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ORIGINAL RESEARCH ARTICLE

Colonies of *Gyrosigma eximium*: a new phenomenon in Arctic tidal flats

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Summary For the first time at Svalbard, a colonial form of the tube-dwelling diatom *Gyrosigma eximium* was found in summer 2010 in the tidal flats on Spitsbergen at 78°N. The colonies take the form of conical, green structures that are 1—2 cm high and are associated with other diatom taxa and cyanobacteria (Oscillatoriaceae). The diatom colonies were associated with rich meiofauna and apparently act as cohesive factors for the fine sediment. In the Arctic tidal flats, this represents the first observation of long-term sediment stabilization and biological enrichment. Since this first observation, this species has apparently colonized broader areas in Advenentelva's tidal flat.

1. Introduction

Arctic tidal flats are unique habitats in which the winter freezes down to the upper 10—20 cm of sediment and forms a solid ice (80—110 cm) cover on the surface that breaks and moves apart in spring with the tides, removing the frozen sediment layer (Węsławski et al., 1999). The removal of this upper layer of sediment causes seasonal defaunation of the seabed and random recolonization of this very unstable fine sediment. The Adventfjorden tidal flat, which is located near Longyearbyen (Spitsbergen) at 78°N, 15°E (Fig. 1), is one of the most intensively studied Arctic coastal habitats (Dobrzyn et al., 2005; Węsławski and Szymelfenig, 1999; Węsławski et al., 1999; Węsławski et al., 1993; Zajączkowski et al.,

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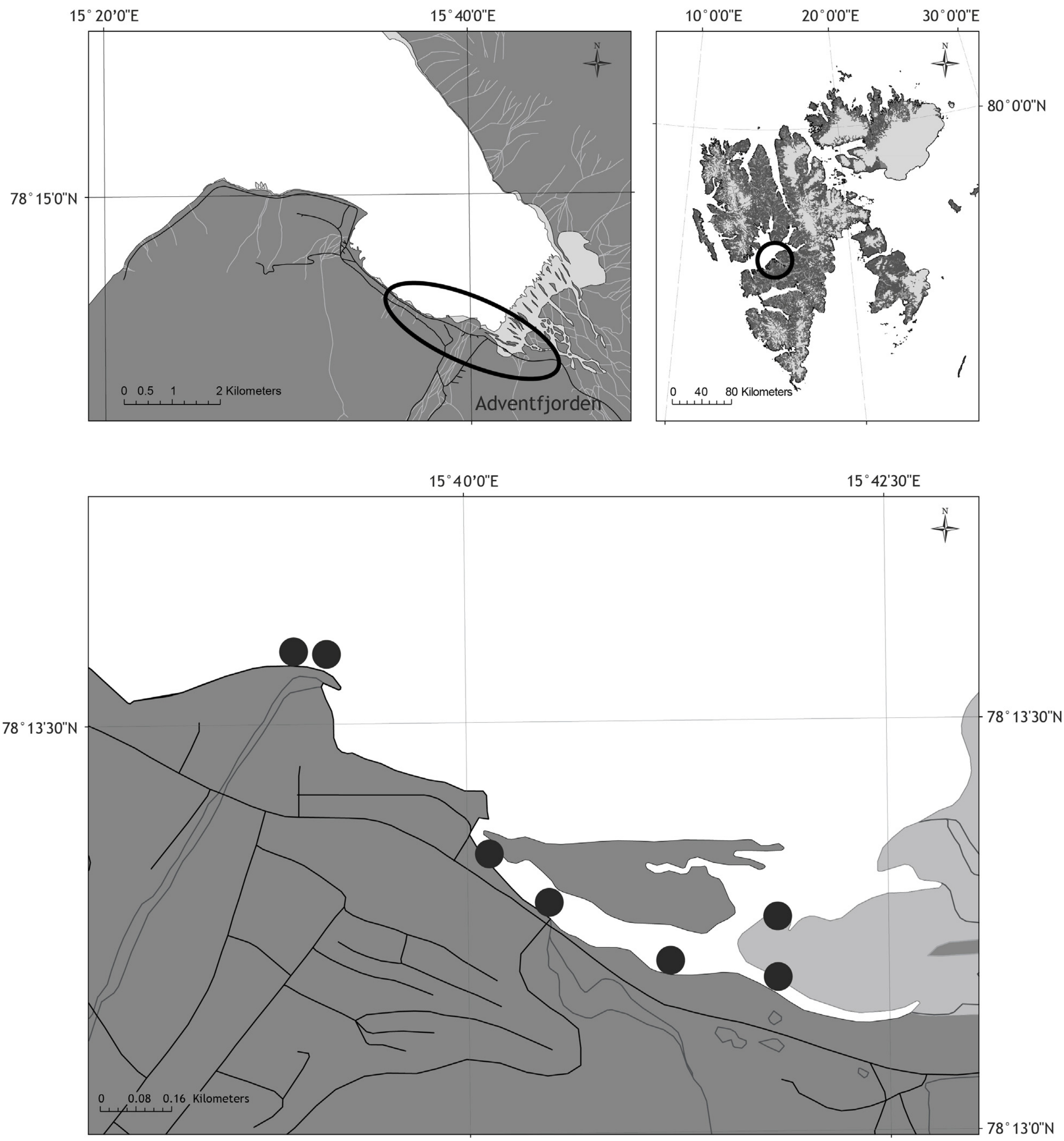

Figure 1 Area of interest and sampling points.

2008). This area is strongly influenced by Adventelva, a river with a flow rate as high as 3.6 $m^3 s^{-1}$ that is loaded with 132—486 g dm^{-3} of mineral suspended matter (Zajączkowski et al., 2004). During low tide, at least the highest parts of the bottom are exposed for approximately 4 h per cycle of regular M2 semidiurnal tide. In this frequently visited (every summer) area, we noted a new and distinctive feature in late summer 2010. This phenomenon seems to be recurrent, and we observed it in consecutive years. During the observation period, the area populated by colonies increased, and green, conical structures cover large parts of this area during low tide (Fig. 2). Since then, the structures have been observed in the same area every summer (July to September). This paper presents the details of our examination of this new phenomenon.

2. Material and methods

Surface sediment samples from areas with green structures were collected from 7 locations in the Adventfjorden tidal flat in the summers of 2010—2013. In 2010, sampling was performed using corers (3.6 cm in diameter). The upper 5 cm were collected and immediately fixed in 4% formaldehyde. In 2011—2013, samples were collected only qualitatively using tweezers and were also fixed in 4% formaldehyde.

(a) (b)

Figure 2 General view of the area covered by *Gyrosigma eximium* colonies (a) and a close-up view of the colonies (b).

For algological analysis, a microscope equipped with differential interference contrast (DIC) and phase contrast and with 10, 40 and 60× (water-immersion) objectives was initially used. To perform a detailed taxonomical determination, diatom frustules that had been cleaned in 30% hydrogen peroxide (H_2O_2) were analysed under a light microscope (magnification 600×) and a scanning electron microscope (SEM). For SEM analyses, few drops of cleaned diatom material were put on aluminum stubs, air-dried, coated with gold and examined under a Philips environmental SEM operating at 10 kV.

Prior to meiofauna analyses, the LUDOX HS silica density gradient centrifugation technique (density of 1.18 g cm^{-3}) was used to extract meiofaunal organisms from the sediment (Heip et al., 1985). After centrifugation, the supernatant was sieved through 500 μm and 38 μm sieves. The samples retained on the 38 μm sieve were stained with Rose Bengal. Subsequently, meiofaunal organisms were identified to the higher taxa level (phylum, class or order), and the abundances of particular taxa were expressed per 10 cm^2.

3. Results and discussion

The structures, which were of a 1—2 cm height and basal width, grew on the higher parts of the tidal flats that emerged during low-tide above the sediment (Fig. 2). They remained exposed for 2—3 h during each tidal cycle. The structure density was approximately 100—160 per m^2, and the estimated biomass (wet weight) was 50 g m^{-2}.

Analyses conducted using high-power light microscopy revealed that these structures consisted of branched tubes that were densely packed with *Gyrosigma eximium* (Thwaites) Boyer arranged in single or multiple rows of cells (Fig. 3).

3.1. Description of the *Gyrosigma eximium*

The valves are linear with obliquely rounded ends. Their length ranges from 53.4 μm to 75.9 μm and the width from 8.8 μm to 12.8 μm. The valves are straight, nearly central, and slightly sigmoid at the ends. The central area is rather large and rounded. Transverse striae (23—25 in 10 μm) and longitudinal striae (27—28 in 10 μm) were observed. The frustules in the gelatinous tubes differed from those of *G. scalproides* (Rabenhorst) Cleve and *G. obtusatum* (Sullivant & Wormley) Boyer in their linear outline and from those of *G. obliquum* (Grunow) Boyer in their rounded ends (Fig. 4).

Type locality: England. Distribution: fresh and brackish water. Rare and local. Reported from the Demerara River, Guiana, and occurs at Rio de Janeiro. It may occur northward.

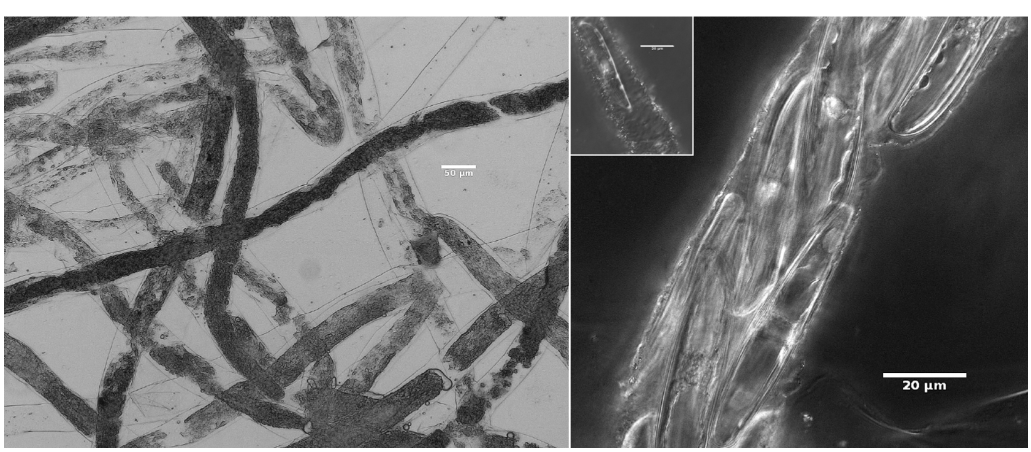

Figure 3 Magnified view of the *Gyrosigma eximium* tubes.

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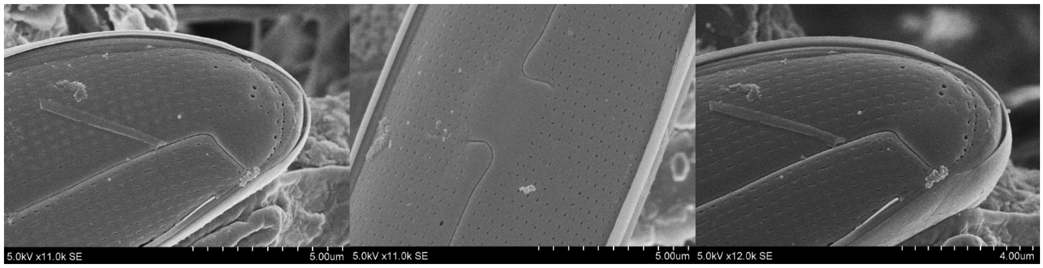

Figure 4 SEM picture of *Gyrosigma eximium* from Adventfjorden tidal flat.

Its ornamentation is characteristic for the section Strigiles (Peragallo, 1890—1981). The longitudinal striae (32—35 in 10 μm) are less spaced and less visible than the transapical ones (22—24 in 10 μm). Although the linear valve outline resembles that of *G. balticum* (Ehrenberg) Rabenhorst or *G. pensacolae* Sterrenburg, the latter two species are longer and broader (200 μm; 25 μm). All three taxa, however, have equal numbers of longitudinal and transapical striae (11—14 in 10 μm). Unlike *G. limosum* Sterrenburg & Underwood, as discussed here, *Gyrosigma* presents linear valves with parallel margins (in contrast to the nearly linear to slightly lanceolate ones of *G. limosum*). Additionally, it has a somewhat median raphe with a tendency to be off centred when approaching the apices; in *G. limosum*, the raphe is practically median throughout the entire valve. Finally, as presented here, *Gyrosigma* has a small terminal hyaline area, triangular in shape and displaced towards the terminal, strongly deflected raphe fissure, whereas that of *G. limosum* is only slightly deflected (Sterrenburg and Underwood, 1997).

3.2. Distribution

Gyrosigma is also known to be a component of ice-associated communities (Poulin, 1991). In tidal flats, this genus was reported by Asmus and Bauerfeind (1994) in the Wadden Sea, whereas Jesus et al. (2009) identified *G. fasciola* (Ehrenberg) Griffith & Henfrey as a microbenthic diatom with 'muddy' preferences. To date, only *G. obliquum* has been noted at sites located outside of the Arctic, as far as the Gulf of Mexico (Krayesky et al., 2009), Samoa (Sterrenburg, 1989) and South China (UNEP, 2008). Some *Gyrosigma* taxa are known for their ability to form tube structures and were previously found further south (45°N), in the Canadian salt marshes of the Bay of Fundy (*G. orbitum* Thaler & Kaczmarska) by Thaler and Kaczmarska (2009), and in western European mudflats (*G. limosum*) by Underwood et al. (1998). According to Sterrenburg (1989), only *G. eximium* exists as tube-dwelling forms. For example, *G. orbitum*, which was described by Thaler and Kaczmarska (2009), forms uniseriate tubes, whereas in Adventfjorden, *G. eximium* forms multiseriate branched tubes.

3.3. Ecological impact

Diatom colonies and their associated cyanobacterial mats constitute a potential factor increasing the transfer of organic carbon to heterotrophic parts of tidal flats. The relatively very high density of meiofauna, exceeding in average 3000 ind. 10 cm^{-2} in comparison with typical for Adventfjorden tidal flat densities of 100 ind. 10 cm^{-2}, in extreme case 1941 ind. 10 cm^{-2} (Table 1) seems to be a confirmation of this statement.

The taxonomic structure of the meiofauna associated with *G. eximium* structures shows a predominance of harpacticoid copepods over nematodes and relatively high density of tardigrades, whereas in previous studies in this region, a clear predominance of nematodes was observed. The most numerous harpacticoid species was the newly described *Nannopus didelphis* Fiers and Kotwicki (2013), which confirms that *Nannopus palustris auct.* is a complex of pseudo-cryptic species (Fiers and Kotwicki, 2013). In general, the Svalbard intertidal meiofauna displayed low density and diversity, with nematodes dominating in total abundance. However, specific microhabitats can create favourable conditions for

Table 1 Abundance [ind. cm^{-2}] of intertidal meiofauna in Isfjorden, Adventfjorden and this study.

Site	Isfjorden mean of 30 sampling points	Adventfjorden only			This study
Taxon	[b]	[a]	[b]	[c]	
Nematoda	113	116	23	1640	1428
Harpacticoida	43	0	3	30	1575
Copepoda nauplii	22	0	0	267	26
Tardigrada	1	0	0	1	38
Polychaeta	1	0	0	0	19
Others	61	0	0	3	0
Total	241	133	26	1941	3086

[a] Włodarska-Kowalczuk et al. (2007).
[b] Szymelfenig et al. (1995).
[c] Węsławski and Szymelfenig (1999).

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abundant meiofaunal communities dominated by other taxa. Besides their nutritional influence, the observed high density of tube-dwelling diatoms may act as an important stabilizer of the surface sediment of tidal flats because excreted extracellular polymeric substances may glue the sediment particles together (Decho, 2000).

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