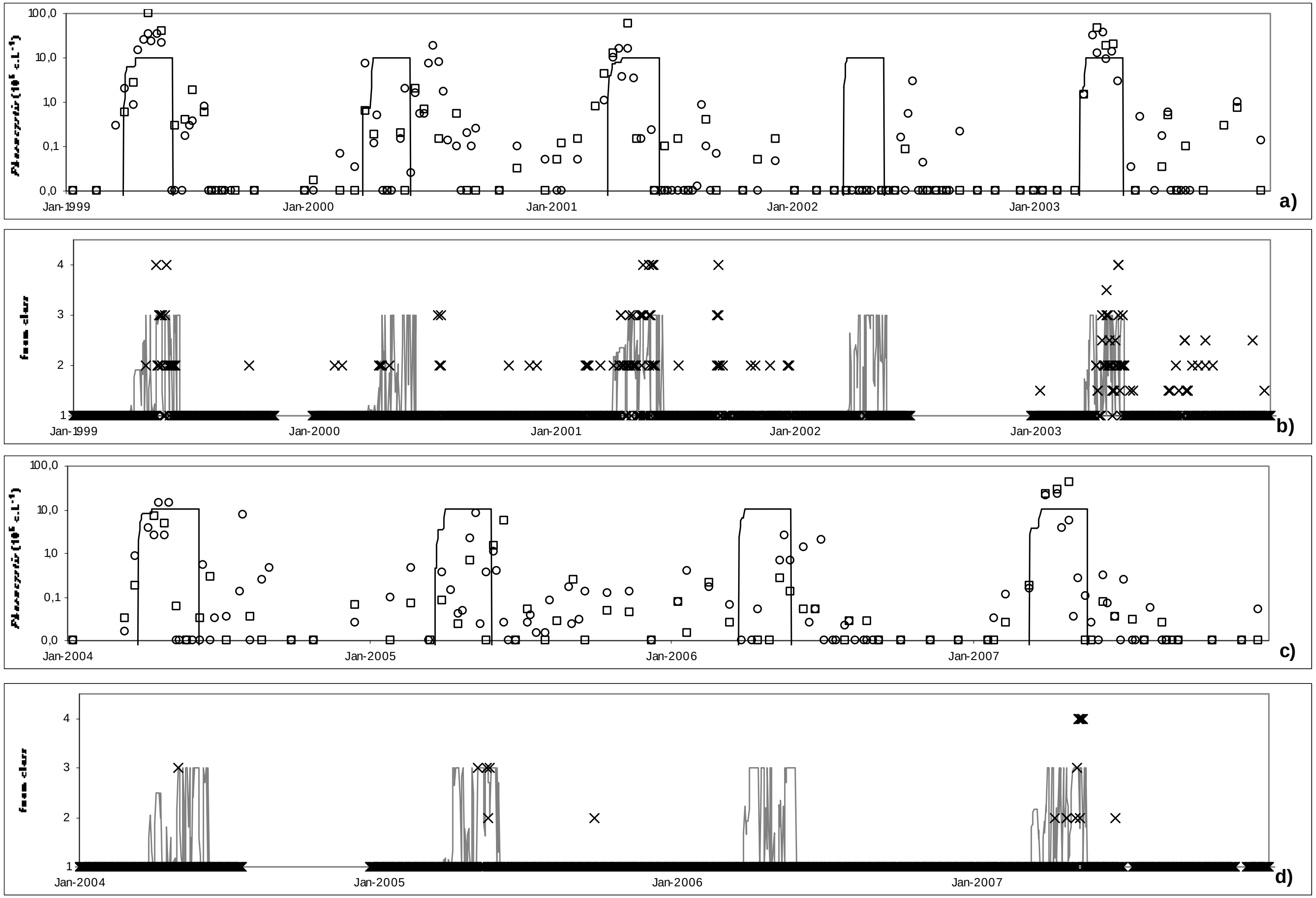
100,0
10,0
1,0
0,1
0,0
Planktothrix (10^5 c.L^-1)
Jan-1999
Jan-2000
Jan-2001
Jan-2002
Jan-2003
a)
4
3
2
1
foam class
Jan-1999
Jan-2000
Jan-2001
Jan-2002
Jan-2003
b)
100,0
10,0
1,0
0,1
0,0
Planktothrix (10^5 c.L^-1)
Jan-2004
Jan-2005
Jan-2006
Jan-2007
c)
4
3
2
1
foam class
Jan-2004
Jan-2005
Jan-2006
Jan-2007
d)

Figure 9

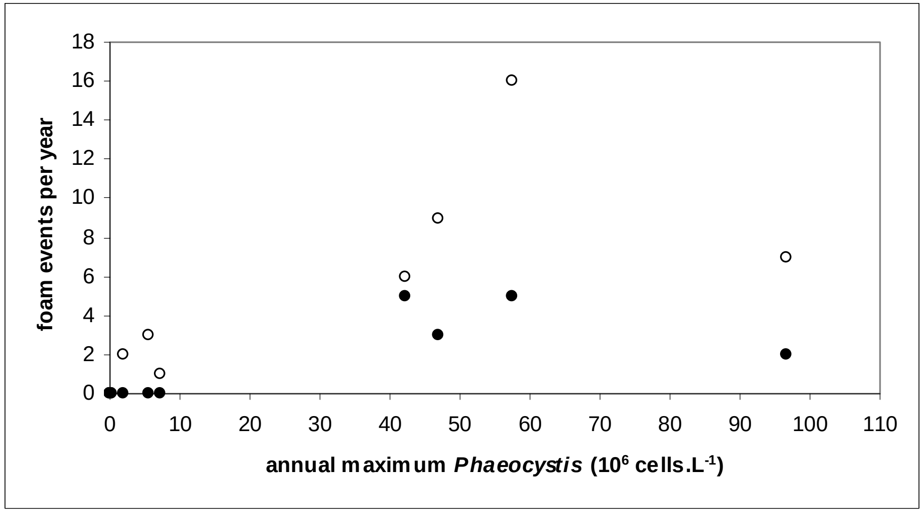
18
16
14
12
10
8
6
4
2
0
foam events per year
0
10
20
30
40
50
60
70
80
90
100
110
annual maximum *Phaeocystis* (10^6 cells.L^{-1})

Figure 10

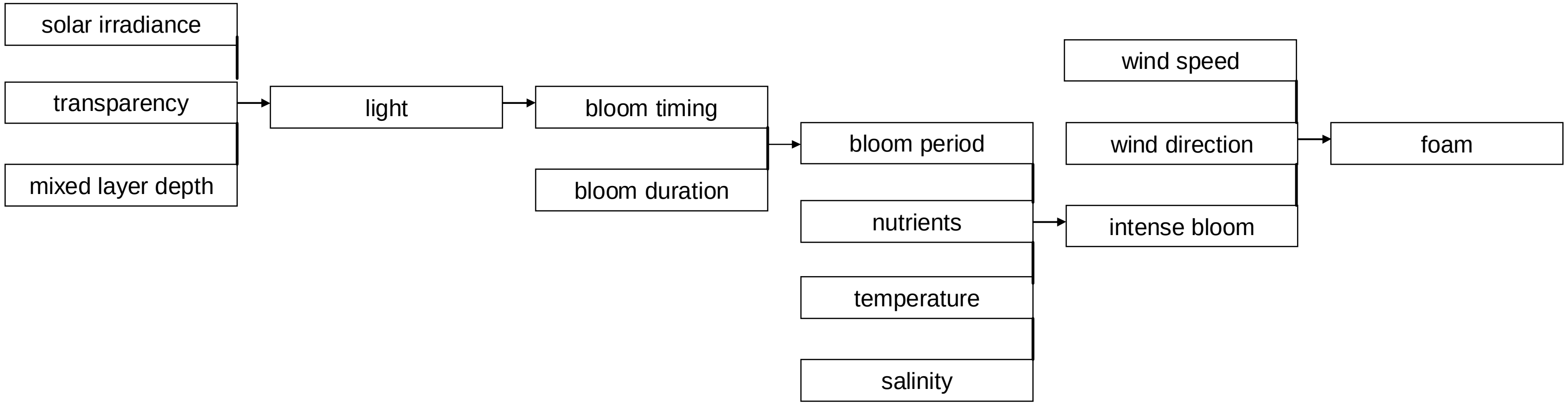
solar irradiance
transparency
mixed layer depth
light
bloom timing
bloom duration
bloom period
nutrients
temperature
salinity
wind speed
wind direction
intense bloom
foam

Figure 11