Journal of Marine Systems 90 (2012) 67–76

Contents lists available at SciVerse ScienceDirect

Journal of Marine Systems

journal homepage: www.elsevier.com/locate/jmarsys

Upwelling events may cause cyanobacteria blooms in the Baltic Sea

Norbert Wasmund *, Günther Nausch, Maren Voss

Leibniz Institute for Baltic Sea Research, Seestrasse 15, 18119 Rostock-Warnemünde, Germany

ARTICLE INFO

Article history:
Received 23 May 2011
Received in revised form 25 July 2011
Accepted 2 September 2011
Available online 14 September 2011

Keywords:
Upwelling
Cyanobacteria
Nodularia
Anabaena
Phosphorus
Baltic Sea

ABSTRACT

Cyanobacteria blooms in the Baltic Sea appear after upwelling events, which transport phosphate-rich intermediate water to the surface. The growth potential of diazotrophic cyanobacteria in upwelled water was studied in a mesocosm (tank) experiment in summer 2007. An *Anabaena* bloom was only induced in the tanks filled with upwelled surface water but not in those filled with surface water from outside the upwelling cell and with intermediate water. The low initial cyanobacteria biomass in the intermediate water could not grow to bloom concentrations within three weeks. It is concluded that mixing of upwelled water with surrounding surface water forms a precondition for a cyanobacteria bloom. An additional mesocosm experiment conducted in 2009 revealed that mixing of intermediate water with surface water had the same stimulating effect on nitrogen fixation and cyanobacteria growth as artificial phosphate input. Phosphate input stimulates the growth of *Nodularia* and *Anabaena* more than that of *Aphanizomenon*. We suggest that the upwelled phosphate-rich intermediate water has to be mixed with the surface water containing physiologically "young" cyanobacteria biomass of at least 20 mg/m^3 as an inoculum in order to initiate a cyanobacteria bloom.

1. Introduction

Cyanobacteria blooms are one of the most impressive features in the Baltic Sea. They occur with varying intensity every summer (Hansson and Öberg, 2008) and are a matter of concern because

(a) they are buoyant and form unpleasant surface accumulations and discolorations at the water surface keeping tourists away and causing economic loss for the tourist industry (Wasmund, 2002),
(b) they may be toxic and sometimes cause death of animals and illness of people (Karjalainen et al., 2007; Luckas et al., 2005; Mazur-Marzec et al., 2006; Sivonen et al., 2007; Uronen, 2007),
(c) they fix nitrogen and therefore contribute substantial amounts of additional nitrogen thus counteracting the measures to reduce eutrophication (Elmgren and Larsson, 2001; Savchuk and Wulff, 1999; Vahtera et al., 2007a)
(d) remineralisation of the biomass consumes oxygen and supports production of hydrogen sulphide. The lack of oxygen releases dissolving phosphorus (P) to the water, which enhances eutrophication (Kuparinen and Tuominen, 2001).

Surface accumulations of buoyant cyanobacteria may appear within a few hours if the surface water is stabilised e.g. by a vertical temperature gradient. These accumulations disappear quickly after wind-induced mixing while the total biomass is not altered. In this study we did not consider these short-term changes, but rather concentrate on processes which lead to an increase in biomass and bloom formation. According to Wasmund (1997), a cyanobacteria biomass (wet weight) exceeding 200 mg/m^3 in the upper mixed layer is termed a "bloom".

The main nitrogen-fixing (diazotrophic) species of the Baltic Sea (*Nodularia spumigena*, *Aphanizomenon* sp., *Anabaena* spp.) form their blooms more or less simultaneously, mainly in July and August. As the genera *Nodularia* and *Aphanizomenon* contain only one bloom-forming species in the open Baltic Sea and differentiation between the *Anabaena* species was not performed, we use simply the genera names in this paper. We do not deal with the separate functional group of picocyanobacteria (e.g. *Synechococcus*) which are incapable of fixing nitrogen, do not possess gas vesicles and are not toxic (Stal et al., 2003).

Cyanobacteria blooms are favoured in the central Baltic Sea because of a general nitrogen-limitation of phytoplankton growth, as indicated by low nitrogen:phosphorus ratios (N:P ratios) in winter (Nausch et al., 2008a; Niemi, 1979; Raateoja et al., 2011). After the spring bloom, excess P is left over in the surface water which favours the growth of diazotrophic cyanobacteria as they are independent of combined nitrogen and therefore generally considered to be P-limited (Rydin et al., 2002). However, Nausch et al. (2008b), Raateoja et al. (2011) and Wasmund et al. (2005) found that the "excess P" remaining after the spring bloom in the upper mixed layer is not sufficient to feed the blooms. Additional P-sources are necessary, which may be delivered by upwelling of intermediate water (Lass et al., 2010).

The Baltic Sea is structured vertically by pycnoclines (Lass and Matthäus, 2008; Leppäranta and Myrberg, 2009). A strong seasonal

* Corresponding author. Tel.: +49 381 5197212; fax: +49 381 5197440.
E-mail address: norbert.wasmund@io-warnemuende.de (N. Wasmund).

0924-7963/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmarsys.2011.09.001

Table 1
Filling scheme of the tanks in 2007. Tanks I7, I7+, S7 and S7+ were filled on 14.7.2007 at station 7 (station depth 91 m) and tanks U8 and U8+ on 15.7.2007 at station 8 (station depth 31 m). From the two replicate tanks, one was left without any addition and one received additional phosphate (+) on 29.7.07. The tank numbers are explained by the characteristics (bold and underlined letters).

Tank number	Filling depth (m)	Characteristics	Temperature (°C)	Salinity (PSU)	DIN ($mmol/m^3$)	PO_4 ($mmol/m^3$)
I7, I7+	26	**I**ntermediate water outside the upwelling cell	4.6	7.19	0.12	0.36
S7, S7+	2	**S**urface water outside the upwelling cell	15.1	7.00	0.34	0.05
U8, U8+	2	**U**pwelled water	12.7	7.07	0.10	0.24

Table 2
Filling scheme of the tanks in 2009. All tanks were filled on 3.7.2009 at station 4 (station depth 125 m). The tank numbers are explained by the characteristics (bold and underlined letters).

Tank number	Filling depth (m)	Characteristics	Temperature (°C)	Salinity (PSU)	NO_2+NO_3 ($mmol/m^3$)	PO_4 ($mmol/m^3$)
I4a, I4b	30	**I**ntermediate water	5.8	7.17	0	0.26
S4a, S4b	1	**S**urface water	17.2	7.19	0.01	0.01
M4a, M4b	1 and 30 mixed	**M**ixture of surface water and intermediate water 1:1	11.5	7.18	0.01	0.13
P4a, P4b	1	**P**hosphate-enriched surface water	17.2	7.19	0.01	0.5

thermocline occurs at a depth of about 15–20 m in the Baltic Proper in summer. It separates the warm surface water (mixed layer) from the cold intermediate water. If wind-driven upwelling transports the surface water off-shore, the intermediate water flows to the surface along the coast (Gidhagen, 1987; Lehmann and Myrberg, 2008; Fennel et al., 2010). As the Baltic intermediate water contains high phosphate concentrations after the spring bloom, but extremely low dissolved inorganic nitrogen (DIN) concentrations (cf. Tables 1, 2), it should provide best conditions for the growth of diazotrophic cyanobacteria. They can, however, not grow in the intermediate water because of light limitation. If the phosphate containing intermediate water is transported to the surface by upwelling, cyanobacteria should find best growth conditions. Upwelling phenomena are wide-spread in the Baltic Sea (e.g. Kowalewski and Ostrowski, 2005). Especially in summer they can be easily identified by satellites because of their lower sea surface temperature (Siegel et al., 2008; cf. sub-map in Fig. 1).

In fact, Kononen et al. (1996) and Vahtera et al. (2005) found blooms in frontal regions and after upwelling events in the western Gulf of Finland and Laanemets et al. (2006) simulated this mechanism in a model. The upwelling situation and the effect of phosphate pumping by upwelling, investigated during our cruises in July/August 2007 and in July 2009 by a field approach, was already assessed by Fennel et al. (2010), Nausch et al. (2009) and Lass et al. (2010). In parallel, we conducted mesocosm ("tank") experiments in order to investigate the potential for growth in the different water masses.

It is supposed that cyanobacteria biomass is low and metabolically less active in the intermediate water due to light limitation. Diazotrophic cyanobacteria grow slowly (e.g. Lehtimäki et al., 1997;

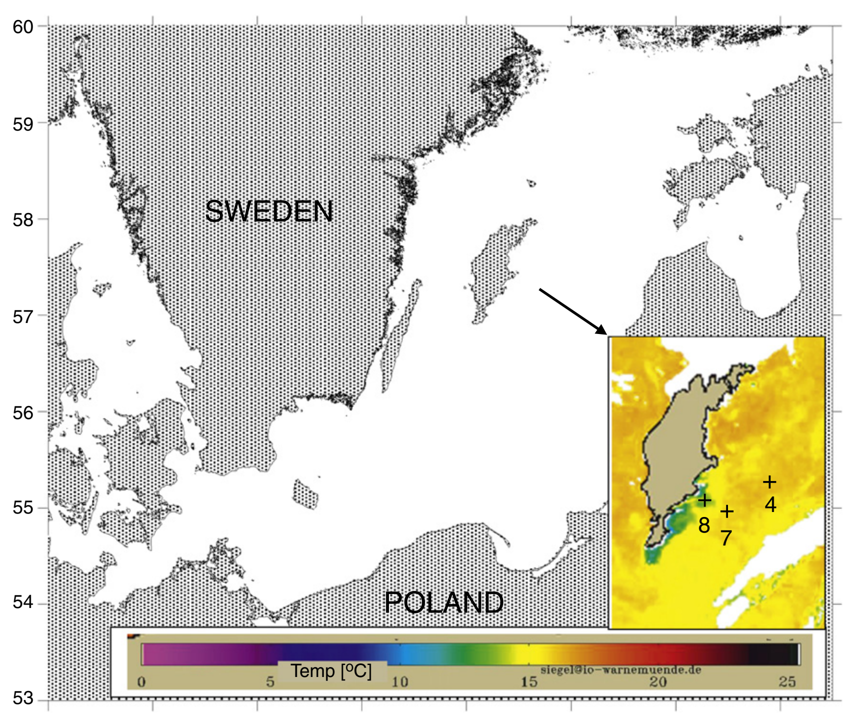

Fig. 1. Map of the western and central Baltic Sea and sub-map showing the sampling stations east of the Island of Gotland. The NOAA-satellite image shows the sea surface temperature on 15 July 2007; data delivered by BSH Hamburg, image by H. Siegel, IOW.