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SNOW ALGAL COMMUNITIES ON ARCTIC PACK ICE FLOES DOMINATED BY *CHLAMYDOMONAS NIVALIS* (BAUER) WILLE

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Abstract: The occurrence of algae on the surface of Arctic ice floes was studied during the expedition ARK VIII/3 with the German research icebreaker RV POLARSTERN in summer 1991. The species *Chlamydomonas nivalis* (BAUER) WILLE *sensu* KOL was observed on all ice floes sampled covering the central part of the Arctic Ocean. At one location a red coloured snow patch contained $1.56 \cdot 10^5$ cells ml^{-1} melted snow of *C. nivalis*. Only akinetic cells were observed. They were coloured bright red and were mostly incorporated into mucilaginous aggregates together with lithogenic sediments. *C. nivalis* was also observed in the top centimetres of the sea ice floes and in a melt pond, which had formed on the sea ice. Gross production estimates, based on volume specific production rates, indicate that surface algae might significantly contribute to microalgal production on Arctic multi-year sea ice floes.

1. Introduction

Polar oceans are characterised by the occurrence of sea ice for at least several months of the year. In the Arctic Ocean, the extent of the ice cover varies between 7 and $14 \cdot 10^6$ km^2 from summer to winter, reaching a thickness normally between 2 and 4 m (MAYKUT, 1985). Most of the ice is formed by freezing of sea water and, thus, contains various amounts of a saline solution within a branched brine channel system. This system is the realm of a specialised community (the so-called sympagic community; HORNER *et al.*, 1992), consisting of bacteria, protists and metazoans (GRADINGER *et al.*, 1991). The Arctic ice flora and fauna lies within the focus of research since it was discovered in the late 19th century (for a review see HORNER, 1985). The freshwater snow and melt pond habitats associated with sea ice received only little attention except for studies of NANSEN (1906) and BURSA (1963), although snow and glacial fields on land were known to be colonised by algae, bacteria, fungi and protozoa (POLLOCK, 1970). Algae occurring in concentrations of more than $5 \cdot 10^5$ cells ml^{-1} can stain snow and glaciers, as has been shown for many parts of the world (see KOL, 1968 for review). The actual colour of the snow and ice, ranging from grey over green to bright red, is characteristic for the algal species (PASCHER, 1927).

Coloration of the surface of Arctic pack ice floes can occur for at least two reasons. Grey to brownish coloration due to lithogenic sediments (so-called "dirty ice") has received increasing interest from marine geologists (*e.g.* NÜRNBERG *et al.*, 1994). First evidence for the occurrence of snow algae on ice floes was given by PARRY (1828;

reference cited from KOL and EUROLA, 1974) who observed red snow patches close to Svalbard at 82°N. Later findings were reported by MELNIKOV (1980) and THIEDE(1988).

In summer 1991, an expedition with the German research icebreaker RV POLARSTERN went into the central Arctic Ocean. In addition to grey, lithogenic sediments, we observed red patches on the surface of the sea ice. In this paper, we report our observations on algae on the surface of Arctic ice floes and discuss their possible life cycle in this unstable environment.

2. Material and Methods

Snow, melt pond water and ice samples were collected during the expedition ARK VIII/3 of RV POLARSTERN from August to October 1991 (FÜTTERER, 1991). Sampling was carried out along a profile starting east of Svalbard at approximately 81°N, crossing the North Pole and ending north-west of Svalbard at *ca.* 82°N (Fig. 1). The surface of dirty ice floes was sampled at 31 locations to analyse the grain size and composition of

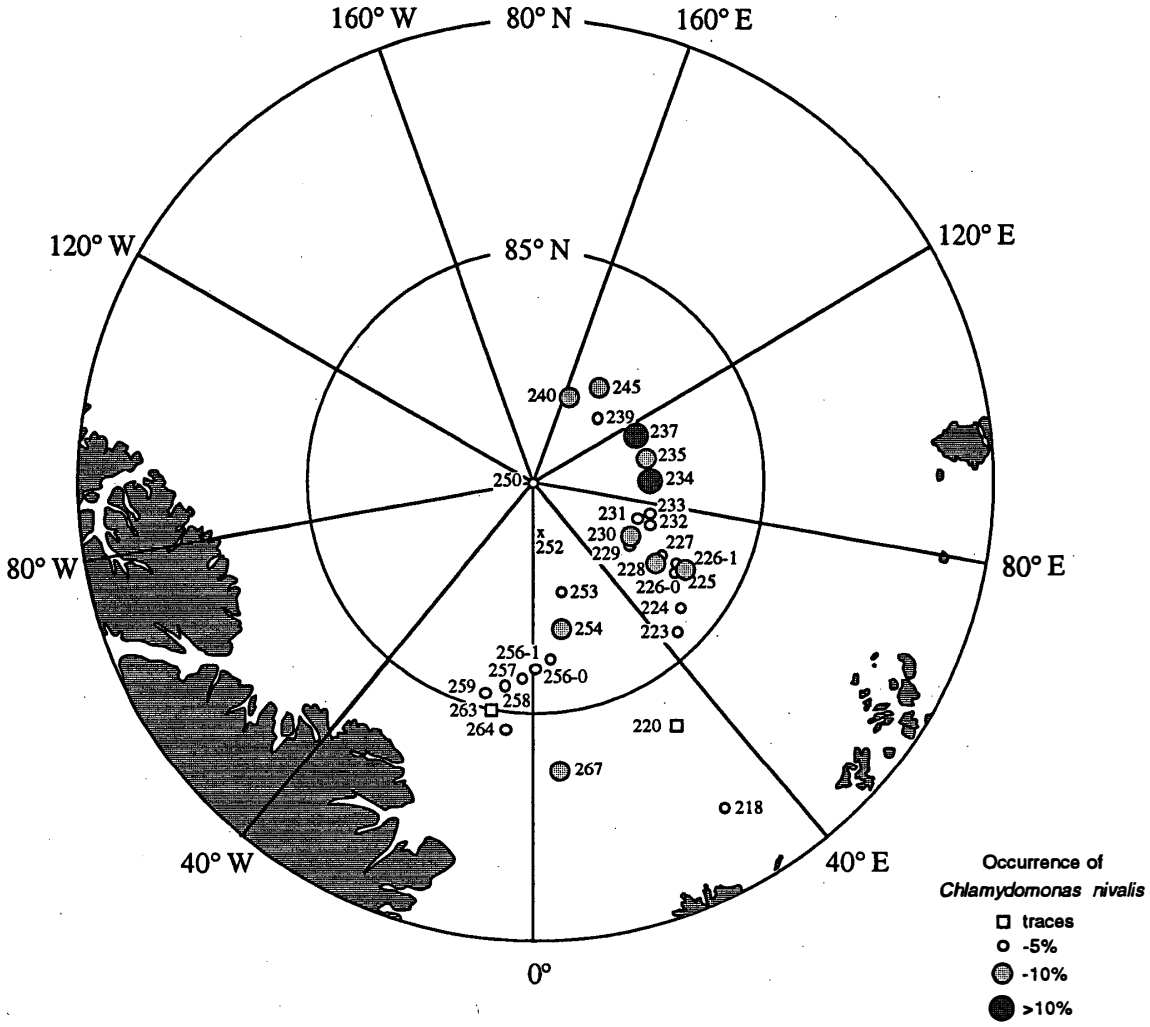

Fig. 1. Occurrence of Chlamydomonas nivalis *in the central Arctic Ocean at 31 stations during the expedition ARK VIII/3 in summer 1991. At station 252 (×) no ice surface but only a melt pond sample was analyzed.*

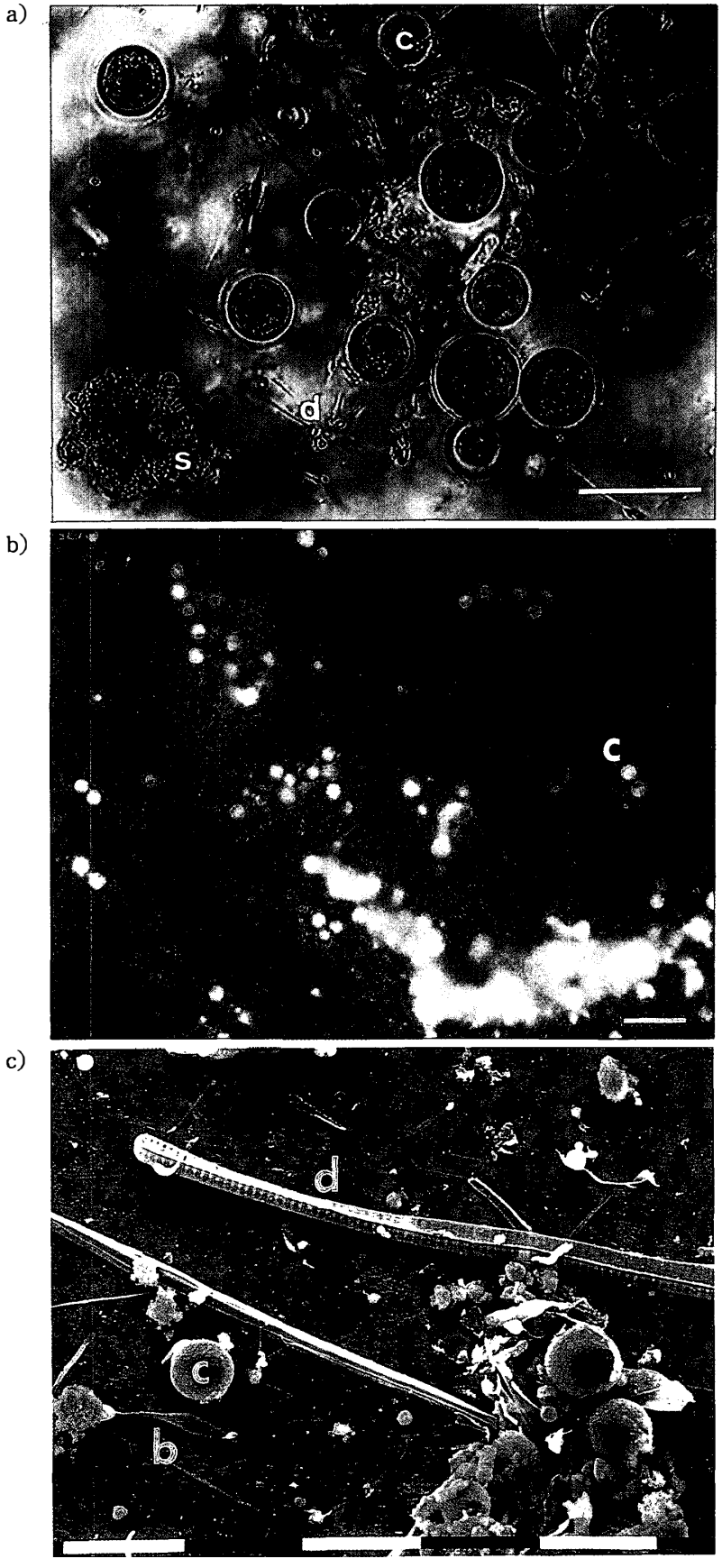

Fig. 2. Chlamydomonas nivalis *from the melted snow sample: a) light microscopy (scale = 20 μm), b) epifluorescence microscopy (blue light excitation; scale = 50 μm) and c) SEM (scale = 10 μm). c* = Chlamydomonas nivalis; *b = hyphenating bacterium (?); s = sediment, p = empty diatom frustule*

the sediment load using a smear slide technique (NÜRNBERG *et al.*, 1994). Algal cells, later identified as *Chlamydomonas nivalis* (BAUER) WILLE *sensu* KOL, could be seen on the slides due to their red colour. At one location (station 237), a red snow patch covering approximately 2 m^2 of the ice surface was sampled and melted at 4 °C in the dark. An ice core was taken at the same location using a 3" SIPRE ice corer and analysed according to GRADINGER *et al.* (1991). A water sample of a melt pond on top of an ice floe was collected at station 252.

All samples for microscopical analysis were fixed with borax-buffered formaldehyde (1% final concentration). Abundances of bacteria and protists were determined using epifluorescence microscopy after DAPI staining (PORTER and FEIG, 1980). Part of the red snow sample was filtered onto a 0.2 μm Nuclepore filter, dried in a critical point drier, coated with gold, and examined with a Philips 515 scanning electron microscope (SEM). The size structure of the snow algae was determined with a video imaging system (Leica Q500MC) attached to a Zeiss Axiovert 135 inverted microscope. A volume to carbon conversion factor of 0.11 pg C μm^{-3} was applied according to HELCOM (1988). Determination of chlorophyll followed EVANS and O'REILLY (1983).

3. Results

Analysis by light microscopy (LM) revealed that the snow algal community from station 237 consisted almost entirely of akinetic round cells (Fig. 2a) with diameters between 5 and 16 μm (Fig. 3a). The median diameter was 8.4 μm, equivalent to 34.1 pg C $cell^{-1}$ (Fig. 3b). The chloroplasts were masked by a red colour which filled the entire cell volume, the pyrenoid was found in a central position of the cell. The cells were

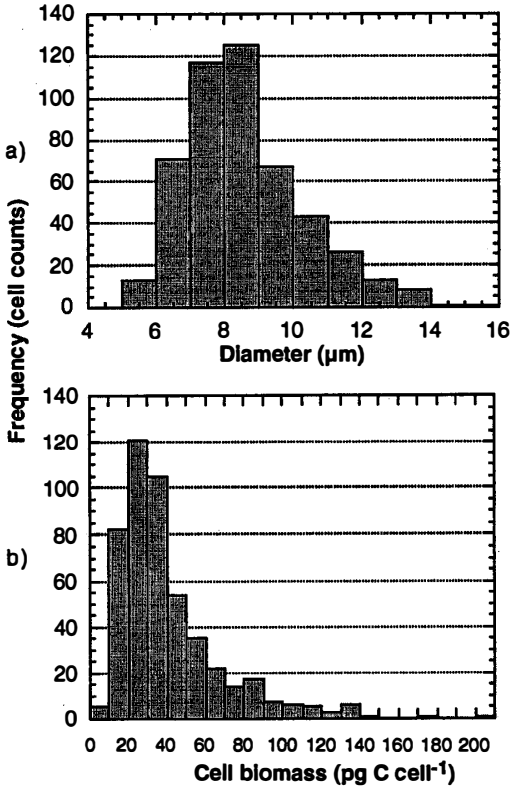

Fig. 3. Cell size (a) and biomass frequency distribution (b) of Chlamydomonas nivalis *taken from the snow sample at station 237.*

Table 1. Abundance of bacteria and Chlamydomonas nivalis *in the melt pond of station 252 and the red snow patch and the upper 20 cm of the ice core at station 237.*

	Snow	Melt pond	Ice
Bacteria (10^5 ml^{-1})	5.3	8.3	68.2
Chlamydomonas nivalis (10^5 ml^{-1})	1.556	0.031	0.003

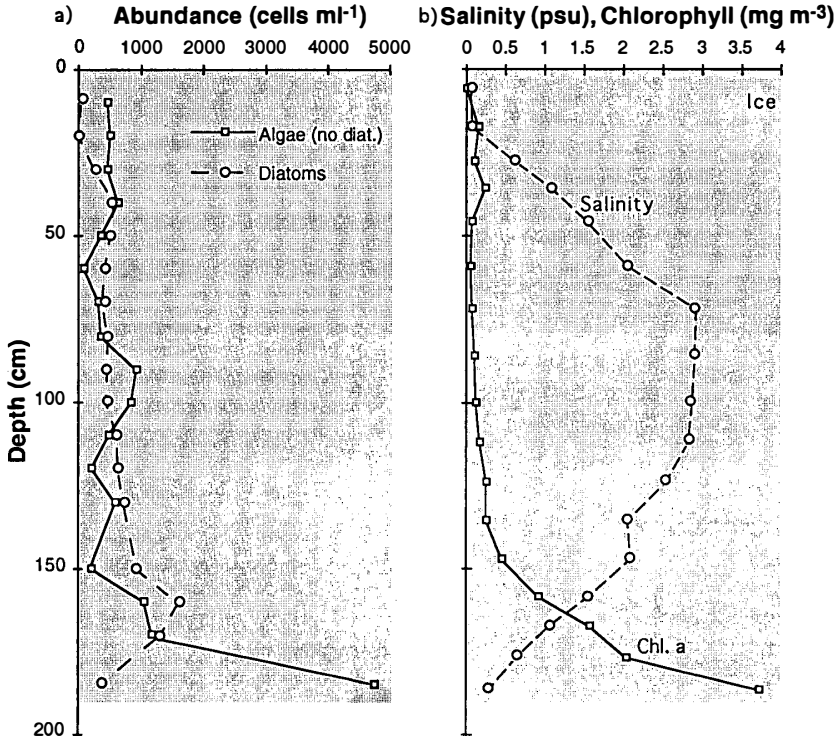

Fig. 4. Vertical distribution of a) diatoms and other algae and b) salinity and Chlorophyll a in an ice core from station 237.

either incorporated in mucilaginous aggregates, together with mineral sediment and empty diatom frustules or occurred as single, isolated cells (Fig. 2). The cell surface was rough and covered by a thin mucilaginous envelope. Based on these characteristics we classified the cells as *Chlamydomonas nivalis* (BAUER) WILLE following KOL (1968): She defined *C. nivalis* as a complex (Nomen Collectivum) of all *Chlamydomonas* species causing red coloration of snow.

Bacteria and phototrophic cells were found in the habitats snow, melt pond and sea ice using epifluorescence microscopy (Table 1, Fig. 4). The red snow sample contained *Chlamydomonas nivalis* in concentrations of $1.56 \cdot 10^5$ cells ml^{-1} melted snow. Living diatoms were not observed in the snow, but empty frustule were seen frequently. *C. nivalis* was also observed in the upper 50 cm of the ice core, but in lower abundances (< 700 cells ml^{-1}, Fig. 4a). The ice algal biomass maximum, as shown by the chlorophyll *a* distribution (Fig. 4b), occurred in the lowermost decimetres of the ice floes and was formed by diatoms and other phototrophic cells (max: 5100 cells ml^{-1}). *C. nivalis* also dominated the melt pond community from station 252, but in concentrations approximately 2 orders of magnitude lower than in the red snow sample (Table 1). Diatoms

were missing.

According to the smear slide analysis, *Chlamydomonas nivalis* occurred regularly in the entire investigation area (Fig. 1). Its relative contribution to the total particle concentration, which includes lithogenic sediment as well as empty diatom frustules, was mostly lower than 10%. Thus, lithogenic components were the dominant compartment of the surface load of Arctic ice floes.

4. Discussion

KOL (1942) identified three different categories for algal communities occurring on snow or glacial fields: 1) "nivalis cryobionts" (major habitat: snow and firn), 2) "glacial cryobionts" (major habitat: pure ice), and 3) "mixo-cryobionts" (no habitat preference). Organisms accidentally transported to snow and glacial fields are called "cryoxens". The community we observed on Arctic ice floes clearly belongs to the "nivalis cryobiont"-complex with *Chlamydomonas nivalis sensu* KOL as the dominant species. *C. nivalis* is the typical red snow alga for the northern hemisphere (KOL, 1968) and is probably the most common and widely distributed snow algal species (HARDY and CURL, 1972). It is known from many Arctic locations such as Svalbard (NEWTON, 1982; KOL and EUROLA, 1974), Greenland (FJERDINGSTAD *et al.*, 1974), Asia (KOL, 1968), and Alaska (KOL, 1942), but also from California (THOMAS, 1972), Australia (MARCHANT, 1982), and Antarctica (AKIYAMA, 1979; FOGG, 1967).

Nevertheless, it has to be questioned whether all these reports refer to the same species. KOL (1968) already mentions that *Chlamydomonas nivalis* (BAUER) WILLE might represent a complex of several species which have not been separated until now. The algae, we found on the sea ice, had characteristic attributes of *C. nivalis* (central pyrenoid, spherical cell form, red colour). The reported size of *C. nivalis* akinetic cells varies between 6 to more than 30 μm, with our observations being similar to those from Svalbard (KOL and EUROLA, 1974: 8–13 μm). The cell form, the wall thickness and the tendency to form mucilaginous aggregate with non-living materials are in coincidence with the observations of NEWTON (1982) and MARCHANT (1982). Related species like *Chlamydomonas sanguinea* Lagerheim can be excluded due to these attributes. In contrast to our observations, WEISS (1983) observed no structures on the outer surface of *C. nivalis* akinetic cells. This difference may be either the result of the already mentioned taxonomic uncertainties in relation to the *C. nivalis* complex or a physiological response of the mucus production by *C. nivalis* cells to different environmental conditions. For a further elucidation of the species identification problem, a detailed description of all stages of the entire life cycle (spores, zygote, motile forms) is needed. As we observed only one akinetic stage, our species determination cannot be unequivocally clarified. Here, a combination of morphometric data with the application of genetical techniques (*e.g.* RNA fingerprinting) will help to solve the still existing uncertainties concerning the species *C. nivalis*.

The species composition within snow algal patches is highly variable. NEWTON (1982) and KOL and EUROLA (1974) observed up to 32 algal species in snow samples from different Arctic locations. Our data are similar to findings in Antarctica (AKIYAMA, 1979) where red snow patches consisted of 99% *Chlamydomonas nivalis*. How-

ever, other algal species may also occur on Arctic ice floes. According to MELNIKOV (1980) several chlorophyte (*Ancylonema* sp., *Chlorella* sp.) and one cyanophyte species (*Stigonema ocellatum f. paniformes*) were found in addition to *C. nivalis* during the Russian ice drift studies "North Pole 22" in 1975 and "North Pole 23" in 1979 in the central Arctic Ocean, whereas diatoms were absent. The lack of living diatoms is typical for all temporary snow fields, which are mostly dominated by *Chlamydomonadaceae* such as *C. nivalis* (WHARTON and VINYARD, 1983). The occurrence of empty diatom frustules on the ice surface (ABELMANN, 1992) is not the result of active growth in the snow-ice interface as observed in Antarctica (SPINDLER, 1990), but results from passive accumulation due to ice melting.

Table 2. Abundance of snow algae from various locations.

Author	Abundance (10^3 cells ml^{-1} snow)	Location	Snow colour
AKIYAMA (1979)	160–530	Antarctica	Green/orange/red
FOGG (1967)	400	Antarctica	
POLLOCK (1970)	max. 500	U. S. A.	Red
THOMAS (1972)	max. 135	California	Red
KOL and EUROLA (1973)	10–17	Finland	Red
KOL and EUROLA (1974)	6–372	Svalbard	Red
MELNIKOV (1980)	0.002–0.015	Arctic Ocean	
This study	156	Arctic Ocean	Red

The concentrations of snow algae in coloured patches from different locations on earth vary between 6 and $530 \cdot 10^3$ cells ml^{-1} (Table 2). These high concentrations may be the result of either *in-situ* growth or passive accumulation. In the case of Arctic sea ice, *Chlamydomonas nivalis* is probably passively dispersed in the Arctic Ocean as part of the aeroplankton by northwards going winds similar to pollutants emitted in North America or Europe (OPEN UNIVERSITY TEAM, 1991). This mechanism was already proposed by NEWTON (1982) based on his observations in Svalbard. On the ice floes *C. nivalis* is exposed to a wide range of temperature and light conditions. As a psychrophilic species *C. nivalis* is able to survives temperatures down to -35°C (TROLL, 1973). During the Arctic summer growth of *C. nivalis* on Arctic ice floes was already measured by THIEDE (1988) with a primary production rate of 87 mg C m^{-3} snow d^{-1} (light intensity: 350 μmol photons m^{-2} s^{-1}) within a red snow patch. This rate was even higher than the production by an ice floe bottom community (30 mg C m^{-3} d^{-1} at 56 μmol photons m^{-2} s^{-1}). In addition to active growth passive redistribution of *C. nivalis* occurs during the spring and summer melting of the snow cover of the ice floes. By this process *C. nivalis* cells are advected into the surface melt ponds and the upper decimetres of the ice floes, where we observed *C. nivalis* in our study as well. Conclusively, we assume that *C. nivalis* populations inside red snow patches on Arctic ice floes formed by *in-situ* growth during the entire Arctic summer, partly due to the protection of this species against UV radiation by their red carotinoid pigments (KOL, 1968).

Production estimates for algae on the surface of Arctic ice floes are rather sparse. In addition to the data of THIEDE (1988), MELNIKOV (1980) measured low production rates of 0.2–4 mg C m^{-2} d^{-1} for samples from Arctic ice floes. However, he probably did not sample within coloured snow patches, as can be seen from his low concentration

estimates (Table 2). Snow algae from California (THOMAS, 1972) had higher volume specific incorporation rates ($5.7 - 34.2 \cdot 10^{-3}$ mg C mm^{-3} cell volume h^{-1}) than those from Antarctica (FOGG, 1967: 2 to $864 \cdot 10^{-6}$ mg C mm^{-3} cell volume h^{-1}). Based on FOGG's data we calculated the potential production of *C. nivalis* in the red snow patch of station 237 to be 3–1203.4 mg C m^{-3} snow d^{-1}. THOMAS (1972) demonstrated that the algal distribution inside the snow cover is extremely patchy. Assuming that only the uppermost centimetre of the snow contained *C. nivalis* in extremely high concentrations, a maximum potential production by *C. nivalis* within the red patch was calculated to be 12 mg C m^{-2} d^{-1}. A similar calculation based on the data of THOMAS (1972) leads to a maximal value of 476 mg C m^{-2} d^{-1}. These production figures are only gross estimates. They indicate, however, that algae on the surface of ice floes may be important primary producers, in particular if compared with data of LEGENDRE *et al.* (1992) who estimated a total annual microalgal production for Arctic multi-year ice floes of 600 mg C m^{-2}. Thus, we propose that investigations on surface algae be included in future Arctic ecosystem research plans in order to estimate their contribution to Arctic carbon cycling.

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References

ABELMANN, A. (1992): Diatom assemblages in Arctic sea ice–indicator for ice drift pathways. Deep-Sea Res., **39**, 525–538.

AKIYAMA, M. (1979): Some ecological and taxonomical observations on the colored snow algae found in Rumpa and Skarvsnes, Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **11**, 27–34.

BURSA, A. (1963): Phytoplankton in coastal waters of the Arctic Ocean at Point Barrow, Alaska. Arctic, **16**, 239–262.

EVANS, C.A. and O'REILLY, J.E. (1983): A handbook for the measurement of chlorophyll *a* in netplankton and nanoplankton. SCAR/BIOMASS Handbook, **9**, 1–44.

FJERDINGSTAD, E., KEMP, K., FJERDINGSTAD, E. and VANGGAARD, L. (1974): Chemical analysis of red "snow" from East-Greenland with remarks on *Chlamydomonas nivalis* (BAU.) WILLE. Arch. Hydrobiol., **73**, 70–83.

FOGG, G.E. (1967): Observations on the snow algae of the South Orkney Islands. Philos. Trans. R. Soc. London, B, **252**, 279–294.

FÜTTERER, D.K. (1991): ARCTIC '91: Die Expedition ARK-VIII/3 mit FS "POLARSTERN" 1991. Ber. Polarforsch., **107**, 1–267.

GRADINGER, R., SPINDLER, M. and HENSCHEL, D. (1991): Development of Arctic sea-ice organisms under

graded snow cover. Polar Res., **10**, 295–308.
HARDY, J.T. and CURL, H. (1972): The candy colored, snow-flaked alpine biome. Nat. Hist., **9**, 75–78.
HELCOM (1988): Guidelines for the Baltic Monitoring Programme for the Third Stage. Part D. Biological Determinants. Helsinki, Finn. Governm. Print. Centr., 161 p.
HORNER, R. (1985): Sea Ice Biota. Boca Raton, CRC Press, 215 p.
HORNER, R., ACKLEY, S.F., DIECKMANN, G.S., GULLIKSEN, B., HOSHIAI, T., LEGENDRE, L., MELNIKOV, I.A., REEBURGH, W.S., SPINDLER, M. and SULLIVAN, C.W. (1992): Ecology of sea ice biota. 1. Habitat, terminology, and methodology. Polar Biol., **12**, 417–427.
KOL, E. (1942): The snow and ice algae of Alaska. Smithson. Misc. Coll., **101**, 1–36.
KOL, E. (1968): Kryobiologie. Biologie und Limnologie des Schnees und Eises. 1. Kryovegetation. Stuttgart, E. Schweizerbart'sche Vlg., 205 p.
KOL, E. and EUROLA, S. (1973): Red snow in the Kilpisjärvi region, North Finland. Astarte, **6**, 75–86.
KOL, E. and EUROLA, S. (1974): Red snow algae from Spitsbergen. Astarte, **7**, 61–66.
LEGENDRE, L., ACKLEY, S.F., DIECKMANN, G.S., GULLIKSEN, B., HORNER, R., HOSHIAI, T., MELNIKOV, I.A., REEBURGH, W.S., SPINDLER, M. and SULLIVAN, C.W. (1992): Ecology of sea ice biota. 2. Global significance. Polar Biol., **12**, 429–444.
MARCHANT, H.J. (1982): Snow algae from the Australian snowy mountains. Phycologia, **21**, 178–184.
MAYKUT, G.A. (1985): The ice environment. Sea Ice Biota, ed. by R. HORNER. Boca Raton, CRC Press, 21–82.
MELNIKOV, I.A. (1980): Ecosystem of the Arctic drifting ice. Biology of the Central Arctic Ocean, ed. by M.E. VINOGRADOV and I.A. MELNIKOV. Moskva, Nauka, 61–97.
NANSEN, F. (1906): Protozoa on the ice-floes of the North Polar Sea. Sci. Res. Norw. N. Polar Exped., **5**, 1–22.
NEWTON, A.P.W. (1982): Red-coloured snow algae in Svalbard–Some environmental factors determining the distribution of *Chlamydomonas nivalis* (Chlorophyta Volvocales). Polar Biol., **1**, 167–172.
NÜRNBERG, D., WOLLENBURG, I., DETHLEFF, D., EICKEN, H., KASSENS, H., LETZIG T., REIMNITZ, E. and THIEDE, J. (1994): Sediments in Arctic sea ice: Implications for entrainment, transport and release. Mar. Geol., **119**, 185–214.
OPEN UNIVERSITY TEAM (1991): Case Studies in Oceanography and Marine Studies. Oxford, Pergamon Press, 248 p.
PARRY, W.E. (1828): Narrative of an attempt to reach the North Pole, in boats fitted for the purpose, and attached to his Majesty's ship Hecla in the year 1827, under the command of captain W.E. Perry. London
PASCHER, A. (1927): Volvocales = Phytomonadina. Die Süßwasserflora Deutschlands, Österreichs und der Schweiz, ed. by A. PASCHER. Jena, Fischer, 1–506.
POLLOCK, R. (1970): What colors the mountain snow? Sierra Club Bull., **4**, 18–20.
PORTER, K.G., and FEIG, Y.S. (1980): The use of DAPI for identifying and counting aquatic microflora. Limnol. Oceanogr., **25**, 943–948.
SPINDLER, M. (1990): A comparison of Arctic and Antarctic sea ice and the effects of different properties on sea ice biota. Geological History of the Polar Oceans: Arctic *versus* Antarctic, ed. by U. BLEIL and J. THIEDE. Kluwer Academic Publ., 173–186.
THIEDE, J., comp. (1988): Scientific cruise report of the Arctic expedition ARK IV/3. Phytoplankton studies (RWTH). Ber. Polarforsch., **43**, 88–92.
THOMAS, W.H. (1972): Observations on snow algae in California. J. Phycol., **8**, 1–9.
TROLL, W. (1973): Allgemeine Botanik. Stuttgart, Enke Vlg., 994 p.
WEISS, R.L. (1983): Fine structure of the snow alga (*Chlamydomonas nivalis*) and associated bacteria. J. Phycol., **19**, 200–204.
WHARTON, R.A.J. and VINYARD, W.C. (1983): Distribution of snow and ice algae in western North America. Madrono, **30**, 201–209.

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