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Cyanobacteria blooms in the Gulf of Finland triggered by saltwater inflow into the Baltic Sea

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ABSTRACT: In the 1980s and 1990s prior to 1995, massive blooms of the diazotrophic cyanobacterium *Nodularia spumigena* occurred in the Baltic Sea Proper but never extended into the central and eastern Gulf of Finland. The absence of nitrogen-fixing cyanobacteria blooms in parts of the Baltic Sea with a high N:P ratio (e.g. Gulf of Finland) has been explained by their reduced competitive advantage in conditions of P limitation. Starting with the summer of 1995, massive blooms of *N. spumigena* occurred in the central and eastern Gulf of Finland, as detected by both satellite sensors and *in situ* monitoring. We propose that the eastward expansion of *N. spumigena* blooms was triggered by the 1993 saltwater inflow into the Baltic. With the arrival of the saline and oxygen-depleted waters in the Gulf of Finland in 1995, stratification in the bottom layers increased, oxygen concentrations decreased, and increased amounts of phosphate were released from the sediments. The subsequent decrease in the N:P ratio may have caused the reoccurring *N. spumigena* blooms.

KEY WORDS: Cyanobacteria · *Nodularia* · Nutrients · Gulf of Finland · Baltic Sea

INTRODUCTION

Summer blooms of nitrogen-fixing cyanobacteria are common in the brackish waters of the Baltic Sea (Horstmann 1975, Kononen 1992, Sellner 1997). The initiation of cyanobacteria blooms in the Baltic Sea has been traditionally related to the low N:P ratio (Niemi 1979), resulting from the high concentrations of phosphorus in the low-oxygen or anoxic bottom layers (Niemistö et al. 1989). Most conspicuous are the blooms of the hepatotoxic *Nodularia spumigena*. In later stages of a bloom, *N. spumigena* filaments become positively buoyant and aggregate into large agglomerates in the surface layer, giving the impression of yellow snowflakes (e.g. Kahru et al. 1994). The filaments are highly reflective at visible and near-infrared wavelengths due to the refractive index of the gas vesicles. At low wind speeds, the agglomerates accumulate in the top few meters and can be observed with broad-band satellite sensors (Horstmann 1975, Öström 1976). *N. spumigena* blooms in the Baltic have received much attention due to their toxicity and potential nitrogen-enrichment capability. A quantitative time series of satellite-detected total area of cyanobacteria accumulations in the Baltic Sea between 1982 and 1994 showed a cyclic pattern, with variations between 0 and 100 000 km^2 (Kahru et al. 1994, Kahru 1997). In some years the extensive cyanobacteria accumulations in the northern Baltic extended into the westernmost Gulf of Finland, but not further eastward. In the more eutrophic central and eastern Gulf of Finland, cyanobacteria surface blooms were reported in the 1970s and early 1980s (Kononen & Niemi 1984, Niemistö et al. 1989), but between 1982 and 1994 no accumulations were detected, in contrast to the massive accumulations elsewhere (Kahru 1997). It is possible that due to limitations resulting from cloud cover and reduced avail-

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ability of satellite data in the early 1980s, some blooms (e.g. Persson et al. 1984) were undetected by the satellite observations; however, the absence of large-scale accumulations is almost certain.

Since 1995, massive blooms containing *Nodularia spumigena* have occurred throughout the whole Gulf of Finland, including its eastern portion. We attribute the emergence of the massive cyanobacteria blooms in the Gulf of Finland to an increase in the phosphate concentration and a corresponding decrease in the N:P ratio caused by the inflow of saline water into the Baltic Sea in 1993.

MATERIALS AND METHODS

Detection of cyanobacteria accumulations from images of the advanced very high resolution radiometer (AVHRR) on the NOAA series of satellites is described in Kahru et al. (1994) and Kahru (1997). In short, the algorithm is a supervised classification method that uses the high reflectance of the accumulations in the visible AVHRR band (570 to 700 nm). Other sources of high reflectance (clouds, haze, sun-glint) are filtered out through a series of thresholds using combinations of visible, near-infrared and thermal infrared bands. The method is only applicable for near-noon passes in cloud-free areas. Maps of accumulations detected on individual images were composited into cumulative maps over longer time periods. A cumulative map shows the pixels where accumulations were detected at least once on any of the individual images available for the time period. As the *N. spumigena* blooms can occur only from mid-June to mid-August, an annual cumulative map is indicative of the maximum extension of the accumulations during the approximately 2 mo period.

Vertical profiles of salinity, oxygen and nutrient concentrations were collected by the Finnish Institute of Marine Research. Additionally, salinity data collected by many Baltic Sea institutions and compiled in the Baltic Environmental Database at Stockholm University (Sokolov & Wulff 1999) were used to follow the propagation of saline waters. The locations of the sampling stations are shown in Fig. 1.

Surface-layer chlorophyll, temperature and salinity were monitored by unattended underway sampling from a passenger ferry, 'Finnjet', which crossed the whole Baltic Proper and the western Gulf of Finland (Leppänen et al. 1995). Every week, 24 water samples were collected for phytoplankton species counts and fluorometric chlorophyll *a* analysis (Rantajärvi et al. 1998).

RESULTS

Annual cumulative maps of *Nodularia spumigena* accumulations (Fig. 2) show that in the summers of 1991 to 1994 they occurred annually in the northern Baltic Proper but never extended into the central and eastern Gulf of Finland east of ca 24° 30′ E. The eastern boundary of the accumulations approximately coincides with the quasi-stationary frontal system in the western Gulf of Finland (Kahru et al. 1995, Kononen et al. 1996). From 1995 to 1997, the accumulations occurred every summer and over the whole Gulf of Finland. The most extensive surface accumulations were recorded in 1997, when exceptionally warm and calm weather favoured the growth and surface accumulation of cyanobacteria. Due to cloudy and rainy weather, the summer of 1998 was unfavourable for both the generation of cyanobacteria accumulations and for their detection. In 1999 the extent of the accumulations was similar to 1997, but no quantitative data are available. Although the annual accumulation maps are based on many individual images, they are still affected by the occurrence of

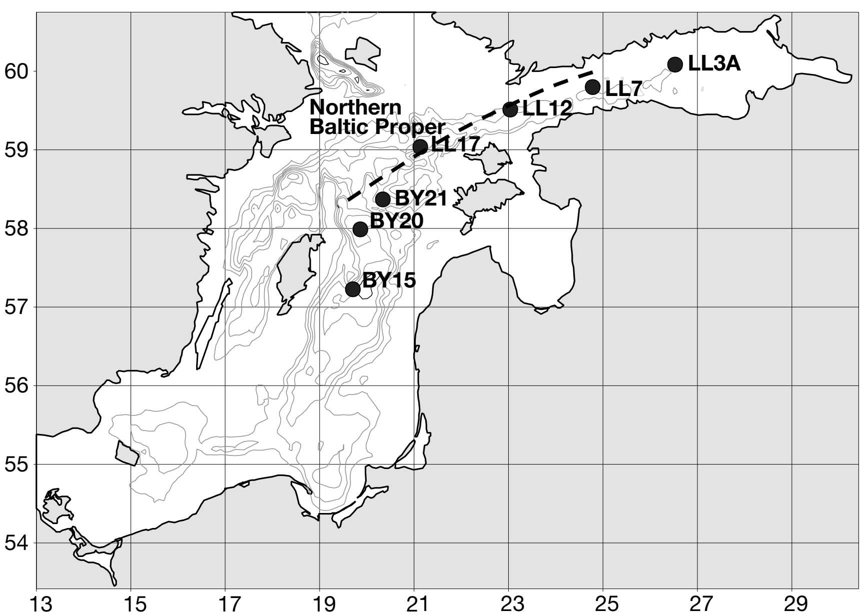

Fig. 1. Map of study area and locations of hydrography and nutrient sampling stations (●) and the ferry transect (dashed line: only northern part of transect shown here). Depth isolines are 60, 80, 100, 120, 150, 200, and 250 m

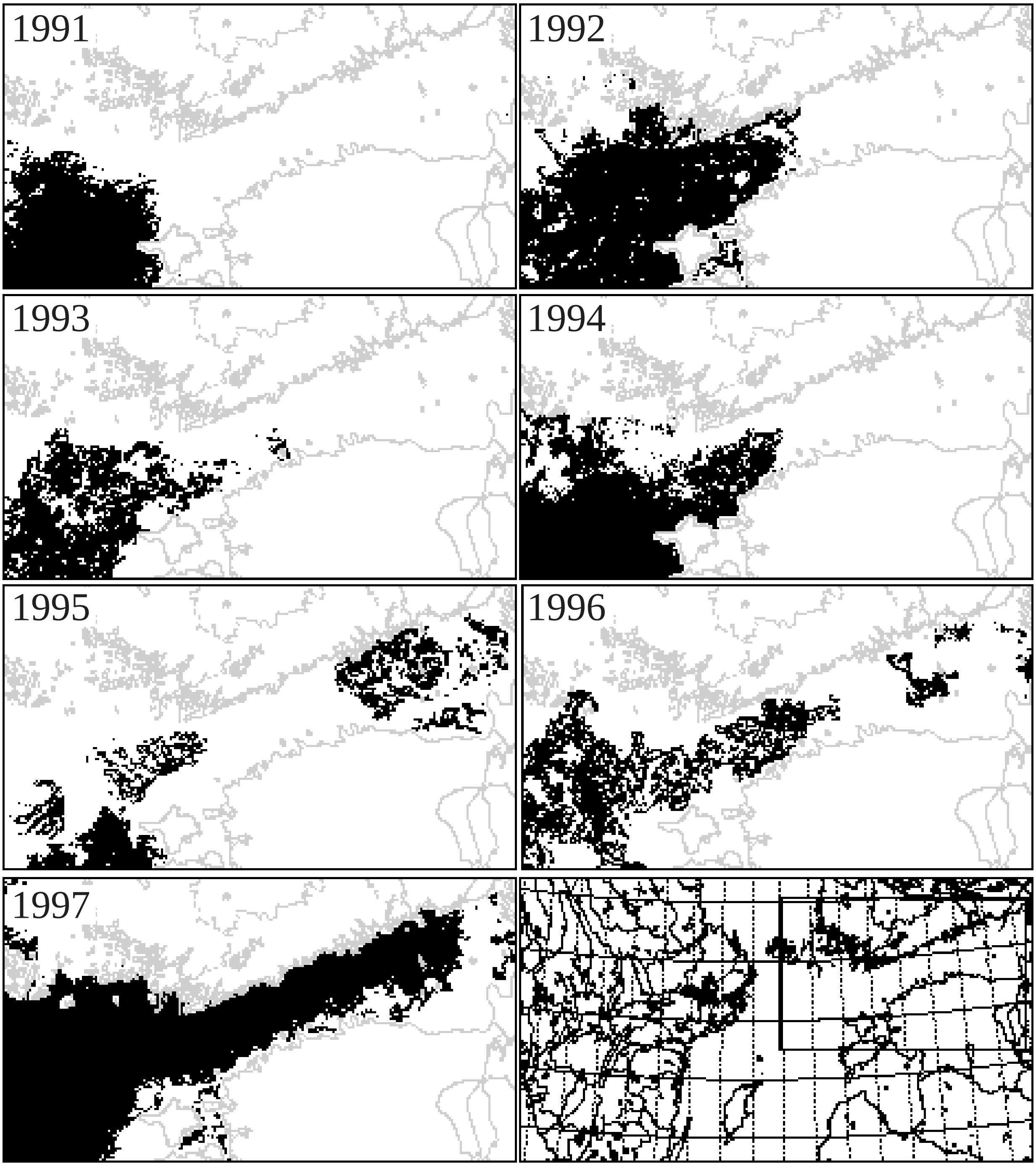

Fig. 2. *Nodularia spumigena*. Distribution maps of cyanobacteria surface accumulations in the Gulf of Finland and northeast Baltic Proper from 1991 to 1997. Location of study area is shown in bottom right-hand panel. Note emergence of cyanobacteria accumulations in the central and eastern Gulf of Finland during 1995 to 1997

cloudy periods when accumulations cannot be detected. In order to increase the reliability of the annual maps, they were composited over several years. The multi-annual maps corresponding to the time periods 1991 to 1994 and 1995 to 1997 clearly show the eastward expansion of the accumulations, starting from 1995 (Fig. 3).

In situ monitoring data from the ferry 'Finnjet' confirm the peak abundance of *Nodularia spumigena* and chlorophyll *a* concentration in 1997. A gradual in-

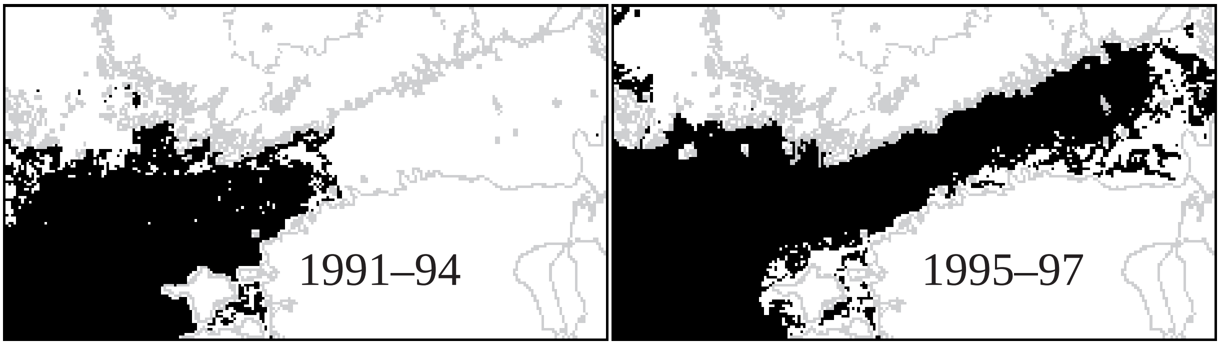

Fig. 3. *Nodularia spumigena*. Cumulative distributions of cyanobacteria accumulations in the Gulf of Finland and northeast Baltic Proper for the years of 1991 to 1994 and 1995 to 1997, respectively

crease in the summer chlorophyll *a* concentration from 1994 to 1997 was observed. As cyanobacteria make up a significant part of the summer phytoplankton biomass, the 1997 increase is consistent with the increased *N. spumigena* accumulations shown by the satellite imagery. Unfortunately, ferry data is not available for the central and eastern Gulf of Finland.

The intrusion of high-salinity North Sea water into the bottom layers of the Baltic Sea in 1993 caused an increase in the salinity of the Baltic deep waters. In the Gotland Deep (Stn BY15: Fig. 1) salinity increased abruptly in the spring of 1994, whereas in the Northern Baltic Proper (Stns BY21 and LL17: Fig. 1) a steady increase was noted until 1995, followed by a more subtle increase between 1995 and 1998. In the Gulf of Finland, the increase in salinity coincided with a decrease in oxygen and increase in phosphate concentrations. Although seasonal and year-to-year fluctuations were strong, the correlated variations in salinity, oxygen and phosphate concentrations have resulted in a decrease of the N:P ratio since 1995, especially in the eastern part of the Gulf of Finland (Fig. 4). Both in the northern Baltic Proper and in the Gulf of Finland, the average oxygen concentration decreased and the phosphorus concentration increased: compare the periods 1991 to 1994 and 1995 to 1998, respectively (Fig. 5).

DISCUSSION AND CONCLUSIONS

Blooms of diazotrophic cyanobacteria in the Baltic Sea are major environmental concerns because of their toxicity and potential nitrogen-enrichment capability (fertilising effect). Paleoenvironmental reconstructions imply that similar blooms occurred as far back as 7000 yr BP (Bianchi et al. 2000). Intense *Nodularia spumigena* blooms were common in the central Gulf of Finland in the 1970s and early 1980s (Kononen & Niemi 1984, Niemistö et al. 1989), but were absent from at least 1984 (Kononen 1992) until their re-emergence in 1995, coincident with an increase in P concentrations and a decrease in the N:P ratio of the bot-

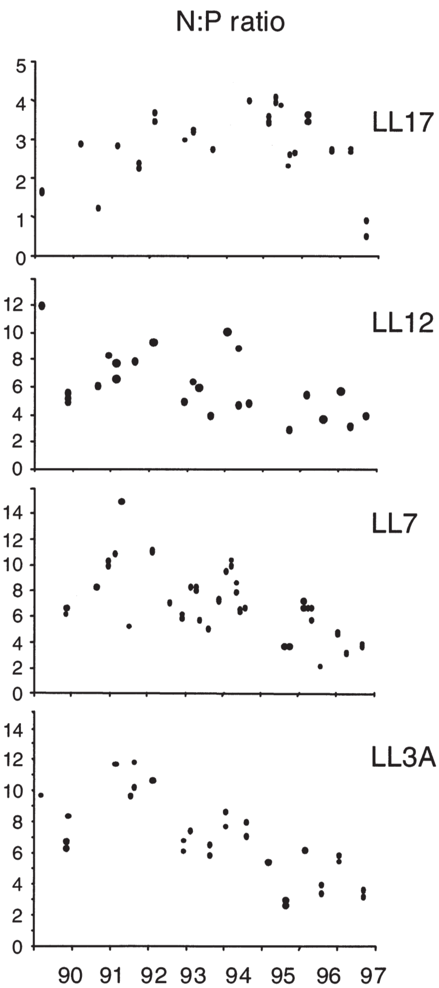

Fig. 4. Temporal variation in N:P molecular ratio of the bottom waters of the northern Baltic Proper and Gulf of Finland in 1991 to 1997 (stations are shown in Fig. 1)

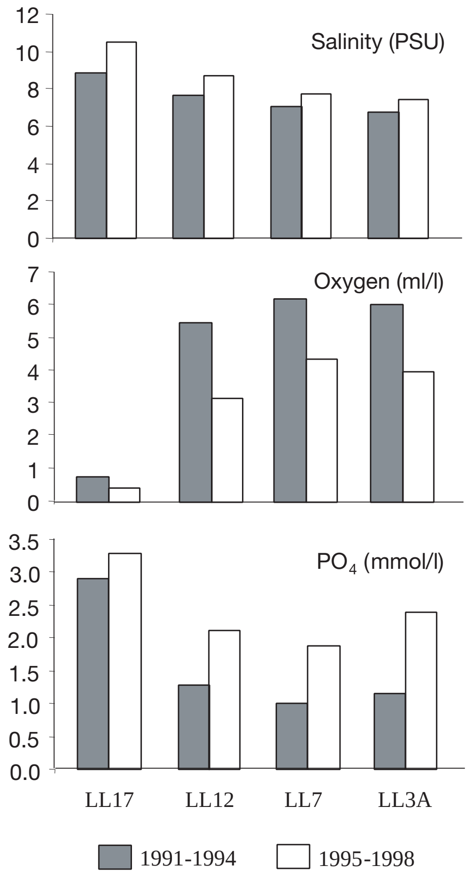

Fig. 5. Average salinity, oxygen and phosphate concentrations in bottom layer of the northern Baltic Proper and Gulf of Finland in 1991 to 1994 and in 1995 to 1998, respectively

tom waters, possibly triggered by the inflow of the saline North Sea waters in 1993.

Although oxic marine sediments can leak some phosphate, mass release of phosphorus stored in oxic sediments occurs when the sediment becomes anoxic (e.g. Gunnars & Blomquist 1997). Anthropogenic inputs of phosphorus to the Gulf of Finland have decreased since the 1980s, but the reserves in the bottom sediments are high (Lehtoranta et al. 1997). The oxygen concentration in the bottom waters is related to the vertical stratification of the water column, which limits wind-induced mixing and thermal convection. Vertical stratification is maintained by inflows of saline water from the North Sea. During periods without such inflows, the deep layers in the Baltic Proper tend to stagnate and become anoxic due to biochemical oxygen consumption. The occurrence of inflow events is governed by a combination of oceanographic and meteorological pre-conditions (Matthäus & Franck 1992). Prior to 1993, the last major inflow occurred in the winter of 1975/1976. During the 10 yr following a relatively weak inflow event of 1983, the salinity and oxygen concentration in the bottom waters of the Baltic Proper decreased to the lowest recorded values (Matthäus & Lass 1995). In contrast to the Baltic Proper, in the Gulf of Finland, the stagnation period resulted in increased oxygen levels through enhanced vertical mixing arising from decreased salinity and weaker vertical stratification. Here the stagnation period ended in 1995 with the arrival of saline, but oxygen-depleted, waters.

It is difficult to detect a correlation between earlier inflows into the Baltic Sea and *Nodularia spumigena* accumulations in the Gulf of Finland because of the scarcity of data. The moderate 1983 inflow did not produce satellite-detectable accumulations in the 1985 to 1987 period, assuming the same 2 to 4 yr time lag from inflow to cyanobacteria accumulations. The 1985 to 1988 period was very unfavourable for cyanobacteria blooms throughout the whole Baltic, possibly due to lower than average surface irradiance and sunshine duration (Kahru et al. 1994), and no accumulations were detected in the northern Baltic Proper (Kahru 1997). The influence of the major inflows in 1975/1976 on the *N. spumigena* blooms in the Gulf of Finland are difficult to demonstrate, as no continuous satellite data exist from this period. The *in situ* data presented by Kononen & Niemi (1984) do show cyanobacteria blooms in 1979 and 1980. However, the different nutrient conditions in the 1970s compared to the 1990s could have altered the relationship between the inflows and accumulations. It is also possible that since the inflows of North Sea water were much less frequent in the 1980s and 1990s than in earlier years, their effects were also different. Future inflows — if and when they happen — will show if the relationship between inflow events and *N. spumigena* blooms is valid.

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