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Scientific note

The Arctic sea ice biological communities in recent environmental changes

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Abstract: Biological materials obtained at the former Soviet Union ice station "North Pole-22" (NP-22) within the Beaufort Gyre in 1975–1981 have shown that the multi-year ice and ice-water interface is a rich and diverse environment inhabited by large numbers of diatoms and invertebrates. Recent data from the ice camp SHEBA (Surface Heat Budget of the Arctic Ocean) from the Beaufort Gyre in 1997–1998, comparable to the NP-22 data, demonstrate the following changes: (i) populations of sea ice diatoms are now very scarce by numbers of species and abundance; (ii) fresh water green algae, previously abundant only on the upper sea ice surface or within the uppermost sea ice layers, now dominate the entire sea ice thickness; (iii) populations of invertebrate animals like nematodes, copepods, amphipods, and turbellarians previously common within the sea ice interior are now not found in the multi-year ice and newly formed sea ice; (iv) cryopelagic fauna associated with the bottom sea ice surface as well as the under-ice zooplankton are also now scarce by numbers of species and abundance. These changes in the composition and structure of the sea ice communities within the Beaufort Gyre may be explained by increased melting of the sea ice cover during the last decade, and subsequent changes to the physical makeup of the sea ice.

1. Introduction

The Arctic Ocean is one of the major components of the world's atmosphere-ocean system and within this ocean, sea ice is the key dominant environmental feature. This 2–4 m thick sea ice cover affects the magnitude of both heat and gas fluxes between the atmosphere and upper ocean and supports a unique and tightly coupled biological community—the sea ice ecosystem. Observations made in 1970–1980 have shown that in spite of interannual variability in environmental factors the physical structure, chemical compounds, species composition, and species distribution within the sea ice were stable and predictable from year to year across the Arctic Ocean. The Arctic Ocean sea-ice can therefore be considered an integral and stable ecological system (Melnikov, 1997).

Recent environmental changes in the Arctic Ocean during the last two decades have been widely discussed in the literature, with many models predicting a greenhouse gas-induced warming in polar regions associated with warming of the upper ocean and a substantial retreat of the sea ice cover (Walsh, 1991; McPhee *et al.*, 1998; Johannessen *et al.*, 1995, 1999; Vinnikov *et al.*, 1999). Analysis of the climate trends in the Arctic indicates considerable warming over the landmasses of Eurasia and North America, particularly in winter and spring (Chapman and Walsh, 1993). Over the last three decades, trends toward higher temperatures have been up to 1.5℃ per decade (Weller, 1999). On results of recent research on Arctic climate oscillatory behavior, a standing surface level pressure oscillation over much of the northern hemisphere was shown to be associated with a sea ice anomaly propagating anticyclonically around the Arctic Ocean (Mysak and Venegas, 1998), the upper ocean and ice circulation (Carmack *et al*., 1995; Morison *et al*., 1998) and river discharge (Johnson *et al*., 1999). Hydrographic data obtained during the last decade (*e.g*., AOS 1994, SCICEX cruises, 1993–1997) have supplied intriguing evidence that Atlantic Water flows into the Arctic Ocean had been warmed relative to previous years and inflow had increased in volume by about 20% (Carmack *et al*., 1995; Morison *et al*., 1998). Warming relative to historical data and also freshening of the upper ocean were observed. A warm core of the Atlantic Water with temperatures of 0.5° to 1.7℃ was observed above the Lomonosov Ridge, and another less apparent warm core with temperature of 1℃ existed over Mendeleev Ridge. According to Carmack *et al*. (1995) and Morison *et al*. (1998), these data indicate a fundamental change in the circulation of the Arctic Ocean since the early 1990s.

Recent field and satellite-based observations show a rapid decrease in the Arctic Ocean sea ice extent during the past 46 years (Cavalieri *et al*., 1997; Johannessen *et al*., 1999; Vinnikov *et al*., 1999). Satellite observations indicate a decrease in areal ice extent of nearly 3% per decade since the late 1970s, accelerating in the last decade (Cavalieri *et al*., 1997). Johannessen *et al*. (1995) reported a reduction of the annual mean ice cover of the Arctic Ocean during 1978 to 1994. Using satellite-derived ice maps, they estimated a decrease of the total sea ice extent of 0.05×10^6 km^2/yr, of which 14% was due to reduction of the multi-year ice area. Reduction of the sea ice cover is very noticeable in the Canadian Basin of the Arctic Ocean. Rothrock *et al*. (1999) compared sea ice thickness data acquired by the Scientific Ice Expedition (SCICEX) in the mid-1990s with data from 1958 and 1976, finding a mean decrease of 1.3-m (around 40%) in ice thickness over the deep Arctic Ocean with greater decreases in the eastern and central Arctic than in the western Arctic.

During the period 1975–1981, the former Soviet Union's "North Pole-22" ice station (NP-22) drifted within the Beaufort Gyre in the Canadian Basin of the Arctic Ocean. Twenty-plus years later and also within the Beaufort Gyre, in 1997–1998, the USA National Science Foundation conducted the year-round experiment SHEBA (Surface Heat Budget of the Arctic Ocean) supported by the Canadian Coast Guard icebreaker Des Groseilliers (Perovich *et al*., 1999). At both the NP-22 and SHEBA ice camps we made multi-disciplinary biological studies of the sea ice-water system including sea ice observations and observations of the upper ocean (Melnikov, 1997; Melnikov *et al*., 2000; Sherr *et al*., 2000). The main goal of this paper is to show how do the environmental changes observed recently in the Arctic Ocean impact the physical-chemical composition of the sea-ice and sea ice-associated biological communities.

2. Material and methods

This research is based on material collected during the winter at the ice camps NP-22 from January to April 1980 and SHEBA from October 1997 to March 1998 within the

Beaufort Gyre. The field observations sampling methods and laboratory procedures were similar in both expeditions, giving a good opportunity for comparison of data obtained within the Beaufort Gyre across two decades. At each location we took first-year (FY) and multi-year (MY) ice cores on pristine floes away from the influence of the camp, in order to monitor the physical, chemical, and biological characteristics of the ice. Cores were taken with a 120-mm internal diameter SIPRE-style corer through the entire ice column. The total ice core length was measured, the surface cleaned and the whole ice core divided into equal 10 or 20-cm parts. Each ice section was crushed into small pieces, put into plastic bottles and melted at room temperature. For comparison of results, at the SHEBA ice camp we did not melt ice in filtered sea water to keep the same procedure that was used at NP-22. Salinity, silicate, phosphate, and chlorophyll *a* concentrations were measured on subsamples of the melt water. Aliquots of samples were preserved for species identifications in 4% formalin and processed six months later in the P.P. Shirshov Institute of Oceanology laboratory by standard planktonology methods. See Melnikov (1997) for details of field and lab methods.

3. Results

3.1. Sea ice interior

3.1.1. Physical, chemical, and biological components

The total data set includes 18 MY cores (7 from NP-22 and 11 from SHEBA) and 16 FY ice cores (4 from NP-22 and 12 from SHEBA). Dates and positions of sea ice core samplings, mean and standard deviations of salinity, silicate and chlorophyll *a* concentration are summarized in Table 1. Mean SHEBA values of the MY ice salinity are about half those of NP-22, but the FY values are twice as high. The most curious feature of the SHEBA ice samples is very low concentrations of Si in the MY and FY sea ice, an order of magnitude less than at NP-22: 3.76 μM and 2.18 μM in the MY and FY ice at NP-22, and 0.40 μM and 0.28 μM at SHEBA, respectively. The main feature of chlorophyll *a* concentrations in the ice cores is the two-fold decrease in SHEBA multi-year ice compared to NP-22, and three-fold increased chlorophyll *a* concentrations in first-year ice.

3.1.2. Flora

We found a total of 102 species of ice algae, 76% at NP-22 and 23% at SHEBA. The similarity between species was only 8%. The prevalence of diatoms characterizes both MY and FY sea ice at NP-22 with 79 species compared to SHEBA with only 18 species (Table 2). Fresh water algae (mostly Chlorophyta) were detected only on the upper surface of ice at NP-22. The obvious predominance of fresh water algae compared with diatoms was the main peculiarity of the algal populations at SHEBA where fresh water algae were dominant and were distributed within both MY and FY ice interiors from top to bottom.

3.1.3. Fauna

The outstanding feature of the MY and FY sea ice populations is the absolute absence of interstitial fauna within the sea ice interior in the SHEBA ice samples compared with the consistently high numbers found in the NP-22 samples. Ten species including Protozoa, Foraminifera, Acarina, Nematoda, Turbellaria, Harpacticoida and Amphipoda, in both the MY and FY sea ice, were found at NP-22, whereas only one species of Foraminifera was found at SHEBA (Table 3). Notable was the abundance of the free-living nematode

Table 1. Summary of ice thickness, date of sampling position, physical and chemical variables of MY and FY ice cores at the NP-22 and SHEBA ice camps. Data are mean ± 1SD.

Core #	Thick (cm)	Sampling date	Latitude	Longitude	Salinity (‰)	Silicate (mM/l)	Chl *a* (mg/l)
			NP-22, multi-year ice				
1	404 (11)	15 Feb 80	77°53′N	153°49′E	2.02 ± 1.69	6.1 ± 2.11	0.45 ± 0.44
2	350 (9)	11 Mar 80	78°17′N	153°35′E	2.42 ± 1.43	2.6 ± 0.53	0.23 ± 0.18
3	163 (5)	31 Mar 80	78°21′N	153°07′E	5.60 ± 2.14	3.51 ± 4.05	0.18 ± 0.22
4	199 (6)	01 Apr 80	78°22′N	153°01′E	5.07 ± 0.48	2.21 ± 0.43	0.09 ± 0.01
5	162 (5)	04 Apr 80	78°22′N	152°30′E	5.52 ± 0.86	3.93 ± 0.5	0.06 ± 0.04
6	339 (11)	18 Apr 80	78°35′N	151°52′E	3.17 ± 0.56	3.2 ± 1.33	0.61 ± 0.34
7	211 (4)	20 Apr 80	78°39′N	151°48′E	4.86 ± 4.21	4.68 ± 2.39	0.24 ± 0.18
				Mean:	4.09 ± 1.62	3.76 ± 1.62	0.35 ± 0.20
			NP-22, first-year ice				
1	104 (3)	23 Jan 80	77°40′N	154°99′E	0.99 ± 0.09	1.90 ± 0.69	0.05 ± 0.01
2	114 (4)	01 Feb 80	77°48′N	153°54′E	0.84 ± 0.19	ND	ND
3	129 (4)	26 Feb 80	78°05′N	154°36′E	0.88 ± 0.22	1.98 ± 0.33	0.09 ± 0.07
4	167 (4)	28 Feb 80	78°07′N	153°54′E	1.28 ± 0.25	2.67 ± 0.70	0.06 ± 0.03
				Mean:	0.99 ± 0.19	2.18 ± 0.57	0.06 ± 0.03
			SHEBA, multi-year ice				
1	244 (10)	27 Oct 97	75°17′N	143°31′W	ND	ND	0.12 ± 0.08
2	235 (12)	12 Nov 97	76°09′N	146°26′W	1.43 ± 0.96	0.12 ± 0.16	0.24 ± 0.19
3	185 (9)	28 Nov 97	75°07′N	147°33′W	1.67 ± 1.08	0.16 ± 0.14	0.09 ± 0.15
4	216 (11)	10 Dec 97	75°44′N	150°25′W	2.16 ± 1.36	ND	0.31 ± 0.53
5	178 (9)	29 Dec 97	75°17′N	149°59′W	2.62 ± 1.60	0.72 ± 0.43	0.13 ± 0.05
6	177 (9)	12 Jan 98	74°51′N	150°25′W	2.97 ± 1.87	0.74 ± 0.37	0.11 ± 0.05
7	260 (13)	27 Jan 98	74°51′N	155°38′W	2.10 ± 1.30	0.46 ± 0.27	0.31 ± 0.32
8	281 (14)	18 Feb 98	74°54′N	157°50′W	2.55 ± 1.58	0.35 ± 0.22	0.05 ± 0.04
9	417 (21)	09 Mar 98	75°28′N	160°18′W	2.08 ± 0.95	0.08 ± 0.05	0.17 ± 0.13
10	287 (15)	29 Apr 98	75°57′N	166°13′W	2.50 ± 2.02	0.45 ± 0.37	0.09 ± 0.09
11	291 (14)	25 May 98	76°24′N	167°11′W	0.94 ± 0.50	0.56 ± 0.18	0.11 ± 0.13
				Mean:	2.10 ± 1.32	0.40 ± 0.24	0.16 ± 0.16
			SHEBA, first-year ice				
1	62 (6)	19 Oct 97	75°20′N	144°29′W	0.41 ± 0.19	ND	0.20 ± 0.07
2	66 (6)	27 Oct 97	75°17′N	143°31′W	0.58 ± 0.32	ND	0.46 ± 0.50
3	77 (7)	11 Nov 97	76°09′N	146°23′W	1.74 ± 0.89	0.08 ± 0.01	0.13 ± 0.10
4	79 (8)	26 Nov 97	76°13′N	147°43′W	3.03 ± 1.85	0.36 ± 0.27	0.41 ± 0.25
5	116 (6)	12 Dec 97	75°41′N	150°44′W	2.42 ± 1.54	ND	0.14 ± 0.09
6	95 (9)	27 Dec 97	77°17′N	149°57′W	2.86 ± 1.56	0.44 ± 0.26	0.10 ± 0.11
7	137 (7)	11 Jan 98	74°53′N	150°12′W	2.86 ± 1.62	0.45 ± 0.19	0.05 ± 0.02
8	150 (8)	24 Jan 98	74°38′N	153°25′W	3.42 ± 1.99	0.14 ± 0.05	0.06 ± 0.04
9	132 (7)	16 Feb 98	74°53′N	157°50′W	3.31 ± 1.58	0.11 ± 0.03	0.13 ± 0.07
10	171 (9)	09 Mar 98	75°28′N	160°18′W	3.39 ± 1.75	0.05 ± 0.03	0.12 ± 0.08
11	142 (7)	29 Apr 98	75°57′N	166°13′W	ND	0.25 ± 0.09	0.18 ± 0.16
12	138 (7)	25 May 98	76°24′N	167°11′W	ND	0.67 ± 0.28	0.20 ± 0.16
				Mean:	2.4 ± 1.33	0.28 ± 0.13	0.18 ± 0.13

ND-no data; number of ice sections in parenthesis.

Theristus melnikovi associated with the MY sea ice interior at NP-22; yet it was never detected at SHEBA.

Table 2. Number of algal species present within sea ice interior in samples collected from ice camps NP-22 (winter 1979–1980) and SHEBA (winter 1997–1998), Beaufort Gyre, Canadian Basin of the Arctic Ocean.

Taxon	NP-22	SHEBA
Bacillariophyta	79	18
Dinophyta	NO	5
Chrysophyta	NO	1
Chlorophyta	NO	1
Silicoflagellatae	5	1

NO-not observed.

Table 3. Number of fauna species associated with the sea ice interior in samples from the ice camps NP-22 (winter 1979–1980) and SHEBA (winter 1997–1998), Beaufort Gyre, Canadian Basin of the Arctic Ocean.

Taxon	NP-22	SHEBA
Protozoa	3	NO
Foraminifera	1	1
Acarina	1	NO
Nematoda	2	NO
Turbellaria	1	NO
Harpacticoida	1	NO
Amphipoda	1	NO

NO-not observed.

Table 4. Average concentrations of silicate (Si), dissolved oxygen (O_2) and chlorophyll a (Chl a) in the 0–30 m surface water from ice camps NP-22 (1975–1976) and SHEBA (1997–1998), Beaufort Gyre, Canadian Basin of the Arctic Ocean.

Ice camp	Si (μM)		O_2 (m*l*/*l*)		Chl *a* (μg/*l*)	
	winter	summer	winter	summer	winter	summer
SHEBA	4.75	8.0	8.94	9.35	0.067	0.34
NP-22	11.4	13.2	8.30	8.31	0.061	0.22

3.2. Sea ice/water interface

3.2.1. Chemical and biological components

The mean annual values of silicate concentrations (μM) in the 0–30 m water column at SHEBA are decreased about 60% in winter and about 40% in summer compared with NP-22 (Table 4). The SHEBA mean seasonal O_2 concentrations are increased by 8% in winter within 0–30 m comparable to NP-22 and 13% in summer. The NP-22 O_2 concentrations were seasonally stable and the SHEBA winter O_2 concentrations were similar, but the summer concentrations are 55% higher than summer values at NP-22. The annual chlorophyll *a* concentrations were 0.273 μg/*l* at SHEBA, and 0.159 μg/*l* at NP-22, respectively.

3.2.2. Flora

A total of 85 species were identified in samples collected at NP-22 and SHEBA from the bottom ice surface (Melnikov *et al.*, 2000) as shown in Table 5. The main features of the SHEBA and NP-22 algal populations associated with the bottom surface of ice are:

1) A decrease of diatom species from 46 or 96% of total algal populations (NP-22) to

Table 5. Number of algal species present in samples collected at the water/ice interface from ice camps NP-22 (winter 1979–1980) and SHEBA (winter 1997–1998), Beaufort Gyre, Canadian Basin of the Arctic Ocean.

Taxon	NP-22	SHEBA
Bacillariophyta	46	22
Dinophyta	1	19
Chrysophyta	NO	1
Chlorophyta	NO	1
Silicoflagellatae	1	1

NO–not observed.

22 or 51% (SHEBA);

2) A remarkable difference in species composition between two collections: only three species of diatoms (*Chaetoceros socialis*, *Cylindrotheca closterium*, *Thalassionema nitzschioides*), one species of dinoflagelate (*Dinophysis acuta*) and one silicoflagelate (*Dictyocha speculum* var. *octonarius*) were common for both algal communities; similarity between species from the SHEBA and NP-22 algal populations was only 8%;

3) A remarkable increase of Dinophyta in the SHEBA samples with 19 species compared to the NP-22 with only one species;

4) Extensive development of high-density aggregations of green algae Ulothrix implexa (Chlorophyta) at SHEBA. It is a very common brackish- water species (Lokhorst, 1978) and has not been reported before in the high marine Arctic.

Table 6. Number of fauna species associated with the bottom sea-ice surface in samples collected from the ice camps NP-22 (winter 1979–1980) and SHEBA (winter 1997–1998), Beaufort Gyre, Canadian Basin of the Arctic Ocean.

Taxon	NP-22	SHEBA
Protozoa	2	3
Hydrozoa	2	3
Syphonophora	1	1
Ctenophora	1	1
Turbellaria	NO	1
Nematoda	1	NO
Nemertini	1	1
Polychaeta	2	2
Ostracoda	1	1
Copepoda	17	17
Cyclopoida	6	5
Harpacticoida	4	3
Mysida	1	1
Isopoda	2	NO
Amphipoda	14	5
Euphausidaceae	1	1
Decapoda	2	NO
Gastropoda	2	2
Chaetognatha	2	2
Appendicularia	2	3

NO–not observed.

3.2.3. Fauna

At the bottom ice surface we identified 75 species, 64 from NP-22 and 52 from SHEBA. There were only 21 species or 37% of the total common to both ice camps (Melnikov *et al*., 2000). The most notable difference was observed in amphipods, with 14 species or 33% of total faunal species at NP-22 and only 5 species or 11% of total species at SHEBA. Other dominant cryopelagic fauna collected at NP-22 like the polychaete *Antinoella sarsi* were not observed at SHEBA. At the same time the numbers of gelatinous plankton species like appendicularians, medusas and benthic larvae were much higher at SHEBA that at NP-22 (Table 6).

4. Concluding remarks

Observations over the last two decades which showed noticeable changes within the sea ice biological communities in the Arctic Ocean are as follows:

- Sea ice diatoms at SHEBA were very scarce by numbers of species and abundance both in the multi-year and in the newly formed ice;
- Fresh water green algae previously developed only on the upper-ice surface and/or within the upper sea ice layers (NP-22) now dominated within the whole sea ice interior (SHEBA);
- Populations of invertebrate like nematodes, copepods, amphipods, and turbellarians previously found within the sea ice interior (NP-22) were not found in the multi-year and first-year sea ice at SHEBA;
- In the SHEBA samples, fauna associated with the bottom sea-ice surface were also scarce by numbers of species and abundance.

We interpret these data to suggest that remarkable environmental changes have occurred in the last two decades between samplings at the ice camps NP-22 (1975–1981) and SHEBA (1997–1998) in the Beaufort Gyre. The multi-year ice cover thickness has decreased from the average 3–5-m thick at NP-22 to 1.5–2-m at SHEBA, and this is correlated with a decrease in MY ice salinity. At the same time, surface Si concentrations decreased as the freshwater layer thickened and/or the density difference increased, reducing the reinjection of deeper dissolved Si into the surface layer where sea-ice diatoms could use it. This in turn resulted in a marked decrease in diatoms, an increase in freshwater species, and a decrease in primary production (in term of chlorophyll *a* concentration) within MY ice. Faunal diversity also decreased dramatically, probably resulting from a combination of decreased *in situ* primary production and a freshening of interstitial water in summer, eliminating stenohaline forms. Increases in chlorophyll *a* and oxygen content in the water-ice interface suggest that total primary production has increased, probably because decreasing ice and snow thickness has allowed more light to reach the water column, but this possible overall increase in Arctic Ocean productivity has decreased the relative importance of the multi-year ice community to total energy flow.

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