THE CANADA BASIN ZOOPLANKTON IN RECENT ENVIRONMENTAL CHANGES IN THE ARCTIC OCEAN

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ABSTRACT - During the SHEBA (Surface Heat Budget in the Arctic Ocean) year-long experiment in the Canada Basin of the Arctic Ocean, stratified zooplankton tows were made between 0 m and 1000 m in the water column from December 1997 through October 1998. The species composition, distribution and biomass were determined and compared with earlier observations at the ice station "North Pole-22" (NP-22) which drifted in the same region in the mid 1970s. Mean seasonal values of silicate, phosphate, dissolved oxygen and chlorophyll a concentrations in surface and subsurface waters were also compared between SHEBA and NP-22. Against a background of remarkable environmental changes that have occurred during the last two decades we found: (1) changes in the species composition and biomass of zooplankton in the top 1000 m of the water column; (2) an appearance of species imported from the North Pacific; (3) variations in seasonal cycling of the dominant zooplankton species. Ice melting and the spring bloom commenced within the first 10 days of June at SHEBA but not until the middle of July at NP-22. Correspondingly, there was an earlier migration of copepods Calanus hyperboreus, C. glacialis, Metridia longa, Oithona similis and Pareuchaeta glacialis, the main zooplankton biomass contributors. Several North Pacific zooplankton species were found for the first time during the SHEBA drift: copepods Calanus marshallae, Eucalanus bungii, Metridia pacifica, Lucicutia ovaliformis, Heterorhabdus pacificus, amphipod Scina pusilla, hydromedusas Atolla tenera and Pantachogon haeckeli. These species were not found in the Canada Basin during NP-22 (1975-1976) and other expeditions that sampled this region during the 1960s and '70s. Recent changes in the Arctic Ocean include (1) changes in water circulation and distribution, (2) changes in the temperature of the Atlantic layer, (3) change in the Pacific inflow, (4) a noticeable shrinking of sea-ice cover especially in the marginal seas, (5) a freshening of the surface waters associated with increased runoff and sea-ice melt all forced probably by change in global atmosphere circulation We conclude that zooplankton in the Canada Basin have, similarly, undergone change and therefore provide a sensitive indicator of the response of the biological system to these physical changes.

KEY WORDS: Canada Basin, SHEBA, zooplankton, environmental changes, Arctic Ocean

INTRODUCTION

A warming trend has been observed in the Northern and Southern hemispheres and, in agreement with climate models, the warming is more noticeable in the Arctic than elsewhere. 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, temperatures have increased by up to 1.5°C per decade (Weller, 1998). Recent research on Arctic climate has shown a standing surface level pressure oscillation over much of the northern hemisphere associated with a sea ice anomaly propagating anticyclonically around the Arctic Ocean (Mysak and Venegas, 1998) and forcing the upper ocean and ice circulation (Carmack et al., 1995; Morison et al., 1998) and river discharge (Johnson et al., 1999).

Fundamental changes in the Arctic Ocean have led to remarkable environmental changes in the Canada Basin where observations show: (1) a noticeable shrinking of the sea-ice cover since the 1970s (Johannessen *et al.*, 1995; Cavalieri *et al.*, 1997; Vinnikov *et al.*, 1999), (2) a rise in temperature of the Atlantic layer (Carmack et al., 1997), (3) an alteration of the distribution of Atlantic and Pacific waters (McLaughlin et al., 1996; Morrison et al., 1998), (4) a freshening of the Arctic surface waters associated with runoff and sea-ice melting (Serreze and Maslanik, 1997; McPhee et al., 1998; Macdonald et al., 1999) and change in the Pacfic Inflow (Aagaard, pers comm.). These environmental changes in the air-ice-water system have had consequent effects on the composition of biological communities in the upper water column. Data collected during SHEBA (Surface Heat Budget in the Arctic Ocean), which drifted in the Canada Basin for a full year in 1997-1998 (Perovich et al., 1999) show that populations of ice diatoms and invertebrate animals observed in the interior ocean during the 1970s were remarkably decreased both in species and numbers (Melnikov, 2000). Cryopelagic fauna associated with the bottom of the sea-ice surface and under-ice zooplankton were also scarce (Melnikov et al., 2000). The main physical factors accompanying these biological changes were: (1) drainage of fresh water throughout the sea ice interior; (2) accumulation of fresh water beneath the ice; (3) formation of stable and sharp halocline at around 30 m (Melnikov et al., 1998).

A crucial question is how have these physical changes witnessed throughout the Arctic Ocean affect-

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ed the distribution of zooplankton populations in the Canada Basin? During the SHEBA drift, zooplankton was caught from the under-ice surface down to a depth of 1000 m. The sampling strategy and lab procedures at SHEBA were similar to those at the ice station North Pole-22 (NP-22; 1975-1981) which, because both platforms drifted in the same area, provide a good opportunity to compare data taken two decades apart. Here, we will use SHEBA and NP-22 historical data (Melnikov, 1976; 1989; 1997; Melnikov and Pavlov, 1978) to show how environmental changes in the ice-water system are manifested in species composition, biomass and vertical distribution of zooplankton in the Canada Basin.

MATERIAL AND METHODS

This research is based on data collected during the SHEBA ice camp drift from October 1997 (75°N and 142°W) to October 1998 (81°N and 166°W). From Oc-

tober 1997 to February 1998 SHEBA drifted westward over the Canada Abyssal Plain along 75° in < 3800 m water depth. In February-September, 1998 the ice camp crossed the Chukchi Plateau at 300-1000 m depth heading northwest, and then again drifted northward to the Mendeleyev Abyssal Plain <3300 m water depth in September-October, 1998, (Fig. 1). Figure 1 also shows the NP-22 drift in the Beaufort Gyre from May 1975 (83°N and 167°W) to May 1976 (83°N and 142°W).

At both SHEBA and NP-22, vertical plankton tows (Table 1) were carried out with a Juday net (150- μ m mesh size filtering cone) with a 37-cm wide flat top. The following strata, in metres, were sampled by the tows: 0-35, 35-50, 50-150, 150-300, 300-1000 m (SHE-BA) and 0-25, 25-50, 50-100, 100-200, 200-300, 300-500, 500-1000 and 1000-bottom (NP-22). In this paper, we will use samples taken only from 0-1000 m in the water column, relating them to water mass characteris-

Table 1. Station data for zooplankton samples from SHEBA Ice Camp in 1997-1998and drifting station NP-22 in 1975-1976.

Station	Sampling	Position			
number	date				
	•	SHEBA			
1	19.12.97	75 32N	150 17W		
2	30.12.98	75 15N	149 59W		
3	12.01.98	74 51N	150 25W		
4	30.01.98	75 05N	156 21W		
5	11.02.98	74 54N	157 47W		
6	26.02.98	75 03N	159 39W		
7	06.03.98	75 13N	159 57W		
8	03.05.98	76 00N	165 30W		
9	22.05.98	76 20N	166 35W		
10	17.06.98	77 17N	166 28W		
11	02.07.98	78 07N	166 48W		
12	15.07.98	78 05N	166 08W		
13	01.08.98	78 19N	161 25W		
14	27.08.98	79 34N	160 01W		
15	10.09.98	79 38N	162 00W		
16	21.09.98	80 14N	164 42W		
17	01.10.98	80 14N	166 00W		
	NP-22				
1	20.05.75	83 54N	167 58W		
2	05.06.75	84 22N	167 02W		
3	20.06.75	84 02N	168 34W		
4	05.07.75	84 27N	166 42W		
5	22.07.75	83 45N	163 45W		
6	06.08.75	83 02N	161 32W		
7	25.08.75	82 56N	163 12W		
8	13.09.75	83 07N	162 57W		
9	19.10.75	83 17N	155 43 W		
10	12.04.76	83 31N	141 54W		
11	01.05.76	83 39N	142 22W		

tics from parallel CTD data. Plankton samples were concentrated on nylon gauze (mesh size 150 μ m) and fixed with 5% formaldehyde for each set collection. Both collections were processed by common planktonological methods (Kisilev, 1969). In the laboratory, enumeration and species composition were conducted for each sample using plankton counting tray and light microscope at 300x.

The zooplankton biomass was calculated using the animal body-size measurements under laboratory conditions as follows: each animal body size was measured and biomass was calculated by the formula: $W = k \tilde{o} L^3$, where W is animal weight in mg, L is length in mm, and k is coefficient (Vinogradov and Shushkina, 1987). The NP-22 zooplankton biomass was measured under field conditions using the volumetric method (Yashnov, 1959). It is well known that the values obtained by titration method (volume measurements) overestimate the biomass values measured by the body-size method (Kisilev, 1969). In the former case, the volume is higher due to the presence of other substances such as phytoplankton cells and/or particles of detritus. In the latter case, the biomass is based only on the number and body-size of the animals. A comparison of zooplankton biomass values measured for similar samples at NP-22 (1975-1976) using the titration method under field conditions (Melnikov and Pavlov, 1978) and using the animal body-size measurements under laboratory conditions (Kosobokova, 1981; 1982) is shown in Fig. 2 for the 0-100-m and 100-1000-m layers, respectively. The largest differences were found in the upper layer (R^2 =0.53), where phytoplankton cells are present in the summer during photosynthesis and would, probably, increase volumetric values. In the winter when phytoplankton cells are limited mainly to the water-ice interface, phytoplankton abundance in the 0-100-m water column is negligible and contributes little to the titration volume of sample. The lowest differences (R^2 =0.88) were found for the deepest layer. The difference between zooplankton biomass values obtained by these two methods is not significant for the 0-1000 m.

For data interpretation we used the Similarity-Index for a similarity species assessment between zooplankton collections (Sorenson, 1948).

RESULTS

Environmental conditions

The general vertical structure of the Canadian Basin water masses is well known: a cold fresh surface layer (0 to \sim 35 m), halocline (\sim 50 to 200 m), the rela-



Fig. 1. SHEBA and NP-22 plankton stations in the Canadian Basin of the Arctic Ocean. Positions and date of samplings are shown in Table 1.

Table 2. Mean seasonal values of silicate (Si), phosphate (P), oxygen and chlorophyll <i>a</i> concentrations calculate
for the surface and subsurface water in the Canadian Basin of the Arctic Ocean during the winter and summer
period at SHEBA (1997-1998) and NP-22 (1975-1976).

Ice Camp	Layer, m	Si, µg-at/l		P , μg-at/l		
		Winter	Summer	Winter	Summer	
	0-30	4,75	8.0	0.72	0.94	
SHEBA	30-100	15.6	23.8	1.27	1.56	
	0-30	11.4	13.2	1.13	0.76	
NP-22	30-100	19.0	20.0	1.56	1.16	
Oxygen, ml/l						
		Winter		Summer	Production	
SHEBA	0-50	8	.94	9.35	0.41	
NP-22	0-50	8.30		8.31	0.01	
Chlorophyll <i>a</i> (µg/l)						
		W	inter	Summer	Production	
SHEBA	0	0.	.067	0.34	0.273	
NP-22	0	0.	.061	0.22	0.159	

tively warm and saline Atlantic layer (~200 to 750 m), and a colder transitional layer into deep water (Aagaard *et al.*, 1985; Carmack, 1990; Swift et al., 1997). Temperature (T) and salinity (S) distribution within the top 100 m of the water column is shown in Fig. 3 for October 1975 (NP-22) and for October 1997 (SHEBA). Also shown is the T/S distribution at the AIDJEX ice camp, which drifted in the same region in October 1975. Between the mid 1970s, and the mid 1990s, T/S characteristics changed remarkably within the surface mixed layer (0 to ~35 m): salinity values decreased from 31‰ (NP-22 and AIDJEX in 1975) to 27‰ (SHEBA, 1997) but temperature increased up to 0.2°C (McPhee *et al.*, 1998). The increase in fresh water in the top 0-30 m layer may derive partly from the loss of ice during the



Fig. 2. Comparison of zooplankton biomass values obtained by volume titration method (Yashnov, 1959) and calculated by body-size measurement method (Vinogradov and Shushkina, 1987). Biomass values were obtained in the field conditions at NP-22 (1975-1976 using titration method (Melnikov and Pavlov, 1978) and later in the same samples in lab conditions using body-size measurement method (Kosobokova, 1981). Explanations are in text.

past two decades (Rothrock *et al.*, 1999; McPhee *et al.*, 1998) but it may also derive from change in the storage of runoff (Macdonald *et al.*, 1999; Ekwurzel, 2001). The most important feature of the hydrological regime during the winter period of the SHEBA drift (up to April) was a strong and steady pycnocline 2-3 m thick at the depth of 30-35 m, which provided a barrier between the surface mixed layer and deeper water masses. The water properties beneath halocline also changed: salinity was less and the temperature was warmer (Fig. 3).

Mean seasonal values of silicate, phosphate, dissolved oxygen and chlorophyll a concentrations calculated for the surface and subsurface waters both for the summer and winter seasons at the SHEBA and NP-22 sites are given in Tab. 2. For both programs, the summer and winter silicate and phosphate concentrations in the top 30 m were much less than in the water beneath the pycnocline (30-100 m). However, the contrast between surface and deep-water mean seasonal concentrations was greater for SHEBA (a factor of 2.4 in winter and 1.7 in summer) than for NP-22 (1.6 in winter and 0.8 in summer). In the top 50 m, mean concentrations of dissolved oxygen were 8.94 ml/l in winter and 9.35 ml/l in the summer at SHEBA and 8.3 ml/l and 8.31 ml/l at NP-22, correspondingly. Accordingly, the average O₂ was 0.64 ml/l (7%) greater in winter and 1.04 ml/l (13%) greater in summer at SHEBA compared to NP-22. Mean winter values of chlorophyll a concentrations in underice water were not significantly different between SHE-BA (0.067 μ g/l) and NP-22 (0.061 μ g/l) but in summer, SHEBA had about 50% more chl a (0.34 µg/l compared to 0.22 μ g/l). We infer from the difference in chlorophyll a concentration values in the summer that photosynthesis was more intense at SHEBA than at NP-22, which in turn would explain the higher mean values of oxygen concentration as discussed above. The simplest explanation for higher under-ice photosynthesis at SHE-BA would be the general decrease in sea-ice thickness (Rothrock *et al.*, 1999), which, undoubtedly, would lead to greater light penetration at SHEBA.

Zooplankton species composition

The list of zooplankton species identified in the top 1000 m of the water column at SHEBA and NP-22, shown in Table 3, does not include data for *Protozoa* and larvacean plankton which were not found at NP-22. A total of 96 species including 81 species from SHEBA and 69 species from NP-22 were identified. *Copepoda* was the most important group in terms of species abundance (47% of the total list of species). The next important groups were *Hydrozoa* (12,5%), *Amphipoda* (10,4%), *Cyclopoida* (7,3%), *Polychaeta* (5,2%), *Appendicularia* (4,2%) and *Chaetognatha* (3,1%). Single species from other taxonomic groups were considerably less important (Table 3).

The most diverse group by species was *Copepoda* with 37 species from SHEBA and 34 species from NP-22 but only 26 species were common in both collections (similarity index 0.73). The main difference between the SHEBA and NP-22 collections was found for the abyssal and rare species: *Undinella oblonga, Scaphocalanus polaris, Lucicutia pseudopolaris, Euaugaptilus hyperboreus, Pseudoaugaptilus polaris, Hyalopontius tipicus* (NP-22), *Amallothtix valida* (SHEBA) and bathypelagical species like *Pareuchaeta polaris* (NP-22), *Pareuchaeta barbata, Xanthocalanus borealis* (SHE-BA). A striking contrast between the two collections was the absence of expatriated species (using terminol-

ogy of Johnson, 1963) from the North Pacific in NP-22 samples, whereas Pacific expatriates, which are common and abundant in the Bering Sea, were found during SHEBA (e.g., copepods Calanus marschallae, Eucalanus bungii, Metridia pacifica, Lucicutia ovaliformis and Heterorhabdus pacificus, as well as hydromedusas Atolla tenera and Pantachogon haeckeli.) Of the expatriate species observed, we note especially the Pacific amphipod Scina pusilla (SHEBA Stn.5, 143-300 m) which has never been reported for the Arctic Ocean. Scina pusilla was found in association with other Pacific species like copepods C. marschallae and M. pacifica suggesting a recent intrusion of water from the North Pacific to the Canada Basin. The Pacific species expatriates were found at stations 4-7 off the Chukchi plateau and stations 8-9 directly over the plateau (Fig. 1).

Vertical distribution of zooplankton species and biomass

The SHEBA zooplankton species abundance at different depths from December 1997 (Stn. 1) to October 1998 (Stn. 17) is shown in Fig. 4a. A minimum number of species is found near the surface and a maximum is found in the Atlantic layer, which corresponds with the general concept of vertical distribution of zooplankton species abundance in the Arctic Ocean (Brodsky, 1957; Virketis, 1957; 1959). The vertical species distribution has seasonal variations that are most readily explained by ontogenetic migration. That is, in the March-May period (stations 7-9), the number of species in the depth ranges 150-300 m and 300-1000 m rapidly decreased by two to threefold matched almost simultaneously by a twofold increase in the top 50 m. In



Fig. 3. Temperature and Salinity profiles from the Ice Stations drifted in the Beaufort Gyre: NP-22 (21 Oct 1975), AIDJEX (01 Oct 1975), and SHEBA (23 Oct 1997). Adopted from McPhee et al. (1998).

summer, predominantly temporary fauna like the younger stages of deeper living species (*Calanus glacialis*, *C. hyperboreus, Metridia longa, Pareuchaeta glacialis*) inhabit this Arctic surface layer. In the middle July (Stn.12), the migration back to depth began and by August (Stn. 13-14) the number of species has returned to winter values at each depth interval. The seasonal variation in vertical distribution of zooplankton biomass is determined mainly by the life cycling of dominant species and their ontogenetic migration from depth to surface during the vegetation period in summer for reproduction and growth, and back from the surface to the depth of water masses where they winter. Neverthess, zooplankton migrates within the

Table 3. List of zooplankton taxa in the 0-1000-m water column found in the Canadian Basin of the ArcticOcean, ice camps NP-22 (1975-1976) and SHEBA (1997-1998): "+" found and "-"non-found.

Species	SHEBA	NP-22
Hydrozoa		
Aeginopsis laurentii	+	+
Aglantha digitale	+	+
Atolla tenella	+	-
Aurelia aurita	+	-
Botrynema ellinorae	+	+
Corymorpha flammea	+	-
Jacovia polinae	+	-
Nausithoe limpida	+	-
Pantachogon haeckeli	+	-
Plotocnide borealis	+	-
Ptychogena hyperborea	-	+
Smithea arctica	-	+
Syphonophora		
Dimophyses arctica	+	+
Ctenophora		
Mertensia ovum	+	+
Pteronoda		
Clione limacina	+	+
Limacina helicina	+	+
Polychaeta		
Pelagobia gen.sp.	+	+
Podon leucartii	+	_
Thyphoscolex gen.sp.	+	+
Tomopteris gen sp	+	_
Travisiopsis gen.sp.	+	-
Ostracoda		
Boroecia maxima	+	+
Cirrenedia		
Cirrinedia cypris	+	
Amphipoda		
Cyclocaris guilelmi	+	+
Eusirus holmi		+
Lanceola clausi	+	+
Pseudalibrotus birulai	+	-
Pseudalibrotus glacialis		+
Pseudalibrotus nanseni		+
Scina borealis	+	-
Scina pusilla	+	-
Themisto abyssorium	+	+
Themisto libellula	+	+
Cananada	1	'
A cartia longiremis	+	_
		-

Table 3. Continued.

Aetideopsis multiserrata	+	+
Aetideopsis rostrata	+	+
Amallothrix validae	+	-
Augaptilus glacialis	+	+
Calanus glacialis	+	+
Calanus hyperboreus	+	+
Calanus marschallae	+	-
Chiridiella reductella	+	+
Ciridius obtusifrons	+	+
Euaugaptilus hyperboreus	-	+
Eucalanus bungii	+	-
Gaetanus brevispinus	+	+
Gaetanus tenuispinus	+	+
Haloptilus acutifrons	+	+
Heterorhabdus compactus	+	+
Heterorhabdus norvegicus	+	+
Heterorhabdus pacificus	+	-
Jaschnovia brevis	+	+
Licicutia ovaliformis	+	-
Lucicutia pseudopolaris	-	+
Metridia longa	+	+
Metridia pacifica	+	-
Microcalanus pygmaeus	+	+
Pachyptilus pacificus	-	+
Pareuchaeta barbata	+	-
Pareuchaeta glacialias	+	+
Pareuchaeta polaris	-	+
Pseudoaugaptilus polaris	-	+
Pseudocalanus minutus	+	+
Pseudochirella spectabilis	+	+
Scaphocalanus brevicornis	+	+
Scaphocalanus magnus	+	+
Scaphocalanus polaris	-	+
Scolecithricella minor	+	+
Spinocalanus antarcticus	+	+
Spinocalanus elongatus	+	+
Spinocalanus horridus	-	+
Spinocalanus longicornis	+	+
Spinocalanus longispinus	+	-
Spinocalanus polaris	+	+
Temora logicornis	+	-
Temorites brevis	+	+
Undinella oblonga	-	+
Xanthocalanus borealis	+	-
Cyclopoida		
Lubbockia glacialis	+	+
Hyalopontius tipicus	-	+
Mormonilla polaris	+	+

Oitona similis	+	+
Oncaea borealis	+	+
Oncaea minuta	-	+
Oncaea notopus	+	+
Harpacticoida		
Harpacticus superflexus	+	-
Microsetella norvegica	+	+
Tisbe furcata	+	+
Euphausiacea		
Thysanoessa raschii	+	+
Decapoda		
Hymenodora glacialis	+	+
Appendicularia		
Fritillaria borealis	+	+
Fritillaria polaris	+	-
Oikopleura labradoriensis	+	+
Oikopleura vanhoffeni	+	-
Chaetognatha		
Eukrohnia hamata	+	+
Parasagitta elegans	+	+
Sagitta maxima	-	+
Total number: 97	81	69

Table 3. Continued.

whole water column and large biomass variations occur in summer within the top 150 m (Fig. 4b). The biomass maximum (300 mg/m³) was found in the 0-35 m layer, comprised mainly of copepods including *Calanus glacialis, C. hyperboreus* and *Metridia longa* (up to 85-90% of the total zooplankton biomass). Here, biomass ranged from 10 mg/m³ in winter to 150-200 mg/m³ in summer. In the 150-300 m layer, biomass variations are less than 10 mg/m³ but deeper, in the 300-1000 m depth range, biomass varies insignificantly during the whole year (< 1 mg/m³).

A comparison of the SHEBA and NP-22 total zooplankton biomasses (mg/m²) averaged for 0-1000 m for the May-October period is presented in Fig. 5. The highest biomass, produced by upward migration of copepods from depth to the surface where they graze, occurred in June at SHEBA but not until August-October at NP-22. For a short period of time from May 22 (Stn. 9) to June 17 (Stn. 10) the biomass in the top 30 m at SHEBA increased rapidly by up to twenty fold from 14 mg/m³ to 302 mg/m³. By September 10 (Stn. 15) the biomass values decreased to 33 mg/m³ (Fig. 4b). The NP-22 biomass in the 0-50 m layer increased slowly from a minimum of 20 mg/m³ on May 20 (Stn. 1) to 140 mg/ m^3 on August 27 (Stn. 7). Thus, there is a two-month difference between the zooplankton biomass maximum at SHEBA (June 1998) and NP-22 (August, 1975). It is important to note that the migration, feeding and spawning cycle of dominant copepods from SHEBA show significant deviations from well-known "traditional" timing for the Central Arctic Ocean (Virketis, 1957,1959; Grainger, 1965; Pavshtiks, 1977; Heinrich *et al.*, 1980; Kosobokova, 1982). We found that the spawning period of *Calanus hyperboreus*, *C. glacialis* and *Metridia longa*, the main zooplankton biomass contributors, began at least a month earlier at SHEBA than at NP-22 (Kolosova and Melnikov, 2001, in press).

DISCUSSION

In the recent polar literature there is an active discussion of environmental change in the Arctic and, in particular, in the Arctic Ocean (cf Macdonald, 1996; Dickson, 1999). These changes extend to water-mass balance and circulation of the Pacific and Atlantic waters (McLaughlin *et al.*, 1996; Morison *et al.*, 1998; Carmack *et al.*, 1997; Maslowski *et al.*, 1999), in the global atmosphere circulation (Proshutinsky and Johnson, 1997; Johnson *et al.*, 1999), in the substantial retreat of the sea ice cover (Rothrock *et al.*, 1999; Vinnikov *et al.*, 1999), in freshening and warming of the upper ocean (McPhee *et al.*, 1998; Morison *et al.*, 1998; Macdonald *et al.*, 1999; Ekwurzel *et al.*, 2001).

Hydrographic data collected during the last decade (e.g., AOS 1994 and SCICEX cruises, 1993-1997) shows intriguing evidence that Atlantic water flowing into the Arctic Ocean has warmed relative to climatological values (Swift et al., 1997) and inflow increased in volume by about 20% (Carmack *et al.*, 1995; Morison *et al.*, 1998). A warm core of Atlantic water with temperatures of 0.5 to 1.7°C was observed above Lomonosov Ridge and the domain of influence of waters originating from the Atlantic now extends well into the Canada Basin, at least as far as the Mendeleev Ridge (McLaughlin *et al.*, 1996). These data signal fundamental and rapid change in the circulation of the Arctic Ocean toward the end of the 1980s. Furthermore, the inflow and properties of Pacific water entering the Arctic Ocean from the Bering Sea appear also to have changed in the 1990s, being fresher (Aagaard, pers. comm.) and perhaps stronger (Maslowski and Walczowski, 2000). The inflow from the Pacific (~0.8 Sv – Roach *et al.*, 1995) dominates the Chukchi Shelf.

The forcing for these changes is thought to originate in atmospheric pressure fields (Proshutinsky and Johnson, 1996; Thompson and Wallace, 1998) which may, in turn, be influenced by warming in the Northern hemisphere. Within the Canada Basin, the period of cold daytime temperatures was longer in the early 1970s than in the late 1990s. For example, the coldest month at NP-22 was March, but at the SHEBA it was December; in autumn (September), it was twice as warm during the SHEBA period than that of NP-22 (Melnikov, 2000). As a consequence of warming and other changes that have occurred recently in the Canada Basin, the SHE-BA drift (1997-1998) experienced a remarkable difference in environmental parameters in the upper ocean and sea ice cover compared with NP-22 (1975-1976). The decrease in sea ice thickness was noticeable (Perovich et al., 1999) as was the accumulation of sea-ice melt water directly beneath the ice, freshening and warming of the upper 30 to 35 m by both ice melt and runoff (Macdonald et al., 1999), and the formation of a strong pycnocline of 2-3 m thickness at a depth between 30-35 m (McPhee et al., 1998). Furthermore, mean silicate and phosphate concentrations were less in the top 100 m of the water column, there was more dissolved O, in



Fig. 4. Zooplankton species abundance distribution (a) and biomass variation (b) at different stratum within the 0-1,000 m water column in the Canadian Basin of the Arctic Ocean, SHEBA Ice Camp, December, 1997-October, 1998. Date of sampling and positions of plankton stations shown in Table 1.

the surface water beneath the ice, and chlorophyll *a* was in greater concentration at SHEBA compared to NP-22, two decades earlier. The higher chlorophyll *a* concentration (approximately 30%) may be explained by an increase in the growing period at SHEBA relative to that of NP-22 produced perhaps by thinner ice and greater light penetration.

The species composition, biomass distribution, population structure and timing of seasonal vertical migration of zooplankton have been well studied in the Canada Basin due to the numerous ice stations that have drifted in the Beaufort Gyre prior to the 1980s, specifically: NP-2, 7, 11, 22 (Brodsky and Nikitin, 1955; Virketis, 1957,1959; Pavshtiks, 1980, 1984; Heinrich et al., 1980; Melnikov and Kulikov, 1980; Kosobokova, 1981; 1982; Melnikov, 1989), T-3 (Grainger, 1965; Hunkins, 1965; Harding, 1966; Huges, 1968), Alpha (Johnson, 1963), Arlis II (Minoda, 1967). Year-round sampling at SHEBA has shown that, compared to historical data in the Canada Basin, there were: (1) changes in the species composition and biomass of zooplankton in the 0-1000 m water column; (2) an appearance of the species-expatriates from the North Pacific; (3) variations in seasonal cycling of the dominant zooplankton species.

Increased species abundance at SHEBA (81) compared to NP-22 (69) is mainly due to two taxonomic groups: *Hydrozoa* (from 5 at NP-22 to 10 at SHEBA) and *Polychaeta* (2 and 5, respectively). The number of species in other groups changed insignificantly, although the similarity of species composition within these groups was remarkably low. For example, the species similarity index within the most abundant and representative group *Copepoda* in both collections (55 species) was less than 0.6. We cannot discuss here all of the potential reasons for these observed changes in species composition of zooplankton in the Canada Basin but, in our opinion, a major factor is the change in water circulation in the Arctic Ocean (Morison *et al.*, 1998; Carmack *et al.*,



Fig. 5. Monthly averaged zooplankton biomass (mg/m?) within the 0-1000-m water column in the Canada Basin of the Arctic Ocean. NP-22 biomass values are from Melnikov and Pavlov (1978).

1997; Serreze and Maslanik, 1997; Maslowski and Walczowski, 2000) forced by change in atmosphere circulation patterns (Thompson and Wallace, 1998, Proshutinsky and Johnson, 1997; Johnson *et al.*, 1999).

Mean monthly zooplankton biomass inventories (mg/m^2) in the top 1000 m of the water column were approximately the same at SHEBA and NP-22 except for June, when biomass at SHEBA was twice that at NP-22, and October when biomass at SHEBA was one third that at NP-22. It is well known that the Arctic zooplankton (mainly, copepods) migrate seasonally from the depth of the Atlantic water where they spend winter to the surface water in summer (Sars, 1900; Bogorov, 1946; Virketis, 1957, 1959; Brodsky and Nikitin, 1955; Johnson, 1963; Grainger, 1965; Harding, 1966; Huges, 1968; Kosobokova, 1981, 1982; Pavshtiks, 1977, 1980, 1984; Heinrich et al., 1980; etc.). The comparatively high biomass at SHEBA during June can be explained by earlier upward vertical migration of copepods compared to the migration at NP-22. Melt season and spring bloom occurred at SHEBA in the first 10 days of June (Melnikov et al., 2001, in press) but not until mid August at NP-22 (Melnikov and Pavlov, 1978). The spring bloom corresponds to the beginning of the upward vertical migration of numerical dominants of the zooplankton community like copepods Calanus hyperboreus, C. glacialis, Metridia longa, Oithona similis and Pareuchaeta glacialis, being the main zooplankton biomass contributors (Brodsky and Nikitin, 1955; Virketis, 1959; Pavshtiks, 1980; Kosobokova, 1980 etc). Furthermore, spawning of Calanus hyperboreus, C. glacialis, Metridia longa began at least a month earlier at SHEBA compared to copepod spawning at NP-22 (Kolosova and Melnikov, 2001, in press).

The appearance of North Pacific and North Atlantic species in zooplankton communities of the Central Arctic Basin has been repeatedly discussed in the literature. Atlantic water species such as Oithona atlantica and Globigerina bulloides were found in waters of the Laptev and East-Siberian Seas during the "Sadko" expedition in 1935-1937 (Bogorov, 1946). Guryanova (1957) found amphipod Orchonella pacifica of the North Pacific origin nearby the geographical North Pole (ice station NP-17, 1968-1969). Brodsky (1957) found the copepod Calanus pacifica in the region of Lomonosov Ridge. There is evidence of Pacific deepwater species up to the western sector of the Amerasian Subbasin (Pavshtiks, 1980). Kosobokova and Hirche (2000) have also recorded five copepods (Chiridiella reductella, Lucicutia anomala, L. polaris, Spinocalanus polaris and Hyalopontius typicus) in the Eurasian Basin for the first time and a copepod, Xanthocalanus groenlandicus, for the first time in the Makarov Basin. The appearance of these species in the Arctic Ocean, undoubtedly, is connected to the water exchange with the Atlantic Ocean at Fram Strait and the Pacific Ocean at Bering Strait. Species of Atlantic origin penetrate into the Arctic basin within warm Atlantic water masses circulating cyclonically within the depth range of 300-1000 m. The movement of ice and surface water from the shelf of Chukchi and East-Siberian Seas (cf. Rigor, 1992) could deliver North Pacific species to the region of the Pole.

In our SHEBA zooplankton collection we found the North Pacific species: copepods *Calanus marshallae, Eucalanus bungii, Metridia pacifica, Lucicutia ovaliformis, Heterorhabdus pacificus*, amphipod *Scina pusilla* and hydromedusas *Atolla tenera* and *Pantachogon haeckeli*. These species have never been reported in zooplankton collections from drifting ice stations in the Canada Basin: NP-22 during 1975-1976 (Kosobokova, 1981; 1982); T-3 in 1958 (Grainger, 1965); "Cancolim II" in 1951; "Salvelinus" in 1960-1962 (Grainger, 1965). The North Pacific copepod *Metridia pacifica* was found in 200 – 300 m depth range at T-3 in 1966-1967 when the ice station drifted along the continental slope of the Beaufort Sea (Huges, 1968).

There are two large-scale domains of ice circulation in the Arctic Ocean: the Trans-polar drift and the anticyclonic Beaufort Gyre centered at 77°N and 150°W (Gordienko, 1958). When the North Pacific water passes through Bering Strait, the De Long coastal current directs one branch northwest toward the trans-polar drift but the Alaskan coastal current turns second branch northeast along the continental slope of the Beaufort Sea to the Canadian Archipelago (Rusanov, 1980). We propose that the North Pacific water actively transports plankton species to regions mentioned above. The anticyclonic Beaufort Gyre, which moves ice from east to west across the Chukchi Sea, runs counter to the Alaskan coastal current in the Beaufort Sea but follows the Trans-Arctic drift along the margins of the East Siberian and Laptev Seas. This general circulation appears to provide a barrier for the penetration of the Pacific water species to the center of the Canada Basin. On the shelf of the shallow Chukchi Sea the Beaufort Gyre water either "throws out" the Pacific species back to the Bering Strait or "draws" them into the Trans-Arctic drift.

Satellite observations starting the 1970s together with drifting buoys (Rigor, 1992) show that drift in the Beaufort Gyre exhibits two circulation modes termed "anticyclinic" and "cyclonic" (Johnson et al., 1999; Proshutinsky and Johnson, 1998). Change in the largescale circulation from "anticyclonic" to "cyclonic" undoubtedly would affect the transport and exchange of Pacific water with the interior Arctic Ocean with consequent effects on the transport of Pacific species-expatriates to the center of the Canada Basin. North Pacific zooplankton species (copepods Calanus marshallae, Eucalanus bungii, Metridia pacifica, Lucicutia ovaliformis, Heterorhabdus pacificus, amphipod Scina pusilla and hydromedusas Atolla tenera and Pantachogon haeckeli.) found along the SHEBA drift track in 1997-1998 but absent in the same region during 1975-1976 (NP-22) may be due to the difference in circulation which was anticylconic in the mid 1970s and cyclonic in the 1990s (Proshutinsky and Johnson, 1998).

From the data provided here, it is clear that zooplankton provide a sensitive indicator of change, affected by recent alterations in Arctic Ocean circulation. We urgently need year-round collections of plankton from this region, better to understand the changes that have occurred, and from other regions to understand how the large-scale changes in Arctic Ocean circulation and ice climate have impacted lower portion of the Arctic's marine food chain.

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