Biological Oceanography Committee

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REPORT OF THE WORKING GROUP ON PHYTOPLANKTON ECOLOGY

The Hague, Netherlands

29–31 March 1995

International Council for the Exploration of the Sea

Conseil International pour l'Exploration de la Mer

Palægade 2–4 DK-1261 Copenhagen K Denmark

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1 OPENING OF THE MEETING

The meeting was opened by the Chairman, Dr F. Colijn at 10.30 hours on 29 March 1995. The meeting was attended by 8 scientists representing 7 countries. A list of participants is given in Annex 1. The draft agenda was discussed and adopted unchanged by the Working Group. The agenda is attached as Annex 2. Prof. Dr Ted Smayda was appointed as rapporteur. The Chairman emphasised the importance of ICES as input for monitoring studies within the framework of organisations like OSPARCOM. He also emphasised the importance of studies on nutrient phytoplankton interactions because of eutrophication problems in several parts of the ICES area, the relations between eutrophication and monitoring programmes and the relevance of making recommendations on new techniques to study phytoplankton in the sea, but without forgetting the theoretical hypothesis formation needed in science, particularly in marine science. New techniques e.g., to study phytoplankton biomass and production, are now rapidly evolving and their significance for incorporation in ICES studies or institutes should be considered, especially in the framework of monitoring the marine environment.

The following members were absent with notice: Elspeth MacDonald (Scotland), Bert Wetsteijn (the Netherlands), Egil Sakshaug (Norway), Serge Maestrini (France); no other members have given notice.

At the end of the introduction the Chairman disseminated information on the Aarhus 1975 Revisited Symposium organised by ICES in July, and on the Theme Session during the coming Annual Science Symposium entitled "Consequences of manipulation /management of nutrient fluxes on nutrient-foodweb interactions", co-conveners F. Colijn and R. Laane. This meeting will take place in September 1995 in Aalborg, Denmark.

2 TERMS OF REFERENCE

The Chairman informed the Working Group on Phytoplankton Ecology regarding the Council Resolution 1994/2:48 which states:

The Working Group on Phytoplankton Ecology (Chairman Dr F. Colijn, Netherlands) will meet in The Hague, The Netherlands from 29–31 March 1995 to:

a) consider the suitability for and mechanisms of promoting use of an ICES standard method for determining primary production employing the incubator which has been developed through the efforts of the Working Group;

b) review and assess possible new techniques to measure algal biomass, growth rates and primary production and report to ACME;

c) develop an understanding of nutrient to growth relationships in eutrophic coastal areas;

d) summarise the first results on the use of automatic equipment on buoys and ferries for monitoring the spatial and temporal distribution of phytoplankton and chlorophyll;

e) develop plans for a possible future workshop/symposium to evaluate the use of long term time series in primary production etc., in order to partition natural from man-induced environmental effects;

f) evaluate the suitability of plankton population parameters for monitoring nutrient fluxes and changes in nutrient fluxes in and to the coastal zone, and report to ACME (OSPAR 1.5).

The Working Group will report to the Biological Oceanography Committee (Reference Marine Environment Quality Committee and Hydrography Committee). The Chairman explained and gave his ideas about the terms of reference and their priorities (for f)) and gave a short overview of the background of the working group. Moreover he announced that he had invited several speakers from the hosting institute to give short presentations on topics related to the terms of reference , especially on b)).

3 GENERAL DISCUSSIONS OF TERMS OF REFERENCE

(a, b, c, d, e and f refer to the terms of reference)

a. consider the suitability for and mechanisms of promoting use of an ICES standard method for determining primary production employing the incubator which has been developed through the efforts of the Working Group;

Due to the absence of two of the participants of the intercomparison exercise in Middelburg last year not much progress has been reported. However, a report on the measurement of irradiance in the incubator has been prepared, which shows the reliability of the irradiance field in the incubator. The authors of this study have given a few suggestions to improve the irradiance distribution and the spectrum in the incubator. The latter could be made more comparable to natural light if the TL 33 was replaced by another (halogen) type illumination. The report and the manuscript of the incubator have been thoroughly reviewed during the meeting by the members Subba-Rao and Gudmundsson and the following decisions have been taken: after correction the manuscript will be submitted to a journal, because this was felt as a mechanism to promote the use of the standard method. As one of the activities for next year O. Lindahl from Sweden will write a draft manual how to use the incubator for the purposes it has been developed. The report and the manuscript will be finalised by Wetsteijn in co-operation with the Chairman, who also announced that he would try to run some additional measurements with the incubator in his new institute in Germany.

b. review and assess possible new techniques to measure algal biomass, growth rates and primary production and report to ACME;

In the discussions during the meeting mention was made to different coming new methodologies for the type of measurements mentioned in the terms of reference. However, most of these methods are still either in a test phase or late phase of development and the Working Group felt that no clear recommendations were possible to make at this stage. However the different methodologies were considered so promising that the Working Group strongly encourages its testing among the members that are able to do it, in order to gather experience. Most of these new techniques are based on the use of chlorophyll fluorescence properties.

Mr. Y. Althuis from the RIKZ in The Hague, who was invited by the Chairman, presented the principles of PAM (pulse amplitude modulated fluorescence) to measure electron flow in photosynthesis of phytoplankton. The great advantage of the method is that samples do not need to be confined in a jar or bottle and that short (minutes) measurements can be made. Moreover only photosynthetic reactions are measured. However a few problems have to be solved e.g., the conversion of electron transport into carbon fixed and the measurement of the absorption cross section of the algal cells. A few nice examples of direct measurements were presented showing the potential power of this method which is based on similar principles as Falkowski's pump-and-probe method, but differs with respect to the intensities of the flashes and to the time intervals between the flashes.

Another relatively new method for studying phytoplankton is flow-cytometry. Mr. Kees Peeters of RIKZ in Middelburg, also on invitation of the chairman, presented an overview of the development of optical plankton analysers in the Netherlands. Attempts to develop such instruments have been taken place since the early 80s. Emphasis has been laid on a high dynamic range and low flow shear in the measuring cuvette. The dynamic range of a typical machine is from 0.5 um to about 500 um cross-section and up to 3 mm length. This enables measuring colonial cells or long filaments. Using combinations of lasers several taxonomic groups can be discriminated based on their characteristic pigment composition. By including other parameters like TOF (time of flight) cell size can be measured and used as a parameter to distinguish species.

The latest developments have taken place in a European MAST project EUROPA (European Optical Plankton Analyser). These new developments are image in flow - a video system to get a real time picture of the cells - a diffraction module - giving extra information on the cell structure and surface - and pulse shape analysis - a technique to use information of the fluorescence signal of individual cells e.g., on chloroplast density and location. All this extra information facilitates the identification of cells within groups, sometimes to the species level.

Another part of the discussion on this term of reference was dedicated to one chapter of the SCOR report: Phytoplankton Pigments in Oceanography, (Draft of Chapter 9: Evaluation of Methods and Solvents for Pigment Extraction). Unfortunately, the other chapters of this report are still not available for discussion.

The Working Group welcomed the initiative of SCOR in producing such a valuable document. Unfortunately only one chapter of the planned document was available for comments at the time of the Working Group meeting so no recommendations can be done at this stage.

The available chapter focuses on pigment extraction methods and solvents. In the 1994 Working Group meeting an action point was defined and Drs Egil Sakshaug and Francisco. Rey got the task of reading and commenting the document and making suggestions to this year meeting. The Working Group discussed briefly the document and the written comments by Sakshaug and agreed that HPLC is the best method if the objective is to get a complete spectra of pigments with absolute values for each of them. However, this is seldom the objective among most of phytoplankton ecologists. The Working Group emphasises that what is really needed is a reliable method to measure chlorophyll *a* as an index of phytoplankton biomass.

The SCOR-report recommended extraction with methanol + sonication as the best choice for HPLC pigment work. Although the best results were obtained with dimethylformamide, this solvent presents serious health risks and so it is difficult to recommend especially for field work. The Working Group agreed on this. The SCOR-report also concluded that in many cases, acetone is still a suitable extraction solvent when diatoms and naked flagellates are the dominant groups. The Working Group did not find it necessary to present conclusive recommendations about pigment measurements until the complete report becomes available for comments.

However, a few suggestions can be made at this stage in order to improve the existing SCOR-UNESCO method from 1966. These improvements are mainly focused on diminishing the problem of pigment degradation during extraction and in special cases where species with high concentrations of acid cell sap and/or high chlorophyllase activity are present. In these cases, sonication with a probe can radically reduce extraction time compared to soaking, although not necessarily reduce extraction efficiency. Reducing extraction time can reduce degradation. Also, introducing a two step extraction procedure is suggested. This include first extraction with 100% acetone, followed by sonication and then addition of destilled water to make up to 90% followed again by sonication. Eventual more conclusive recommendations on pigment extraction can be made later on after going through the complete SCOR report.

During the discussion of this matter it became also clear that today there are different national standard methods for measurement of chlorophyll *a*. These have to be taken into consideration in case ICES decides to recommend a standard method for its members countries.

Mention was given of an initiative of the Danish Water Quality Institute to prepare and sell pigment standards for HPLC measurements.

It was decided to take up these points again during next years meeting and to try where possible to recommend on the use of these techniques within the ICES community. This especially holds for the pigment measurements, but also for the new production methods. Members Rey and Sakshaug will take up this point for next year, whereas the Chairman will organise the item on production methods.

c. **develop an understanding of nutrient to growth relationships in eutrophic coastal areas; (this TOR is combined with f))**

d. **summarise the first results on the use of automatic equipment on buoys and ferries for monitoring the spatial and temporal distribution of phytoplankton and chlorophyll;**

An introduction to this term of reference was given by Juha Leppänen and by the Chairman. The high variation in the growth and distribution of plankton is based on a hierarchy of processes operating at various spatial and temporal scales (e.g., Kononen, 1992). Consequently, the monitoring of pelagic dynamics requires an appropriate spatial and temporal sampling frequency that is difficult to obtain using the traditional methods. Methods to detect and to cope with the natural variation of plankton are available. The use of ships of opportunity technique for horizontal, buoys for vertical high-resolution profiling and satellite imagery are used for these purposes. Networks of automated buoy stations are operational or under construction in several countries (Norway, Germany, the Netherlands). The ship of opportunity technique has been used in the CPR programme (UK) for long time. Some new high-frequency recording systems are operational in some areas. Pilot studies to use commercial ships in recording spatial and temporal variation in the surface layer of parameters such as chlorophyll fluorescence, temperature and salinity have been carried out in the Channel by Dutch scientists during two successive years (Swertz *et al.*, in prep.). An extensive phytoplankton monitoring and early-warning programme is in operational use in the Baltic Sea by the Finnish Institute of Marine Research. The data collection is based on unattended recording of surface layer chlorophyll fluorescence, temperature and salinity on ferries. The high-frequency recordings are supplemented with discrete water samples for laboratory determination of phytoplankton species and nutrients. In this programme NOAA/AVHRR images are used to estimate the extent of the cyanobacterial drifting layers accumulated at the surface. A more detailed description of the method is given in Annex 3a and b. The use of these methods is also discussed under f)) as a recommendation.

The development of a suitable batfish for vertical profiling to be used from the commercial ships and the new sensors and analysers which make possible a more reliable estimate of phytoplankton biomass as well as an index of photosynthetic activity most possibly will improve the ship of opportunity approach.

The new generation flow-cytometers which can analyse the size spectrum of phytoplankton and differentiate between the main phytoplankton groups offer an effective tool to analyse rapidly large sample sets (see also section on flow cytometry and MAST EUROPA).

Several new ocean colour sensors available in a few years will enhance the use of satellite imagery in plankton research.

No single method offers a solution to monitor all the effects of eutrophication, instead a combination of approaches have to be selected. The methodology should be adapted according to the spatial and temporal variation in the components of the specific ecosystem. The design of an appropriate sampling strategy and the careful selection of key parameters according to the problem and region is of primary importance. In general, all monitoring activities should be closely connected to the scientific research activities carried out in the region.

Presently most of the research vessels are equipped with some continuous profiling flow-through analysers. There are possibilities to use these more effectively and to combine this information regularly. There might be a need to harmonise the flow-through equipment in order to increase the compatibility of the results.

e. **develop plans for a possible future workshop/symposium to evaluate the use of long term time series in primary production etc., in order to partition natural from man-induced environmental effects;**

This term of reference was taken up again because last year's statement/recommendation has not led to any initiative within ICES. The Chairman introduced this point by explaining that long-term time series have already attracted much attention. In 1995 alone 2 symposia are dedicated to this topic, one which had recently been held in Arcachon (France) and one which will be held in Denmark in July (Aarhus 1975 Revisited). Therefore scope and goals of such a meeting to be organised by ICES would be crucial to get enough support. Also the period would be of importance to prevent overlapping with other important symposia.

The Working Group is strongly in favour to support the idea of such a workshop which could be held separately or in direct conjunction with the ICES Annual Science Conference. It was felt that a full three days would be needed and therefore that incorporation in the Annual Science Conference was not ideal. The Working Group decided to make a recommendation to ACME and BOC on this topic including a justification. The Chairman invited Ted Smayda to help him in writing this section.

f. **evaluate the suitability of plankton population parameters for monitoring nutrient fluxes and changes in nutrient fluxes in and to the coastal zone, and report to ACME (OSPAR 1.5). (see c)**

This term of reference was a result of tasks given by OSPAR to ICES and after discussions during last year's ACME meeting. It has been given high priority during the meeting of the Working Group by the Chairman, who had invited three members (Ted Smayda, Wolfgang Hickel and Odd Lindahl) to prepare the discussion on this item also considering a discussion paper written earlier by Tom Osborne (see Annex 5).

In a short presentation all three members gave their ideas and presented new data on the effects of nutrients on phytoplankton growth or production. Their presentations can be summarised as follows.

Trends of increasing nutrient concentrations characterise coastal waters, particularly NO_3 and PO_4 concentrations, the sources of which include increasing agricultural use of crop fertilisers, agro-industrial waste water discharge, and other watershed management effects. The mechanisms of enrichment include river discharge, air-borne nutrient fluxes, and long-distance transport through current systems. Available data collectively indicate that chronic delivery of elevated nutrient concentrations negatively influences several aspects of phytoplankton behaviour: phytoplankton production increases; phytoplankton biomass increases; phytoplankton community composition is altered, and, perhaps stimulate increased bloom occurrences of novel, nuisance, noxious or harmful algal species.

These connections between increased nutrient concentrations and phytoplankton and associated ecosystem responses have become evident from long-term data sets available for coastal waters. Evaluation of site-specific events often indicates seemingly paradoxical responses, however. Very high production rates may occur during periods of non-detectable nutrient levels, or relatively low biomass concentrations. Such correlations reveal that the more meaningful measurements of nutrient levels are not the residual nutrient concentrations available to the phytoplankton, but their turnover, or recycling rates, also indicated by the term fluxes. For example, during summer bloom events the initial supply of nitrogen must be replaced every 2–4 hours daily to support measured production rates. In many pristine coastal embayments, the initial supply of nutrients must be replaced 8 to 20 times per year, i.e., every 2 to 6 weeks. The source of this resupply rate, called the flux rate, include river discharge, excretion by pelagic and benthic grazers, other benthic demineralisation processes and vertical fluxes to the euphotic zone from deeper water. Hence, measurements to estimate nutrient regulation of phytoplankton growth must not be restricted to the instantaneous levels, but must include the flux from the diverse sources.

Flux measurements alone, however, will not account for observed dynamics. The growth characteristics, duration, magnitude and timing of bloom events, bloom species selection, the fate of the increased phytoplankton biomass etc., are the outcome of several processes which influence population growth which determine the balance between growth and losses. Population growth is the result of differences between the cellular growth rates of the individual species present in the community and their losses due to advection, sinking, grazing and natural mortality. Thus, measurements of nutrient fluxes must be accompanied by measurements of the loss terms. Evaluation of advection requires physical oceanographic measurements; sinking losses can be evaluated from sediment trap deployments. Grazing impacts can be assessed directly through experimentation or, indirectly from determination of herbivorous zooplankton biomass levels. Natural mortality can not be measured, but is usually considered to be only 10–15% of total abundance levels. Quantitative evaluation and the regulation of phytoplankton dynamics by nutrient fluxes clearly do require a multidisciplinary process-oriented approach. Monitoring of nutrient fluxes and their effects may document the parallel associations between nutrient enrichment and phytoplankton and ecosystem dynamics. Nutrient fluxes however, will not be able to quantify the actual causes of the observed outcome, which will be a result of the factors given above, with the relative importance of advection, sinking and grazing varying seasonally and regionally.

Thus, at least two different approaches are recommended in evaluating the effects of nutrient fluxes on phytoplankton. Descriptive, non-process oriented, time-series studies of phytoplankton biomass and/or production and nutrient concentrations, including seasonal riverine delivery levels, in representative coastal regions are desirable, particularly when extensive data gaps exist, and in regions where such data are unavailable. This will provide general insight into the nutrient-phytoplankton relationship. At selected, representative sites more detailed process-oriented studies should be carried out to provide generically useful insights in those regions where routine monitoring is to be carried out. This should include a gradient analysis approach, with the monitoring stations established along an onshore-offshore line of decreasing nutrient levels, decreased benthic-pelagic coupling, and decreased coastal current dispersion. The discussion gave rise to the following conclusions.

1) Nutrient fluxes and their changes (by anthropogenic influences) are the more adequate measure for the understanding of marine ecosystems than just concentrations. Phytoplankton populations take a very important part in these fluxes, and are themselves a main object of enquiry: as poisonous or otherwise unwanted species they are a matter even of public concern. Changes of phytoplankton species composition can alter the whole food web towards an unwanted direction. Indirect effects such as oxygen depletion in the bottom water by accumulated biomass can seriously affect the benthic populations.

   Monitoring programmes in some North Sea coastal areas have shown that primary production and phytoplankton biomass were enhanced due to nutrient enrichment (QSR, 1993), but no systematic change of large phytoplankton in the southern North Sea that can be attributed to nutrient enrichment was observed (CPR-data, QSR, 1993). It is likely to assume that if nutrients were enriched an enhancement in primary production also will occur offshore, e.g., in the open North Sea. Thus, by measuring the primary production it would be possible to monitor the enhanced flux of nutrients in eutrophified coastal areas as well as offshore. The flux of nutrient (and carbon) uptake by the phytoplankton community can be measured directly or indirectly by a number of methods and under very different nominal time scales (Platt and Sathyendranath, 1993).

2) Though measurements of fluxes of nutrients and other essential elements in the sea are of great value, they are expensive, require special equipment and a well-trained scientific staff. Therefore, they are not the first choice when the available funds are limited. This is particularly true if a good coverage of the respective sea areas in time and space is attempted.

   Therefore, such flux rate measurements should be restricted to a few "model areas", which are typical for a sea area. They could include "hot spots" in the sea, where effects of eutrophication are detected most clearly. Marine institutes with appropriate capacity and infrastructure (research vessels) should be in charge for this task.

   To be able to identify an effect of eutrophication using the fluxes of nutrients or carbon in coastal or offshore water, time-series of high frequency in selected areas are needed. The primary production will have to be measured at least 20 times a year if a good estimate of the annual production or flux of nutrients should be calculated. However, at present all methods for measuring fluxes in direct connection with the phytoplankton community will be time and resource consuming. Further, if different methods are used in different monitoring programmes it will be difficult to interpret the results due to the uncertainties whether net or gross production is measured.

3) An adequate monitoring of sea areas with a good coverage in space and time can be achieved only by using relatively simple and cheap methods. The fluorometric plankton pigment analysis is among the most successful parameters for measuring phytoplankton populations. This type of measurement can be automatised, even in unattended systems on ships and buoys.

   We recommend to install automatic recording fluorometers on ferry boats on regular routes which are particularly suited for the problem at hand. Besides chlorophyll measurements by fluorimetry, as a measure of phytoplankton stocks, discrete samples should be taken for phytoplankton samples in which qualitative species analysis can be made, and for dissolved inorganic nutrient analysis.

Such an automatic device has been tested and used already in the Baltic Sea, installed on a ferry which operates between Germany and Helsinki resp. St. Petersburg. Similar devices should be installed in North Sea ferries. Frequently repeated transects through parts of the North Sea and the Baltic allow for analyses of annual and interannual variations and, if continued long enough, of (anthropogenic) trends.

4) In addition, a standardised method for plankton and nutrient monitoring should be carried out from Marine Stations situated at the seaside, where frequent sampling can be cheaply and conveniently be carried out. A number of (existing and new) coastal water monitoring stations can thus be established at low extra cost.

The relation between total primary production and the "export production" has been proven to be a good measure of the trophic state of an marine area. This export production can be measured as sedimentation of organic matter into sediment traps below the trophic layer (Wassman, 1992). This parameter was well correlated with the oxygen consumption in the bottom water of stratified areas. We recommend to use standardised sediment trap techniques to measure this export production in suited vertically stratified areas with restricted bottom water exchange.

4 ANY OTHER BUSINESS

The limited attendance to the meeting was shortly discussed. One obvious reason certainly is lack of travel funding, but some members indicated the possibility that the Working Group on Harmful Algal Blooms might be competing on the same group of scientists. The Chairman explained his efforts to hold the Working Group meeting together with the other working groups at the same time and same place but that he could not arrange agreement on the date for such a meeting.

A possible place for next years meeting has been discussed. Gudmundsson will consider the possibilities to convene in Iceland, although March may be still quite cold. Another possibility would be Copenhagen, or a combined meeting with the WG HAB. The latter opportunity would depend on their preference.

5 ACTION LIST FOR NEXT YEAR:

a) Lindahl: to propose a working manual for the ICES incubator;

b) Wetsteijn and Colijn: to finish work on the ICES incubator, including the irradiance improvements and correction of manuscript;

c) Sakshaug & Rey: to recommend new pigment procedures based on the SCOR report;

d) Smayda and Colijn: to prepare a symposium on long term series on plankton after consent of the ICES Annual Delegates Meeting;

e) Colijn: to organise a discussion on the application of new techniques for primary production and biomass estimates.

6 RECOMMENDATIONS

The ICES Working Group on Phytoplankton Ecology recommends to hold a symposium on the variability of plankton and their habitat (physical-chemical environment). This ICES-sponsored symposium could be held in conjunction with the ICES Annual Science Conference, or convened as a separate symposium with ICES sponsorship, similar to the Aarhus 1975 Revisited Symposium. Prof. Ted Smayda and Prof. Franciscus Colijn are willing to co-convene with other specialists in the field such a symposium. To prepare this symposium and to enable scientists to analyse their long-term time series we suggest 1997 as the earliest date for this meeting. Moreover we suggest to use a location in Europe.

Justification.

Natural or intrinsic variability in phytoplankton and zooplankton dynamics is one of the least quantified properties in the sea. Moreover knowledge of this intrinsic variability is essential in understanding human impacts on the plankton dynamics and behaviour of the sea. Without knowing these features monitoring of anthropogenic influences on phytoplankton and zooplankton is without much meaning, i.e., a distinction between human induced changes e.g., eutrophication, and natural variation can not properly be made. Measurement of long term series in phytoplankton and zooplankton ecology belong to the "endangered species" because after retirement of the scientists responsible for such measurements, no guarantee exists for prolongation of the series. This symposium should stimulate the working up and presentation of long-term time series that otherwise would not have been done because of either lack of funding, retirement or disinterest. Moreover the presentation of such long-term time series from a diversity of sources and habitats will allow identification of the common characteristics of plankton variability as distinguished from site specific or regional specific variations.

We are also hopeful that the collective presentation of such time series data will allow the development of concepts suitable for future experimental and field validation.

Such hypothesis testing recommendations is essential in order for more effective utilisation of the significant newer techniques being developed for quantification of plankton biomass and processes. While the focus during this meeting is on plankton, we would like to stress the importance of plankton for other parts of the marine food web dynamics.

One of the applications and benefits of this meeting could be the proper design of monitoring programmes, and managerial decisions regarding mitigating and early warning measures.

7 ADOPTION OF THE WG REPORT

The working report has not been adopted by the members during the meeting, because the final text was not yet available. The members have expressed their confidence in the Chairman to write the report based on the written contributions of the members which were already available.

8 CLOSING OF THE MEETING

The meeting was closed on Friday afternoon at about 15.30 hours. The Chairman asked the members to support his idea of writing a short acknowledgement to the Director of the hosting institute, RIKZ. This idea was approved. The Chairman wished all members a safe journey home.

Annex 1

List of participants

Name	Address	Telephone	Telefax	E-mail
A. Bode	Instituto Español de Oceanografia Centro Costero, Apdo 1301 15080 La Coruña Spain	+34 81 205362	+34 81 229077	
F. Colijn (Chairman)	FTZ, Hafentörn 25761 Büsum Germany	+ 49 4834604200	+49 4834604299	
L. Edler	SMHI Doktorsgatan 9D 26252 Ängelholm Sweden	+46 43180854	+ 46 43183167	
K. Gudmundsson	Marine Research Institute Skúlagata 4 121 Reykjavík Iceland	+354 120240	+354 1623790	kristinn@hafro.is
W. Hickel	Biologische Anstalt Helgoland Notkestrasse 31 22607 Hamburg Germany	+49 4089693203	+49 4089693115	
J.-M. Leppänen	Finnish Institute of Marine Research P.O. Box 33 00931 Helsinki Finland	+358 0613941	+358 061394494	jukkis@fimr.fi
O. Lindahl	Kristineberg Marine Research Station Kristineberg 2130 450 34 Fiskebäckskil Sweden	+46 52318500	+46 52318502	o.lindahl@kmf.gu.se
T. MacMahon	Fisheries Research Centre Department of the Marine Abbottstown Dublin 15 Ireland	+353 18210111	+353 18205078	
F. Rey	Institute of Marine Research P.O. Box 1870, Nordnes 5024 Bergen Norway	+47 55238500	+47 55238584	francisco.rey@imr.no

List of participants (continued)

Name	Address	Telephone	Telefax	E-mail
E. Sakshaug	Trondheim Biological Station University of Trondheim Bynesveien 46 7018 Trondheim Norway	+47 73591583	+47 73591597	
T. Smayda	Graduate School of Oceanography University of Rhode Island Kingston, R.I. 02881 USA	+1 4017926171	+1 4017926682	tsmayda@gsusun. 1.gso.uri.edu
D.V. Subba-Rao	Habitat Ecology Division. Bedford Institute of Oceanography P.O. Box 1006, Dartmouth, NS, B2Y 4AZ Canada	+1 9024263837	+1 9024267827	durvas@bionet. bio.dfo.ca
P. Williams	School of Marine Sciences University of Wales, Bangor Wales LL57 2UW United Kingdom			

Annex 2

Agenda of the meeting

1. Opening of the meeting by the chairman
2. Adoption of the agenda, appointment of rapporteur
3. General introduction to the meeting by the chairman
4. Discussions on the subjects from the terms of reference
5. Any other business
6. Action list for working group members
7. Recommendations to ICES committees
8. Adoption of the Working Group Report
9. Closing of the meeting

Unattended algal monitoring system - a high resolution method for detection of phytoplankton blooms in the Baltic Sea

Juha-Markku Leppänen 1), Eija Rantajärvi 1), Matti Maunumaa 1) Mika Larinmaa& Jukka Pajala 2)

1)Finnish Institute of Marine Research
P.O. Box 33
FIN-00931 Helsinki, Finland

2) Navarc Oy
Tornikatu 3 A 1
FIN-21200 Raisio, Finland

Abstract - The present paper describes a method to record unattended, with high spatial and temporal resolution, phytoplankton biomass and related parameters on merchant ships. The system consists of a flow-through fluorometer, temperature and conductivity sensors, a GPS navigator, and a automated water sampler, all controlled by a Personal Computer. The logged data is transferred via a mobile telephone connection while the ferry enters into the harbour. The dense spatial sampling in combination with the frequent voyages make possible to detect the patchy plankton blooms reliably. The high-resolution sampling provides comprehensive data for long-term time series and trend analysis. The system has proved to be an appropriate tool for an operational warning system for exceptional and eventually harmful algal blooms in the Baltic Sea area.

I. INTRODUCTION

The aim of this paper is to describe a method to record unattended, with high spatial and temporal frequency, phytoplankton biomass and related parameters on merchant ships for long-term trend monitoring as well as for early-warning of harmful algal blooms.

Eutrophication and related to this plankton blooms have become frequent in the coastal waters of the whole world. Also toxic blooms are expected to have intensified and they cause economic loss by disturbing aquacultures and are a healthy risk for man. The pelagic ecosystem is a problematic object to monitor reliably because of its high temporal and spatial heterogeneity [1, 2]. It is impossible, in practice, to collect enough samples for e.g. long-term trend analysis using the traditional sampling technique, which is based on sampling on few fixed stations with relatively sparse temporal frequency. For early-warning of harmful blooms, on-line type information is needed.

Autonomous buoys and remote sensing by satellites are used for detecting algal blooms and to monitor the planktonic ecosystem. The buoys give high-frequency time series but the spatial coverage is limited to vertical profiling. With satellite images, it is possible to cover large areas but the lack of suitable sensors and the clouds are the weak points on the method at the moment. On research vessels the use of quasi-continuous underway measurements have long traditions [3] but the autonomous use of these kind of recording has not been widely used [4]. The Finnish Institute of Marine Research has developed an autonomous analyzer combination that can operate unattended on merchant ships and record with high spatial and temporal frequency the variability in the plankton [5]. Based on these recording, it has been possible to deliver almost on-line information on the development of algal blooms to various environmental authorities around the Baltic Sea. The project has been financed partly by the Nordic Council of Ministers.

II. DESCRIPTION OF THE METHOD

The aim of the project has been to develop a versatile data acquisition system which can be equipped with various commercially available analyzers and sensors in order to record unattended the spatial and temporal variability in phytoplankton on commercial ships with regular schedules. The system is controlled through a Personal Computer with a special software for logging and telecommunication. It enables to connect practically all kind of analyzers and sensors which can transmit digital or analogous signal (Fig. 1).

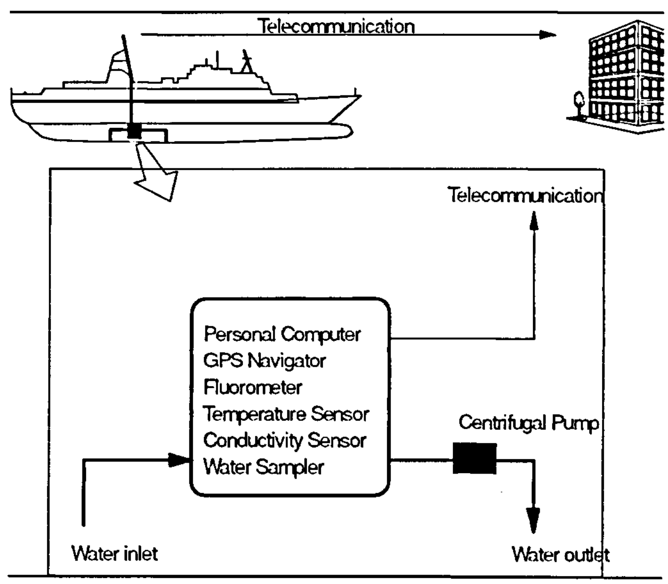

Fig. 1. Schematic representation of an unattended flow-through measuring system

Data can be received via RS-232 links, via AD-converters or via data network. Every channel can be configured according to the output of the specific analyzer/sensor. The water for the sensors is pumped constantly from a fixed depth while the ship is moving. The data is logged with an adjustable time interval and stored on the hard disk. When the ship enters the harbor, logging is interrupted and the data is transferred to the receiver by a mobile telephone connection. The receiving laboratory is provided with a software package which contains modules for data receiving and processing.

The system can be completely independent including all the necessary components or may be connected e.g. to the navigation system or weather station of the ship.

III. APPLICATIONS IN THE BALTIC SEA

In the Baltic Sea, an independent system have been tested on several ferries since 1990 [4]. The system has consisted of a flow-through fluorometer, temperature and conductivity sensors, a GPS navigator, and a automated water sampler. The chlorophyll *a in vivo* fluorescence has been used as an indicator of phytoplankton biomass [5]. Combined with a particle analyzer (particle size distribution and amount) valuable additional information on the seston can be obtained. The automated water sampler which can be controlled by the PC is elementary to the system. In the laboratory, the water samples make possible to determine the phytoplankton species composition and to quantify various chemical components such as chlorophyll *a* and nutrients. The laboratory determination of chlorophyll *a* concentrations make possible to convert the *in vivo* fluorescence recordings to chlorophyll *a* concentrations. The determination of the phytoplankton species composition is essential for the early-warning of harmful blooms.

The phytoplankton biomass in the Baltic Sea is usually suspended in the 0...10 m mixed surface layer and thus sampled reliably with the present method. Due to the small scale patchiness of the phytoplankton a spatial sampling interval of 100-200 has been proved to be suitable in the Baltic Sea. The seasonal pattern of the plankton succession can be recorded by weekly sampling, but while monitoring the dynamics of a bloom, a sampling frequency close to one day is needed.

The eutrophication has intensified the phytoplankton blooms in the Baltic Sea [6]. The recordings on a ferry 'Finnjet', crossing the whole Baltic Proper 4 times per week from Helsinki to Travemünde, reveal clearly the regional differences in the duration and intensities of the spring bloom (Fig. 2).

The cyanobacterial blooms, occurring quite regularly in late summer, are a typical phenomenon in the Baltic Sea. One dominant species, *Nodularia spumigena*, is toxic [7]. When the floats have been drifted to the archipelago or to the coast, *Nodularia* toxin has caused intoxications of domestic animals. The cyanobacterial floats are seen as irregular peaks along the ship transect from St. Petersburg to Travemünde (Fig. 3). The sea area off St. Petersburg is highly eutrophied, and the intensive phytoplankton blooms occur during the whole growth season [8].

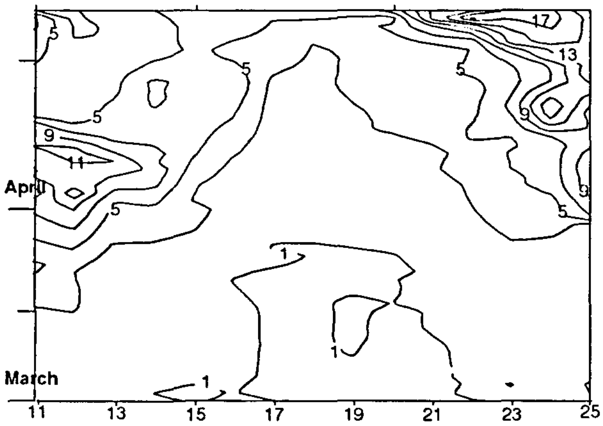

Fig. 2. The succesion of the phytoplankton spring bloom in the Baltic Sea in 1994 expressed as the concentrations of chlorophyll *a* (mg $^{-3}$). The y axis refers to date and x axis to the latitude. The route of the ferry 'Finnjet' is presented in Fig. 3.

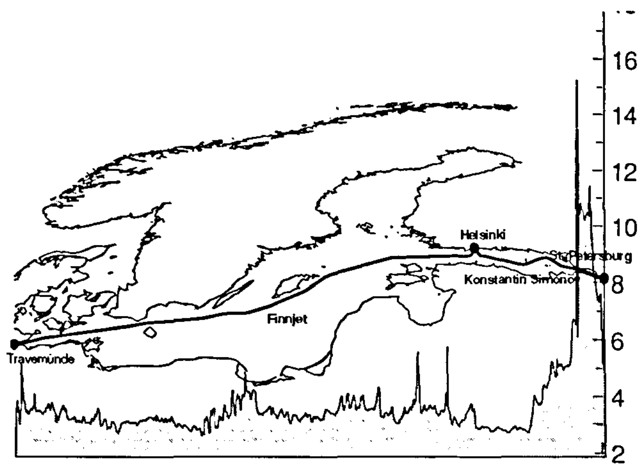

Fig. 3. The variability in the chlorophyll a concentrations (mg m^{-3}) in the Baltic Sea in 1-3 August 1993 as measured on the ferries 'Finnjet' and 'Konstantin Simonov'.

The intensive sampling on board ferries (Travemünde - Helsinki - St. Petersburg) in 1993 reveled the occurrence of ca. 20 potentially toxic phytoplankton species or genera, some of them with high constancy [9]. The occurrence of some species was regionally restricted while others were present in all sea areas (Fig. 4.).

The high-frequency recordings on the ferries have been a basis for a comprehensive and fast information exchange on algal blooms between the environmental authorities and research institutes in the countries surrounding the Baltic Sea [9]. The ferry data have been supplemented with satellite images (NOAA/AVHRR) which extend the ship borne measurements basin wide. The unattended flow-through measurements can serve as reference data for satellite images. A software that is able to pick up data from the satellite images corresponding to the ferry data is available, too.

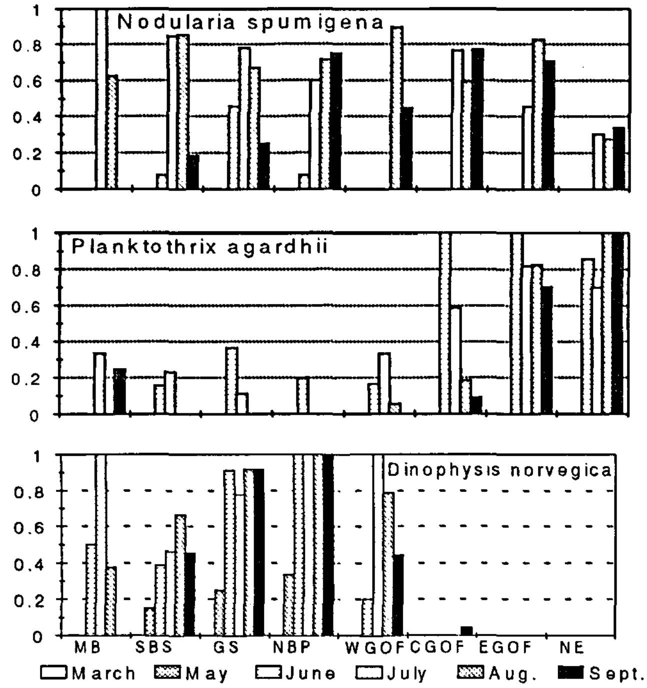

Fig. 4. Constancy (the ratio of the number of samples with the species present to the total number of samples analyzed in the respective area) of some potentially toxic phytoplankton species in the Baltic Sea in 1993. NE=Neva Estuary; EGOF=Eastern Gulf of Finland; CGOF=Central Gulf of Finland; WGOF=Western Gulf of Finland; NBP=Northern Baltic Proper; GS=Gotland Sea; SBS=Southern Baltic Sea; MB=Mecklenburg Bight.

IV. CONCLUSIONS

The present system has several practical advantages. The versatility and openness of the system make possible to tailor the combination of sensors and analyzers according to the specific requirements of the user. The basic equipment is relatively inexpensive and the final costs are determined by the prices of the sensors. The environmental circumstances on ferries correspond almost to those in laboratories and therefore no special requirements for the analyzers and sensors are needed. The regular visits of the ships in the harbours make the maintenance of the system easy to carry out and enable to get the water samples rapidly for the laboratory analysis.

The dense spatial sampling in combination with the frequent voyages make possible to detect the patchy plankton blooms reliably. The high-resolution sampling provides comprehensive data for long-term time series and trend analysis. On the basis of fluorescence recordings, the water samples for time-consuming phytoplankton species determination can be preselected: only samples that coincide the bloom peaks are analyzed. The number of samples analyzed can be reduced but the necessary information on the bloom forming species is still obtained. The system has proved to be an appropriate for an operational warning system for exceptional and eventually harmful algal blooms in the Baltic Sea area. It is most probably suitable for other sea areas where phytoplankton can be sampled representatively from one fixed depth in the surface layer.

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Annex 3b

SUBMITTED TO JOURNAL OF PLANKTON RESEACH

Unattended monitoring of potentially toxic phytoplankton species in the Baltic Sea in 1993

Juha-Markku Leppänen[1], Eija Rantajärvi[1], Seija Hällfors[1], Mikaela Kruskopf[1] and Vesa Laine[2]

1) Finnish Institute of Marine Research
PO. Box 33
FIN-00931 Helsinki

2) Finnish Institute of Meteorology
Siltasaarenkatu 12 A
FIN-00530 Helsinki

Abstract

Variabilities in chlorophyll *a* fluorescence, temperature and salinity in the surface were recorded unattended on board two merchant ships in the Baltic Sea. When these recordings were complemented with automated water sampling, the phytoplankton species composition was possible to analyze in 426 samples. In total, 22 potentially toxic phytoplankton species or genera were detected. *Nodularia spumigena* was the only species that formed extensive blooms. The system has proved to be an effective early warning method for exceptional and eventually harmful algal blooms. The possibilities to use this method as an alternative - or a complement - to conventional methods in marine phytoplankton monitoring are discussed.

Introduction

The aim of the publication is to present the results of a project that studies phytoplankton dynamics in the Baltic Sea by using unattended data collection on merchant ships. The main emphasis has been the development of sampling methods for reliably monitoring the changes in the plankton community. These data should serve as early warning tools for potentially harmful algal blooms as well.

In the Baltic Sea phytoplankton blooms have intensified and toxic ones occur (Grönlund and Leppänen, 1992, Kononen, 1992). The reliable monitoring of the pelagic ecosystem has proved to be problematic because of its high temporal and spatial heterogeneity (e.g. Kahru *et al.*, 1986, Dybern and Hansen, 1989). The response of the pelagic ecosystem to eutrophication appears as rapid changes in the pelagic community, i.e. blooms. Algal blooms are extremely 'patchy' both temporally and spatially. Consequently, they often remain unobserved using the traditional sampling methods based on temporally sparse sampling at a few fixed stations (*cf.* Helcom, 1990). Furthermore, the traditional programmes are usually unable to rapidly report the observations in the case of exceptional blooms.

The quasi-continuous flow-through measurements of chlorophyll *a* have already been used since 1960s to record phytoplankton variability (Lorenzen, 1966). In the Baltic Sea, Kahru and Nömman (1990) were the first who used the system extensively on a research vessel. Not until 1990 was the system applied on merchant ships for unattended use (Leppänen *et al.*, 1991a, 1991b). The use of merchant ships is economical compared to research vessels and enables temporally and spatially extensive sampling in monitoring the marine environment.

The present research strategy is based on a combination of methods: The basic mapping of the phytoplankton variability is done by using unattended recording of chlorophyll *a* fluorescence on board merchant ships. This data is complemented with phytoplankton species identification in water samples taken automatically during the voyages. Satellite images are used to give supplemental information on the basin wide variability in the surface waters.

Material and methods

The data were collected unattended on two merchant ships in the Baltic Sea (Figure 1).

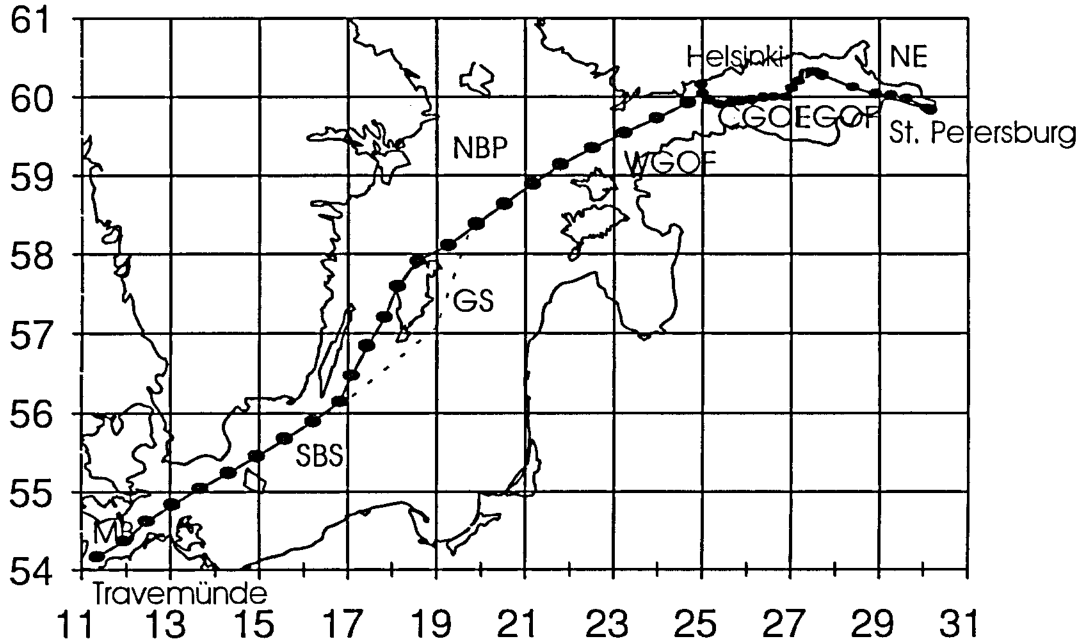

Fig. 1. Route map of the ferries 'Finnjet' in the Baltic Sea Proper and 'Konstantin Simonov' in the Gulf of Finland. The sampling points for phytoplankton species determination are depicted with dots. MB = Mecklenburgh Bight, SBS = Southern Baltic Sea, GS = Gotland Sea, NBP = Northern Baltic Proper, WGOF = Western Gulf of Finland, CGOF = Central Gulf of Finland, EGOF = Eastern Gulf of Finland, NE = Neva Estuary.

'Finnjet' crossed the whole Baltic Proper when cruising from Helsinki to Travemünde. It had two regular weekly cruises during the whole year except in the period 1 May - 20 September. Then three weekly cruises were made. In the Gotland Sea, the ship had two alternative routes, either on the eastern or western side of Gotland Island. 'Konstantin Simonov' cruised in the Gulf of Finland between Helsinki and St. Petersburg. Two weekly cruises were made in the period 1 July - 25 October. The route of the ship was constant.

The water for the sensors was pumped constantly from a fixed depth (5 m) while the ships were moving. The frequently measured (spatial resolution 100-200 m) parameters were *in vivo* fluorescence of chlorophyll a, temperature and salinity. *In vivo* fluorescence of chlorophyll a is used as an indicator of algal biomass. It is measured with a Turner Design Model AU-10 fluorometer. Temperature and salinity were recorded with an Anderaa thermosalinograph. The positions of the measurements were determined with a GPS navigator. The analyzers were controlled and data logged by a personal computer. The system was equipped with an automated water sampler (ISCO) in order to obtain material for the analysis of phytoplankton species composition. Every week, 24 water samples were taken during one voyage of the ship (Figure 1). The samples were kept refrigerated (4 ^{o}C) and in the dark before the analysis. Phytoplankton samples were preserved with Lugol AA solution and the species were determined using the inverted microscope technique (Utermöhl, 1958). The relative abundance of the phytoplankton species was determined in the 426 samples (Table 1) using semiquantitative ranking (1-5). A few samples were studied with an electron microscope (TEM) for identification of scaled nanoplankton species.

All samples collected during a weekly transect were analyzed once or twice a month. During the other transects the selections of water samples for microscopic analyses were based on the simultaneous fluorescence recordings: only samples collected at or close to fluorescence peaks were selected.

Table 1. Number of phytoplankton samples analyzed in various sea areas in the Baltic Sea in 1993

	Mecklenburg Bight	Southern Baltic Sea	Gotland Sea	Northern Baltic Proper	Western Gulf of Finland	Central Gulf of Finland	Eastern Gulf of Finland	Neva Estuary	Total
March	2	8	7	2	5				24
May	4	13	8	3	6				34
June	4	13	11	5	10	12	9	7	71
July	3	13	9	5	3	17	11	10	71
August	8	27	24	7	19	22	17	11	135
September	4	11	12	4	9	22	17	12	91
Total	25	85	71	26	52	73	54	40	426

In reporting, the data is pooled to seven sea areas (Table 2).

Table 2. The division and abbreviations of the various sea areas

Sea area	Latitude (N)/longitude (E) range
Neva Estuary (NE)	Longitude >29°
Eastern Gulf of Finland (EGOF)	Longitude 27°- 29°
Central Gulf of Finland (CGOF)	Longitide 25°- 27°
Western Gulf of Finland	Longitude 23°- 25°
Northern Baltic Proper (NBP)	Latitude 58° 30"- 60° 16"
Gotland Sea (GS)	Latitude 56° 10"- 58° 30"
Southern Baltic Sea (SBS)	Longitude 54° 30"- 56° 10"
Mecklenburg Bight	Longitude <54° 30"

AVHRR (Advanced Very High Resolution Radiometer) data from the polar-orbiting NOAA satellites were processed to detect the phytoplankton surface blooms. The size of the picture element (pixel) used in this study was 1.1 x 1.1 km. The ratio of the radiances in the NOAA satellite's Channel 1 (effective wavelength 0.65 mm) and Channel 2 (effective wavelength 0.85 mm) was used. For details of the method see Laine 1992. The satellite image information was complemented with observations made by the coastguard's aircraft pilots.

Results

Seasonal succession of phytoplankton

In 1993, the succession of the phytoplankton biomass and species composition in the Baltic Sea Proper and in the Gulf of Finland followed a typical seasonal pattern with a distinct vernal maximum (Figure 2), a summer minimum (Figure 3, June 27) and a cyanobacterial bloom period in late summer (Figure 3, July 18). In the southernmost region of the study area, an autumnal plankton bloom was recorded (Figure 3, October 14). In the Neva Estuary heavy phytoplankton blooms prevailed during the whole study period (Figure 4).

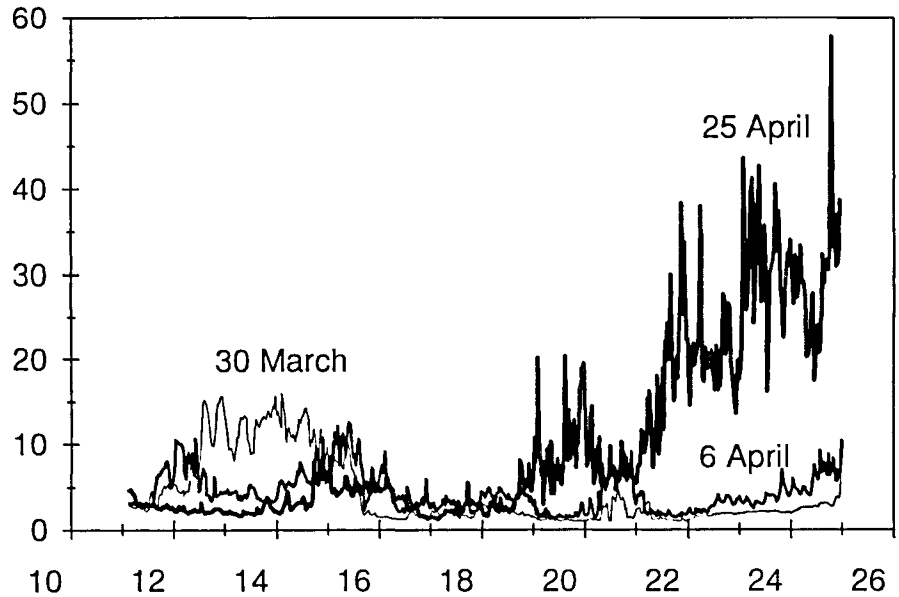

Fig. 2. Variability in the chlorophyll *a* concentrations (y axis, mg m^{-3}) in the surface layer of the Baltic Sea Proper between Helsinki and Travemünde during selected transects in spring 1993. The x-axis refers to the degrees of longitude.

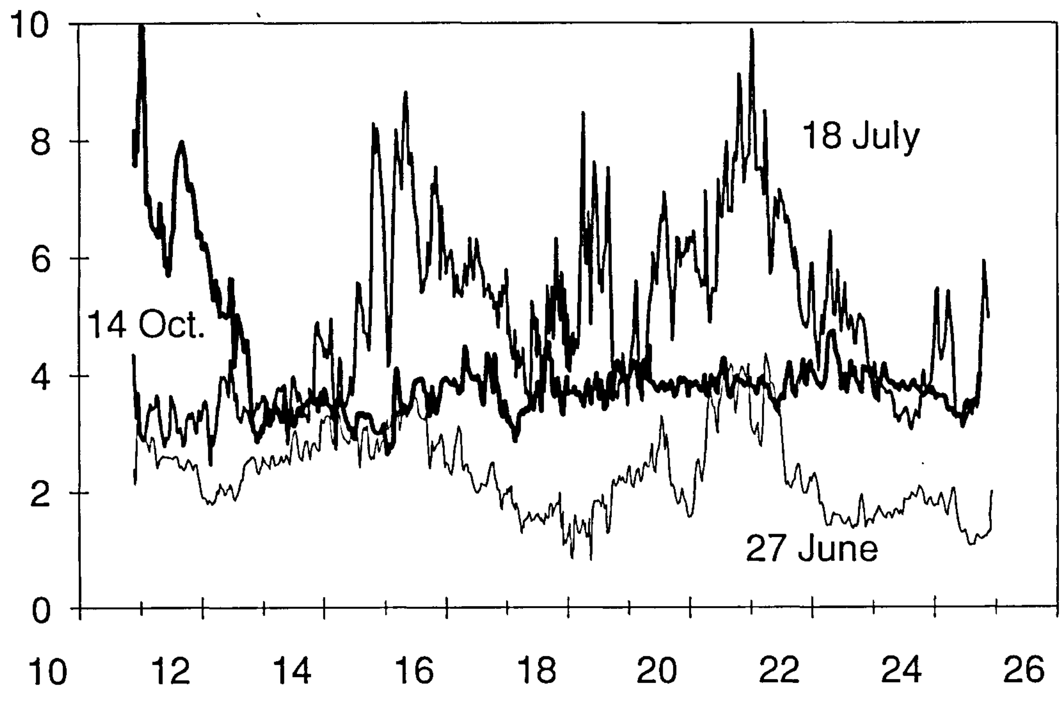

Fig. 3. Variability in the chlorophyll *a* concentrations (y axis, mg m^{-3}) in the surface layer of the Baltic Sea Proper between Helsinki and Travemünde during selected transects in summer and autumn 1993. The x-axis refers to the degrees of longitude.

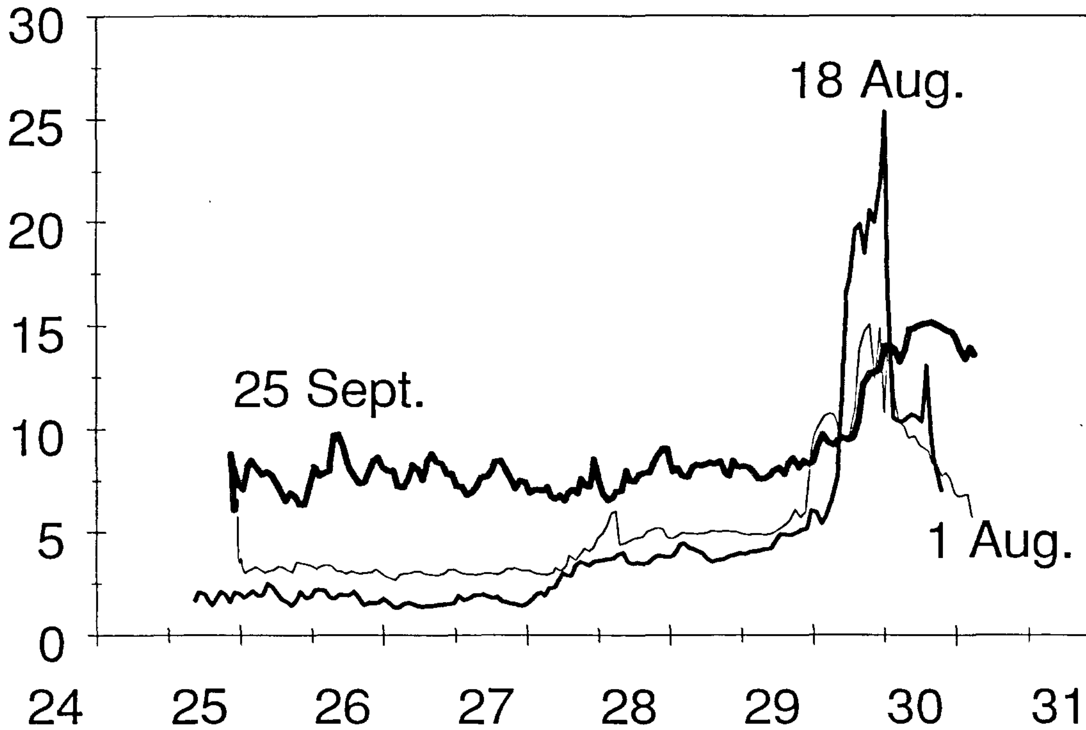

Fig. 4. Variability in the chlorophyll *a* concentrations (y axis, mg m^{-3}) in the surface layer of the Gulf of Finland between Helsinki and St. Petersburg during selected transects in summer and autumn 1993. The x-axis refers to the degrees of longitude.

Occurrence of potentially toxic species

During the growth period in 1993 a total of 22 potentially toxic species or genera were observed (Table 3). The selection of potentially toxic taxa was based on literature reviews on the toxic cyanobacteria, dinoflagellates and prymnesiophytes (Larsen and Moestrup, 1989, Tanskanen, 1990).

Table 3. Potentially toxic phytoplankton taxa determined in the water samples collected on Finnjet and Konstantin Simonov in 1993.

Nostocophyceae	Dinophyceae	Dictyocophyceae
Anabaena flos-aquae	Alexandrium spp.	Dictyoca speculum
A.lemmermannii	Dinophysis acuminata	
Anabaena spp	D. acuta	**Prymnesiophyceae**
Aphanizomenon flos-aquae	D. rotundata	Chrysocromulina spp.
Coelosphaerium kuetzingianum	D. norvegica	Prymnesium spp.
Gomphosphaeria lacustris	Gymnodinium spp.	
Microcystis aeruginosa	Heterocapsa triquetra	
.M. flos-aquae	Prorocentrum minimum	
Nodularia spumigena		
Oscillatoria spp.		
Planktothrix agardhii		

Aphanizomenon flos-aquae was present in all sea areas during the whole study period while the other cyanobacteria species were more concentrated to the late summer and autumn (Figure 5). *Nodularia spumigena* formed large surface blooms in July-September. The blooms were well detectable in satellite images (Figure 6). In the eastern parts of the Gulf of Finland *Planktothrix agardhii* and *Oscillatoria* species were the dominant and most constant cyanobacteria (Figure 5).

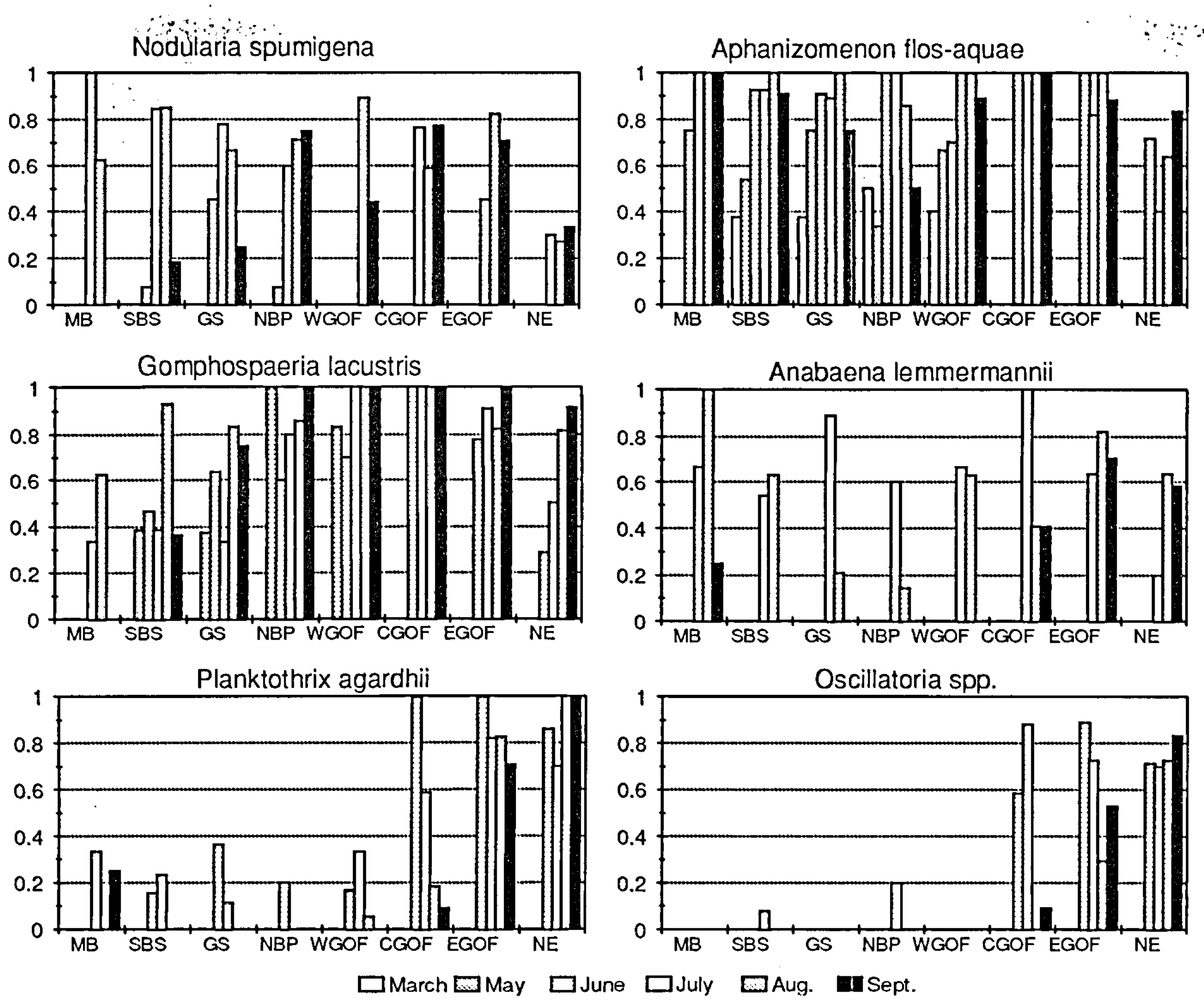

Fig. 5. Constancy (the ratio of the number of samples with the species present to the total number of samples analyzed in the respective area) of the potentially toxic species of Nostocophyceae in the Baltic Sea Proper and in the Gulf of Finland in 1993. The abbreviations of the sea areas are presented in Table 2. For a sampling schedule see Table 1.

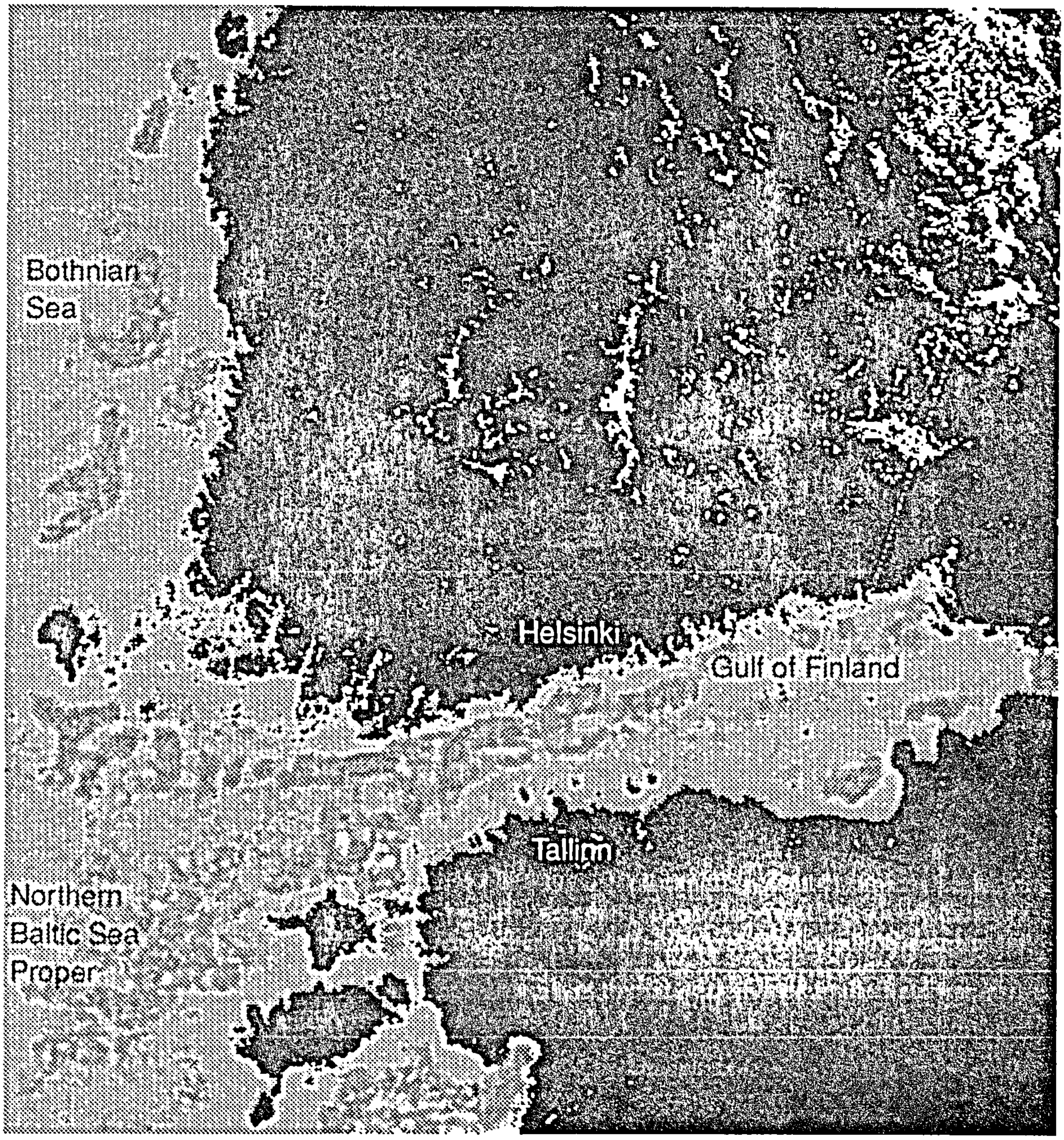

Fig. 6. The extent of surface cyanobacterial blooms in 1993 in the northern Baltic Sea. The figure is compiled from the results obtained from the satellite images, the ferries' recordings, and reports of the coastguard's aircraft pilots.

Dinophysis acuminata and *Gymnodinium* species were the most constant dinoflagellates (Figure 7). The potentially toxic dinoflagellates did not form marked blooms in 1993. *Prorocentrum minimum* was constant in the Southern Baltic Sea and Northern Baltic Proper in September. In the Mecklenburg Bight it was abundant in August-September.

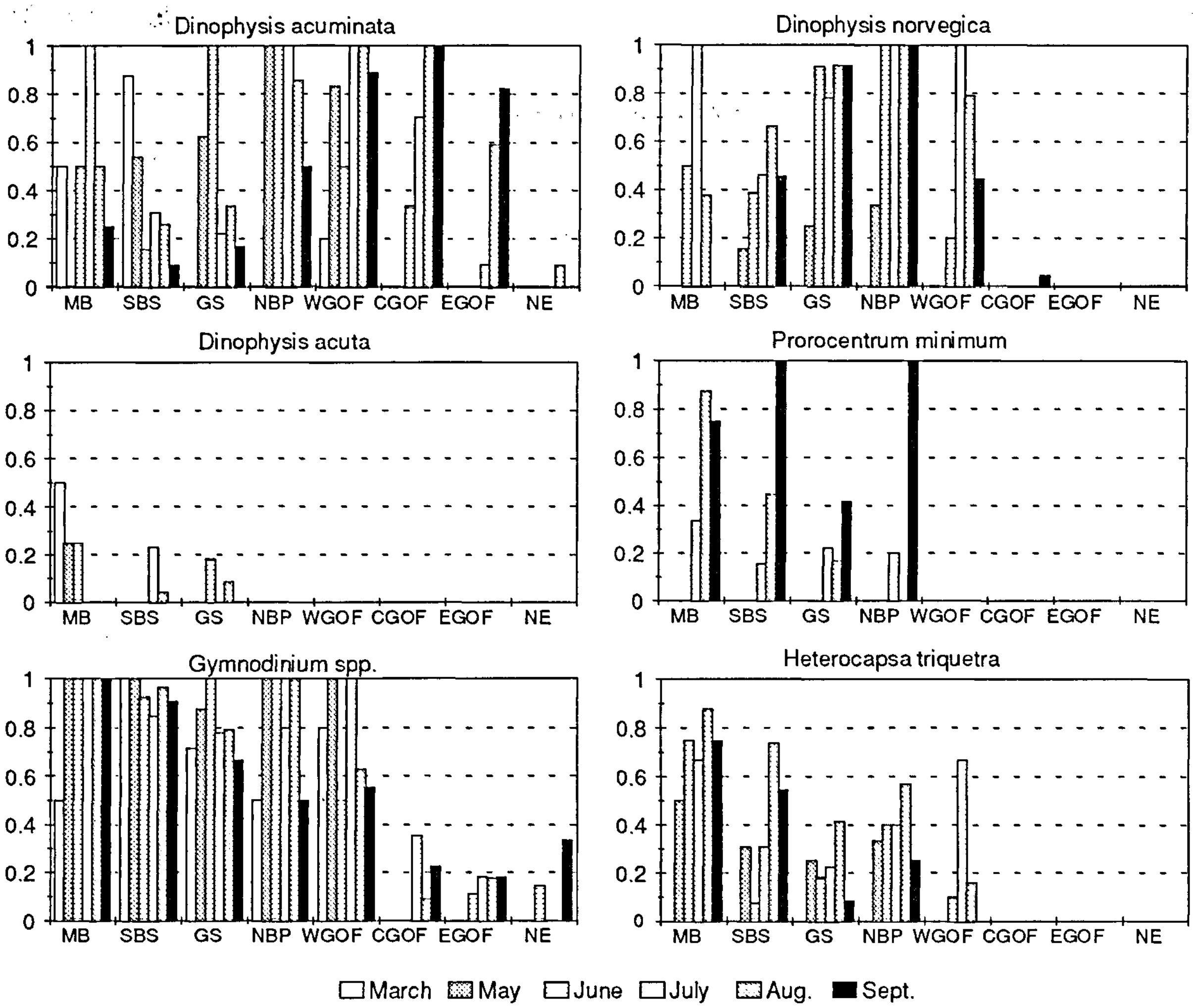

Fig. 7. Constancy (the ratio of the number of samples with the species present to the total number of samples analyzed in the respective area) of the potentially toxic species of Dinophyceae in the Baltic Sea Proper and in the Gulf of Finland in 1993. The abbreviations of the sea areas are presented in Table 2. For a sampling schedule see Table 1.

Chrysochromulina (Prymnesiophyceae) species were almost constantly present in all areas (Figure 8). For the present, the species identification by TEM has been made only for a few samples with the highest cell numbers. *Chrysochromulina ericina, C. hirta and C. spinifera* were the most abundant species in the samples collected from the Northern Baltic Proper (6 July, 14-17 x 10^6 cells l^{-1}), but also *C. alifera, C. brevifilum, C. leadbeateri, C. minor* and *C. polylepis* were identified.

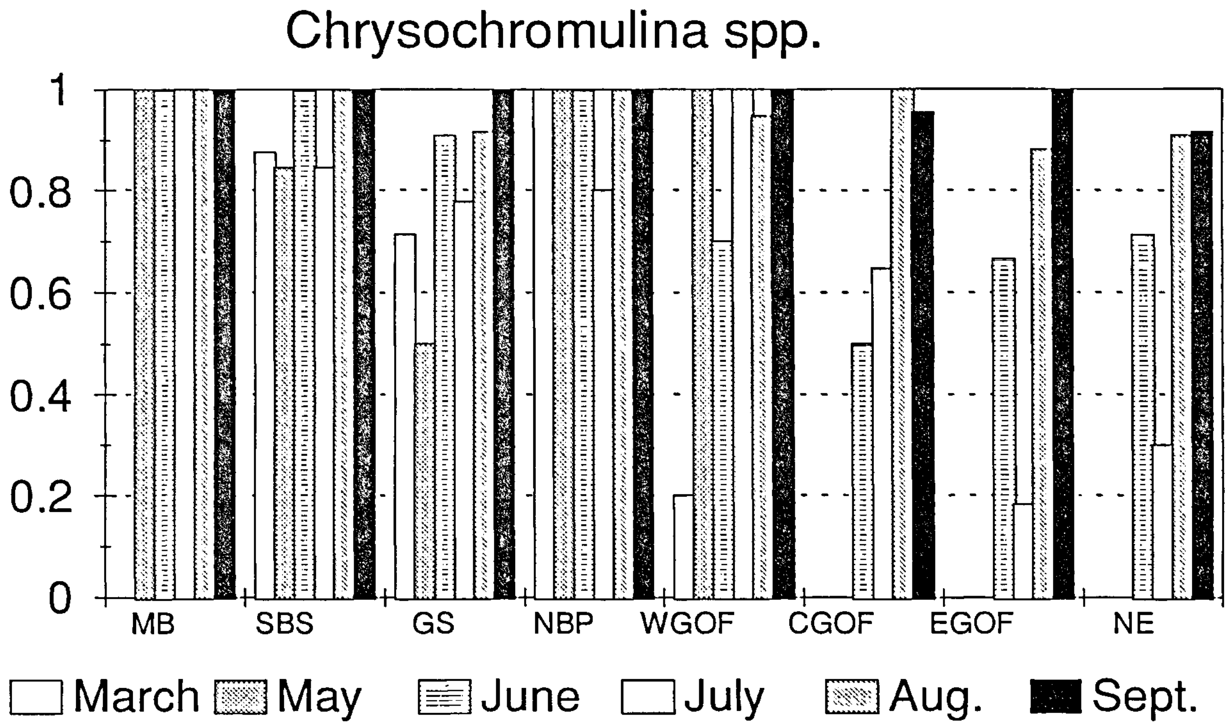

Fig. 8. Constancy (the ratio of the number of samples with the species present to the total number of samples analyzed in the respective area) of *Chrysochromulina* spp. in the Baltic Sea Proper and in the Gulf of Finland in 1993. The abbreviations of the sea areas are presented in Table 2. For a sampling schedule see Table 1.

Discussion

Even though a number of potentially toxic phytoplankton species exist in the Baltic Sea, no human fatalities caused by the toxic algal blooms have ever been reported in the area. Deaths of domestic animals caused by the cyanobacterial blooms have been observed in some coastal areas (Lindstrøm, 1976, Lind *et al.*, 1983, Lundberg *et al.*, 1983, Persson *et al.*, 1984, Gussmann *et al.*, 1985, Edler *et al.*, 1985). The toxicity is caused by *Nodularia spumigena* and has been verified by a mouse bioassay and the toxin chemically determined (Sivonen *et al.*, 1989). Other cyanobacteria have not clearly proven to be toxic in the Baltic Sea.

Chrysochromulina polylepis has caused mass fatalities in fish and benthic animals in the Kattegat-Skagerrak area in spring 1988 (Dahl *et al.*, 1989) and *Prymnesium parvum* has killed fish in the southwestern coast of Finland (Lindholm and Virtanen, 1992). In a restricted bay close to Stockholm in Sweden mass fatalities of fish were reported in 1991 and 1992. The deaths were believed to have been caused by *Prymnesium parvum*, but also *Chrysochromulina parva* occurred in high numbers (G. Anèer, personal communication). The mass fatalities of birds and seals in the Eastern Gulf of Finland was assumed to be caused by some toxic vernal bloom species (Kauppi, 1993). The dinoflagellates have not been reported to have caused any toxicity in the Baltic Sea, most probably because the Baltic mussels are not a human food source.

In 1993, according to our results, 22 potentially toxic phytoplankton species or genera were detected in the samples, majority of them rather constantly. Only the cyanobacteria *Nodularia spumigena* and *Aphanizomenon flos-aquae* formed extensive blooms. The patchy blooms of *Nodularia spumigena* covered the whole Baltic Sea Proper and the Gulf of Finland in July-September. The Finnish coastguard reported large blooms in the Bothnian Sea, too. In the easternmost Gulf of Finland, the cyanobacteria *Planktothrix agardhii* and *Oscillatoria* species dominated in the blooms. The cyanobacteria had a tendency to be most constant in the eastern Gulf of Finland, while the dinoflagellates in the southern areas.

Chrysochromulina species made small peaks along the ship routes and were abundant in several areas. *C. leadbeateri* and *C. polylepis* were present only in small numbers. The two last-mentioned species have formed toxic blooms in more saline waters (Graneli *et al.* 1993). *Prymnesium* cells occured in some samples, but were not verified with TEM.

At the entrance to the Gulf of Finland, the samples collected on board R/V Aranda at the end of July were all hepatotoxic (K. Sivonen, personal communication). In the Porvoo archipelago in the northern coast of the Gulf of Finland, an intoxication of a dog was suspected to have been caused by a cyanobacterial bloom at the end of September. No samples for toxicity analyses were collected in that area. Unusual late cyanobacterial blooms were detected in late October in the coastal areas of the Åland archipelago in Finland as well as in the Stockholm archipelago in Sweden. In the Stockholm archipelago the death of a dog was assumed to be caused by cyanobacterial intoxication. The samples collected from the area were hepatotoxic (G. Anéer, personal communication). No intoxications were reported in the Åland area.

The large salt water intrusion to the Baltic Sea in early winter 1993 was expected to cause the nutrient rich Baltic deep-water to move and eventually to upwell into the euphotic layer. This was expected to intensify the phytoplankton blooms. These phenomena were not observed in our recordings nor reported elsewhere.

The unattended sampling method on ferries was found to be an effective tool in collecting data on algal blooms. The dense spatial sampling in combination with the frequent voyages made it possible to detect the patchy blooms reliably. In the early warning monitoring of harmful blooms, it was possible to select the samples for analyses, if the simultaneously measured chlorophyll *a* fluorescence values were high, indicating bloom formation. The number of samples analyzed was reduced but the necessary information on the bloom forming species was still obtained. On the basis of these results, authorities were rapidly informed of the algal bloom situation.

Acknowledgements

We would like to thank the 'Silja line' shipping company for allowing us to carry out the measurements on board the ferry 'Finnjet'. Special thanks are due to the crew of 'Finnjet' for their kind technical assistance.

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Annex 5

MONITORING NUTRIENT FLUXES

AND

THEIR EFFECTS

Parts of this paper were produced as background material for a discussion of monitoring by the Advisory Committee on the Marine Environment at its June 1994 meeting. Many of the scientific ideas came from discussions with other colleagues, both inside and outside ICES. Errors and Opinions are solely the responsibility of the author.

Thomas Osborn

In the late 19th Century, political institutions in the northern countries of the North Atlantic set up corps of government scientists in laboratories, mainly to answer the following questions: `What is fish food, where does it come from, and how does it affect stocks and exploitation of fish?' Within a few decades, these scientists had already provided the wisdom of the classical paradigm as part of the answer. Later, the methods were extended to other oceanographic systems (the tropics, the Mediterranean, monsoon systems, the Antarctic). Then in the 1970s and 1980s, it seemed as if the rediscovery of the picoplankton and the discovery of the microbial loop would show the old paradigm to be too simplistic. Now, however, it is becoming clear that the new information, although adding interesting ecological details, is of little overall relevance to the fish-food question: the classical paradigm has survived essentially unscathed.

Over the last 30 years, people have become much more aware about how different modes of economic and ecological production and fluxes interact. As a result, political institutions are now asking the successors of these scientists new questions, such as `How, and how much, may coastal enrichment be changing DMS production, global warming and the occurrence of toxic and slimy blooms?'; `What is the role of the oceans in the draw-down of new CO_2?'. The classical paradigm is largely irrelevant to such new questions, for which new paradigms are being extracted from both old and new data. Such new paradigms may generally have to include some of the interesting ecological details (such as the picoplankton, parasites, viruses, the microbial loop, DOM, aggregations and rheological modification of flow fields, toxins and telemediators, regulation of growth by grazing) that the economic paradigm could successfully ignore.

(Wyatt and Jenkinson, 1993)

I. INTRODUCTION

Many monitoring programs have come and gone and many more will do so in the future. Funding problems tend to remove or diminish monitoring programs. Environmental problems or disasters tend to foster new monitoring programs. Countries do not have the resources to cure the funding situation nor the ability to predict and/or prevent disasters. Pressures on coastal waters and national budgets are only going to increase!

II. MONITORING ENHANCED NUTRIENT SUPPLY AND EUTROPHICATION

II.1. Introduction

Nutrient trends in the continental and UK rivers for the last 60 years show increasing input of nutrients (NO_3 and PO_4). Much effort has been expended to relate the increasing input to a trend of increasing nutrient levels in the North Sea. WHY? Presumably to show that the nutrient supply has a role in eutrophication by increasing the level of nutrients in the water column.

There are problems with the data analysis.

1) There is a shortage of data. The early nitrate data was flawed. Coverage is erratic.

2) In order to avoid effects of biological production, comparisons use in-situ values from January and February data under the assumption that biological production is minimal. A recent paper by Dickson and Kirkwood (1992) indicates a significant annual cycle with the minimum in mid-late February.

3) The flushing time of the North Sea is on the order of one year and the major nutrient input is during the spring runoff. Waiting until the following winter to measure nutrients allows significant loss of the input.

4) Intercomparison between different vessels in the same location show significant fluctuation in nutrient levels on similar water samples. While the root-mean-square error was relatively low, the ship to ship variation was such as to mask natural variations or a mean trend for many years.

5) Tracking nutrient concentrations is the wrong indicator, especially in winter during the low growth season. Nutrients are the wrong indicator! The problem is excessive or obnoxious plant

growth, phytoplankton, macroalgae and periphyton. There is no known relation between the nutrient concentrations in the water column and the contentment of the citizenry.

II.2. ICES past contributions

Much time and effort was spent by ICES' staff and Working/Study Groups over the past several years. Unfortunately the QSR 1993 still may not reflect a clear understanding of the situation. Comparison of phosphate measurements with the 1935/1936 Poseidon data show the enhanced nutrient levels to be along the continental coastline, from the Rhine outlet, along the Dutch and German coasts and then up the Danish coast (Figure 3-19 of the 1993 North Sea QSR). It should be noted that this calculation and figure were first produced during an ICES Shelf Sea Working Group meeting in Copenhagen, and relied upon the expertise of the Hydrographer, the data base at ICES and the discussion of the Study Group.

II.3. Flux of Nutrients into plant material is the crucial parameter

Examination of the sources of nutrient to the North Sea indicate that the anthropogenic sources are small relative to the input from the Atlantic Ocean through the Dover Strait and around Scotland. Were it not for the fact that the input is trapped in the continental coastal zone by the circulation pattern (rather than completely mixed into the open North Sea) the effect would be significantly less, perhaps impossible to detect.

However it is the circulation, specifically the fact that the fresh water input acts less like water running down a gutter but instead functions as a source of buoyancy along the coast - hence a quasi geostrophic balance between the pressure gradient, the Coriolis force and the bottom drag. There is little mixing because the two watermasses differ in salinity, and hydrodynamic characteristics.

Many coastal regions have a similar situation where rivers and estuaries supply relatively fresh plumes to the surface. The plumes are often directed along the coast by the Coriolis force - turning to the right in the northern hemisphere. Once in the coastal ocean the dynamics become rather complicated with wind forcing bottom drag, tidal currents and the Coriolis force all playing a part. The flow is not a simple extension of the river and estuary flowing along the coast - like water along the street in the gutter next to the curb. Rather the effect becomes like a front with higher water along the coast and lower water out to sea, this produces an offshore pressure gradient which leads to semi-geostrophic flow. This flow reaches its maximum speed away from the shore where the lateral density gradient (and hence the pressure gradient) is largest. Sloping bottom topography can severely restrict the tendency to meander and hence reduce lateral mixing. Thus the trapping of the nutrients along the coast and the lack of mixing into the larger North Sea is related to the physical dynamics.

The short-term fate of the nutrients is to be absorbed into plant and secondly animal tissue. The long-term fate is to be deposited on the ocean bottom (above or below the water line) or else be flushed out to sea. Society is most concerned with those nutrients that lead to enhanced plant growth on the shoreline or bottom sedimentation that results in oxygen depletion. If it is the plant growth that bothers us, why don't we monitor that rather than the nutrient concentration in the water column. Presumably the continuing (and in the past ever increasing) flux of nutrients down the rivers is leading to an increase in the net plant production.

What could be done to monitor the situation more appropriately and to monitor the changes due to efforts to decrease the input flux? The monitoring should be focused on the net production of plant material.

1) How much is growing on selected portions of the shoreline?
2) How much is being washed ashore as obnoxious plankton biomass?
3) Are there changes in species composition?

The problems we now get into are major research areas in biological oceanography and remote sensing

II.4. Scientific Questions for ICES Working/Study Groups

The fate of the nutrients in the North Sea involves all the different specific oceanographic disciplines. The riverine input becomes part of a buoyant plume and coastal current. For some reason the mixing is limited and this plume continues along the coast. What defines the limits of the fresh water influence? How do these physical processes interact with the population dynamics of the plankton to affect the utilization of the nutrients? What is the role of convergence and divergence at the plume boundaries in concentrating and dispersing plankton blooms?

Monitoring and developing an understanding of the biomass and productivity of the plankton is crucial. Are the present programs on production measurements (e.g. C^{14}) going to provide the insight we need? Would we be better advised to develop relationships between the optical properties and the net and gross production? Sakshaug and Slagstad gave significant talks on the relations between light, plant production and hydrodynamics at the Mare Nor Symposium in December 1994. There is at present a lot of work on relating optical properties of the water column (both inherent and apparent) to the material in situ. Would aircraft remote sensing, combined with vertical profiling (from ships) of optical properties give us a better measure of biomass and production than the classical net tows and C^{14}? For example

AVIRIS has resolution of the ocean surface to 20m per pixel and 220 wavelengths between 0.4 μm and 2.45 μm (Green, 1993). Such a system can differentiate between phytoplankton types. The pump-and-probe fluorescence technique can profile both biomass and productivity (Kolber et al., 1990). Gentien and Lunven (1993) have developed an in-situ probe for particle size measurement as well as total particle load.

II.5. Conclusions on nutrient monitoring

1) The past approach, concentrations of nutrients in the water column, has been inappropriate for assessing the role of nutrients in eutrophication of the North Sea.
2) Understanding of the situation has been slow in coming.
3) Integration across disciplines was relatively weak.
4) New technology and a new approach would allow monitoring that would more directly answer the societally important questions.

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