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**Monitoring and prediction of phytoplankton dynamics in the North Sea**

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## Summary

The North Sea is a coastal shelf sea receiving water from many large rivers. Therefore the North Sea is rich in nutrients and phytoplankton. Phytoplankton forms the base of the marine food web and produces approximately 50% of total global primary production. Through the uptake of carbon dioxide for growth phytoplankton strongly affects the global climate. However, too high concentrations phytoplankton can also have negative impacts on ecosystems, such as oxygen depletion and shellfish mortality. To reduce negative impacts of algal blooms, countries bordering the North Sea agreed to reduce nutrient inputs from rivers with 50% compared to peak levels in 1985. They also agreed to regularly monitor concentrations of nutrients, phytoplankton and oxygen to check if eutrophication problems were reduced. Since then, measurements show a strong reduction of phosphate concentrations and a modest reduction of nitrate concentrations. A significant decrease of phytoplankton concentrations has not been observed. The absence of a significant trend may imply that nutrient reduction has not affected phytoplankton concentrations. Alternatively, phytoplankton concentrations may have decreased but this was not detected because the natural variability of phytoplankton concentrations masked this trend or because the monitoring frequency was too low to detect a significant trend.

During recent years, monitoring vessels of Rijkswaterstaat have collected water samples at fixed locations at sea to measure concentrations of phytoplankton and other variables. The monitoring frequency and the number of monitoring stations have been reduced in several phases to reduce costs. Yet, phytoplankton concentrations are strongly variable in space and time. Therefore, a high monitoring frequency at many locations is required to capture the natural variability of phytoplankton and detect trends. Novel automated monitoring methods are being developed that can acquire information on phytoplankton abundance at a high resolution in space and time, such as satellite remote sensing, moorings and automated measurements from ferries. The resulting high-resolution data sets enable characterization of phytoplankton variability at different time scales and identification of the mechanisms driving phytoplankton variability.

In this thesis phytoplankton variability in the North Sea is investigated with a range of traditional and novel monitoring methods. We characterized the variability in space and time and analysed the drivers of this variability at different time scales with various methods for data analysis and modeling. In this way we gained experience with the analysis and interpretation of data from automated monitoring methods. Our results demonstrate the potential power of these novel techniques, providing a much improved understanding of population fluctuations at several different time scales. Based on this

understanding appropriate monitoring strategies can be designed to assess the response of phytoplankton to changes in nutrient inputs and global climate change.

Phytoplankton requires nutrients and light to maintain growth. Based on the availability of nutrients and light and current patterns we could reproduce observed spatial and seasonal patterns of phytoplankton in the southern North Sea with the Generic Ecological Model (GEM). Algal blooms of the species *Phaeocystis* can cause large economic losses for mussel farmers in the Eastern Scheldt and foam accumulation on beaches. We tested the feasibility of an early-warning system for *Phaeocystis* blooms in the Eastern Scheldt area combining satellite remote sensing, field measurements and the GEM model. For this purpose, we checked to what extent information on total phytoplankton and *Phaeocystis* in spring 2003 agreed between these different data sources. The bloom period of total phytoplankton was similar in the different data sources. Available field data for *Phaeocystis* had too low temporal and spatial resolution to assess if model results for *Phaeocystis* and satellite data of chlorophyll were a good approximation of actual *Phaeocystis* concentrations.

As alternative approach to predict nuisance *Phaeocystis* bloom events we developed a fuzzy logic model. Fuzzy logic models use knowledge rules based on patterns in observed data and understanding of relevant processes. With this model the initiation of *Phaeocystis* blooms in Dutch coastal waters could be reproduced. Differences in long-term averaged *Phaeocystis* concentrations between stations were strongly associated with differences in local nutrient concentrations. Interannual variation in *Phaeocystis* concentrations could not be reliably assessed with the available data series, due to the low sampling frequency of once or twice per month. Video images of the beach with ARGUS camera's from a light house provided information on foam presence on the beach with an hourly resolution. These data showed a strong dependence of foam accumulation on wind conditions: foam was only visible during moderate to strong landward winds. Within the European research project HABES (Harmful Algal Blooms Expert Systems) similar fuzzy logic models have been developed for the 5 dominant harmful algal species in 5 marine areas throughout Europe. This showed that fuzzy logic models offer a good approach to synthesize all available knowledge about specific harmful algal blooms and use it for predictions. The approach enables to include all known aspects of bloom formation, even if not all underlying processes are understood in detail.

In the previous analyses the temporal resolution of observed data was often limiting a good assessment of phytoplankton variability. Automated moorings can provide data series with high temporal resolution. We analysed the data of four mooring stations in the North Sea to assess the extent and the drivers of phytoplankton variability. In coastal waters near the Thames estuary the tidal cycle was the dominant driver of short-term phytoplankton variability. Phytoplankton fluctuations showed strong 6-hour periodicity

in phase with fluctuations in tidal current speeds, 12-hour periodicity in phase with ebb and flood and 15-day periodicity in phase with the spring-neap tidal cycle. This suggests that phytoplankton not only moves back and forth with the tide (with a 12-hour periodicity) but also sinks during decreasing tidal currents and mixes back to the surface at increasing tidal currents (with a 6-hour and 15-day periodicity); as if they dance with the tide. In deeper waters in the central North Sea, the tide had little impact on phytoplankton. Phytoplankton fluctuations in this area were predominantly controlled by vertical mixing and sinking induced by fluctuations in wind and solar irradiance. In Dutch coastal waters phytoplankton fluctuations were strongly associated with fluctuations in salinity due to the influence of fresh water from the river Rhine. At all four moorings sinking and mixing of phytoplankton particles appeared to be a dominant driver of fluctuations in phytoplankton concentrations.

The analyses in this thesis have shown that data series of high temporal resolution are required to detect changes in phytoplankton concentrations and underlying mechanisms. For accurate assessment of interannual variability in phytoplankton concentrations a sampling frequency of once or twice per week seems to be sufficient. To detect relations between phytoplankton change and environmental conditions an hourly to daily sampling frequency is required. Novel automated monitoring methods such as satellite remote sensing, moorings and sensors on board of ferries enable data acquisition at such high resolution.





## Samenvatting

De Noordzee is een relatief ondiepe zee, waarin veel grote rivieren uitmonden. Hierdoor is de Noordzee rijk aan nutriënten en fytoplankton. Fytoplankton vormt de basis voor het mariene voedselweb, is verantwoordelijk voor ca. 50% van de totale primaire productie op aarde, en heeft door de vastlegging van CO<sub>2</sub> een belangrijke invloed op het klimaat. Te hoge concentraties fytoplankton kunnen echter negatieve effecten hebben op het milieu, zoals zuurstofloosheid van het water en sterfte van schelpdierpopulaties. Om negatieve effecten door dergelijke algenbloeien te beperken is door de landen rond de Noordzee afgesproken om de aanvoer van nutriënten door rivieren naar de Noordzee te halveren ten opzichte van 1985, toen de aanvoer op zijn hoogst was. Ook is afgesproken om de concentraties van nutriënten, fytoplankton en zuurstof regelmatig te meten om te controleren of de problemen door overmatige algengroei (eutrofiëring) afnemen. Sindsdien laten metingen een sterke afname zien van het nutriënt fosfaat en een bescheiden afname van het nutriënt nitraat. Significante trends in fytoplanktonconcentraties als gevolg van deze afname in nutriëntenconcentraties zijn nog niet waargenomen. Dit kan verschillende oorzaken hebben. Het kan zijn dat fytoplanktonconcentraties niet zijn afgenomen, of dat de natuurlijke variatie in algenconcentraties zo groot is dat de trend daardoor niet kan worden vastgesteld, of dat de meetfrequentie te laag was om effecten vast te stellen.

Voor het meten van concentraties fytoplankton en andere variabelen hebben schepen van Rijkswaterstaat de afgelopen tientallen jaren watermonsters genomen op een netwerk van vaste meetlocaties op zee. Om kosten te besparen is de frequentie van de metingen en het aantal meetlocaties in een aantal stappen verlaagd. Fytoplanktonconcentraties variëren sterk in tijd en ruimte, waardoor eigenlijk een hoge meetfrequentie nodig is op een groot aantal locaties om een goed beeld te krijgen van de fytoplanktondynamiek en om eventuele veranderingen hierin te detecteren. Nieuwe geautomatiseerde meetmethoden zijn in ontwikkeling om informatie over fytoplanktonconcentraties te verkrijgen met een grotere resolutie in ruimte en tijd, zoals satellietbeelden, meetboeien en automatische metingen vanaf veerboten. Hierdoor komen nu meetgegevens beschikbaar waarmee de mate van variabiliteit in fytoplankton zichtbaar wordt en waarmee de oorzaken van deze variabiliteit kunnen worden onderzocht.

In dit proefschrift is onderzocht in hoeverre de variabiliteit van fytoplankton in de Noordzee kan worden verklaard door variabiliteit in milieuomstandigheden. Hierbij is gebruik gemaakt van gegevens van traditionele en nieuwe geautomatiseerde meetmethoden en van diverse methoden voor analyse en modellering. Op basis hiervan kan

worden ingeschat wat de mogelijke gevolgen zijn van veranderingen in nutriëntenaanvoer of klimaat en hoe deze het beste kunnen worden gemeten.

Fytoplankton heeft nutriënten en licht nodig om te kunnen groeien. Op basis van de beschikbaarheid van nutriënten en licht en stromingspatronen konden we met het Generiek Ecologisch Model (GEM) de ruimtelijke patronen en seizoensdynamiek van fytoplankton in de zuidelijke Noordzee goed reproduceren. Algenbloeien van de soort *Phaeocystis globosa* kunnen grote schade veroorzaken voor mosselkwekers in de Oosterschelde en leiden vaak tot schuimophoping op het strand. We hebben een waarschuwingssysteem ontwikkeld voor *Phaeocystis* bloeien in de Oosterschelde op basis van satellietmetingen, veldmetingen en het GEM model. Hiervoor hebben we gekeken in hoeverre de informatie uit deze verschillende informatiebronnen overeen kwam voor totaal fytoplankton en *Phaeocystis* in het voorjaar van 2003. De bloeiperiode van totaal fytoplankton was vergelijkbaar in de verschillende datasets. De beschikbare veldmetingen van *Phaeocystis* hadden een te lage ruimtelijke en temporele resolutie om te zien of de modelresultaten voor *Phaeocystis* of de satellietmetingen van chlorofyl goed overeen kwamen met de werkelijke *Phaeocystis* concentraties.

Als alternatieve benadering om *Phaeocystis* bloeien te voorspellen hebben we een fuzzy logic model gemaakt. In fuzzy logic wordt gebruik gemaakt van kennisregels op basis van patronen in beschikbare meetgegevens en globale kennis over relevante processen. Het model kon de start van het bloeiseizoen van *Phaeocystis* in Nederlandse kustwateren goed reproduceren. Verschillen tussen stations in het langjarig gemiddelde van de *Phaeocystis* concentraties vertoonden een sterk verband met lokale nutriëntenconcentraties. Verschillen in *Phaeocystis* concentraties tussen jaren konden met de beschikbare meetgegevens niet goed worden gekwantificeerd, door de lage meetfrequentie van 1 tot 2 keer per maand. Videobeelden van het strand met ARGUS camera's leverden uurlijkse informatie over het voorkomen van schuim op het strand bij Noordwijk. Hierdoor kon een sterke relatie met windomstandigheden worden aangetoond: schuim kwam alleen voor bij sterke aanlandige wind. Binnen het Europese onderzoeksproject HABES zijn soortgelijke fuzzy logic modellen ontwikkeld voor de belangrijkste schadelijke algensoorten in Europa. Hieruit bleek dat fuzzy logic modellering een goede manier is om alle beschikbare informatie over bloeien van een algensoort te bundelen en toetsbaar te maken. Hierdoor kunnen de meest relevante aspecten worden meegenomen in de analyse van algenbloeien, voordat alle onderliggende processen tot in detail bekend zijn.

In de voorgaande analyses was de temporele resolutie van meetgegevens vaak een beperkende factor om de variabiliteit in fytoplankton concentraties goed in beeld te krijgen. Met geautomatiseerde meetboeien kunnen meetreeksen met hoge temporele resolutie worden verkregen. We hebben de meetgegevens van vier meetboeien in de

Noordzee geanalyseerd om te achterhalen welke processen verantwoordelijk zijn voor fluctuaties in fytoplankton concentraties. In zuid-Engelse kustwateren bleek het getij de belangrijkste oorzaak: fytoplankton concentraties vertoonden sterke 6-uurlijkse fluctuaties in fase met fluctuaties in de stroomsnelheden van het opkomend en neergaand getij, 12-uurlijkse fluctuaties in fase met eb en vloed, en 15-daagse fluctuaties in fase met de springtij doodtij cyclus. Dit suggereert dat deze microscopisch kleine algen niet alleen heen en weer stromen met het getij (met een 12-uurlijkse cyclus), maar ook zinken tijdens afnemende getijstroming en opwervelen bij toenemende getijstroming (met een 6-uurlijkse en 15-daagse cyclus). Ze dansen als het ware op het ritme van het getij op en neer. In de diepe wateren van de centrale Noordzee was de invloed van het getij gering en waren korte termijn fluctuaties in algenconcentraties voornamelijk gekoppeld aan verticale menging onder invloed van wind and zoninstraling. Langs de Nederlandse Noordzee kust waren korte termijn fluctuaties in algenconcentraties voornamelijk gerelateerd aan fluctuaties in zoutgehalte veroorzaakt door de menging met zoet rivierwater van de Rijn. Op alle stations bleek het zinken en opwervelen van algen een belangrijke oorzaak van de fluctuaties in fytoplankton concentraties.

De analyses in dit proefschrift hebben duidelijk gemaakt dat meetreeksen met hoge temporele resolutie noodzakelijk zijn om veranderingen in fytoplankton concentraties en de onderliggende oorzaken in beeld te brengen. Voor het betrouwbaar schatten van verschillen in algenconcentraties tussen jaren lijkt een wekelijkse frequentie toereikend. Om relaties met omgevingsfactoren zichtbaar te maken is een uurlijkse tot dagelijkse meetfrequentie nodig. Dergelijke hoge meetfrequenties worden mogelijk gemaakt door automatische meetmethoden, zoals meetboeien, sensoren aan boord van veerboten en satellietbeelden.



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## Curriculum Vitae

Anouk Blauw was born in Rotterdam on 26 April 1972. After finishing high school at the Coornhert Gymnasium in Gouda she studied environmental science in Wageningen from 1990 to 1996. During her studies she specialized in ecological water management. After her studies she worked at the consulting company Witteveen and Bos on mostly urban water management. In 1998 she joined Deltares (formerly called WL | Delft Hydraulics) where she worked on ecological modelling of coastal waters, with a focus on phytoplankton. Both as project leader and team member she has participated in national and international projects on marine phytoplankton. These included studies aiming at reduction of eutrophication in the North Sea, the Philippines and the Sea of Marmara using Delft3D modelling. Also she used Delft3D to estimate carrying capacity for shellfish aquaculture in Dutch, Irish and Scottish waters. From 2000 to 2003 Anouk Blauw led the European research project HABES (Harmful Algal Blooms Expert System). In this project fuzzy logic models were developed predicting harmful algal blooms of the 5 dominant harmful algal species in five marine areas across Europe. Subsequently she contributed to the development of a harmful algal bloom information service for the Eastern Scheldt in the Netherlands combining operational Delft3D modelling, with near real time satellite remote sensing and field measurements. In 2009 she started a PhD-project on "Integrated monitoring of the carrying capacity of coastal waters" at the University of Amsterdam, which resulted in this PhD-thesis. At present Anouk works as senior scientist at Deltares again on monitoring strategies and prediction of phytoplankton dynamics, including harmful algal blooms.



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