AVHRR imagery reveals interannual variations of surface cyanobacterial accumulations in the Baltic Sea

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ABSTRACT

With the aid of a large number of processed and analysed satellite scenes from the Advanced Very High Resolution Radiometer (AVHRR) sensor on the NOAA satellites, it has been shown that during the 1980th to the early 1990th the interannual variations of surface cyanobacterial accumulations in the Baltic Proper were considerable. The time period showed two peaks of accumulation, the first during 1982-84 and the second starting in 1990 and onward. The last period included the 1993 season, in spite of the unfavourable conditions during that summer. The total area covered by cyanobacterial accumulation as detected by AVHRR imagery, ranged from zero in the mid 1980s to over 62 000 km^2 in 1992. In 1992 the accumulation also appeared for the first time in the Gulf of Riga and reappeared in the western Gulf of Finland. The algorithm to detect the cyanobacterial accumulations relies on their increased reflectance in AVHRR channel 1, together with their high spectral structure. Apart from AVHRR, Coastal Zone Colour Scanner (CZCS) data have also been analysed for the occurrence of cyanobacterial accumulations. The variations, or maybe increase, in the 1990th of the amount of cyanobacterial accumulations could represent a structural shift in the planktonic communities. The increased input of atmospheric nitrogen (via N_2 fixation by cyanobacteria) and the consumption of deep water supplied phosphorus could for example lead to higher levels of eutrophication. A full understanding of the mechanism behind the algal bloom variations requires an integrated approach between remote sensing and marine biological and ecological sciences. During 1994 a successful attempt was carried out to use locally received AVHRR data for near real time monitoring of the extensive bloom that summer. The present study contributes with a description of the spatial and temporal dynamics of the surface cyanobacterial accumulations.

1. INTRODUCTION

In the Baltic Sea regularly occurring blooms of nitrogen-fixing filamentous cyanobacteria, pose a major environmental and even health hazard. The conspicuous late summer blooms in the open sea are dominated by the species *Nodularia spumigena* and *Aphanizomenon flos-aquae*, the first one being facultatively hepatotoxic in the Baltic Sea (Kononen, 1992). Although the first reports of dense cyanobacterial blooms date back to the mid 19th century (references in Wallström, 1991), it has been suggested that the extent and intensity of the blooms has increased due to anthropogenic eutrophication (Horstmann, 1975). However, due to the inherent spatial and temporal variability, the long-term changes are difficult to prove using data from conventional shipboard monitoring.

At some stage of the bloom, cyanobacterial filaments become positively buoyant and flocculate near the sea surface in a process called inverted sedimentation (Horstmann et al., 1986). At low wind speeds these cyanobacterial agglomerates accumulate at the surface and become clearly visible even on low-sensitive satellite imagery (Öström, 1976). Various satellite imagery of the Baltic Sea (Landsat / MSS and TM, Nimbus-7 / CZCS, NOAA / AVHRR) is available since the mid 1970s and could be used for detecting the dynamics of cyanobacterial blooms during the last couple of decades. Especially useful in that respect is the AVHRR which has a wide swath width, frequent coverage, has been flown on the NOAA series of satellites with little modifications since 1979, and is comparatively inexpensive to achieve and process. All these characteristics are important in creating a high-volume, long-term database.

2. DATA SOURCES AND PROCESSING

AVHRR data from various NOAA satellites for the years between 1982 and 1993, covering the period from late

June until the end of August, were analysed for the possible occurence of surface cyanobacterial accumulations. This analysis was done manually by an adaptive enhancement of each available digital data scene. After a final selection of sufficiently cloud free scenes, 135 day passes were digitally processed for the calculation of cyanobacterial areal coverage and geometrically corrected and registered to an Albers equal area projection (Baldwin and Emery, 1993).

An ad hoc procedure to detect cyanobacterial accumulations in AVHRR data were designed as follows: The digital filter uses multiple thresholding and differences of AVHRR bands 1, 2, 4 and 5. It was determined empirically that the band 1 albedo of cyanobacterial accumulations was between 2.3% and 4%, with lower values classified as water and higher values classified as clouds. To account for the characteristic spatial texture, variance in a 3x3 pixel window was calculated. Only areas with the variance above a certain threshold were considered further. Pixels with band 2 albedo exceeding the corresponding band 1 albedo by 0.2% values were classified as land or error. Pixels with the band 4 radiance temperature colder than a certain threshold and with the band 4 and band 5 difference greater than 2°C were considered to be clouds.

Apart from the NOAA AVHRR imagery, constituting the bulk of the data set, a number of CZCS scenes has also been checked for the occurrence of surface accumulations. The use of CZCS imagery for a retrospective study of the interannual cyanobacterial variations is conducted within the programme "Use of historical CZCS data in application demonstration projects".

High resolution imagery, Landsat TM, has been used to study the surface accumulations in more detail, and also in a comparison with AVHRR data. The TM scene, registered on the 8th of July 1992, covered a bloom situation in the southern Baltic. From the same bloom there were also AVHRR images available together with shipboard samples taken from the ferry "Finnjet", which plies between Helsinki, Finland, and Travemünde, Germany. The bloom situation showed an example of how cyanobacterial plumes, with an increased albedo compared to the surrounding sea area, caused increases in SST by up to 1.5° C (Kahru et al., 1993).

3. INTERANNUAL VARIATIONS

For each year (1982-1993) maps of the cumulative area as well as the total area covered by the accumulations were compiled (**Figs. 1,2**). The extensive bloom during July - August 1994 has not yet been fully included in the comparison. The seasonal interval for the detected accumulations ranged from June, 30 (1990) to August, 24 (1984). No obvious trend of a shift in the bloom period during the investigated twelve years could be seen.

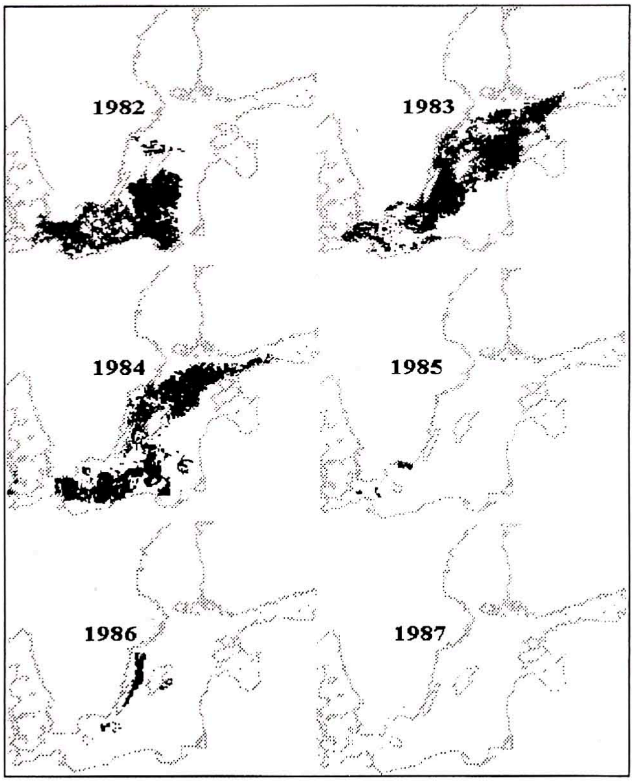

Figure 1a - Annual cumulative distribution of cyanobacterial accumulations in the Baltic Sea during 1982-1987 as detected from NOAA/AVHRR imagery

Two periods of increased cyanobacterial coverage can be detected: from 1982 to 1984 and from 1990 to 1993 (**Fig. 2**). The decrease from 1992 to 1993 can be a response to the windy conditions in July-August 1993 which was unfavourable for the accumulations to appear at the surface. The values of cyanobacterial accumulations can only be regarded as the lower bounds of the true total areas due to incomplete satellite sampling and obscuring cloud cover.

4. INCREASING ACCUMULATIONS OR NATURAL VARIATIONS?

The appearance of the surface accumulations depends both on the amount of cyanobacterial filaments in the water column, and on conditions causing their inverted sedimentation. It is generally considered that *Nodularia* blooms in the Baltic are initiated if sufficient phosphorus is available and the water temperature exceeds 16°C (Horstmann, 1975, Niemi, 1979, Niemistö et al., 1989). These conditions, even if generally valid, are hardly sufficient to predict or model the actual bloom areas. As expected, years with more sunshine in July-August tend to have more cyanobacterial accumulations. Therefore, some of the interannual variation in the extent of accumulations can be explained by the variation in the amount of sunshine. However, the area covered by the accumulations in 1991-1993 seems to be disproportional high, even when considering the higher sunshine duration.

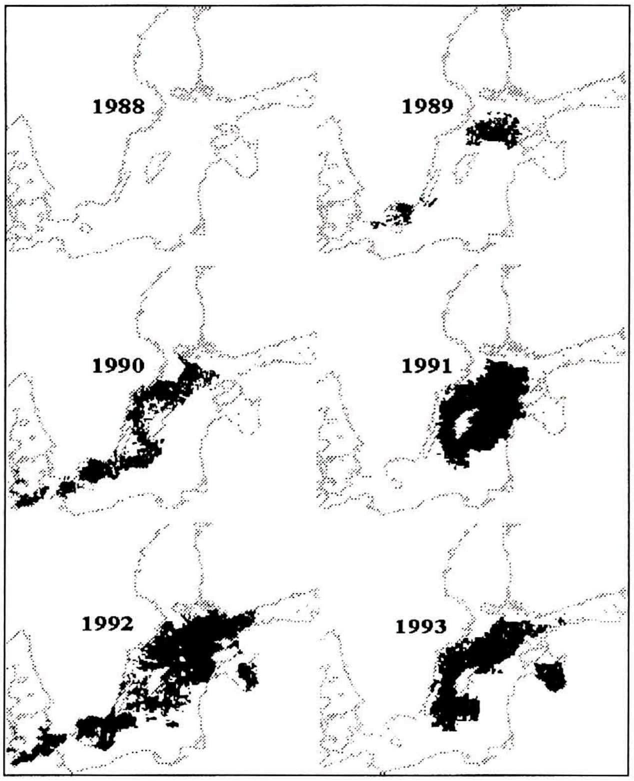

Figure 1b - Annual cumulative distribution of cyanobacterial accumulations in the Baltic Sea during 1988-1993 as detected from NOAA/AVHRR imagery.

Since 1992 the cyanobacterial accumulations reappeared in the western Gulf of Finland where they have been missing after 1984, which is in accordance with *in situ* observations (Kononen, 1992). In 1992-1993 massive visible accumulations were observed for the first time on satellite imagery in the Gulf of Riga, even though summer blooms of cyanobacteria are a regular phenomenon there. No obvious accumulation could be detected in the Gulf of Riga in 1994.

The variations, or maybe increase in the 1990th, of the amount of cyanobacterial accumulations could represent a structural shift in the planktonic communities. The increased input of atmospheric nitrogen (via N_2 fixation by cyanobacteria) and the consumption of deep water supplied phosphorus could for example lead to higher levels of eutrophication. Possible causing factors are variations in the riverine phosphorus input and/or changes in the phosphorus to nitrogen ratio. Other factors that could be involved are changes in the total nutrient levels, micronutrients and trace metals, as well as changes in the phyto - zooplankton relations. A clue to the identification of the dominant factor(s) could be achieved by studying different

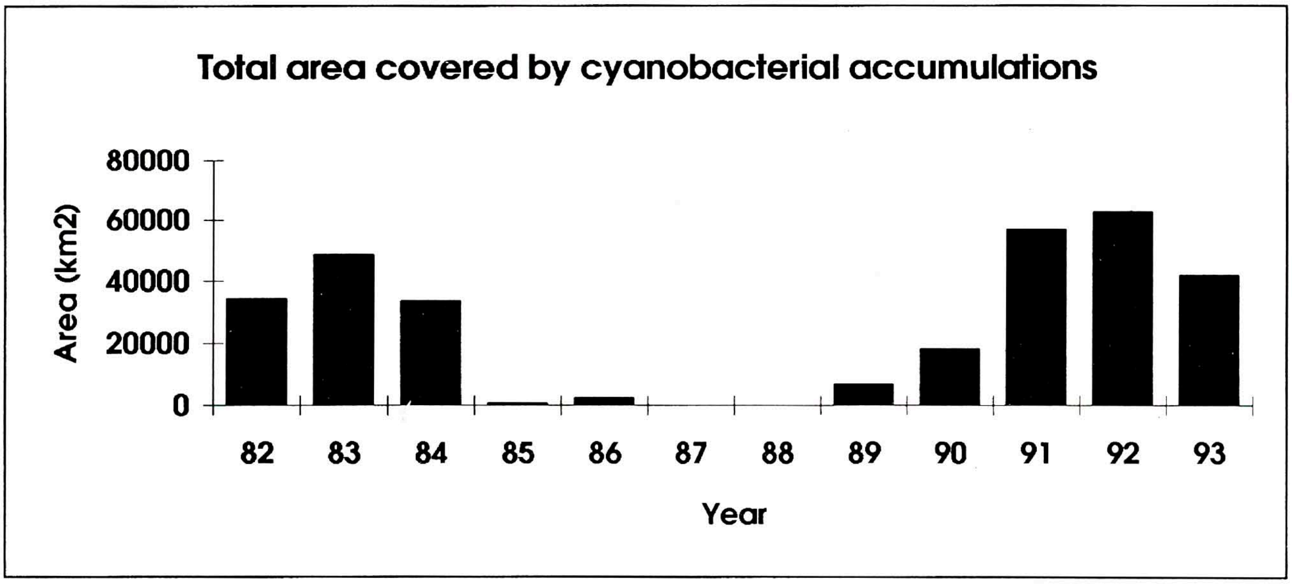

Figure 2 - Interannual dynamics of the total area covered by satellite detected cyanobacterial accumulations in the Baltic Sea from 1982 to 1993.

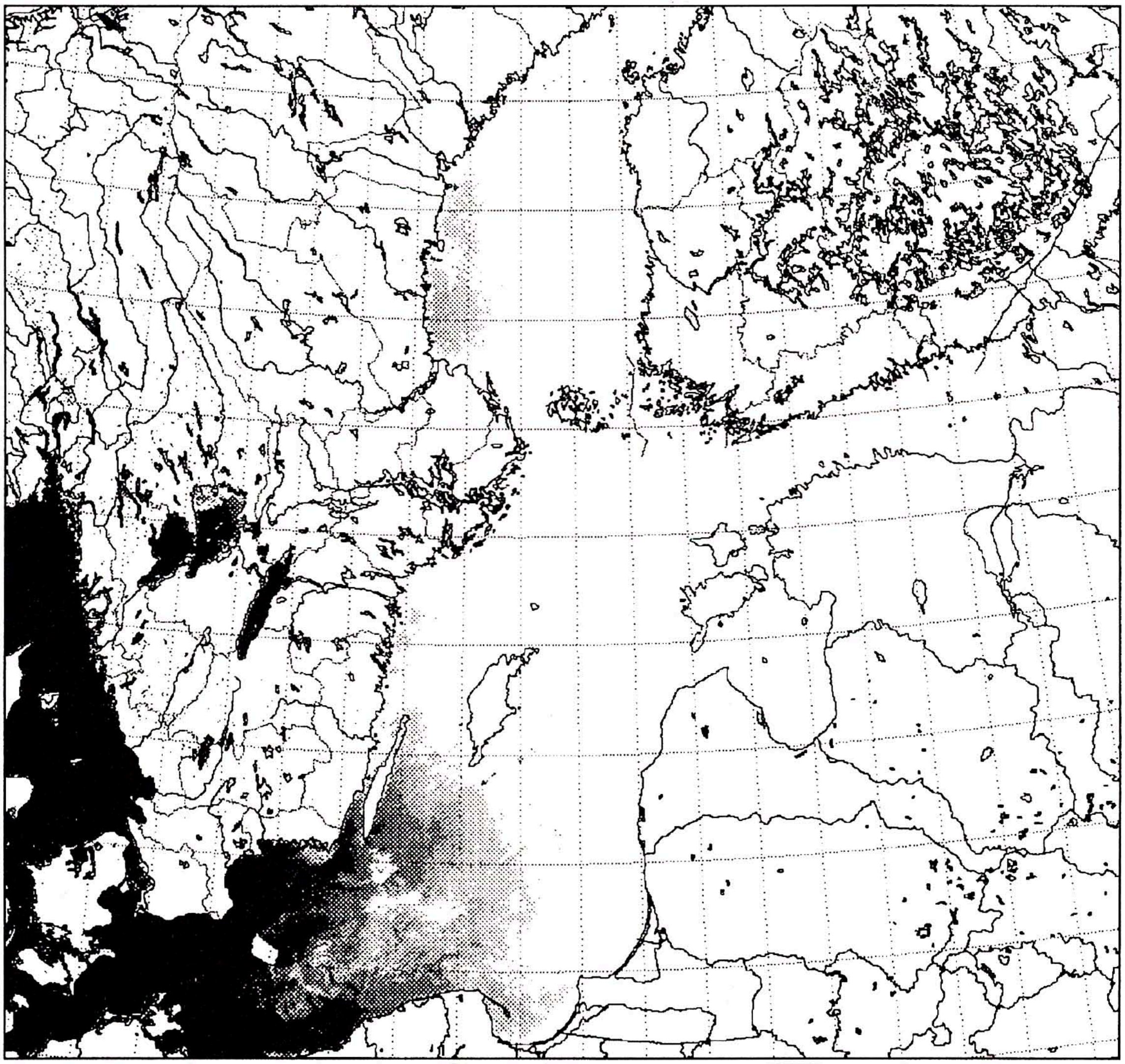

Figure 3 - The first clearly detectable cyanobacterial accumulation in 1994 were recorded on July 20, 15.29 UTC by NOAA 11. The surface accumulation is visible as black and white patterns in the southern Baltic Proper from Bornholm and eastwards to the Bay of Gdansk. There are some scattered clouds over the northern Baltic Proper but the strong contrast enhancement has caused the whole area to be white. On the following day, large parts of the middle and northern Baltic Proper were covered by surface accumulations.

sea areas where the accumulations appear more frequent than in other areas. An example of a frequently affected area is the Hanö bight on the south-eastern coast of Sweden, while the Bay of Gdansk on the Polish coast is an area where visible surface accumulations have been missing after 1984. Preliminary results indicate that the opposite were the case during the 1994 season.

5. POSSIBILITIES FOR NEAR REAL TIME MONITORING

During the summer of 1994 a large number of AVHRR images were received and processed for the occurrence of cyanobacterial accumulations. The information is presently being processed for further analysis of the interannual variations.

The 1994 bloom was first detected in AVHRR imagery on the 20th of July, covering a large part of the southern Baltic Proper from Bornholm to the outer parts of the Bay of Gdansk **(Fig. 3)**. Already on the 14th of July there was some weak indications of a bloom north-east of Gotland. The indications at that time and the following days were not strong enough to inform regional and local authorities that a bloom had started. On the 20th of July the information flow started to work. AVHRR images were received and processed at least twice a day at the Department of Physical Geography, Stockholm University, during the whole period (July 20th - August 10th), when the bloom was detectable. Accumulation maps, based on interpreted images, were distributed to both the "Information centre for the Baltic Proper" at the county administration in Stockholm, and the Finnish Institute of Marine Research in Helsinki. Almost real time information of the spatial bloom status could then be transferred to local authorities and different mass media.

6. CONCLUSIONS

A full understanding of the mechanism behind the algal bloom variations requires an integrated approach between the remote sensing and the marine biological and ecological sciences. The spatial and temporal dynamics of the cyanobacterial accumulations supplied by the remote sensing technique is one source of information in the search of the causing mechanisms for the cyanobacterial blooms. Satellite based monitoring of the distribution of cyanobacterial accumulations can be a valuable operational tool for environmental monitoring, both in real time and as a mean of detecting variations in the decade time scale. The possibilities for a successful monitoring increases when more marine adapted satellite-sensor systems will be available for the next couple of decades.

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