



Nuisance foam events and *Phaeocystis globosa* blooms in Dutch coastal waters analyzed with fuzzy logic

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ABSTRACT

Phaeocystis globosa is a nuisance algal species because it can cause foam on beaches which are associated with coastal blooms. Models of *Phaeocystis* have considered its bloom dynamics, but not the 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 $\mu\text{mol photons m}^{-2} \text{s}^{-1}$. Peak bloom intensity was higher at monitoring stations with higher nutrient availability, although bloom termination did not coincide with nutrient depletion. Foam events occurred on Dutch beaches during and following *Phaeocystis* blooms, when the wind direction was landward. Over the period 2003–2007, 90% of observed foam events were correctly predicted by the model, however, there were many false positives. The fuzzy logic approach proved helpful in screening and adjusting hypotheses on the dynamics of *Phaeocystis* and associated foam events. The resulting model communicates current understanding of foam formation, enhances the predictability of these events, and provides a basis for more detailed modelling efforts.

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1. Introduction

Harmful algal blooms cause severe economic and ecological damage in both marine and freshwater systems worldwide (Hallegraeff, 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 with 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 intensity and duration in Dutch coastal waters from the 1970s to the early 1990s and to decrease after 1994 (Cadée and Hegeman, 2002), presumably due to eutrophication and subsequent reductions in nutrient availability.

Understanding of the human impact on harmful algal blooms, and vice versa, is needed for mitigating measures. Prediction of blooms would enable damage reduction, for example by moving shellfish stocks or by nutrient reduction measures. Models can serve both the goal of improved understanding and of prediction based on that understanding. Several models have been studied to improve the general understanding of algal bloom development (e.g., Franks, 1997; Huisman et al., 1999; Huppert et al., 2002). These simple models usually focus on a few relevant processes, isolated from other complexities that play a role in the real world. They are not designed for a direct comparison with field data, but are intended to provide more insights into specific ecological mechanisms. In this paper we will focus on models used for the explanation and prediction of *Phaeocystis* blooms and associated foam events in the field. Both freshwater and marine studies often use large deterministic models consisting of many 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 process of foam formation and its relation to *Phaeocystis* and other factors involved are poorly understood, and the formation of nuisance foam associated with

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Phaeocystis blooms has to our knowledge not yet been described by deterministic models.

A disadvantage of many deterministic models applied in large-scale ecosystem studies is their technical complexity, which often makes model responses and uncertainties difficult to interpret and hampers validation in geographic areas other than that for which the model was specifically designed. Moreover, 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 an alternative 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 into 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.

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 successfully 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 Harmful Algal Blooms Expert System (HABES) project, the fuzzy logic approach was successfully 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 and Laanemets (2006), Estrada et al. (2008) and Raine et al. (2010-this issue). This paper describes the results for the pilot study on *P. 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. For this purpose, we designed a fuzzy logic model that can be used for real-time predictions, so only variables that are available in real-time were used as model input.

Our study is performed in 4 steps. First, we review the existing literature on *Phaeocystis* blooms and foam formation to select the most important variables and relations for the fuzzy logic model. Second, we define the set-up of our fuzzy logic model selecting only those input variables for which real-time data are available. Third, we calibrate the model by testing and quantification of the cause-effect relations in the model, through analysis of available data for the period 1991–2002. Fourth, we validate the model by comparing model predictions against available data for the period 2003–2007.

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 (Fig. 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 water temperature is ‘warm’ and wind speed is ‘low’ then cyanobacterial scum layers ‘may develop’. 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 fulfilment). 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.

Rule-based models typically predict whether a certain event (such as a harmful algal bloom) will occur or not. Therefore these models describe ranges for the input variables when a bloom may occur and when it may not occur. In contrast deterministic models and statistical models describe the most likely bloom intensity corresponding with a specific value of the input parameter. This means that in a scatter plot of data points with the input parameter on the x-axis and the bloom intensity on the y-axis, the deterministic and statistical models will represent the data as a trend line through the data, whereas the rule-based model will represent the data as contour lines around clusters (classes) of data points.

2.2. Current knowledge of *Phaeocystis*

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* blooms are not only characterized by high cell numbers but also by a life cycle transition from single cells to colonial cells (Whipple et al., 2005; Rousseau et al., 2007). The colonial cells are embedded in a mucilaginous matrix of polysaccharides, which is widely held responsible for foam formation (Lancelot, 1995). 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). *Phaeocystis* blooms in the Marsdiep area, a tidal inlet between the Wadden Sea and Dutch coastal waters, often occur in spring following diatom blooms (Cadée and Hegeman, 2002). 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 $\sim 100 \text{ Wh m}^{-2} \text{ d}^{-1}$ 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 $\sim 100 \text{ Wh m}^{-2} \text{ d}^{-1}$ at 15°C . Assuming a 12-hour light period in spring, this threshold corresponds to an instantaneous light intensity of $\sim 38 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$ or $19 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$ averaged over the day. This closely matches results from 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 $36 \mu\text{mol m}^{-2} \text{ s}^{-1}$. Lancelot et al. (1998) give an

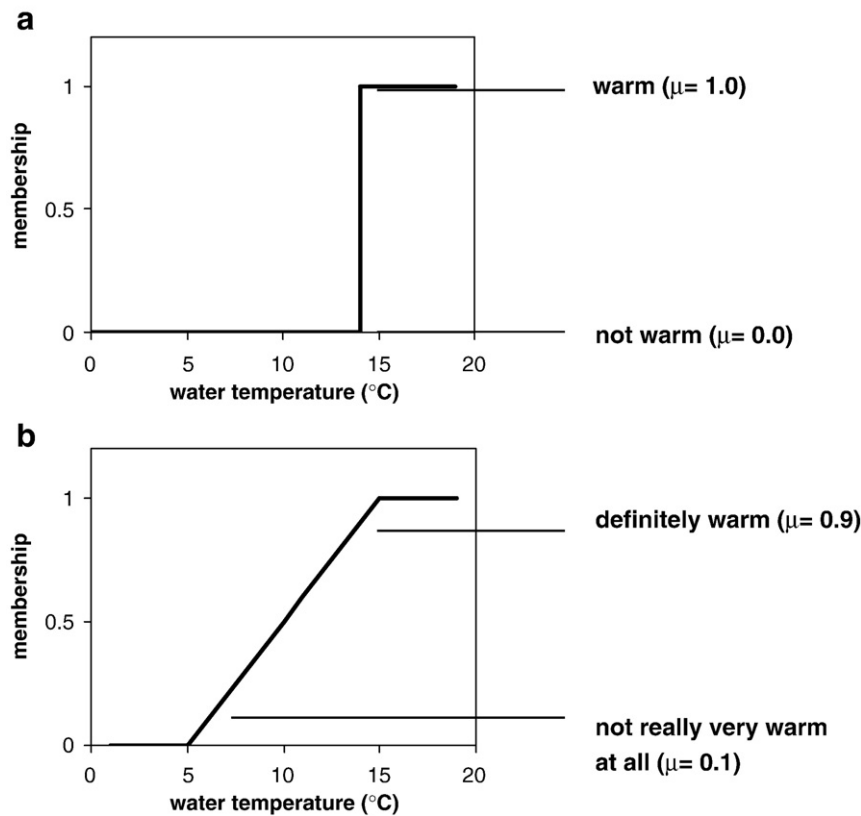


Fig. 1. Illustration of a fuzzy logic membership function for water temperature. a) Crisp classification of water temperature and b) fuzzy classification of water temperature.

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 ranged between 91 and 180 $\mu\text{mol m}^{-2} \text{s}^{-1}$. This corresponds with the I_k of 180 $\mu\text{mol m}^{-2} \text{s}^{-1}$ 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 , whereas concentrations of circa 1 μM phosphate appeared favourable 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 $\mu\text{M P}$). 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, life cycle transitions, 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 salinities below 15 the *Phaeocystis* cells will die. Although colonial cells have been observed at temperatures ranging between -1 and 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, 1986). 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 bloom, *Phaeocystis* colonies were a major component. Near the sediment no traces of *Phaeocystis* were found. Peperzak (2002) found a good correlation between the average timing of *Phaeocystis* blooms and of foam events. Foam events occurred 2 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 is predictable 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 model output) 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 which runs perpendicular to the Dutch coast out into the North Sea. It starts at the town of Noordwijk, where foam observations have been made with video cameras. Stations at 2, 10, 20 and 70 km from the shore are regularly monitored for water quality and phytoplankton composition (Fig. 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, because 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). Intermittent stratification regularly occurs in the Dutch coastal zone, 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.

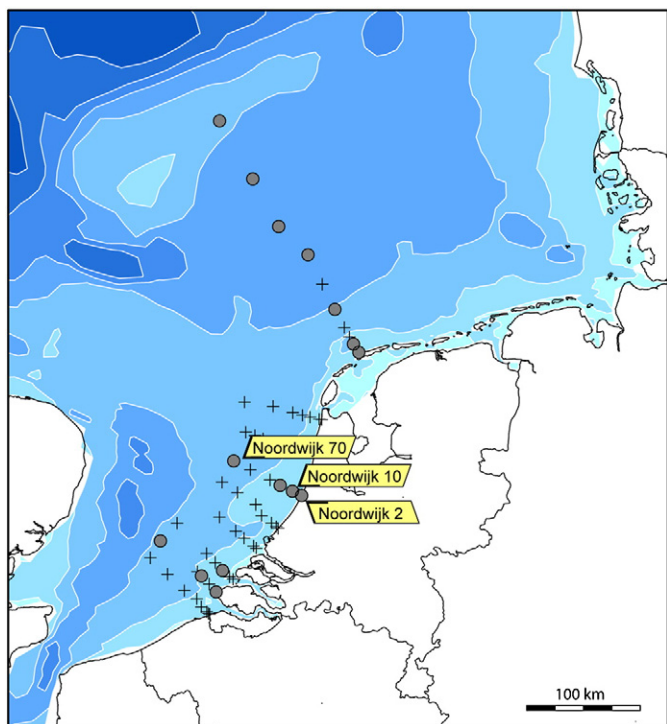


Fig. 2. Location of the monitoring stations in Dutch coastal waters. Crosses represent historic stations, circles represent operational stations. The three labeled stations are mentioned in the text.

2.4. Data sources

Table 1 gives an overview of the data used in this study. The Dutch Ministry of Transport, Public Works and Water Management operates the routine monitoring programme of Dutch coastal waters. The monitoring locations are shown in Fig. 2. The monitoring programme includes phytoplankton species composition, salinity, water temperature, chlorophyll-*a*, suspended matter, nitrate, ammonium, orthophosphate, dissolved silicate and light extinction. Most parameters are determined in surface samples. Vertical profiles at selected monitoring stations are measured for salinity, temperature, chlorophyll 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 <http://www.waterbase.nl>.

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 was originally 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>.

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

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: <http://www.knmi.nl>.

2.5. Model calibration approach

The relations in the conceptual model are quantified through analysis of available data. Our analysis focussed on (1) the effects of light on bloom initiation, (2) the effects of nutrients on bloom development, and (3) the effects 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

Table 1
Overview of data used for the study.

Data source	Parameters	Location	Period	Frequency
Waterbase	Salinity; nutrients (DIN & DIP); <i>Phaeocystis</i> ; chlorophyll- <i>a</i> ; extinction coefficient.	Noordwijk 2; Noordwijk 10; Noordwijk 70; other stations (see Fig. 2).	1991–2007	Monthly in winter, twice per month rest of the year
ARGUS	Images of foam on the beach	Noordwijk beach	1999–2007	Hourly
Smartbuoy	Salinity; chlorophyll fluorescence; extinction coefficient.	Noordwijk 10	2000 and 2001	Every 10 min
KNMI	Wind speed; wind direction; solar irradiance.	De Kooy (near Den Helder)	1991–2007	Daily

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:

$$I_z = I_0 e^{-K_d z} \quad (1)$$

where I_z is the irradiance (in $\mu\text{mol photons m}^{-2} \text{s}^{-1}$; 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:

$$I_M = \frac{1}{z_M} \int_0^{z_M} I_z dz = I_0 (1 - e^{-K_d z_M}) / (K_d z_M) \quad (2)$$

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 $0.5 \times 20 = 10$ at station Noordwijk 10 and $0.25 \times 30 = 7.5$ at station Noordwijk 70, the term $\exp(-K_d z_M)$ approaches zero. The depth-averaged irradiance may therefore be approximated as:

$$I_M = I_0 / (K_d z_M) \quad (3)$$

Daily measurements of total solar irradiance ($\text{J cm}^{-2} \text{d}^{-1}$) 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 $\text{J cm}^{-2} \text{d}^{-1}$ to $\mu\text{mol m}^{-2} \text{s}^{-1}$, assuming 2.77×10^{18} photons per Joule (Kirk, 1994), to arrive at the surface irradiance I_0 .

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. Salinity data from the routine monitoring programme at station Noordwijk 10 near the seafloor, which are available for the years 1994 and 2000–2003 show that bottom salinity is 30.9 on average with a standard deviation of 0.95. Therefore, we assume that if the salinity at the surface is below 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 m (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 all other years, when the Smartbuoy was not deployed at Noordwijk 10, daily measurements of light extinction and mixed-layer depth are not available. For these years, only routine monitoring data are available for station Noordwijk 10, with a sampling frequency of twice per month. This temporal resolution is insufficient to give information on intermittent stratification, which has a major impact on the underwater light climate at this station. Intermittent stratification of water masses with different salinity does not take place at station Noordwijk 70, due to its location 70 km from the coast with

limited impact of freshwater inputs. Also the extinction coefficient shows less variability at this station. The underwater light climate of this station has been approximated, 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 1991–2002 has been used to estimate a threshold irradiance level for *Phaeocystis* bloom formation.

2.5.2. Bloom development

The temporal resolution of the monitoring data during the spring period was biweekly, but often at the beginning of the bloom, the resolution was 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 between 1991 and 2002 of the annual peak in *Phaeocystis* cell concentration and winter nutrient concentration and salinity for all monitoring stations indicated with circles in Fig. 2. In addition, we compared time series of orthophosphate concentrations and *Phaeocystis* abundance at station Noordwijk 10 to see if bloom termination coincided with orthophosphate concentrations becoming depleted.

2.5.3. Foam formation

The video images from 1999 to 2007 have been inspected to assess whether or not foam was present on the beach. The images were visually classified into 4 classes: 1: no foam, 2: some foam, 3: foam, and 4: much foam. We only consider foam that is visible on the beach and disconnected from the surf zone to avoid confusion with breaking waves. 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. Class 2 is defined as isolated patches of foam, class 3 as a continuous line of foam, and class 4 as a continuous band of several meters wide of foam. Examples of each class of foam intensity are shown in Fig. 3. We use the term 'foam events' when foam presence was classified as class 3 or class 4.

3. Results

3.1. Model calibration through 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 Fig. 4a,b. The thin black lines show surface salinity measured by the Smartbuoy. Salinity observations from the routine monitoring programme are shown as black squares (surface salinity) and grey squares (bottom salinity, only measured in 2001). Surface salinity observed by the buoy corresponds to ship-based observations from the routine monitoring programme. When surface salinity was below 28 in the surface a considerable salinity difference over depth was observed, indicating stratification. The bold black line shows the daily mean depth-averaged irradiance assuming that the mixed-layer depth is reduced to 8 m during stratification. This is a conservative estimate since CTD profiles have shown pycnocline depth to range between circa 4.5 and 8 m at station Noordwijk 10. The grey line shows the daily mean depth-averaged irradiance if stratification is not taken into account. Divergence of the black and grey lines indicate the timing of the stratification events based on observed low surface salinities (Fig. 4). Clearly, these stratification events have a strong impact on the depth-averaged irradiance in the mixed layers, favouring suitable light conditions for phytoplankton growth.

During presumed stratified periods, chlorophyll fluorescence first decreases and then increases sharply afterwards (Fig. 4c,d). 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

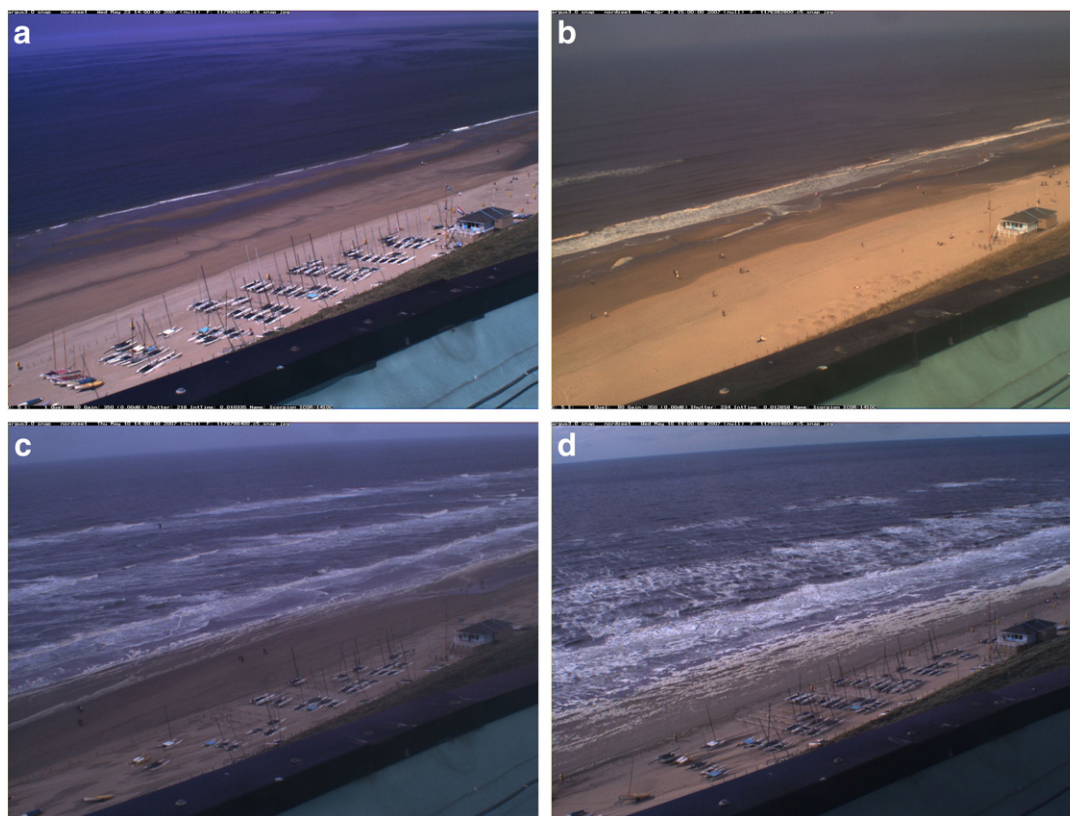


Fig. 3. Examples of foam intensity classes obtained from ARGUS video images: a) no foam (class 1), b) some foam (class 2), c) foam (class 3), and d) much foam (class 4).

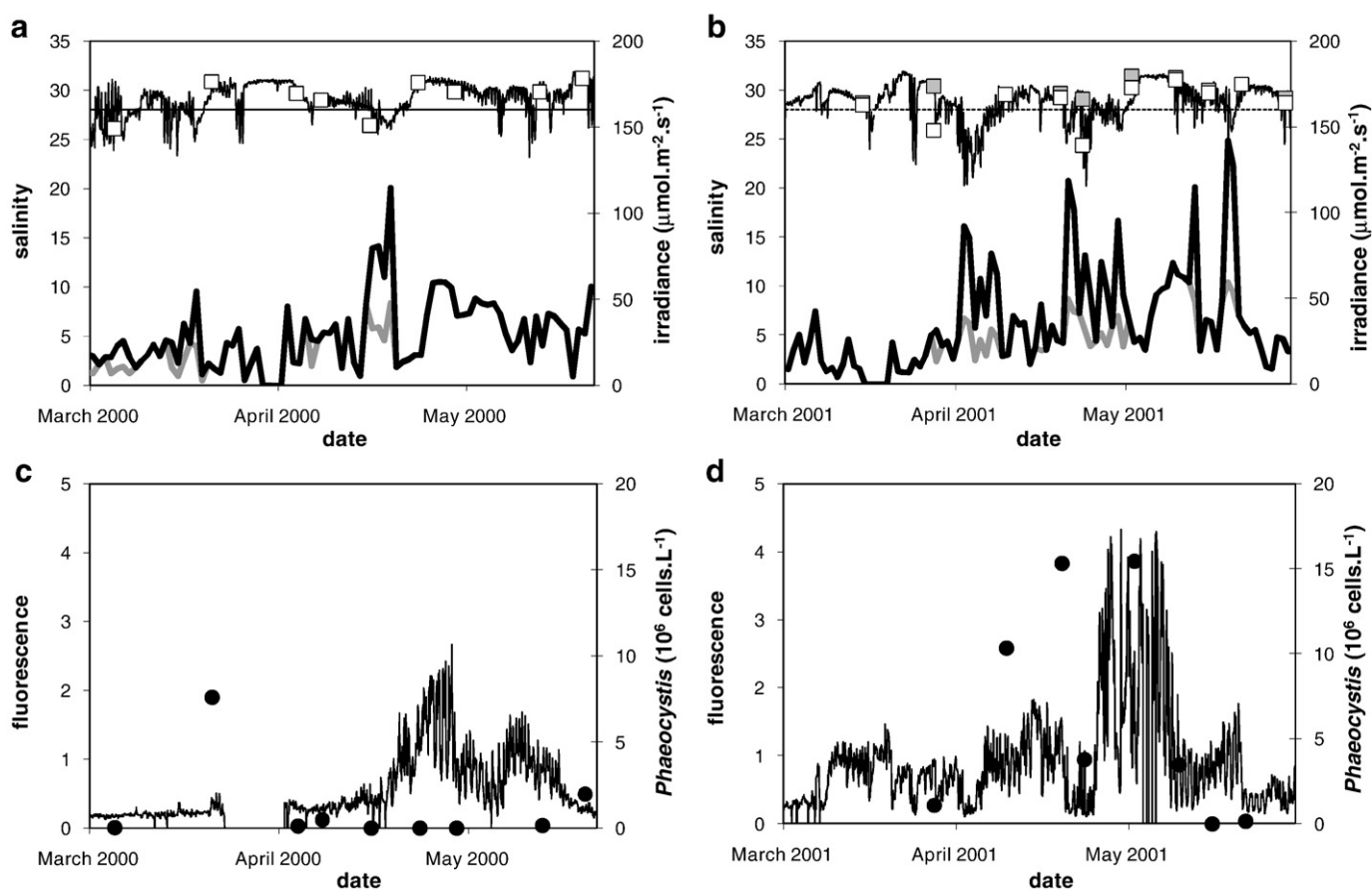


Fig. 4. Time series obtained from the Smartbuoy and routine monitoring programme for (a,c) spring 2000 and (b,d) spring 2001 at station Noordwijk 10. a,b) Surface salinity (black line and open squares), bottom salinity (grey squares) and estimated depth-averaged irradiance, assuming well-mixed conditions (bold black line) and stratified conditions with a mixed-layer depth of 8 m (bold grey line). c,d) Chlorophyll fluorescence (line) and *Phaeocystis* abundance (circles).

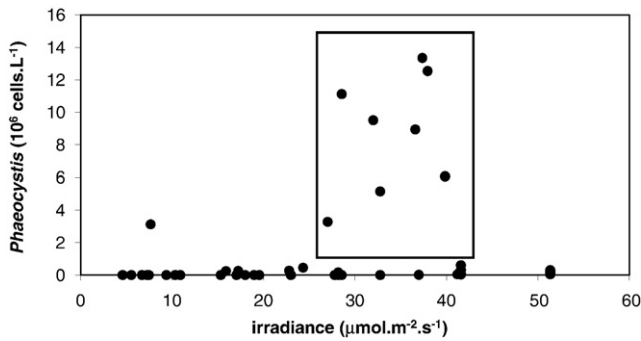


Fig. 5. Spring observations of *Phaeocystis* at station Noordwijk 70 in the years 1991–2002, plotted against the highest weekly mean value of the depth-averaged irradiance in the preceding month.

limited data on the abundance of *Phaeocystis*. The year 2000 showed only one observation of *Phaeocystis* above 1 million cells L^{-1} in spring (Fig. 4c), following a prolonged period of stratification. Two prolonged periods of stratification in spring 2001 are visible in Fig. 4b. After the first stratification event the *Phaeocystis* bloom has started but the chlorophyll fluorescence is similar before and after the stratification event. Chlorophyll fluorescence only increases following the second stratification event.

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 1991–2002,

Phaeocystis blooms (above 1 million cells L^{-1}) developed at station Noordwijk 70 when the weekly mean value of the depth-averaged irradiance exceeded $25\text{--}40 \mu\text{mol photons m}^{-2} \text{s}^{-1}$ in the week before bloom development (Fig. 5). This is higher than the threshold of $19 \mu\text{mol m}^{-2} \text{s}^{-1}$ estimated from laboratory experiments at 15°C . 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 near-shore waters like station Noordwijk 2. At these near-shore 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 shallow water depth at station Noordwijk 2 results in a strong influence of sedimentation and resuspension processes on the underwater light climate. However, sensitivity tests for the years 1991–2002 with various set-ups of the fuzzy logic submodel for bloom initiation (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 indicated a strong influence of stratification (Fig. 4), bloom initiation is better predicted when the tidal phase is taken into account in the model. The sensitivity tests showed that at station Noordwijk 2 the bloom timing was predicted correctly for 6

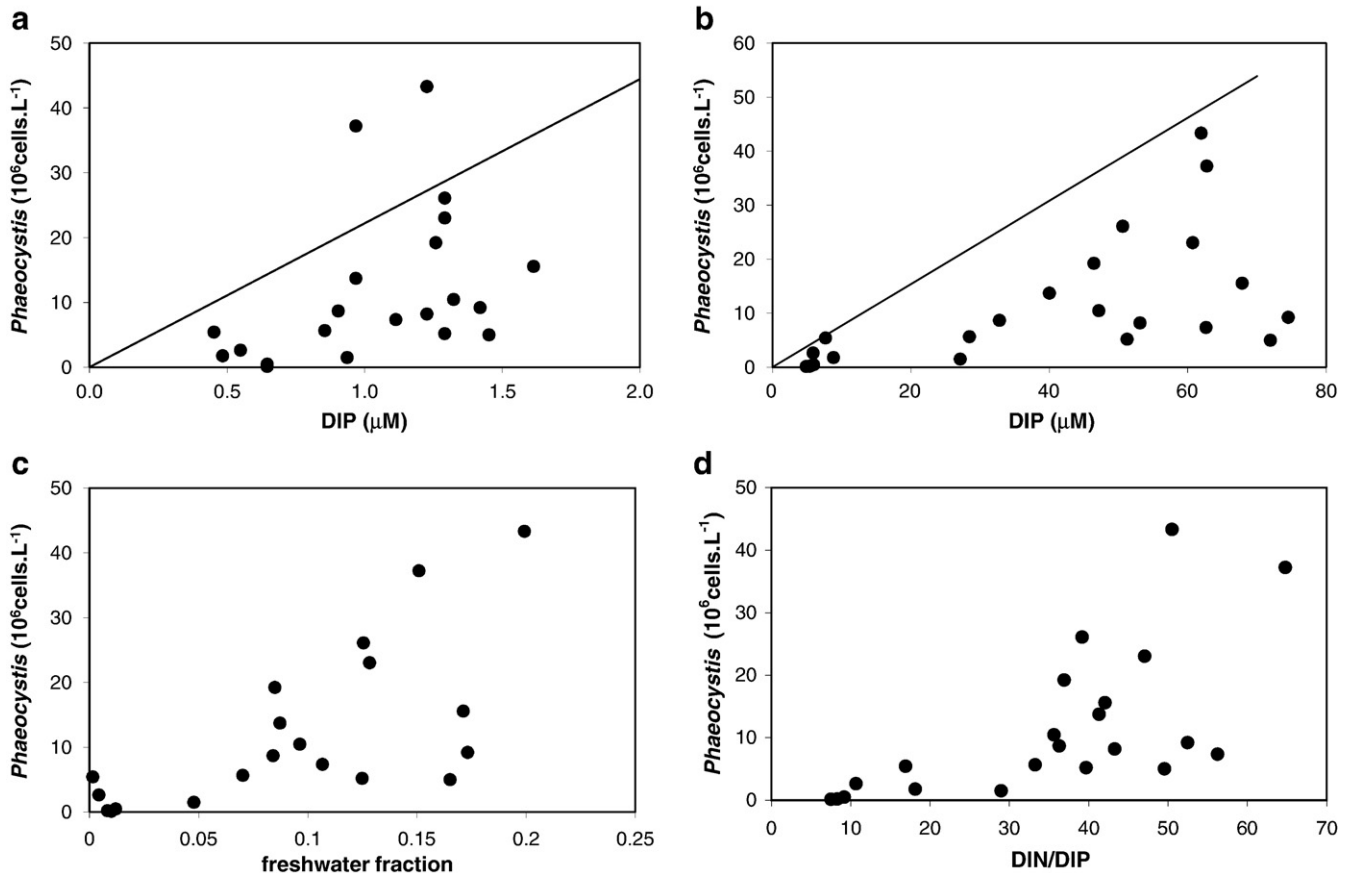


Fig. 6. Median value of the annual peak abundance of *Phaeocystis* during the years 1991–2002, for 22 monitoring stations in the North Sea, plotted against a) median winter concentrations of dissolved inorganic phosphorus (DIP), b) median winter concentrations of dissolved inorganic nitrogen (DIN), c) 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 $0.045 \text{ pmol cell}^{-1}$ (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 an N content of $1.3 \text{ pmol cell}^{-1}$.

out of 12 years when using a threshold of $25 \mu\text{mol photons m}^{-2} \text{s}^{-1}$ and for 9 out of 12 years when using a fuzzy threshold of $25\text{--}35 \mu\text{mol photons m}^{-2} \text{s}^{-1}$. In the years 2000 and 2002 there was no *Phaeocystis* spring bloom at all at Noordwijk 2 and in 2001 the bloom would be predicted too late if a threshold of $20 \mu\text{mol photons m}^{-2} \text{s}^{-1}$ would be applied.

3.1.2. Bloom development

3.1.2.1. 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 median winter (January and February of 1991–2002) nutrient concentrations at 22 monitoring stations in the North Sea. The median value of the annual peak abundance of *Phaeocystis* could reach higher levels at higher nutrient availability, expressed as either the median value of the winter DIP concentration, the winter DIN concentration, the winter N/P ratio or the freshwater fraction (Fig. 6). The freshwater fraction is calculated from salinity as: $(35 - \text{salinity})/35$.

Peak bloom intensity of *Phaeocystis* at different stations in the North Sea is clearly affected by the winter nutrient concentrations (Fig. 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 $0.045 \text{ pmol cell}^{-1}$. 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 $0.375 \text{ pmol cell}^{-1}$ under P sufficient conditions, $0.236 \text{ pmol cell}^{-1}$ under P deficient conditions at 4°C , and $0.053 \text{ pmol cell}^{-1}$ under P deficient conditions ranging from 10 to 18°C . The water temperature during *Phaeocystis* blooms at station Noordwijk 10 is circa 10°C . Hence, the estimate based on Jahnke's experiment under P deficient conditions is the same order of magnitude as the estimate by van Boekel et al. (1992). We therefore used a P content of $0.045 \text{ pmol cell}^{-1}$ to calculate the theoretical maximum *Phaeocystis* abundance as a function of the dissolved inorganic phosphorus concentration. The resulting line is plotted in Fig. 6a. The line roughly follows the upper contour of the data points. At two stations the observed peak bloom intensity was higher than the theoretical maximum. These are the stations Dantzigat and Marsdiep, both located in the Wadden Sea. Possibly, additional phosphorus sources are available in this shallow intertidal area, such as organic phosphorus or phosphate adsorbed to sediment particles (van Raaphorst and Kloosterhuis, 1994). Still, 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 Fig. 6b the N content of *Phaeocystis* cells can be estimated as circa $1.3 \text{ pmol cell}^{-1}$. 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.

3.1.2.2. End of *Phaeocystis* bloom. The *Phaeocystis* blooms at station Noordwijk 10 generally started about 20 to 25 days before the orthophosphate concentrations dropped below $0.2 \mu\text{M}$, and lasted until

about 30 days after the phosphate concentrations had been depleted (Fig. 7). Accordingly, the termination of *Phaeocystis* blooms along the Noordwijk transect did not coincide with phosphate depletion. It is possible that *Phaeocystis* blooms are prolonged 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). Fig. 7 may even suggest that the start of the bloom could coincide with orthophosphate concentrations dropping below $0.3 \mu\text{M}$. This seems to contradict results by Cariou et al. (1994) which suggested that colony formation is hampered below this same orthophosphate threshold. However, the coincidence between phosphate depletion and bloom initiation could also be explained by fast growth of colonial *Phaeocystis* cells quickly taking up orthophosphate and thereby rapidly depleting orthophosphate 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 3.1.2.1, 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, bloom duration at station Marsdiep on the edge of the Wadden Sea 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).

3.1.3. Foam formation

Foam events (classes 3 and 4) at Noordwijk beach occur on days when the wind direction is landward (below 30° and above 215°) and wind speed is above circa 3.5 m s^{-1} (Fig. 8). Days with 'much foam' (class 4) occur only at wind speeds above circa 6 m s^{-1} . Small amounts of foam (class 2) can occur at a wide range of wind speeds and wind directions. However, seaward wind (between 80 and 180°) hampers foam formation.

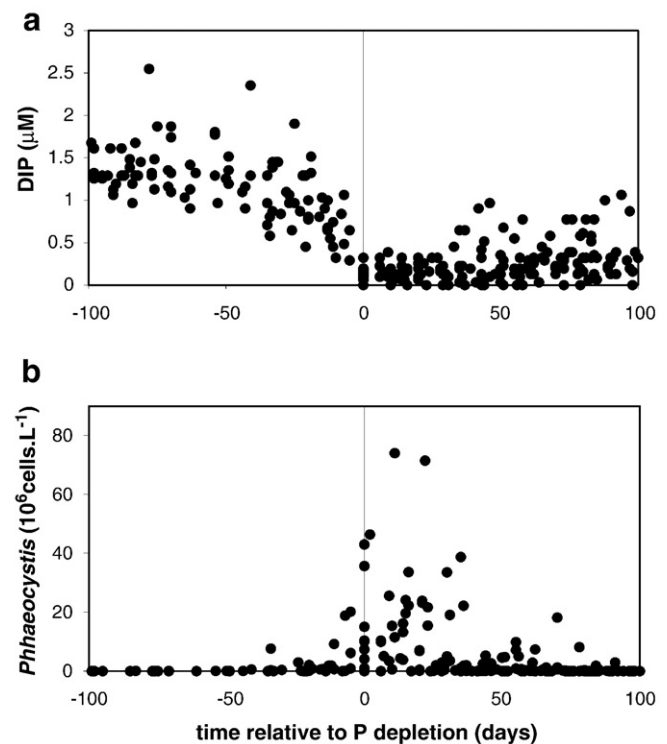


Fig. 7. Time series of (a) dissolved inorganic phosphorus (DIP) and (b) *Phaeocystis* abundance, observed in the years 1991–2002 at station Noordwijk 10. The annual time series are synchronized relative to the first day that phosphate concentrations were observed below $0.2 \mu\text{M}$.

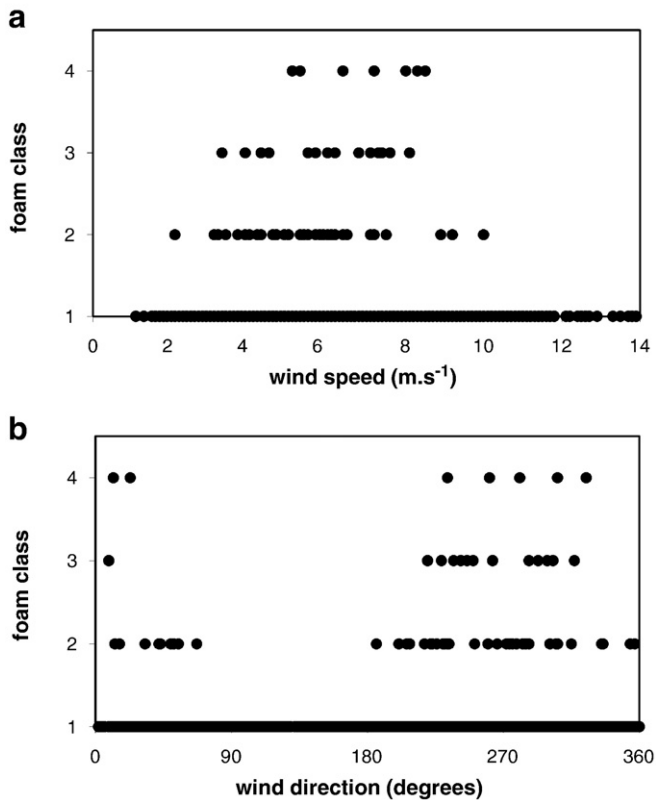


Fig. 8. Foam intensity at Noordwijk beach as a function of (a) wind speed and (b) wind direction. Foam intensity is classified as 'no foam' (class 1), 'some foam' (class 2), 'foam' (class 3), and 'much foam' (class 4).

The timing of foam events and *Phaeocystis* blooms in the Dutch coastal zone for the years 1999–2002 are presented in Fig. 9a. It can be seen that foam events mostly occur when *Phaeocystis* is abundant. In 2002 and 2006 there were no *Phaeocystis* blooms in spring and also no foam was observed. In 2000 there was a summer bloom of *Phaeocystis* instead of a spring bloom and the foam also occurred in summer. The years 1999, 2001, 2003 and 2007 stand out for their extensive foam events. During the same 4 years the peak *Phaeocystis* concentrations at station Noordwijk 2 greatly exceeded 10 million cells L^{-1} . These observations support the hypothesis that the foam on beaches in spring is caused by *Phaeocystis* blooms. The time delay between the first observation of a *Phaeocystis* bloom and the first observation of a foam event (class 3 or more) ranges between 17 and 26 days in most years. However, in 2007 the delay was 5 weeks and in 2005 the foam occurred 4 weeks before a *Phaeocystis* bloom was observed. In 1999, 2001 and 2003 the first foam event was observed in the same week when the first intense bloom (more than 10 million cells L^{-1}) was observed.

3.2. Model 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 conceptual model is shown in Fig. 10.

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 35 $\mu mol\ m^{-2}\ s^{-1}$.
- *Phaeocystis* blooms can occur only if the salinity ranges between 20 and 35, and temperature between 3 and 24 °C.

- Blooms have an average duration of 40 days. The foam period ends 2 weeks after bloom termination.
- Nuisance foam on a beach can occur during a bloom period of *Phaeocystis*, when the maximum bloom intensity in near-shore waters is above 10 million cells L^{-1} , the wind speed is above 3 to 4 $m\ s^{-1}$, and wind direction is landward.
- The peak bloom intensity can exceed 10 million cells L^{-1} in areas where the median winter DIN concentration exceeds 13 μM and the median winter DIP concentration exceeds 0.45 μM (Fig. 6).

The likelihood of a *Phaeocystis* bloom and a foam event at a particular time is calculated by multiplication of the membership values for all relevant input parameters. When all the conditions above are completely true, the model predicts a foam event with a likelihood of 1. If any of the above conditions is not true the likelihood of a foam event is simulated as zero. If any of the above conditions is partly true (for example if the wind speed is between 3 and 4 $m\ s^{-1}$) then the simulated likelihood is between zero and 1. The model outcome can be translated back to real parameter values (defuzzification) to allow comparison with observed data. In this study a likelihood of 1 of a *Phaeocystis* bloom is defuzzified to a *Phaeocystis* abundance of 10 million cells L^{-1} and a likelihood of 1 of a foam event is defuzzified to a foam class of 3.

3.2.2. Site-specific model for Noordwijk beach

The generic model has been validated with foam data at Noordwijk beach during the years 2003–2007. Along the coast near Noordwijk wind is landward when the wind direction is below 25° or above 175° to 210°. 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} .

The model predictions of the bloom period and foam events for the years 2003 to 2007 are shown in Fig. 9c,d. In total, for the period 2003–2007, all observed intense blooms (>10 million cells L^{-1}) were correctly predicted at station Noordwijk 2, and 89% of the observed intense blooms were correctly predicted at station Noordwijk 10 (Table 2). Yet, only 32% of the predicted intense blooms at Noordwijk 2 and only 22% of the predicted intense blooms at Noordwijk 10 corresponded with an observed intense bloom. In other words, the model predictions hardly missed any observed bloom, but many of the predicted *Phaeocystis* blooms were false positives.

The model performance for foam events shows that 93% of the observed foam events were correctly predicted (Table 3). Yet, only 8% of the predicted foam events actually corresponded with a real foam event, while in all other cases little or no foam was actually observed. Thus, almost all observed foam events were predicted by the model, but many of the predicted foam events were false positives.

Foam is often not observed when suitable conditions for foam formation are predicted. Our model predicts equally intense *Phaeocystis* blooms every year, although the observed data in Fig. 9 show large interannual variability in bloom intensity. During some years the observations show no *Phaeocystis* bloom at all. 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. Discussion

The hourly video images of Noordwijk beach showed large temporal variability of foam presence over the day. Often only a few images per day clearly showed foam, that was deposited on the beach after high tide. If only one image per day would be available, many foam events would have been missed. It is possible our observations missed a few foam events that occurred during the night. Usually,

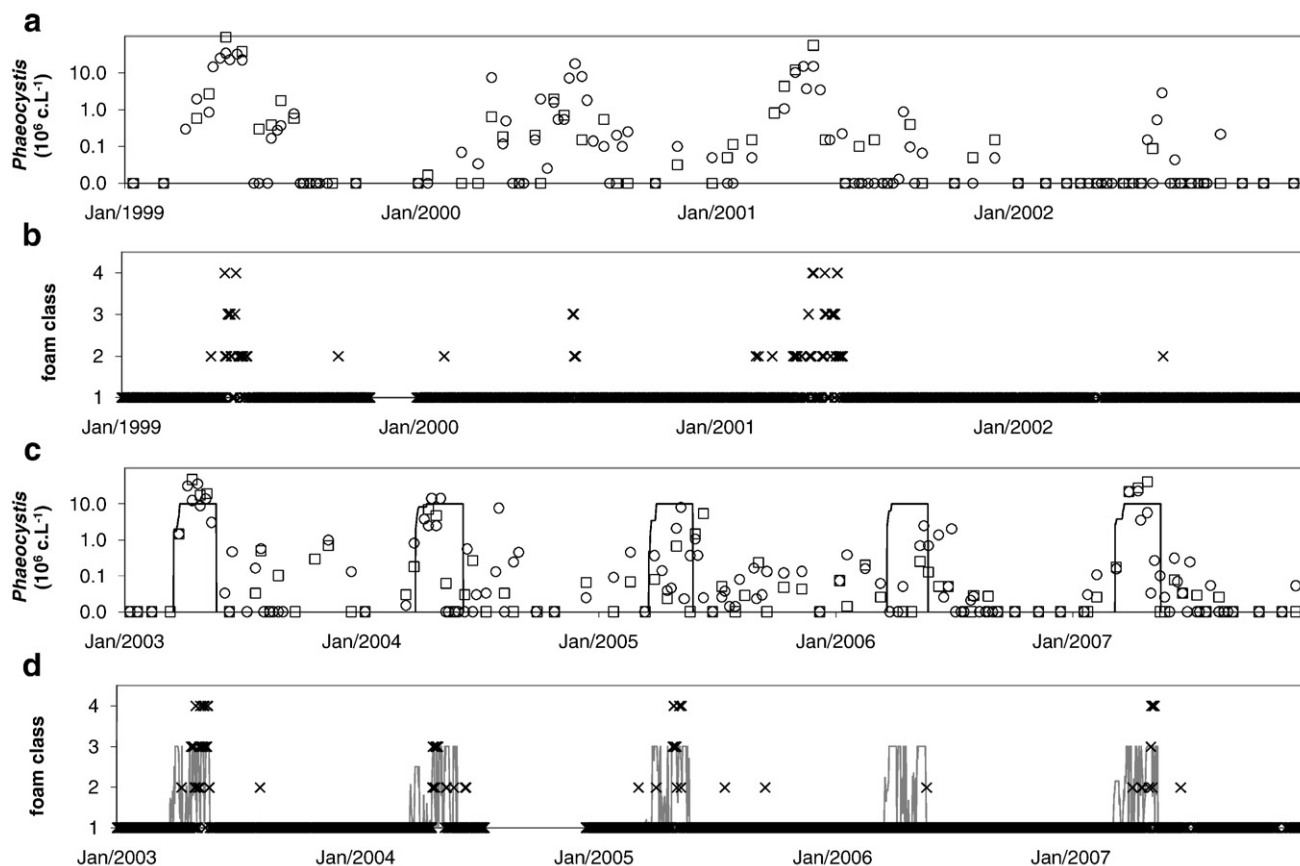


Fig. 9. Observations (symbols) of *Phaeocystis* blooms and foam formation for (a,b) the years 1999–2002 and (c,d) the years 2003–2007. a,c) *Phaeocystis* observations at stations Noordwijk 2 (squares) and Noordwijk 10 (circles). b,d) Foam intensity at Noordwijk beach. The years 2003–2007 were used for validation of the fuzzy logic model, and the model predictions for those years are indicated by solid lines. The fuzzy logic model predicts the likelihoods of *Phaeocystis* blooms and foam events. A likelihood of 1 of a *Phaeocystis* bloom is defuzzified to a *Phaeocystis* abundance of 10 million cells L^{-1} , and a likelihood of 1 of a foam event is defuzzified to a foam class of 3.

though, there were several foam days in a row, sometimes interrupted by periods with landward wind. The temporal scale of the foam periods is therefore in the order of days.

Part of the false positive foam prediction may be due to patchiness of *Phaeocystis* blooms. Our model gives a foam prediction for the

whole Dutch coast, yet it is tested using real-time observations available for only one location. Possibly, foam was present at other locations along the Dutch coast at times when foam was not observed at Noordwijk beach. Stumpf et al. (2009) found that the number of false positive predictions of respiratory irritation associated with toxic

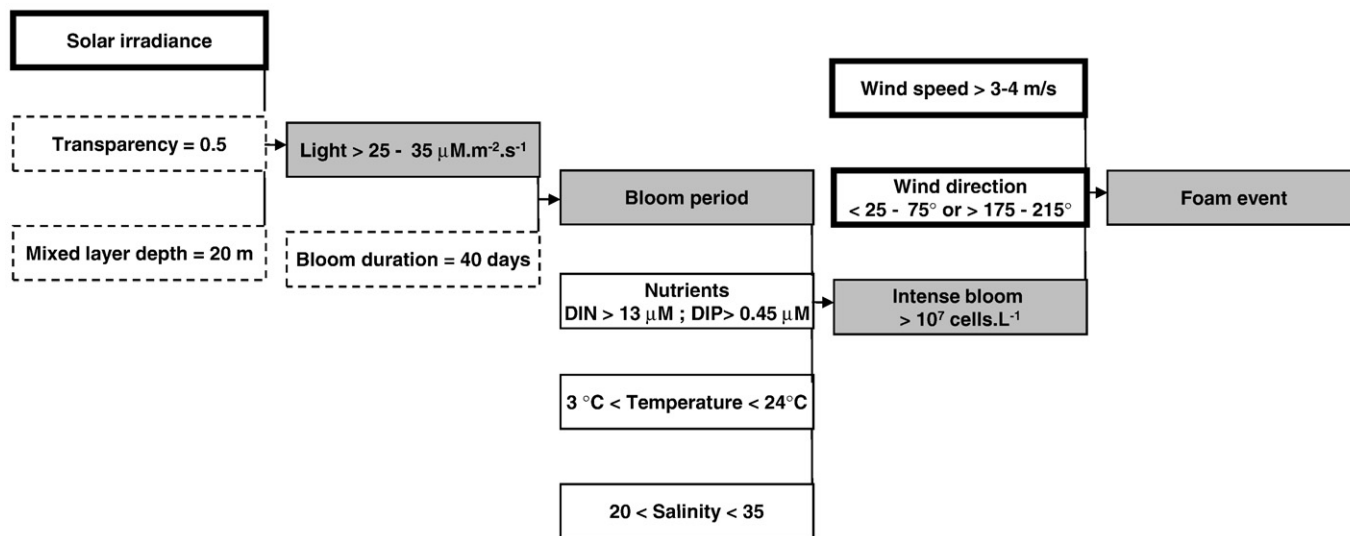


Fig. 10. Structure of the fuzzy logic model for *Phaeocystis* blooms and foam formation. Grey boxes indicate variables that are calculated by the model itself; boxes with bold borders indicate input variables that are available in real-time; boxes with dashed borders have fixed values, being long-term averages; conditions in boxes with normal black borders are assumed to be always sufficient (membership 1) in our application for Noordwijk.

Table 2

Comparison of the number of observations with intense *Phaeocystis* blooms (>10 million cells L^{-1}) against model predictions for 2003–2007, 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		
		Intense bloom	Small or no bloom	Correct predictions (%)
Noordwijk 2	Bloom	6	12	32%
	Likely bloom	0	1	
	Possible bloom	0	3	
	No bloom	0	68	
	Observations predicted correctly (%)	100%	81%	
Noordwijk 10	Bloom	8	26	22%
	Likely bloom	0	2	
	Possible bloom	0	3	
	No bloom	1	102	
	Observations predicted correctly (%)	89%	77%	

dinoflagellate blooms along the Florida coast was greatly reduced when observations were aggregated over larger areas. The present model is a zero-dimensional model, so it does not predict spatial patterns of foam formation. Fuzzy logic models can be developed as two-dimensional models, however, provided that the input data are available as maps (e.g., from satellite data or other models).

Fuzzy logic is designed to deal with uncertainty in 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 cause for limited predictability in this study is not uncertainty on processes in the model but rather lack of understanding on bloom aspects such as bloom termination, summer blooms and interannual variability in bloom intensity. 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 the reason for this variability we cannot simulate it 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). Since interannual variability in bloom dynamics cannot be predicted, operational predictions should be combined with monitoring efforts to reduce the number of false positive predictions.

5. Conclusions

This study showed that a simple 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 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 and 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 35 $\mu mol\ m^{-2}\ s^{-1}$. The trigger for *Phaeocystis* bloom termination could not be found in this study but 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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Table 3

Comparison of the number of observations with foam on Noordwijk beach against model predictions of foam formation for the validation dataset from 2003–2007. 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 (classes 3–4)	Some or no foam (classes 1–2)	Correct predictions (%)
Foam	10	111	100%
Likely foam	3	48	
Possible foam	1	67	
No foam	0	1390	
Observations predicted correctly (%)	93%	90%	

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