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Source: *Ambio*, Vol. 23, No. 8 (Dec., 1994), pp. 469-472
Published by: Allen Press on behalf of Royal Swedish Academy of Sciences
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Report Mati Kahru, Ulrich Horstmann and Ove Rud

Satellite Detection of Increased Cyanobacteria Blooms in the Baltic Sea: Natural Fluctuation or Ecosystem Change?

Using data from the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA series of satellites, an increase in the area covered by cyanobacteria blooms in the Baltic Sea was detected. The time series of satellite data covers a period of 12 years from 1982 to 1993. The total area covered by surface-floating cyanobacteria (blue-green algae) has increased in the 1990s, reaching over 62 000 km in 1992. From 1992, visible accumulations appeared for the first time in the Gulf of Riga and reappeared, in the western Gulf of Finland, after being absent from 1984. Conspicuous surface blooms were also present in the early 1980s, coincident with a period of sunny and calm summers. However, when the influence of variable sunshine duration is taken into account, the increase in 1991–1993 is still distinct, indicating significant changes in the Baltic environment. The causal factors for the increased cyanobacteria blooms are still not clear.

Figure 1. Sea-surface accumulations of cyanobacteria dominated by *Nodularia spumigena* in the open Baltic as seen from onboard ship. Photo: M. Kahru.

NATURAL PHENOMENON OR HUMAN INFLUENCE?

Late summer blooms of nitrogen-fixing, filamentous cyanobacteria (blue-green algae) are a regular phenomenon in the Baltic Sea. As the dominant species of the conspicuous open-sea blooms, *Nodularia spumigena*, is facultatively hepatotoxic and cyanobacterial blooms are a cause of major environmental concern. Cyanobacteria use dissolved molecular N_2 as an additional nitrogen source, which allows them to bloom in the summer when the growth of other phytoplankton is normally limited by nitrogen. Although mass blooms of cyanobacteria in the Baltic have been known since the mid-19th century (1), it has been suggested (2) that the extent and intensity of the blooms has increased because of anthropogenic sources of eutrophication. However, due to the high spatial and temporal variability, and the scarcity of data from the open sea, long-term changes in the extent of cyanobacteria blooms are very difficult to prove using data from conventional shipboard monitoring.

At some stage of the bloom, cyanobacteria filaments become positively buoyant and aggregate in the surface layer in a process of inverted sedimentation (3). The filaments often occur in large agglomerates giving the impression of yellow snowflakes (Fig. 1). At low wind speeds the agglomerates form accumulations at the surface to an extent that they become visible even on low-sensitive satellite imagery.

VIEW FROM SPACE

A number of satellite images of the Baltic Sea, from different sensors and satellite platforms, have been available since the mid-1970s and can be used for mapping near-surface accumulations. In principle, this would allow detection of the interannual dynamics of cyanobacteria surface blooms over the past 20 years. Although frequent cloud cover over the Baltic Sea severely limits analysis using satellite data, accumulations of cyanobacteria usually co-occur with periods of sunny and calm weather, when good imagery is available. Figure 2 shows a dense cyanobacteria accumulation detected by the Thematic Mapper (TM) sensor on the Landsat 5 satellite. High-resolution sensors such as TM and MSS on Landsat, as well as HRV on SPOT, show very detailed distribution patterns. However, considering their narrow swath width, low sampling rate (less than one pass per week, reduced further by clouds), and high costs, the high-resolution imagery is not suitable for large-scale, long-term monitoring.

NOAA/AVHRR

The AVHRR has been flown on the NOAA series of satellites with small modifications since 1978. Due to its wide swath width (over 2500 km), frequent coverage (several passes per day), and availability over the past 15 years, the AVHRR is especially suitable for monitoring purposes. On the other hand, the relatively low spatial resolution ($\approx$ 1 km on the track of the satellite) and coarse spectral information (two broad bands in the visible-near infrared domain) may limit the sensor's capability to distinguish accumulations of cyanobacteria from certain types of clouds and other atmospheric disturbances. For example, part of

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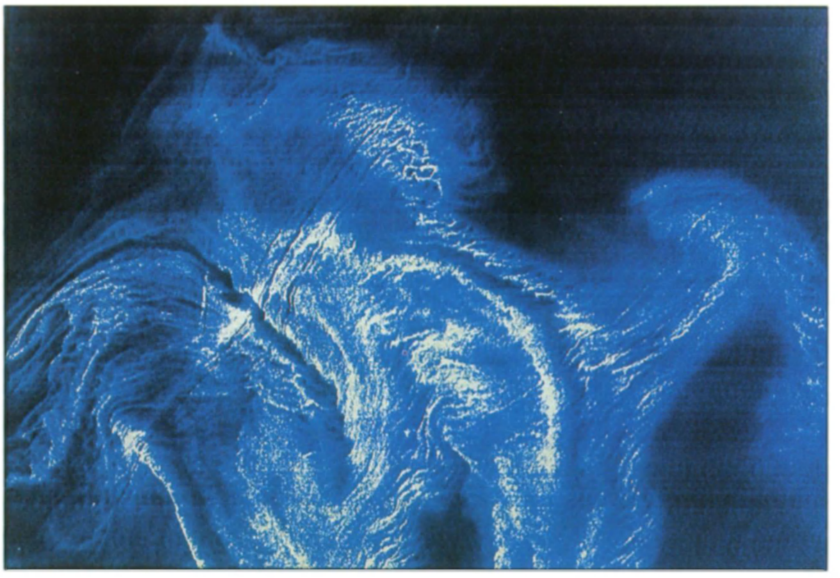

Figure 2. Landsat 5 Thematic Mapper (TM) view of cyanobacterial accumulations off the southeastern coast of Sweden on July 8, 1992, 09:18 UTC. The image is a RGB-composite of three visible bands (TM3, TM2, TM1) and covers an area of 61 km x 61 km with the pixel size of 30 x 30 m.

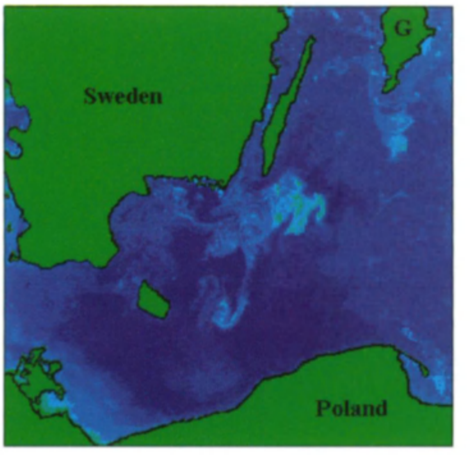

Figure 3. NOAA-11/AVHRR band 1 image of the southern Baltic on July 8, 1992, 13:23 UTC, covering the same accumulation seen in Figure 2, four hours later. The size of the area shown is 398 km x 396 km with the pixel size of 1 km x 1 km. Extensive cyanobacterial accumulations are visible southeast off the coast of Sweden and south of the island of Gotland (G).

an AVHRR image covering southern Baltic and the corresponding TM scene from Figure 2 shown in Figure 3.

An ad hoc procedure (4) designed to detect cyanobacteria accumulations from AVHRR data relies both on their increased reflectance and the presence of spatial texture in the visible band 1 (0.58-0.68 µm). Data in the near-infrared band 2 (0.72–1.10 µm), and the two thermal infrared bands (10.3–11.3 µm and 11.5–12.5 µm) are used to screen clouds, haze, land, and error pixels. Finally, visual inspection and editing is used to eliminate some pixels of variable clouds that pass through the filtering process.

INCREASED SURFACE ACCUMULATIONS IN THE 1990s

A total of 135 sufficiently cloud-free noon passes, covering the period from the last week of June until the end of August between 1982 and 1993 from various NOAA satellites (NOAA 6 to 12), were digitally processed for the occurrence of cyanobacteria accumulations. The images were geometrically corrected and registered to an Albers equal-area projection (5). Additional scenes from the AVHRR, the Coastal Zone Color Scanner and other sensors were visually checked for the occurrence of the accumulations. For each year, maps of the cumulative area as well as the total area covered by accumulations were compiled (Figs 4, 5).

The seasonal interval for the detected accumulations ranged from 30 June (in 1990) to 24 August (in 1984). In the interannual dynamics, two periods of increased cyanobacterial coverage can be detected: from 1982 to 1984 and from 1990 to 1993 (Fig. 5). The decrease in 1993 compared to 1992 can be regarded as a response to the windy and cloudy weather in July–August 1993 which was unfavorable, in that it prevented the cyanobacteria from accumulating at the sea surface. Although the values of detected cyanobacterial coverage can only be regarded as the lower bounds of the true total areas, due to incomplete satellite sampling and frequent clouds obscuring the sea surface during satellite passes, there is no doubt about the existence of the two periods of increased cyanobacteria accumulations.

The appearance of cyanobacteria agglomerates at the sea surface depends both on the amount of cyanobacterial filaments in the water column and on conditions causing their inverted sedimentation. It is generally considered (2, 6, 7) that *Nodularia* blooms in the Baltic are initiated if sufficient phosphorus is available and the water temperature exceeds 16°C. These conditions, even if generally valid, are hardly sufficient to predict or model the actual bloom areas. Regarding inverted sedimentation, it is well known that accumulation appear at the surface in calm and sunny weather. Under conditions of strong heating and light winds, the wind mixing is insufficient to mix the solar heat absorbed near the surface throughout the depth of the early morning mixed layer. As solar heating proceeds, the heat becomes trapped at a progressively shallower stratified layer (8). High solar insolation and the associated strong near-surface stratification may be one of the factors that cause the surface-trapped cyanobacteria to lose their buoyancy regulation and, thus, result in inverted sedimentation. As the presence of cyanobacteria near the surface further increases heating and stratification in the surface layer by absorbing more light via their pigments (9), a positive feedback loop is generated that results in the massive surface accumulation of cyanobacterial aggregates. Although strong wind mixing can quickly redistribute the filaments into deeper layers and make the accumulation disappear from the surface, it has been confirmed (9) that dense accumulation remain clearly detectable on the following day even at wind speeds of 8 m s^{-1}.

Surface irradiance can be estimated both from satellite (10) and *in situ* data. With the exception of one year (1986) the satellite data, averaged over the whole Baltic, agree very well with the average duration of sunshine measured at two Swedish coastal weather stations (Fig. 6). As expected, years with more sunshine in July–August tend to have more cyanobacteria accumulation (the correlation coefficient between the total area and monthly average sunshine duration is 0.79 for the period 1982–1990). Therefore, some of the interannual variation in the extent of the accumulation can be explained by the variation in the amount of sunshine. However, the area covered by the accumulation in 1991–1993, seems to be disproportionately high, even when the higher sunshine duration is considered. By using linear regression to estimate the "predicted" accumulation areas from the July-August sunshine duration, we obtain the residuals, i.e. differences between the observed and the predicted areas. A plot of the "excess" accumulation areas, not accountable for by the sunny weather, reveals an abrupt increase in 1991–1993 (Fig. 7). Also the year 1984 shows higher than "predicted" accumulation. The increase in the extent of cyanobacteria accumulation

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in the 1990s, which looked like a cyclic fluctuation in the original time series (Fig. 5) looks more significant in the sunshine-corrected series.

Although the accumulations correlate well with periods of low wind during the summer (Kahru, unpublished data), on the interannual scale the average wind speeds in July-August have no direct relationship with the extent of the accumulations. In fact, depending on the location of the station, the average wind speed may be positively correlated with the cyanobacteria accumulations. This is due to the association between the wind field and the high-pressure weather patterns that favor the appearance of the accumulation.

Besides increasing in the total area, the accumulations have been expanding into new areas. Since 1992, the cyanobacteria blooms reappeared in the western Gulf of Finland from where they had been absent since 1984, which is in accordance with *in situ* observations (11). In 1992–1993, massive visible accumulations were observed for the first time in the Gulf of Riga. Although summer blooms of cyanobacteria are a regular phenomenon in the Gulf of Riga, their extent has increased significantly during recent years (Maija Balode, pers. comm.).

CAUSAL FACTORS?

As cyanobacteria play a major role in the Baltic ecosystem blooms, a significant increase in the extent of cyanobacteria can represent a structural shift in the planktonic communities. For example, increased cyanobacteria blooms in the Baltic, mean increased input of atmospheric nitrogen (via N_2-fixation by cyanobacteria) and consumption of phosphorus from deep waters, leading to higher levels of eutrophication. The question of which environmental factors caused the increase in the area

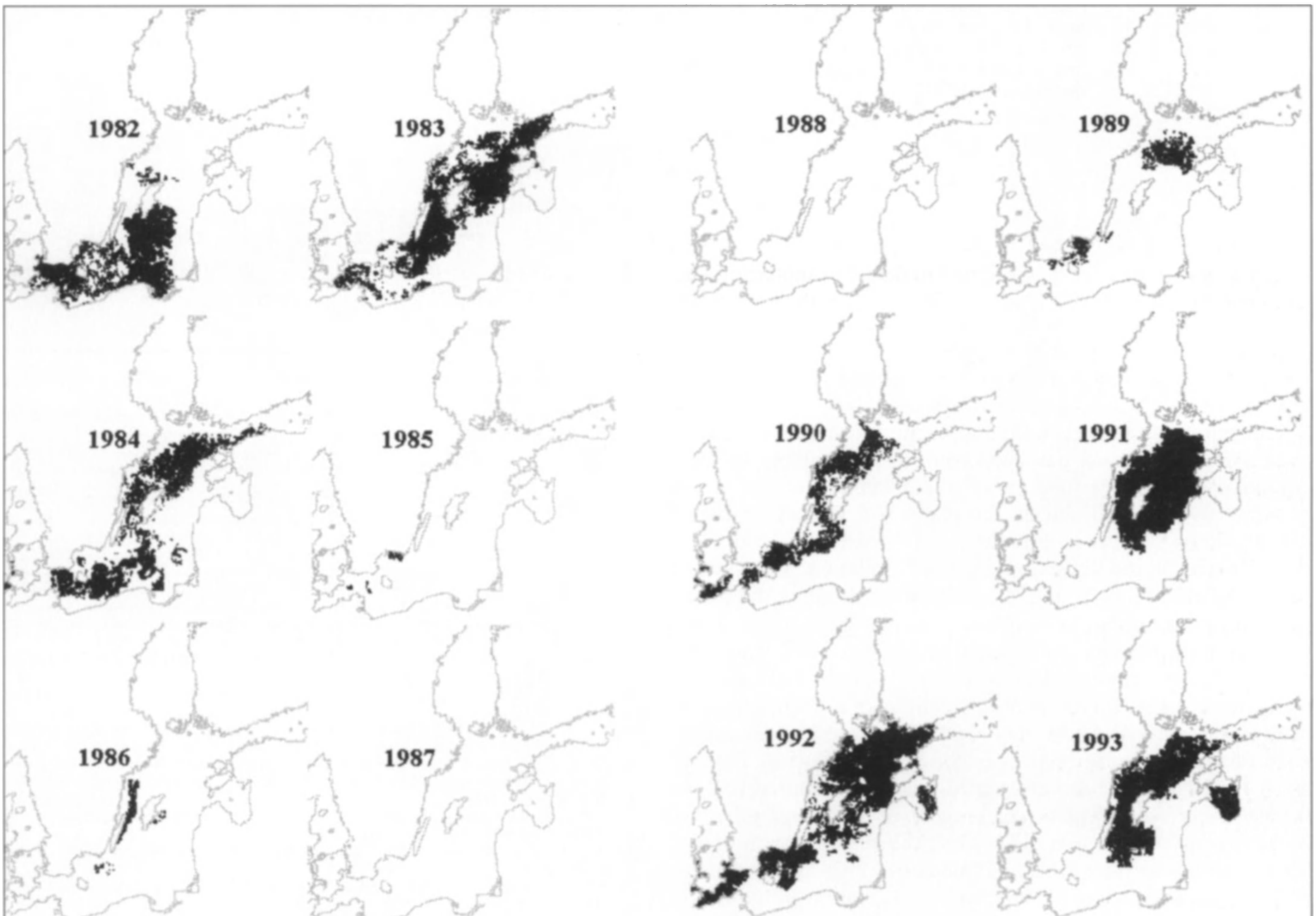

Figure 4. Annual distributions of cyanobacterial accumulations in the Baltic Sea as detected from NOAA/AVHRR imagery.

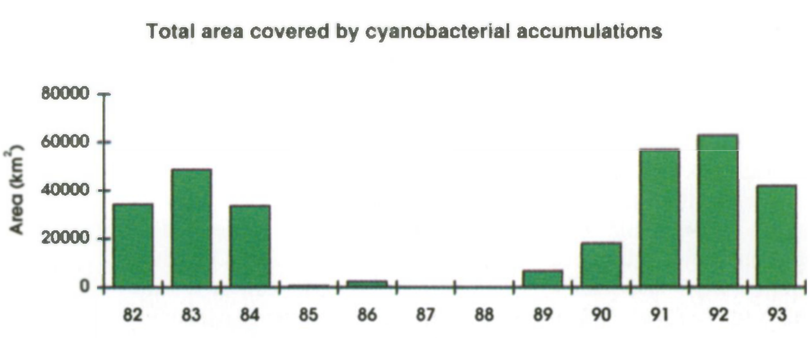

Figure 5. Interannual dynamics of the total area covered by satellite-detected cyanobacterial accumulations in the Baltic Sea.

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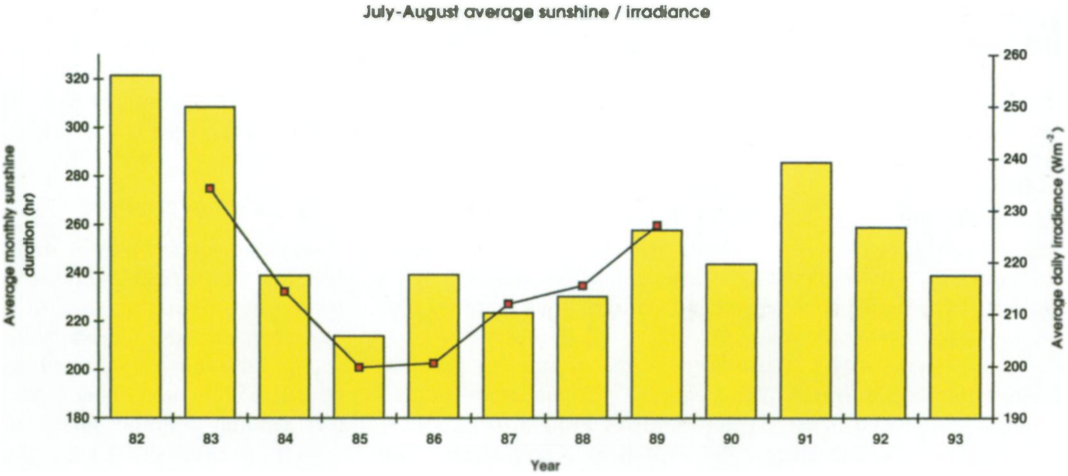

Figure 6. July–August average monthly sunshine duration and daily surface irradiance over the Baltic Sea in 1982–1993. Sunshine duration (bar plot, left scale) is the average of measurements at two stations (Ölands Södra Udde and Visby) by the Swedish Meteorological and Hydrological Institute with pyrheliometers (time > 120 W m^{-2}). Average daily surface irradiance (1983–1989, line plot, right scale) has been compiled from data produced by the International Satellite Cloud Climatology Program (10) and is an average for the Baltic Proper area.

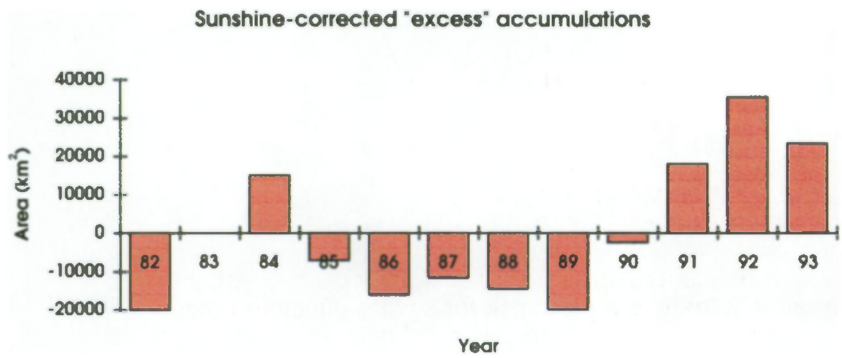

Figure 7. Dynamics of the total area of cyanobacterial accumulations corrected for the monthly average (July–August) sunshine duration.

covered by cyanobacteria remains open. Obvious candidates as causal factors are increased riverine phosphorus input and/or changes in the phosphorus to nitrogen ratio.

As cyanobacteria are not limited by nitrogen, the initiation of cyanobacteria blooms has been traditionally related to their competitive advantage over other phytoplankton where excess phosphorus was available in the water (6). The existence of cyanobacteria blooms in the nitrogen-limited Baltic Proper and their absence in the phosphorus-limited Bothnian Bay, Gulf of Riga, and eastern Gulf of Finland has been used as the major supporting argument. However, the appearance of dense cyanobacteria blooms in the Gulf of Riga in 1992, and even stronger blooms compared to the Baltic Proper in 1993, present a different case as there are no indications of a decreasing N/P ratio in the Gulf (A. Andrushaitis, pers. comm.). The disappearance of cyanobacteria blooms in the western Gulf of Finland since 1985 has also been associated with the increased N/P ratio and the subsequent loss of competitive advantage provided by nitrogen fixation (11). However, the reappearance of the blooms in the western Gulf of Finland in 1992–1993 points to other regulating factors. The period of stagnation in the Baltic due to strongly reduced Atlantic water inflow since 1977 has increased the phosphorus concentration in the near-bottom layers (12). At the same time lower salinities in the deeper layers have destabilized the halocline and consequently favored vertical transport of phosphorus to the euphotic zone. This could have been one of the factors leading to increased cyanobacterial blooms in the Baltic. Other factors that could be involved include changes in the total nutrient levels, micronutrients and trace metals, as well as changes in the phyto-zooplankton relations. A clue to detecting the dominant factors could be in comparing sea areas where blooms appear very often (e.g. the Hanö Bight on the southeastern coast of Sweden) with areas where they are not observed (e.g. the Bay of Gdansk where visible surface blooms have been absent after 1984). Satellite-based monitoring of the distribution of cyanobacterial blooms can be a valuable operational tool for environmental monitoring, especially if we had more knowledge how to explain the observed changes.

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4. 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 3 x 3 pixel windows 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% albedo 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 clouds.
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13. This study has been supported by grants from the Swedish National Space Board and the Swedish Natural Science Research Council.
14. First submitted 30 November 1993, accepted for publication after revision 2 February 1994.

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