

Using pelagic ciliated microzooplankton communities as an indicator for monitoring environmental condition under impact of summer sea-ice reduction in western Arctic Ocean[☆]



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ABSTRACT

To assess the impact of arctic climate change on environmental condition and pelagic biodiversity, spatial variations in ciliated microzooplankton communities were studied at 32 stations (western Arctic Ocean) in summer sea-ice reduction period from August 1 to September 10, 2012. Multivariate and univariate analyses demonstrated that ciliated microzooplankton community structures showed significant differences between the western and eastern parts of the sampling region; consistent with east–west differences in environmental conditions; 16 dominant species (e.g., *Leegaardiella ovalis*, *Strombidium acutum*, and *Mesodinium rubrum*) showed the same spatial distribution pattern and were significantly correlated with physicochemical variables, especially with nitrates and phosphates; and both spatial patterns of community structure and species diversity indices were significantly associated with environmental condition. These results suggest that the summer sea-ice reduction has affected ciliate biodiversity seriously and the pelagic ciliate communities may be useful as robust bioindicators for studying climate change effects under increasing sea-ice melting in the Arctic Ocean.

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1. Introduction

Ciliated microzooplanktons are important components of microplankton communities (Finlay et al., 1979, 1988; Sherr and Sherr, 1987; Caron and Goldmann, 1990; Yang et al., 2004; Jiang et al., 2011a, 2013; Zhu et al., 2012). They play a crucial role in the functioning of microbial food webs as important mediators of energy transfer from pico- and nanoplanktonic production to higher trophic levels (Stoecker and McDowell-Cappuzzo, 1990; Sime-Ngando et al., 1995; Xu et al., 2008; Yang et al., 2008, 2009, 2010, 2011, 2012). With their short life cycle, delicate pellicle, rapid responses to environmental changes, easy sampling, increasing useful taxonomic references and allowing standardization for spatiotemporal discriminations, they have widely been used as robust indicators for bioassessment in marine ecosystems (Kchaou et al., 2009; Jiang et al., 2011b, 2012a,b,c; Xu et al., 2011a,b,c). Although a lot of former studies in temperate and tropical ocean

and freshwater environments have used ciliate community indicators for biological/environmental condition assessments, data on spatiotemporal variations in response to polar climate change and application possibility in monitoring polar marine environmental conditions are still scant (Cairns et al., 1972; Corliss, 2002; Xu et al., 2002; Gong et al., 2005; Elloumi et al., 2006; Jiang et al., 2007; Kim et al., 2007; Tan et al., 2010; Zhang et al., 2012, 2013).

Since the late 1990s, catastrophic sea-ice reductions caused by the effect of the northward branch of the Beaufort Gyre (a basin-scale anticyclonic ocean circulation) during summer have been observed in the Pacific sector of the Arctic Ocean (western Arctic Ocean) (Coachman and Barnes, 1961; Shimada et al., 2001, 2006; Nishino et al., 2008). Regions with decreasing sea ice might experience increased phytoplankton production and diversity compared to ice-covered areas because of the intensification of light in the water column (Lee and Whitledge, 2005) and greater wind-induced mixing serving to replenish sea surface nutrients (e.g., Carmack et al., 2006). Therefore, the water mass distribution and its relationship to the distributions of nutrients and algal biomass have been examined in detail (e.g., Nishino et al., 2008). High pelagic primary productivity provides the basis for enhanced local secondary production (Springer et al., 1989; Lee et al., 2010). However, we still cannot predict whether ongoing climate changes will affect ciliated microzooplankton in Arctic regions because very little is known about them, and species- and community-level observations are

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scarce. Thus, we examined ciliate species distribution, community structure, and its relationship to environmental conditions in a sea-ice melting region of the western Arctic Ocean.

The main objectives of this study were to characterize the systematic taxonomic composition of planktonic ciliates in arctic summer sea-ice reduction period, their distribution, abundance, biomass and biodiversity; reveal the spatial patterns in community structures and determine relationships between ciliated microzooplanktons and abiotic factors in the western Arctic Ocean; and investigate the potential of using pelagic ciliated microzooplankton communities as indicators to study the effects of arctic climate change.

2. Methods

2.1. Study stations

A multidisciplinary survey was conducted onboard the Korean icebreaker *Araon* in the Chukchi Sea of the western Arctic Ocean, encompassing the area from the Mendeleyev Ridge to the Chukchi Borderland (including the Chukchi Plateau and Northwind Ridge) during summer from August 1 to September 10, 2012 (Fig. 1). 32 sampling stations were visited (Fig. 1).

2.2. Sampling and sample processing

In total, 227 samples were collected from the 32 stations during the cruise. Vertical profiles of seawater temperature, salinity, density of water (DOW), and dissolved oxygen (DO) were obtained using a CTD/Rosette system (SeaBird Electronics, SBE 911+) at each sampling station from a depth gradient from the surface to a depth of 150 m.

Water samples for nutrient analysis were collected using the CTD/rosette sampler holding twenty-four 10-l Niskin bottles. Nutrient samples (100 ml) for measuring nitrate + nitrite nitrogen ($\text{NO}_3 + \text{NO}_2\text{-N}$), ammonium nitrogen ($\text{NH}_3\text{-N}$), soluble reactive phosphate (SRP), and silicate concentrations (SiO_2) were analyzed onboard the ship using a Bran and Luebbe model Quatro AA (Auto Analyzer), according to the manufacturer's manual.

Water samples (500–1000 ml) for total chlorophyll-*a* (Chl *a*) concentration were taken from each depth and immediately filtered through glass fiber filter paper (47 mm; Gelman GF/F). Concentrations of Chl *a* were measured onboard using a Turner design trilogy fluorometer after extraction with 90% acetone (Parsons et al., 1984).

To determine the abundance of ciliates, a Niskin rosette sampler was used to take water samples from each depth. For quantitative studies and the identification of ciliates, 500-ml seawater samples were fixed with Lugol's iodine solution (4% final concentration, volume/volume); these were then stored at 4 °C in darkness until analysis (Pitta et al., 2001; Kchaou et al., 2009; Choi et al., 2012; Yang et al., 2012). Preserved samples were allowed to settle in the mass cylinder for at least 48 h. The upper water was then siphoned off, leaving 20 ml. A 1-ml aliquot of each concentrated sample was placed in a Perspex chamber and the ciliates were counted under a light microscope (Olympus BX51) at magnifications of 200–400 \times . Tintinnids were identified using lorica morphology and the species descriptions of Kofoid and Campbell (1929, 1939); other ciliates were identified following references such as Montagnes and Lynn (1991) and Song et al. (2003). The taxonomic scheme used was according to Lynn (2008).

The biovolumes of ciliate cells were determined from measurements of their linear dimensions and by using volume equations for their appropriate geometric shapes (Winberg, 1971). Conversion factors of carbon biomass were 0.19 $\text{pg C } \mu\text{m}^{-3}$ for aloricate

ciliates and 0.053 $\text{pg C } \mu\text{m}^{-3}$ for loricate cells (Putt and Stoecker, 1989; Stoecker et al., 1994).

2.3. Data analysis of samples

For the overview of pelagic ciliated community structure of each sampling station and their spatial variations in response to environmental changes in whole water column, data were depth averaged before further analyses.

The species diversity (Shannon–Wiener H'), evenness (Pielou's J') and richness (Margalef d) of samples were computed following the equations:

$$H' = - \sum_{i=1}^S Pi(\ln Pi)$$

$$J' = \frac{H'}{\ln S}$$

$$d = \frac{S - 1}{\ln N}$$

where H' = observed diversity index, P_i = proportion of the total count arising from the i th species, S = total number of species, and N = total number of individuals.

Multivariate analyses of spatial variations in ciliated microzooplankton communities were conducted using the PRIMER v6.1 package (Clarke and Gorley, 2006) and PERMANOVA+ for PRIMER (Anderson et al., 2008). The spatial patterns both of ciliated microzooplankton communities and environmental status were assigned by routine CLUSTER analysis and MDS (multidimensional scaling), based either on Bray–Curtis similarity matrices for log-transformed species–abundance data or Euclidean distance matrices for log-transformed physicochemical data. The logarithmic transformations were subjected to gradually down weight the dominant taxa and differences between groups of samples were tested with the submodules ANOSIM (Clarke and Gorley, 2006). The spatial differences in ciliate communities and relationships with dominant species among the 32 sampling sites were summarized using the submodule CAP (canonical analysis of principal coordinates) of PERMANOVA+ with Bray–Curtis similarities from log-transformed species–abundance data and using PERMANOVA to test differences between sample clouds which were separated by two CAP axes (Anderson et al., 2008; Xu et al., 2013). The spatial environmental status of the 32 sampling stations was summarized using principal components analysis (PCA) based on log-transformed/normalized abiotic data (Clarke and Gorley, 2006). The contribution of each species to the average Bray–Curtis similarity among stations was analyzed using the SIMPER (Similarity Percentage Analysis) program (Clarke and Gorley, 2006). The significance of biota–environment correlations was tested using the routine RELATE. The submodule BIOENV was used to explore potential relationships between biotic parameters and the abiotic data (Clarke and Gorley, 2006).

Univariate correlation analyses were carried out using the statistical program SPSS v16.0.

3. Results

3.1. Environmental conditions

The temporal variations in Arctic sea-ice extent observed and monitored by the IARC-JAXA information system are shown in Fig. 2. In late summers during the last decade, satellite data have shown that Arctic sea-ice extents are shrinking dramatically. Note

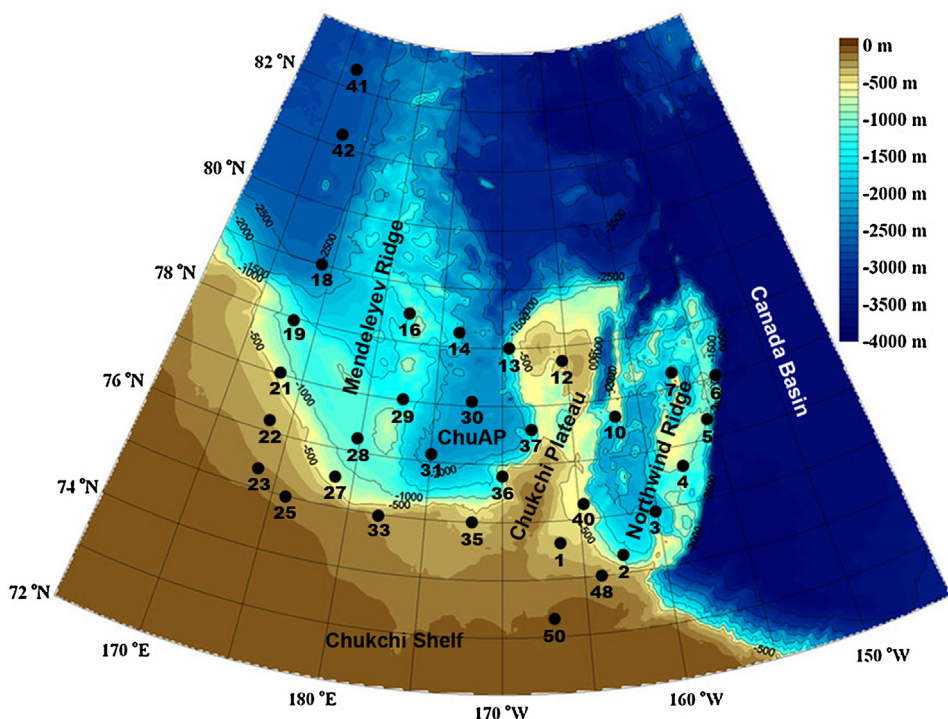


Fig. 1. 32 sampling stations in western Arctic Ocean from August 1 to September 10, 2012. ChuAP, Chukchi Abyssal Plain.

that the annual minimum of the sea-ice extent in 2012 was less than 4 million km², a historical record minimum (Fig. 2).

The ranges of physicochemical parameters at the 32 sampling stations over the sampling period are summarized in Fig. 3. Among these, the curves of salinity, density of water (DOW), silicate concentrations (SiO₂), soluble reactive phosphate (SRP), and nitrate nitrogen + nitrite nitrogen (NO₃ + NO₂-N) showed similar spatial patterns. The values from stations located on the Mendeleev Ridge were higher while those from the Chukchi Borderland were lower (Figs. 1 and 3). The highest concentrations of Chl *a* occurred at stations 19–29, 33–37, 48, and 50. Water temperature showed minor differences between stations, with higher average values at stations 2–7 and 48, and the lowest values at 41, 42, and 50. The concentrations of dissolved oxygen (DO) were usually higher than 10 mg l⁻¹ at all stations, with the minimum average value at station 25 and the maximum at station 50. The concentrations of ammonium nitrogen (NH₃-N) were varied and irregular, with the highest value at station 48 and lowest at station 23 (Fig. 3).

The relationship among the 32 sampling stations based on the environmental data was summarized by clustering (Fig. 4a) and PCA analyses (Fig. 4b). These dendrograms were constructed using Euclidean distance from log-transformed abiotic data. The

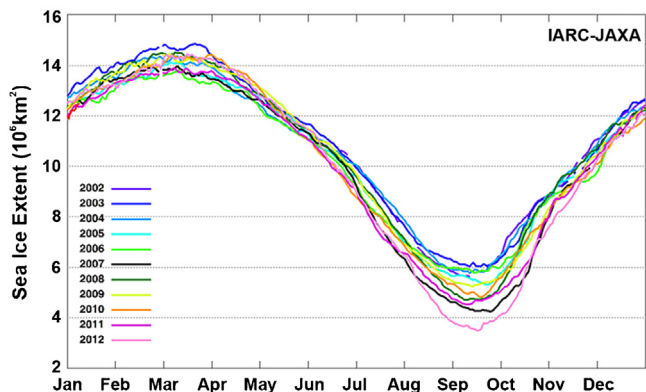


Fig. 2. Time-series results for sea ice extent in Arctic from 2002 to 2012 (http://www.ijs.iarc.uaf.edu/en/home/seaiice_extent.htm).

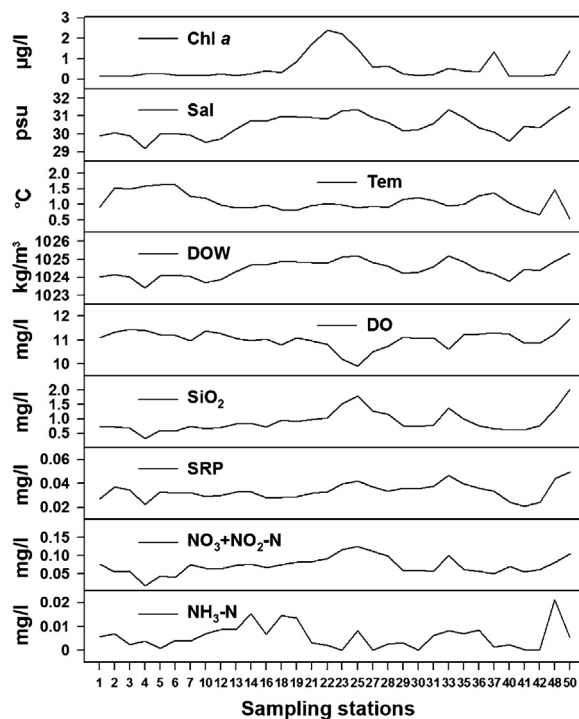


Fig. 3. Spatial distribution of nine environmental variables monitored at 32 sampling stations in western Arctic sea from August 1 to September 10, 2012 (depth mean values for each sampling station). Sal, salinity; Tem, water temperature; Chl *a*, chlorophyll-*a*; DOW, density of water; DO, dissolved oxygen concentration; SiO₂, silicate concentrations; SRP, soluble reactive phosphate; NO₃ + NO₂-N, nitrate + nitrite nitrogen; NH₃-N, ammonium nitrogen.

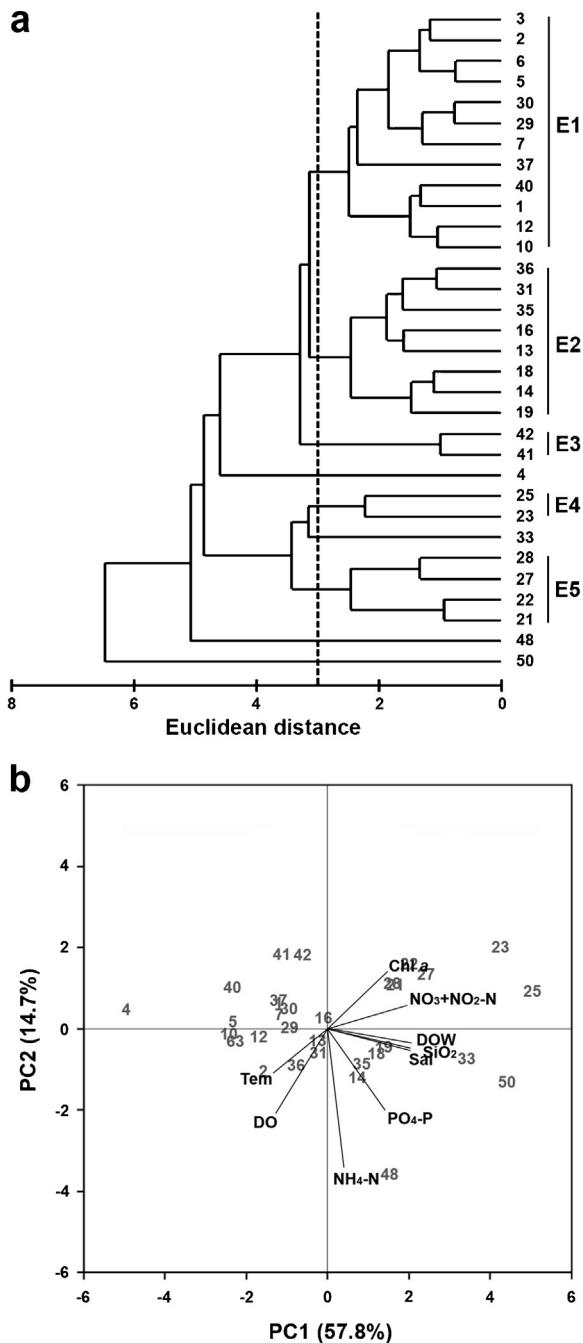


Fig. 4. Cluster analysis (a) and principal component analysis (PCA) plot (b) for spatial changes of environmental conditions based on abiotic data of 32 stations in western Arctic Ocean during the period from August 1 to September 10, 2012. Axes 1 and 2 respectively accounted for 57.8% and 14.7% of the total variation present. E1, environmental group 1; E2, group 2; E3, group 3; E4, group 4; E5, group 5.

clustering result showed that the samples from Chukchi Borderland stations constitute group E1, while group E2 is composed of the stations from the Mendeleev Ridge and Chukchi Abyssal Plain. Likewise, proximate stations such as stations 23 and 25; 41 and 42; and 21, 22, 27, and 28; clustered together as groups E3, E4, and E5, respectively (Figs. 1 and 4a). An ANOSIM test revealed significant differences among the groups ($r=0.878$, $p=0.001$) and between each pair of groups ($p<0.05$).

The two principal components of PCA analysis, explaining 72.5% of the total spatial environmental variability, discriminated the

environmental conditions of the 32 stations in a similar pattern to that shown by the clustering analysis (Fig. 4).

3.2. Taxonomic composition

The taxonomic composition of ciliate communities observed during the survey is summarized in Table 1. In total, 55 ciliate species representing 32 genera and 13 orders (Chlamydomontida, Choreotrichida, Cyrtophorida, Endogenida, Euplotida, Haptorida, Oligotrichida, Philasterida, Pleurostomatida, Prorodontida, Sporadotrichida, Tintinnida, and Urostylida) were recorded (Table 1). Of these, the top 16 ranked contributing species provided a cumulative contribution of 90.73% to ciliate communities and were defined as “dominant,” and their contribution and rank were summarized (Table 1).

3.3. Spatial variations in species number, abundance, and biomass

The average species number, abundance, and biomass of ciliated microzooplankton communities from each sampling site are shown in Fig. 5. Choreotrichids and oligotrichids were primarily responsible for the species components, with the maximum species number occurring at station 21 and the minimum at station 10 (Fig. 5a and d). The species count showed a spatial pattern with higher values at stations from the Mendeleev Ridge and Chukchi Abyssal Plain and lower values from the Chukchi Borderland (Figs. 1 and 5a).

Ciliate abundances and biomasses also exhibited a similar pattern to species number, with high values at stations from the Mendeleev Ridge and Chukchi Abyssal Plain and low values from the Chukchi Borderland (Figs. 1 and 5b and c). Choreotrichids (mainly *Lohmanniella oviformis*), oligotrichids (e.g., *Strombidium acutum*, *Strombidium dalum*, and *Strombidium pollostomum*), and cyclotrichiids (*Mesodinium rubrum* and *Mesodinium pulex*) were responsible for the peak. These three orders were the major contributors to all communities (Fig. 5b and c).

No obvious differences were observed in the spatial patterns of relative species composition among stations (Fig. 5d). In terms of relative abundances and biomass, the oligotrichids dominated the communities, along with the cyclotrichiids and choreotrichids (Fig. 5e and f). Note that the relative biomasses of oligotrichids were greater in communities compared to their relative abundances (Fig. 5 and f).

3.4. Spatial patterns in ciliated microzooplankton communities

Relationships among the 32 sampling stations in terms of ciliated microzooplankton data are summarized by the cluster analysis (Fig. 6a) and MDS (Fig. 6b) ordination in Fig. 6. These dendrograms were constructed using group-average clustering of Bray–Curtis similarities from log-transformed species–abundance data for planktonic ciliates (Fig. 6). This multivariate approach revealed that spatial patterns in ciliate communities were basically consistent with those of environmental variables (Figs. 4 and 6). In both cases, high similarities were observed between stations in the same region. For example, with 60% Bray–Curtis similarity, the communities collected from the Mendeleev Ridge and Chukchi Abyssal Plain clustered together as groups B1 and B4, while the Chukchi Plateau and Northwind Ridge assemblages formed the other three groups (Fig. 6). ANOSIM revealed significant differences among the groups ($r=0.808$, $p=0.001$) and between each pair of groups ($p<0.05$).

Discrimination among the 32 stations was plotted by CAP with Bray–Curtis similarities from log-transformed species–abundance data, and showed a similar spatial pattern to that of ciliate communities (Figs. 6 and 7). The first canonical axis separated the ciliate

Table 1
List of the species recorded in 227 samples at 32 sampling stations from August 1 to September 10, 2012, including mean abundances, mean biomass, occurrence, contribution and rank of 16 dominant species in communities.

Species	Abundance	Biomass	Occurrence (%)	Contribution (%)	Rank
Order: Choreotrichida					
<i>Leegaardiella ovalis</i> ^a	++	++	84	6.55	7
<i>Leegaardiella sol</i> ^a	++	++++	91	7.87	4
<i>Lohmanniella oviformis</i> ^a	+++	++	81	7.75	5
<i>Pelagostrobilidium neptuni</i>	++	++	50	–	–
<i>Pelagostrobilidium sphaerium</i>	+	+++	53	–	–
<i>Pelagostrobilidium spiralis</i> ^a	++	++	69	3.03	10
<i>Rimostrombidium caudatum</i> ^a	++	++	66	1.40	16
<i>Strombidinopsis acuminatum</i>	+	++	19	–	–
<i>Strombidinopsis minima</i>	+	+	3	–	–
<i>Strombidinopsis</i> sp.	+	+	13	–	–
Order: Oligotrichida					
<i>Cyrtostrombidium longisomum</i>	+	+	3	–	–
<i>Laboea strobila</i>	+	+++	56	–	–
<i>Pseudotontonia simplicidens</i>	++	++	59	–	–
<i>Spirotontonia grandis</i> ^a	++	++++	3	1.69	12
<i>Strombidium acutum</i> ^a	+++	++++	100	15.36	1
<i>Strombidium apolatum</i>	+	+	19	–	–
<i>Strombidium capitatum</i> ^a	++	++++	69	1.59	14
<i>Strombidium conicum</i>	+	++	31	–	–
<i>Strombidium dalum</i> ^a	++	+	66	1.66	13
<i>Strombidium emergens</i>	+	++	50	–	–
<i>Strombidium epidemum</i>	+	+	16	–	–
<i>Strombidium globosaneum</i> ^a	+++	+++	78	6.22	8
<i>Strombidium lynni</i>	+	+	16	–	–
<i>Strombidium pollostomum</i> ^a	++	+	66	3.07	9
<i>Strombidium styliferum</i>	+	++	34	–	–
<i>Strombidium sulcatum</i>	+	++	28	–	–
<i>Strombidium tressum</i>	+	+	25	–	–
<i>Strombidium wulffi</i>	++	++	66	–	–
<i>Tontonia</i> sp. ^a	++	+++	78	2.30	11
<i>Tontonia gracillima</i> ^a	++	+++	94	7.58	6
Order: Tintinnida					
<i>Acanthostomella norvegica</i>	+	+	25	–	–
<i>Favella ehrenbergii</i>	+	+	3	–	–
<i>Leprotintinnus pellucidus</i>	+	+	3	–	–
<i>Ptychocyclus urnula</i>	+	++	28	–	–
<i>Salpingella faurei</i>	++	+	41	–	–
<i>Stenosemella pacifica</i>	+	+	3	–	–
<i>Stenosemella ventricosa</i>	+	+	3	–	–
Order: Cyclotrichiida					
<i>Mesodinium pulex</i> ^a	++++	++	97	10.66	3
<i>Mesodinium rubrum</i> ^a	+++	++++	100	12.91	2
Order: Chlamyodontida					
<i>Chlamyodon</i> sp.	+	+	6	–	–
Order: Endogenida					
<i>Acineta</i> c.f. <i>compressa</i>	+	+	3	–	–
Order: Euplotida					
<i>Euplotes</i> c.f. <i>vannus</i>	+	++	19	–	–
Order: Haptorida					
<i>Cyclotrichium</i> c.f. <i>cyclokaryon</i>	+	+	6	–	–
<i>Didinium gargantua</i>	+	+++	19	–	–
Order: Philasterida					
<i>Uronema marinum</i>	+	+	53	–	–
<i>Uronema</i> sp.1	+	+	13	–	–
<i>Uronema</i> sp.2	+	+	6	–	–
<i>Uronema</i> sp.3	+	+	29	–	–
Order: Pleurostomatida					
<i>Loxophyllum</i> c.f. <i>helus</i>	+	+	3	–	–
<i>Pleuronema coronatum</i>	+	+	28	–	–
Order: Prorodontida					
<i>Balanion comatum</i> ^a	++	+	69	1.52	16
<i>Placus salinus</i>	+	+	6	–	–
<i>Tiarina fusus</i>	+	+	13	–	–
<i>Urotricha</i> sp.	+	+	29	–	–
Order: Sporadotrichida					
<i>Oxytricha saltans</i>	+	+	9	–	–

Abundances (ind. ml⁻¹): += 0–10; ++ = 10–50; +++ = 50–100; ++++ = over 100. Biomass (ng l⁻¹): += 0–10; ++ = 10–50; +++ = 50–100; ++++ = over 100.

^a Top 16 contributors of ciliate communities.

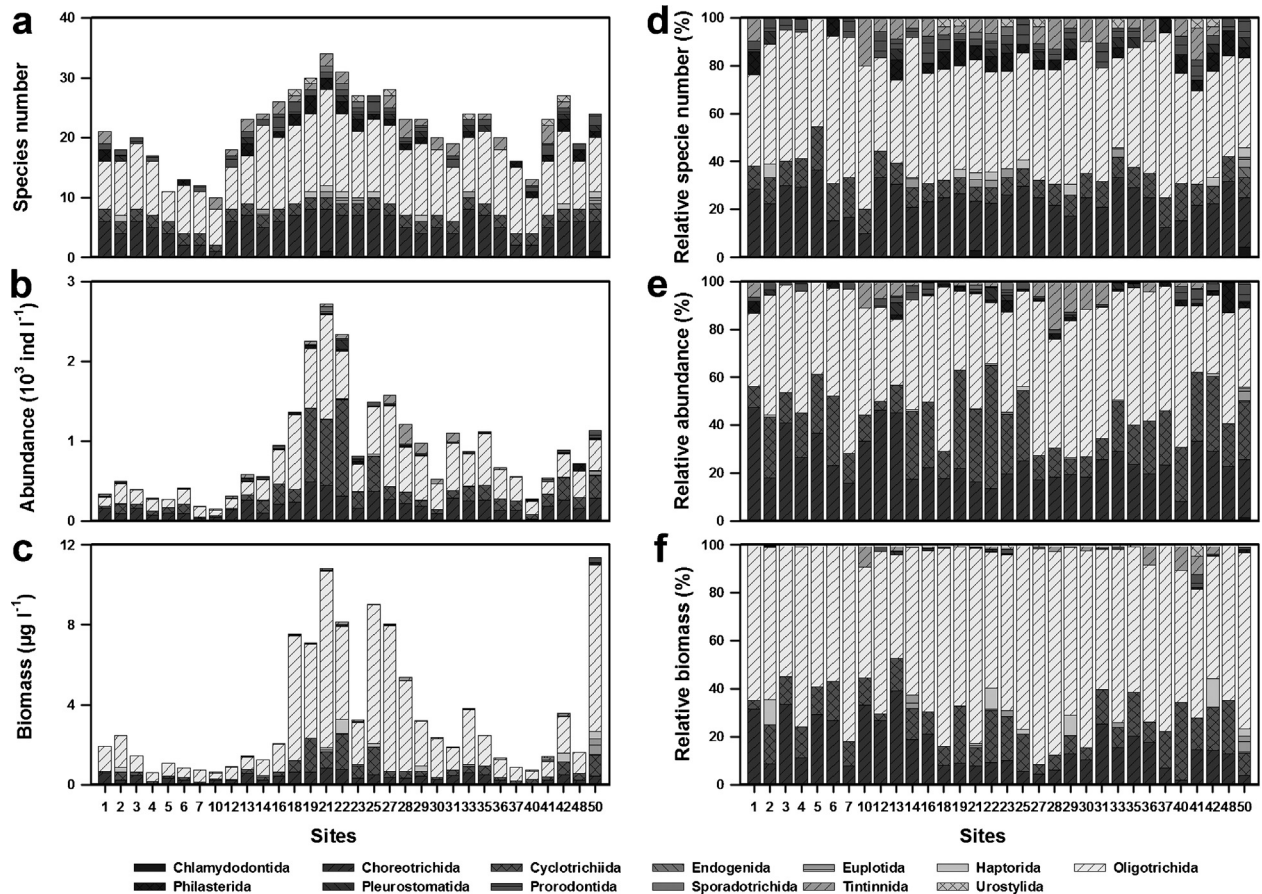


Fig. 5. Spatial variations in species number (a), abundance (b), biomass (c), relative species number (d), relative abundance (e) and relative biomass (f) of planktonic ciliates from 32 stations in western Arctic Ocean from August 1 to September 10, 2012.

communities of groups B1 and B4, sampled at the Mendeleev Ridge and Chukchi Abyssal Plain (on the left) from those of the other three groups from the Chukchi Plateau and Northwind Ridge (on the right), while the second canonical axis discriminated the samples in groups B4 and B5 (upper) from those of the other three groups (lower; Fig. 7). A PERMANOVA test demonstrated a significant difference between each pair of groups ($p < 0.001$).

A vector overlay of the Spearman correlations of the 16 dominant species with the CAP axes is also shown in Fig. 7. Although these taxa were the top ranked contributors across the whole sampling region, the vectors for 15 of the ciliate species pointed toward the sample cloud of group B1 (left), with only one (*Tontonia gracillima*) oriented toward that of group B2 (lower right; Fig. 7).

The spatial variation in three community parameters at the 32 stations during the sampling period is shown in Fig. 8. Species richness (d) and diversity (H') indices showed similar spatial variations, with higher values from stations located in the Mendeleev Ridge and Chukchi Abyssal Plain and lower values from the Chukchi Plateau and Northwind Ridge. The curve of the species evenness (J') index is more complicated and roughly contrary to those of the d and H' indices (Fig. 8).

3.5. Interaction between planktonic ciliate biodiversity and abiotic parameters

RELATE analysis (Mantel test) revealed a significant correlation between spatial variations in planktonic ciliate abundances and changes in environmental variables ($r = 0.818$; $p = 0.001$).

For all 32 stations, the correlations between ciliate abundances and environmental variables were established by multivariate

biota–environment (BIOENV) analysis (Table 2). The results showed that the best match with the ciliates occurred with the combination of $\text{NO}_3\text{-N} + \text{NO}_2\text{-N}$ and SRP ($r = 0.293$, $p = 0.01$). Also note that SiO_2 and the nutrients $\text{NO}_3\text{-N} + \text{NO}_2\text{-N}$ and SRP were the most common variables included in all correlations (Table 2).

Spearman correlations between environmental variables and the abundances of the 16 dominant planktonic ciliates are summarized in Table 3. Twelve of these species, namely *Leegaardiella ovalis*, *Leegaardiella sol*, *L. oviformis*, *M. rubrum*, *Pelagostrobilidium spiralis*, *S. acutum*, *Strombidium capitatum*, *S. dalum*, *Strombidium golbosaneum*, *S. pollostomum*, *T. gracillima*, and *Tontonia* sp., were significantly negatively correlated with nutrients, in particular $\text{NO}_3 + \text{NO}_2\text{-N}$ and SRP in combination with salinity, water density, and SiO_2 , and were positively with Chl *a* and DO ($p < 0.01$). The

Table 2

Summary of results from biota–environment (BIOENV) analysis showing the 10 best matches of combinations of environmental variables with spatial variations in ciliate abundances at 32 sampling stations from August 1 to September 10, 2012.

Rank	<i>R</i>	Environmental variables	<i>P</i>
1	0.293	SRP, $\text{NO}_3\text{-N} + \text{NO}_2\text{-N}$	0.01
2	0.292	SiO_2 , SRP, $\text{NO}_3\text{-N} + \text{NO}_2\text{-N}$	0.01
3	0.290	SiO_2 , $\text{NO}_3\text{-N} + \text{NO}_2\text{-N}$	0.01
4	0.288	$\text{NO}_3\text{-N} + \text{NO}_2\text{-N}$	0.01
5	0.266	SiO_2 , SRP	0.01
6	0.264	SiO_2	0.01
7	0.254	SiO_2 , SRP, $\text{NO}_3\text{-N} + \text{NO}_2\text{-N}$, $\text{NH}_4\text{-N}$	0.01
8	0.247	Tem, SiO_2 , SRP, $\text{NO}_3\text{-N} + \text{NO}_2\text{-N}$	0.01
9	0.242	Chl <i>a</i> , SiO_2 , SRP, $\text{NO}_3\text{-N} + \text{NO}_2\text{-N}$	0.01
10	0.241	SRP, $\text{NO}_3\text{-N} + \text{NO}_2\text{-N}$, $\text{NH}_4\text{-N}$	0.01

r = Spearman correlation coefficient. See Fig. 2 for other abbreviations.

Table 3
Correlations (Spearman analysis) between abundances of 16 dominant ciliates and nine environmental variables at 32 sampling stations in western Arctic Ocean from August 1 to September 10, 2012.

Species	Chl <i>a</i>	Sal	Tem	DOW	DO	SiO ₂	SRP	NO ₃ + NO ₂ -N	NH ₄ -N
<i>Balanion comatum</i>	0.388**	-0.015	-0.111	-0.014	0.138*	0.033	-0.040	-0.020	-0.037
<i>Leegardiella ovalis</i>	0.264**	-0.281**	0.088	-0.280**	0.354**	-0.274**	-0.290**	-0.351**	0.008
<i>Leegardiella sol</i>	0.379**	-0.289**	0.163*	-0.288**	0.353**	-0.241**	-0.234**	-0.290**	0.037
<i>Lohmanniella oviformis</i>	0.469**	-0.110	-0.024	-0.109	0.284**	-0.077	-0.164*	-0.123	-0.173**
<i>Mesodinium pulex</i>	0.346**	-0.012	-0.039	-0.011	0.166*	0.035	-0.035	-0.058	-0.003
<i>Mesodinium rubrum</i>	0.501**	-0.381**	0.190**	-0.380**	0.545**	-0.338**	-0.347**	-0.409**	0.018
<i>Rimostrombidium caudatum</i>	0.353**	-0.065	0.052	-0.064	0.184**	-0.035	-0.055	-0.079	0.102
<i>Pelagostrobilidium spiralis</i>	0.417**	-0.170*	0.031	-0.169*	0.378**	-0.118	-0.176**	-0.195**	0.018
<i>Spirotontonia grandis</i>	0.366**	-0.138*	-0.069	-0.135*	0.239**	-0.098	-0.145*	-0.106	-0.018
<i>Strombidium acutum</i>	0.457**	-0.576**	0.359**	-0.575**	0.570**	-0.513**	-0.531**	-0.565**	0.030
<i>Strombidium capitatum</i>	0.213**	-0.369**	0.149*	-0.369**	0.318**	-0.317**	-0.346**	-0.343**	0.056
<i>Strombidium dalum</i>	0.328**	-0.208**	0.108	-0.207**	0.255**	-0.232**	-0.248**	-0.214**	-0.118
<i>Strombidium globosaneum</i>	0.462**	-0.280**	0.224**	-0.279**	0.399**	-0.237**	-0.227**	-0.278**	0.021
<i>Strombidium pollostomum</i>	0.376**	-0.209**	0.221**	-0.208**	0.243**	-0.210**	-0.216**	-0.202**	0.002
<i>Tontonia gracillima</i>	0.265**	-0.487**	0.352**	-0.486**	0.448**	-0.494**	-0.466**	-0.482**	0.014
<i>Tontonia</i> sp.	0.442**	-0.329**	0.091	-0.328**	0.346**	-0.257**	-0.314**	-0.272**	0.041

See Fig. 2 for abbreviations.

* $p < 0.05$.

** $p < 0.01$.

other four species, *Balanion comatum*, *M. pulex*, *Rimostrombidium veniliae*, and *Spirotontonia grandis*, were all significantly positively correlated with Chl *a* only or with DO ($p < 0.01$; Table 3).

Notably, Spearman correlation analysis also determined that species number, abundance, richness (H'), and diversity (d) indices represented similar correlations, being significantly negative correlated ($p < 0.01$) with salinity, DOW, SiO₂, and the nutrients SRP and NO₃ + NO₂-N, but positively correlated ($p < 0.01$) with Chl *a*, temperature, and DO. The only exception was species evenness (J'), which showed the opposite pattern, being negatively correlated with Chl *a*, temperature, and DO, but positively correlated with salinity, DOW, SiO₂, and the nutrients SPR and NO₃ + NO₂-N ($p < 0.05$; Table 4).

4. Discussion

The Arctic Ocean may be a sensitive indicator of global climate changes (Shimada et al., 2006). In the last decade, the extent of summer Arctic sea ice has decreased dramatically (Serreze et al., 2007; Stroeve et al., 2007; Comiso et al., 2008; Perovich, 2011) and in 2012, the summer sea ice reached its lowest ever recorded extent (Fig. 2). These changes affect both the Arctic and global climate system by altering heat exchanges between the ocean and the atmosphere (Budikova, 2009; Overland, 2011). Recent observations have shown that warm water inflow to the Bering Sea is an important driving force for the rapid reduction in sea ice, associated with increases in the horizontal and vertical fluxes of heat, salt, and momentum (Shimada et al., 2006; Carmack and Melling, 2011). As previously reported, Pacific-origin Summer Water (PSW) reaches the Chukchi Sea and then changes its advective direction toward the northwest along the northern slope of the Chukchi Sea and is delivered to the Chukchi Borderland region consisting of the Northwind Ridge and Chukchi Plateau (Shimada et al., 2006). The horizontal heat transportation and heat release from PSW in that region are the main reasons for the rapid and extensive sea-ice retreat and for changes in the water column structure (Shimada et al., 2006). Consequently, no doubt exists that the organisms living there are facing severe changes in environmental conditions. However, a paucity of knowledge on biological distributions and variations in these areas still exists due to a lack of biological observations and analysis under the rapid Arctic climate changes.

During the last three decades, ciliated protozoans have been demonstrated to play a significant role in the pelagic food web, linking primary production with production at higher trophic levels

(Smetacek, 1981; Caron and Goldmann, 1990; Moritz et al., 2006; Orsi, 2012; Yang et al., 2010, 2011, 2012; Jiang et al., 2013). Ciliated microzooplanktons cover several predatory niches as potential grazers of bacteria, nanoflagellates, phytoplankton, and even copepod eggs, and as potential prey for metazoan microzooplankton and fish larvae (Sherr et al., 1986; Dolan and Coats, 1990; Jensen and Hansen, 2000). The absolute abundance of ciliates in western Arctic and Antarctic waters was shown to be as high as those found in temperate waters (Sorokin, 1977; Heinbokel and Beers, 1979; Smetacek, 1981; Paranjape, 1987; Levinsen et al., 1999; Dolan et al., 2012). In addition, comparing the same spatial distribution trends and strong correlations between ciliates and Chl *a* exhibited in present study supply a further evidence to the linkage between primary production and ciliated predator which has been found by previous studies. Although, predation as a factor that was not measured in present study, also has the potential to structure ciliate communities such as copepods are selective predators on ciliates, choosing ciliates over phytoplankton prey and selecting among ciliate species (Jonsson and Tiselius, 1990; Yang et al., 2010).

Although, the limnological and physiochemical variability could be measured easily by modern technique, the instantaneous measurement could not give enough information to understand how the environmental changes influence the living creatures' habitat condition and food web structure. So, the investigation on biota is still essential and the establishment of reliable bioindicator is urgent (Ismael and Dorgham, 2003; Carmack et al., 2006; Jiang et al., 2007; Hourston et al., 2009; Xu et al., 2011a,b). The taxonomic composition of major ciliated microzooplankton components is hypothesized to follow the trophic status of the water mass rather than a traditional zoogeographical distribution pattern (Stoecker et al., 1994). Increasing numbers of studies have shown the strong relationship between ciliate communities and environmental conditions, especially nutrients and could be used as a bioindicator (Pratt and Cairns, 1985; Sime-Ngando et al., 1995; Xu et al., 2002; Gong et al., 2005; Elloumi et al., 2006; Kim et al., 2007; Kchaou et al., 2009; Jiang et al., 2011a, 2012a, 2013; Xu et al., 2011a,c, 2012, 2013; Zhang et al., 2012). However, the quantitative importance of spatial patterns in ciliated microzooplankton communities in response to climate change has been little investigated, especially in the Arctic Ocean, with most descriptions concentrating on ice-edge communities from polar regions or calculating the total abundance and/or biomass, but lacking taxonomic resolution beyond the tintinnid/oligotrich level (e.g., Paranjape, 1988; Levinsen et al., 1999; Petz, 2003; Petz et al., 2007; Sherr et al., 2009;

Table 4

Correlations (Spearman analysis) between environmental variables and ciliate species number (*S*), abundance (*N*), species richness (*H'*), species evenness (*J'*) and species diversity (*d*) of planktonic ciliates at 32 sites in western Arctic sea from August 1 to September 10, 2012.

	<i>S</i>	<i>N</i>	<i>d</i>	<i>J'</i>	<i>H'</i>
Chl <i>a</i>	0.739**	0.731**	0.701**	-0.395**	0.716**
Sal	-0.482**	-0.543**	-0.419**	0.351**	-0.444**
Tem	0.253**	0.322**	0.193**	-0.157**	0.239**
DOW	-0.479**	-0.541**	-0.416**	0.350**	-0.441**
DO	0.624**	0.669**	0.574**	-0.470**	0.581**
SiO ₂	-0.400**	-0.450**	-0.340**	0.301**	-0.364**
SRP	-0.438**	-0.458**	-0.393**	0.318**	-0.398**
NO ₃ + NO ₂ -N	-0.483**	-0.539**	-0.421**	0.370**	-0.444**
NH ₄ -N	0.010	0.002	0.009	0.073	0.015

See Fig. 2 for abbreviations.

* *p* < 0.05.

** *p* < 0.01.

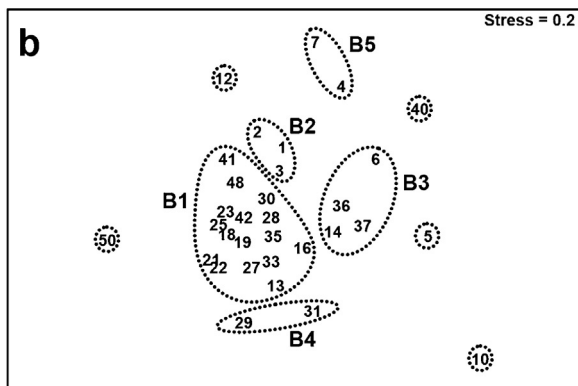
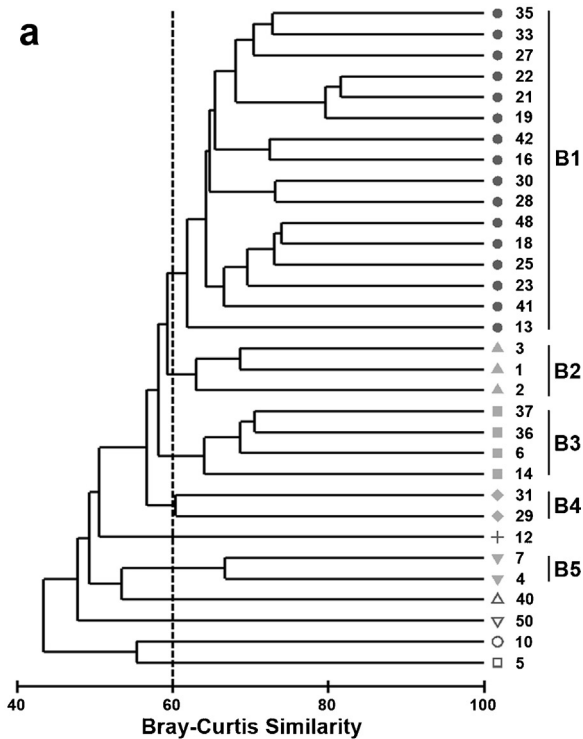


Fig. 6. Cluster analysis (a) and MDS ordination (b) for spatial taxonomic patterns of pelagic ciliate communities on Bray–Curtis similarities for species–abundance data of 32 sampling stations in western Arctic Ocean from August 1 to September 10, 2012. B1, biological group 1; B2, group 2; B3, group 3; B4, group 4; B5, group 5.

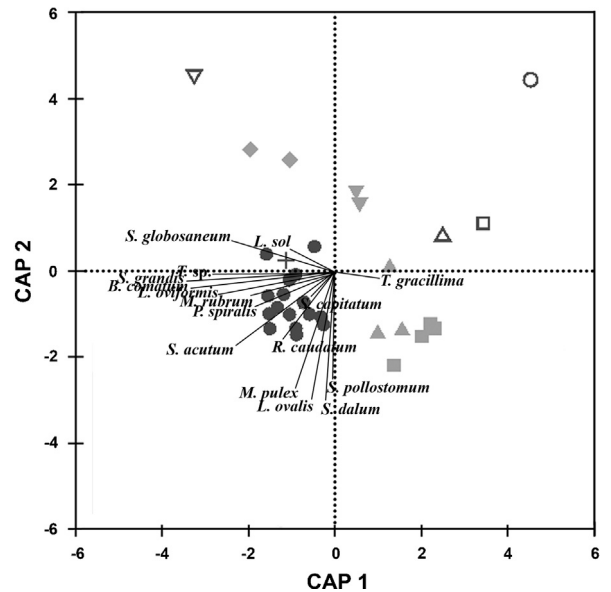


Fig. 7. Canonical analysis of principal coordinates (CAP) on Bray–Curtis similarities from log-transformed species–abundance data of 32 sampling stations in western Arctic Ocean during the period from August 1 to September 10, 2012, and correlations of 16 dominant species with the two CAP axes. *B. comatum*, *Balanion comatum*; *L. ovalis*, *Leegaardiella ovalis*; *L. sol*, *Leegaardiella sol*; *L. oviformis*, *Lohmanniella oviformis*; *M. pulex*, *Mesodinium pulex*; *M. rubrum*, *Mesodinium rubrum*; *R. caudatum*, *Rimostrombidium caudatum*; *P. spiralis*, *Pelagostrobilidium spiralis*; *S. grandis*, *Spirotontonia grandis*; *S. acutum*, *Strombidium acutum*; *S. capitatum*, *Strombidium capitatum*; *S. dalum*, *Strombidium dalum*; *S. globosaneum*, *Strombidium globosaneum*; *S. pollostomum*, *Strombidium pollostomum*; *T. gracillima*, *Tontonia gracillima*; *T. sp.*, *Tontonia sp.*

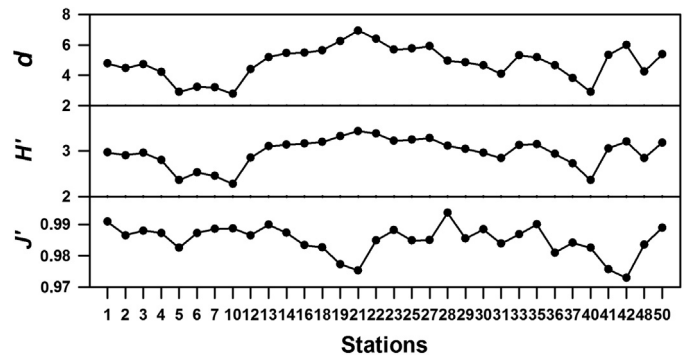


Fig. 8. Spatial distribution of species richness (*d*), diversity (*H'*) and evenness (*J'*) of ciliated microzooplankton communities (depth mean values for each sampling station) in western Arctic Ocean during the period from August 1 to September 10, 2012.

Lovejoy and Potvin, 2011). This lack of taxonomic detail can result in the loss of ecologically relevant information (Wickham et al., 2011). To improve our knowledge on the biological hot spot and assess environmental heterogeneity in the arctic sea-ice melting region, an expedition was conducted by the icebreaker *Araon* to 32 sampling stations in western Arctic Ocean from August 1 to September 10, 2012.

Based on our physicochemical measurements from 32 sampling stations, the sampled area could be basically divided into the western part (Mendeleyev Ridge and Chukchi Abyssal Plain) and eastern part (Chukchi Plateau and Northwind Ridge), with the western edge of the Chukchi Plateau as a dividing line. As shown in Figs. 3 and 4, stations in the eastern part attained higher water temperatures, which are consistent with the hydrographic records of the heat release of PSW (e.g., Shimada et al., 2006). Eastern regions also experienced higher DO, but lower concentrations of Chl *a*, salinity, the density of water, silicates, and nutrients compared to the western part of the sampling region. This kind of east–west difference caused by summer sea-ice reduction has been revealed by previous investigations (e.g., Nishino et al., 2008).

The ciliated microzooplankton community in our sampling region was diverse. Comparing the diversity found in our samples to previous studies is difficult, as sporadic previous work from the Arctic Ocean has concentrated either on sea-ice and ice-edge communities or on total abundance/biomass only (Andersen, 1988; Sherr et al., 1997; Petz, 2003; Petz et al., 2007; Comeau et al., 2011; Lovejoy and Potvin, 2011). In our study, 55 ciliate species representing 32 genera and 13 orders were identified during the surveys. Similarly, Kchaou et al. (2009) and Jiang et al. (2011b) found 56 and 64 planktonic ciliates, respectively, in temperate waters, while the observed diversity in the Antarctic region was higher at 70 species (Wickham et al., 2011). Among these, several species belonging to the orders Endogenida, Euplotida, and Sporadotrichida are not typically pelagic and mainly come from the flow of substrate or the suspension of sediment. As shown in many other studies from various regions, a dominance of aloricate oligotrich ciliates in the community was observed in terms of species number, abundance, and biomass (e.g., Garrison and Buck, 1989; Klaas, 1997; Lovejoy et al., 2002; Kchaou et al., 2009; Santoferrara and Alder, 2009; Jiang et al., 2011a,b, 2012b). Aloricate oligotrich species in our study (choreotrichids and oligotrichids) also had greater species numbers than other assemblages, which was basically consistent with previous reports (e.g., Agatha, 2011).

Spatial variations in planktonic ciliate abundance ranged from 0.16 to 2.74×10^3 ind. l^{-1} , which is closely comparable with both other Arctic reports (Andersen, 1988; Sherr et al., 1997) and Antarctic studies (e.g., Wickham et al., 2011) and is as high as those found in temperate waters (Sorokin, 1977; Heinbokel and Beers, 1979; Smetacek, 1981; Paranjape, 1987; Levinsen et al., 1999; Moritz et al., 2006; Jiang et al., 2011b). Planktonic ciliate biomass also showed a similar pattern to those listed above. In summary, the ciliate abundance and biomass found in the current study are roughly comparable to those reported from previous research.

In addition, our study revealed that planktonic ciliates exhibited clear spatial variation in terms of species composition, abundance, and biomass. For example, high species numbers occurred at stations located in the western study area (Mendeleyev Ridge and Chukchi Abyssal Plain), while low species numbers were found in the eastern area (Chukchi Plateau and Northwind Ridge). Both abundance and biomass showed similar patterns. Obviously, the ciliated microzooplankton biodiversity in west Arctic Ocean has been seriously affected by climate change. We hypothesized this kind of east–west difference in biodiversity might be a response to the environment condition change in eastern area which was caused by PSW with higher water temperatures and lower concentrations of Chl *a*, salinity and nutrients.

Furthermore, the species distributions of the 55 ciliate species, and in particular of the 16 dominant ciliates, represented a clear spatial pattern of higher biodiversity in the western study area than the eastern. Canonical analysis showed that the dominant species mostly pointed toward the samples from the western region. Spearman correlation analysis revealed that most dominant species were significantly negatively correlated with SiO_2 , DOW, $NO_3-N + NO_2-N$, and SRP, but positively correlated with Chl *a*, temperature, and DO. As heterotrophs or mixotrophs, their correlations with Chl *a* are reasonable, and their relationships with other environmental variables, especially nutrients, suggest that the dominant ciliate species may be considered as potential bioindicators for determining the environmental conditions of Arctic marine ecosystems. In these, we found the dominants from genus *Leegaardiella*, *Strombidium* and *Tontonia* have significantly negative correlations with nutrients. And, the *M. rubrum*, which has been under debate for a long time for their role in red tides, also showed strong relationship with nutrients. However, further laboratory experiments focus on these species should be carried out to prove their trophic state sensitivity and indicator possibility.

Multivariate analyses are more sensitive than univariate analyses at detecting changes in complicated biotic and abiotic data. They are also extremely useful for analyzing differences between communities at spatial and temporal scales, and for illustrating how these communities vary along gradients of environmental conditions (Kim et al., 2007; Hourston et al., 2009; Jiang et al., 2011a,b, 2012a; Xu et al., 2011a,b,c). In our study, cluster analysis, MDS ordination, and PCA all revealed clear spatial patterns in environmental conditions. The stations from the west sampling region were separated from those from the east. Otherwise, all clustering analysis, MDS, and CAP ordinations demonstrated that ciliated microzooplankton communities exhibited a similar spatial pattern to that of environmental variables. Furthermore, a Mantel test (routine RELATE in PRIMER) demonstrated that the spatial variations in ciliate community structures were indeed significantly correlated with certain environmental variables. Multivariate correlation analysis (BIOENV) demonstrated that the spatial variation in ciliated microzooplankton communities was significantly related to environmental variables, especially nutrients (e.g., nitrates and phosphates), either alone or in combination with SiO_2 , water temperature, and Chl *a*. Thus, we suggest that the spatial distribution of ciliated microzooplankton communities in our study is significantly related to environmental conditions. These findings suggest that ciliated microzooplankton communities accurately reflect Arctic water quality and have the potential to be used in monitoring the environmental conditions of the sea-ice reduction region in the Arctic Ocean, which is affected by increasing global climate change.

Species diversity, evenness, and richness indices are commonly employed in community-level investigations and are suitable for simple statistical analyses (Connell, 1978; Huston, 1979; Magurran, 1991; Ismael and Dorgham, 2003; Gong et al., 2005; Jiang et al., 2012b; Xu et al., 2012). Generally, the higher these three indices are, the better the water conditions (Ismael and Dorgham, 2003). In our study, species diversity and richness indices had higher values in stations from the Mendeleyev Ridge and Chukchi Abyssal Plain than in those from the Chukchi Plateau and Northwind Ridge, which implied that the western part of the sampling region is preferred as habitat over the eastern part, which is more affected by PSW in summer (Shimada et al., 2006). As regards Pielou's evenness, seems less useful in characterizing community variation along environmental changes than diversity and richness indices which has been shown in previous studies that the evenness index always exhibited lower values in better water quality or irregularly in monitoring process (e.g., Gong et al., 2005; Jiang et al., 2011a). Furthermore, all biodiversity indices were significantly correlated

with environmental variables ($p < 0.01$). These findings suggest that the biodiversity parameters of pelagic ciliates communities especially species diversity and richness indices might be useful in understanding environmental changes in Arctic marine ecosystems. However, we sampled the pelagic community only in the sea-ice reduction area during summer, and it is the first time to discuss the possibility of using those ciliate community parameters as an indicator to study Arctic climate change. So, further investigations over extended time and space are needed.

With easy sampling, relative immobile, increasing availability of easily used taxonomic references and allowing standardization for temporal and spatial comparisons, ciliates have widely been accepted in ecological investigations, and the present case study in western Arctic Ocean also supply positive evidence. So for, bioassessments using ciliate communities have traditionally been based on the identification of ciliates at the lowest possible taxonomic level, usually species. However, this species level resolution requires a skilled taxonomic expertise and is laborious, time-consuming and expensive, and thus limits the use for monitoring cases. Although explorative studies have been carried out in coastal marine ecosystems (e.g., Xu et al., 2011d), similar study in polar region is still scant. So, in order to saving time and reducing the costs of ecological monitoring, further research should be focus on potential surrogate and taxonomic sufficiency.

In summary, the results of this cruise demonstrated that ciliated microzooplankton communities in the western Arctic Ocean show significant spatial patterns, with high diversity in terms of species composition, abundance, and biomass and that either ciliated microzooplankton community structure or biodiversity parameters (species diversity and richness indices) are significantly associated with environmental conditions, and could be used as robust indicators of arctic marine ecosystem. Furthermore, these findings provide basic data and better understanding of variations in the pelagic microzooplankton living in Arctic sea-ice reduction regions under increasing climate change. The ciliated microzooplankton communities as an indicator presented here provides a basis for assessing arctic environmental conditions and has much potential to help answer questions of importance for polar research and protection.

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