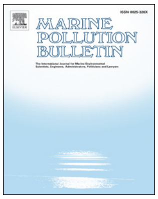
Marine Pollution Bulletin 133 (2018) 182–190

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul



Can pelagic ciliates indicate vertical variation in the water quality status of western Arctic pelagic ecosystems?

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ARTICLE INFO

Keywords:
Pelagic ciliate
Environmental change
Bioassessment
Vertical distribution
Arctic Ocean

ABSTRACT

The vertical pattern of pelagic ciliate communities was observed at eight layers in the Chukchi Sea and the northern Bering Sea of the western Arctic Ocean during the summer sea-ice reduction period (August 5 to August 24, 2016). A total of 44 ciliate species were identified, with seven species dominated the communities in the water column. Multivariate and univariate analyses demonstrated that: (1) community structures of ciliates vary significantly among eight water depths; (2) variations in the vertical distribution of ciliates were significantly correlated with changes in physicochemical variables, especially the ammonia; (3) the distributions of the three dominant species were significantly and positively related to the chlorophyll *a* and ammonia concentrations; and (4) species richness and abundance were significantly and positively correlated with the concentrations of ammonia and chlorophyll *a*. These results suggest that pelagic ciliates may reflect vertical variations in the water quality status of western Arctic ecosystems.

1. Introduction

Pelagic ciliates are important components of the microplankton fauna in marine ecosystems (Finlay et al., 1979, 1988; Sherr and Sherr, 1987; Caron and Goldmann, 1990; Zhu et al., 2012; Jiang et al., 2013, 2014, 2015, 2016; Yang et al., 2016). They play crucial roles in community function and ecosystem processes by mediating the flux of carbon and energy from pico- and nanoplanktonic producers to higher trophic levels (Stoecker and McDowell-Cappuzzo, 1990; Sime-Ngando et al., 1995; Yang et al., 2004, 2009, 2010, 2012, 2016; Xu and Xu, 2017; Xu et al., 2017; Zhong et al., 2017). Ciliates' short life cycles and rapid responses to environmental changes have allowed standardization of observations for spatial and temporal comparisons, and thus they have been employed widely as a bioindicator for bioassessment of water quality in marine ecosystems (Cairns et al., 1972; Kchaou et al., 2009; Jiang et al., 2011, 2013; Xu et al., 2014; Xu and Xu, 2017; Xu et al., 2017; Zhong et al., 2017).

Since the late 1990s, catastrophic sea-ice reductions have had notable effects on plankton production and diversity during summer in the Pacific (western) sector of the Arctic Ocean (Coachman and Barnes, 1961; Shimada et al., 2001, 2006; Nishino et al., 2008; Dolan et al., 2012). Previous studies have shown that phytoplankton production and diversity may increase significantly in these regions compared with ice-covered areas due to an increase of light in the water column and greater wind-induced mixing, which replenishes nutrients at the sea surface (e.g., Dolan and Coats, 1990; Carmack et al., 2006; Lee and Whitledge, 2005; Nishino et al., 2008). Thus, pelagic primary production can significantly influence the vertical distribution of microzooplankton, such as pelagic ciliates (Springer et al., 1989; Lee et al., 2010; Jiang et al., 2014, 2015, 2016). Although Jiang et al. (2015) reported variations in pelagic ciliate community patterns, the usefulness of pelagic ciliates as an indicator for the monitoring of vertical changes in water conditions in polar areas remains undetermined.

In this study, environmental drivers of vertical variation in pelagic ciliate communities were studied based on a dataset from one cruise in the western Arctic Ocean. Our objectives in this study were: (1) to demonstrate the spatial patterns of community structures and biodiversity at various water depths, (2) to identify the relationships between ecological features of pelagic ciliates and environmental conditions, and (3) to confirm the potential of ciliates as a bioindicator for the assessment of vertical variation in water conditions in the western Arctic Ocean.

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https://doi.org/10.1016/j.marpolbul.2018.05.017
Received 31 October 2017; Received in revised form 9 May 2018; Accepted 10 May 2018

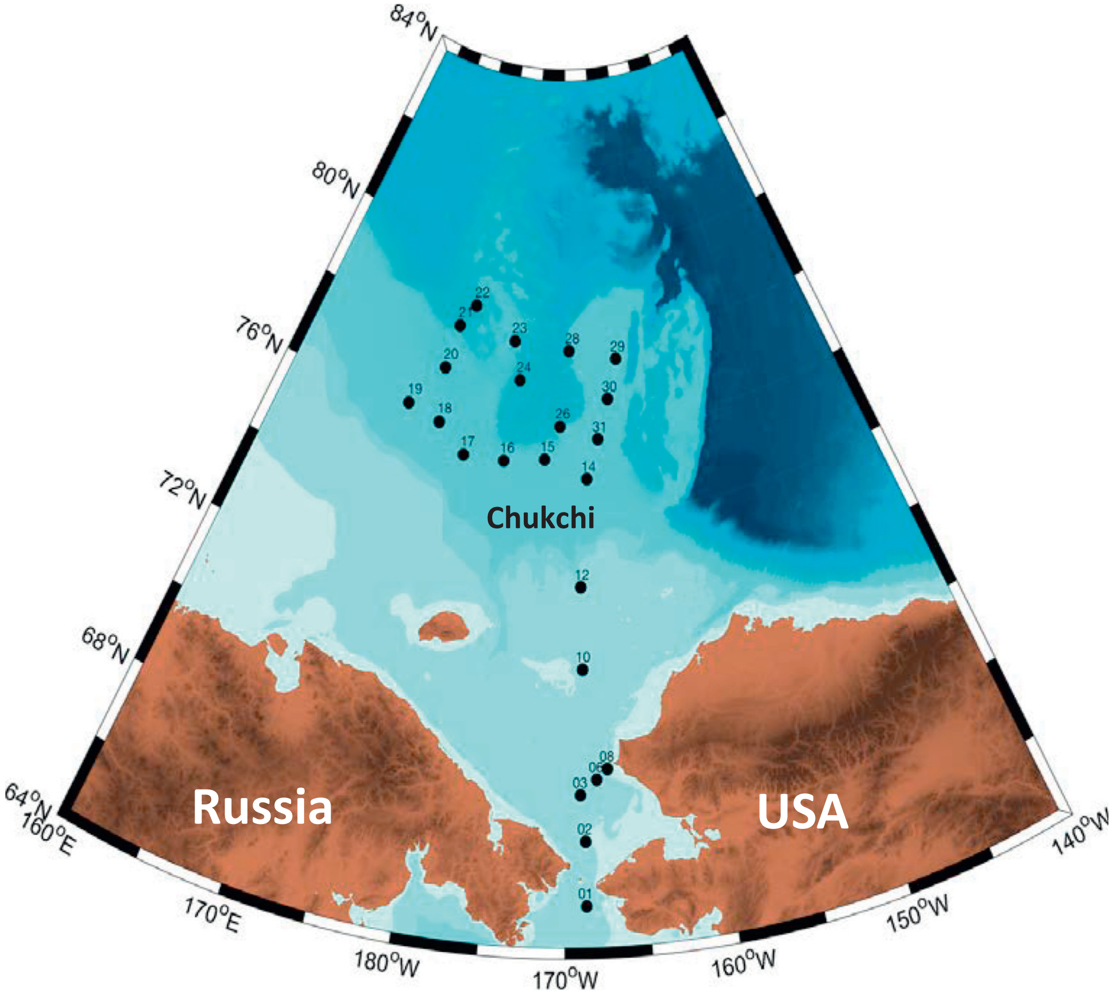

Fig. 1. Sampling stations of the Korean icebreaker Araon in the Bering Sea and Chukchi Sea of the western Arctic Ocean, encompassing an area extending from the Mendeleyev Ridge to the Chukchi Borderland (including the Chukchi Plateau and Northwind Ridge), August 5–24, 2016.

2. Materials and methods

2.1. Study stations

A multidisciplinary survey was conducted onboard the *IBRV* Araon in the northern Bering Sea and the Chukchi Sea of the western Arctic Ocean, encompassing an area extending from the Mendeleyev Ridge to the Chukchi Borderland (including the Chukchi Plateau and Northwind Ridge) during summer (August 5–24, 2016; Fig. 1). A total of 23 sampling stations were visited (Fig. 1).

2.2. Sampling and sample processing

In total, 85 samples were collected from 23 stations during the cruise. Vertical profiles of seawater temperature, salinity, density of water, and dissolved oxygen (DO) were obtained using a CTD rosette system (SBE 911 +; Sea Bird Electronics), which was deployed at each station in a depth profile from the surface to 200 m. Water samples for nutrient analysis were drawn from the CTD rosette sampler, which consists of 24 10-l Niskin bottles, into 50-ml conical tubes and stored immediately in a refrigerator at 2 °C until analysis. Ammonium (NH_4), nitrite + nitrate, ($NO_2 + NO_3$), phosphate (PO_4), and silicic acid [$Si(OH)_4$] were measured onboard within 3 days of sampling using a four-channel continuous auto-analyzer (QuAAtro, Seal Analytical) according to Joint Global Ocean Flux Study protocols. Water samples (300–500 ml) for total chlorophyll *a* (Chl *a*) measurement were collected from each depth and filtered immediately through glass fiber filters (47 mm; Gelman GF/F). Concentrations of Chl *a* were measured onboard using a Turner Trilogy fluorometer after extraction with 90% acetone (Parsons et al., 1984). To determine the abundance of ciliates, a Niskin rosette sampler was used to collect water samples from each depth; 500-ml seawater samples were fixed with Lugol's iodine solution (4% final concentration, volume/volume) and then stored at 4 °C in darkness until analysis (Pitta et al., 2001; Kchaou et al., 2009; Choi et al., 2012; Yang et al., 2016). Preserved samples were allowed to settle in a graduated cylinder for at least 48 h. The upper layer of water was siphoned off, leaving 20 ml of concentrated sample. A 1-ml aliquot of each concentrated sample was placed in an acrylic chamber, and the ciliates were counted under a light microscope (Olympus BX51) at magnifications of 200–400 ×. Tintinnids were identified based on lorica morphology using the species descriptions of Kofoid and Campbell (1929, 1939); other ciliates were identified from references such as Montagnes and Lynn (1991) and Song et al. (2003). The taxonomic scheme of Lynn (2008) was used.

2.3. Data analyses

Multivariate analyses were carried out using PRIMER software (v. 7.0.13; Clarke and Gorley, 2015). The species distributions were summarized using clustering analysis on matrices of “index of association”

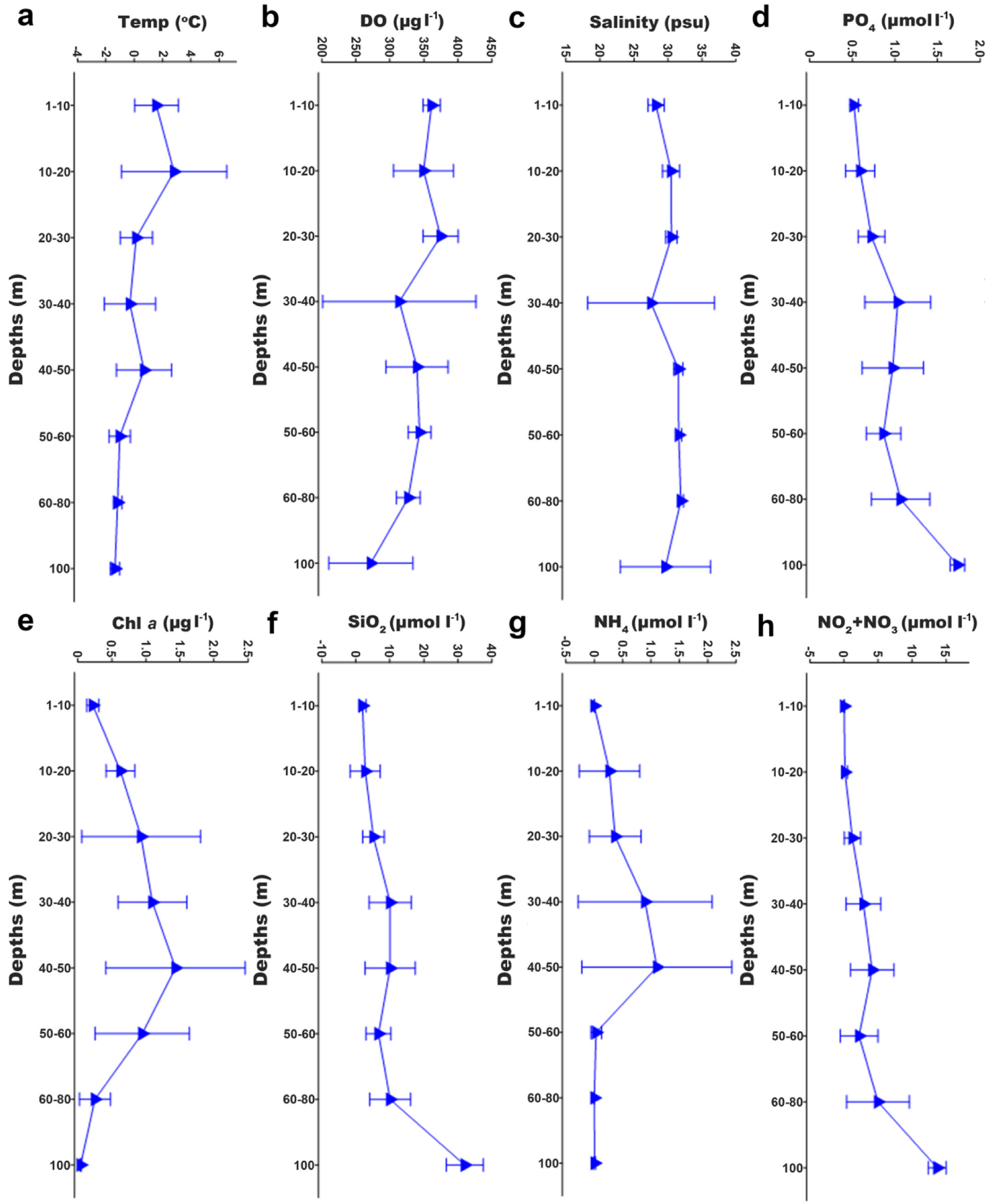

Fig. 2. Environmental conditions: average values of water temperature (a), dissolved oxygen (b), salinity (c), phosphate (d), chlorophyll *a* (e), $Si(OH)_4$ (f), NH_4 (g), and $NO_2 + NO_3$ (h) during the study period.

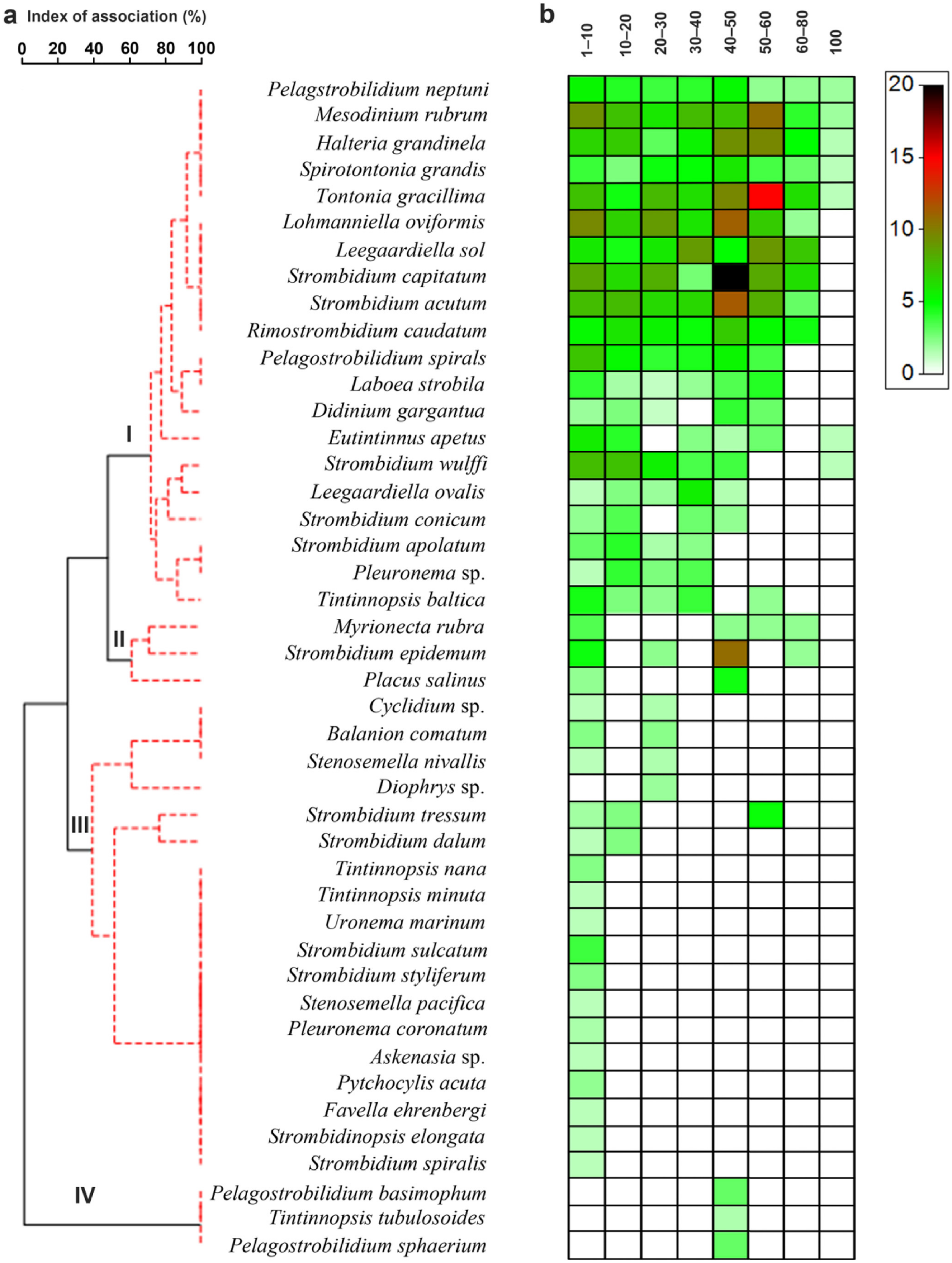

Fig. 3. Clustering analysis of species distributions for the 44 pelagic ciliate species at eight water depths (a) and shade plot of individual abundances (ind. l^{-1}) at each depth (b) during the study period.

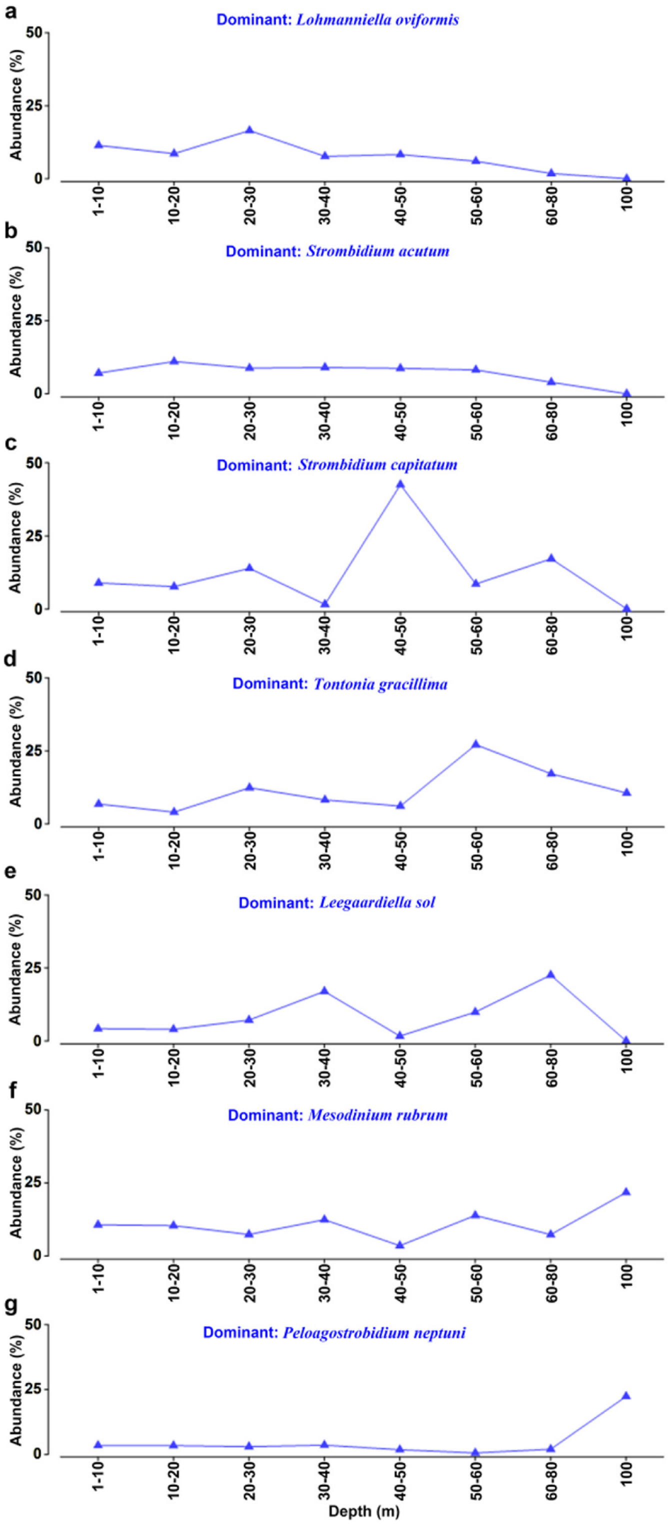

Fig. 4. Succession of the seven dominant ciliate species from 1 m to 100 m during the study period.

computed from standardized species-abundance data (Clarke and Gorley, 2015). The variations in pelagic ciliate community structure and water conditions were ordinated by applying routine CAP (canonical analysis of principal coordinates) on Bray-Curtis similarity matrices from fourth root transformed species-abundance data and Euclidean distance matrices of log-transformed and normalized environmental data, respectively (Clarke and Gorley, 2015). Differences in biotic and abiotic matrices among eight water layers were tested using the PERMANOVA routine (Anderson et al., 2008). Mental analyses were conducted using the RELATE protocol to test the significance of relationships between similarity matrices at the 0.05 level, and the biota-environment (BIOENV) routine was used to identify the best matches among environmental variables to the spatial variations in community structures of pelagic ciliates.

3. Results

3.1. Environmental conditions

The average values for environmental conditions in eight depth ranges are shown in Fig. 2. All eight environmental variables showed clear vertical variation among the eight depth ranges sampled. For example, the average values of water temperature exhibited a decreasing trend, whereas those of $Si(OH)_4$, PO_4, and $NO_2 + NO_3$ showed clear increasing trends from 1 to 10 m to 100 m. The concentrations of Chl *a* and NH_4 were lowest at 100 m and highest at 40–50 m.

3.2. Taxonomic composition and vertical distribution

A total of 44 ciliate species was recorded, along with their distributions, from eight 10 m water depth intervals (Fig. 3). Clustering analysis using the SIMPROF test on index of association values discriminated these ciliates into four groups (Fig. 3a): groups I (20 species) and II (3 species) were generally distributed throughout the eight depths, group III (18 species) generally occurred at depths of 1–30 m, and group IV (3 species) dominated the samples collected at a depth of 30–40 m (Fig. 3b).

With relative abundances of > 20%, seven species were identified as dominant species, and their distributions revealed clear succession from 1 m to 100 m (Fig. 4). For example, *Lohmanniella oviformis* dominated samples from 20 to 30 m, and *Strombidium capitatum* was predominant in the ciliate community at 40–50 m (Fig. 4).

3.3. Vertical variations in species richness and abundance

The species richness had a decreasing trend from 1 to 30 m, and peaked at a depth of 50–60 m (Fig. 5a), whereas ciliate abundance dropped from 1 to 40 m, followed by an increase to a peak at a depth of 40–50 m (Fig. 5b).

3.4. Vertical variations at different depths

The vertical variations in relative species number and relative abundance of the seven dominant species and other species exhibited a clear spatial pattern among the eight depth intervals (Fig. 6).

Based on CAP ordination of the vectors of seven dominant ciliate species, the 84 data points showed a clear spatial pattern among the eight depths (Fig. 7a, b). For example, the data points at 100 m were separated from those of other depths by the second canonical axis (CAP 2). PERMANOVA revealed significant differences among the eight depths, especially between 1 and 60 m and 100 m ($P < 0.05$).

3.5. Linkage between biotic and abiotic factors

To elucidate the relationships between pelagic ciliate community patterns and environmental changes among the eight water depths, CAP ordination of the Euclidean distance matrix was performed, which showed a high degree of consistency with the spatial community patterns (Fig. 7c and d). RELATE analysis revealed a significant correlation between the two matrices ($\rho = 0.291$, $P < 0.05$). BIOENV analysis identified the top nine matches with biota, involving the combination of temperature, DO, salinity, and nutrients, especially PO_4, $NO_2 + NO_3$,

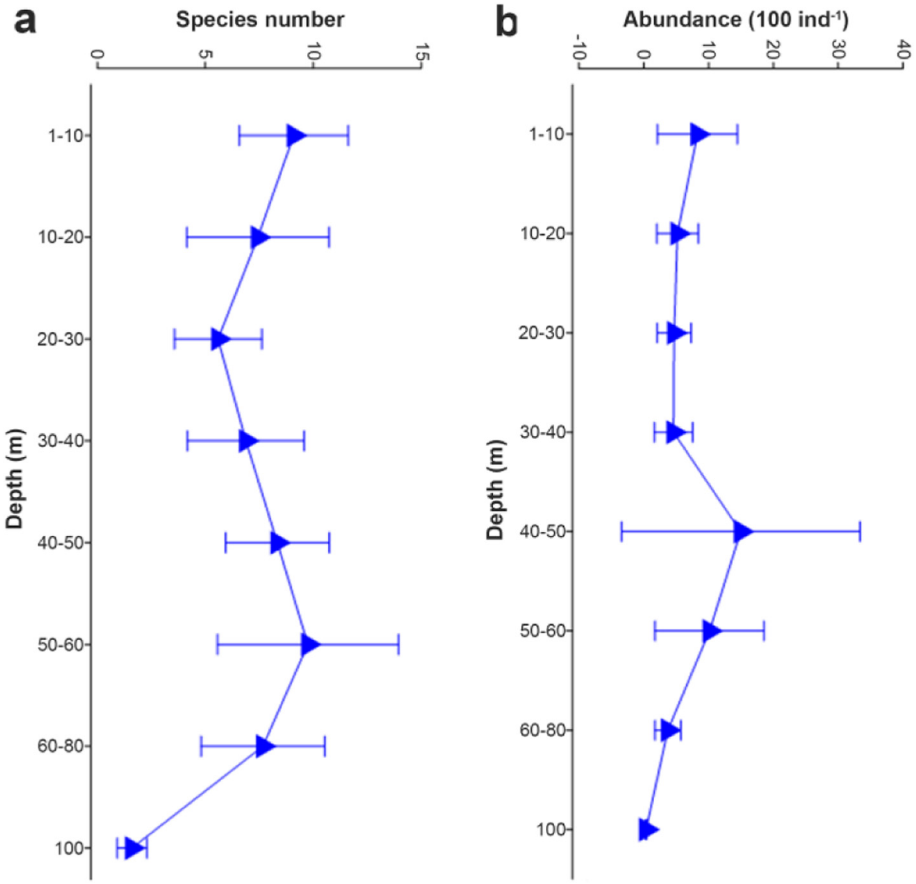

Fig. 5. Vertical variations in species number (a) and abundance (b) from 1 m to 100 m during the study period.

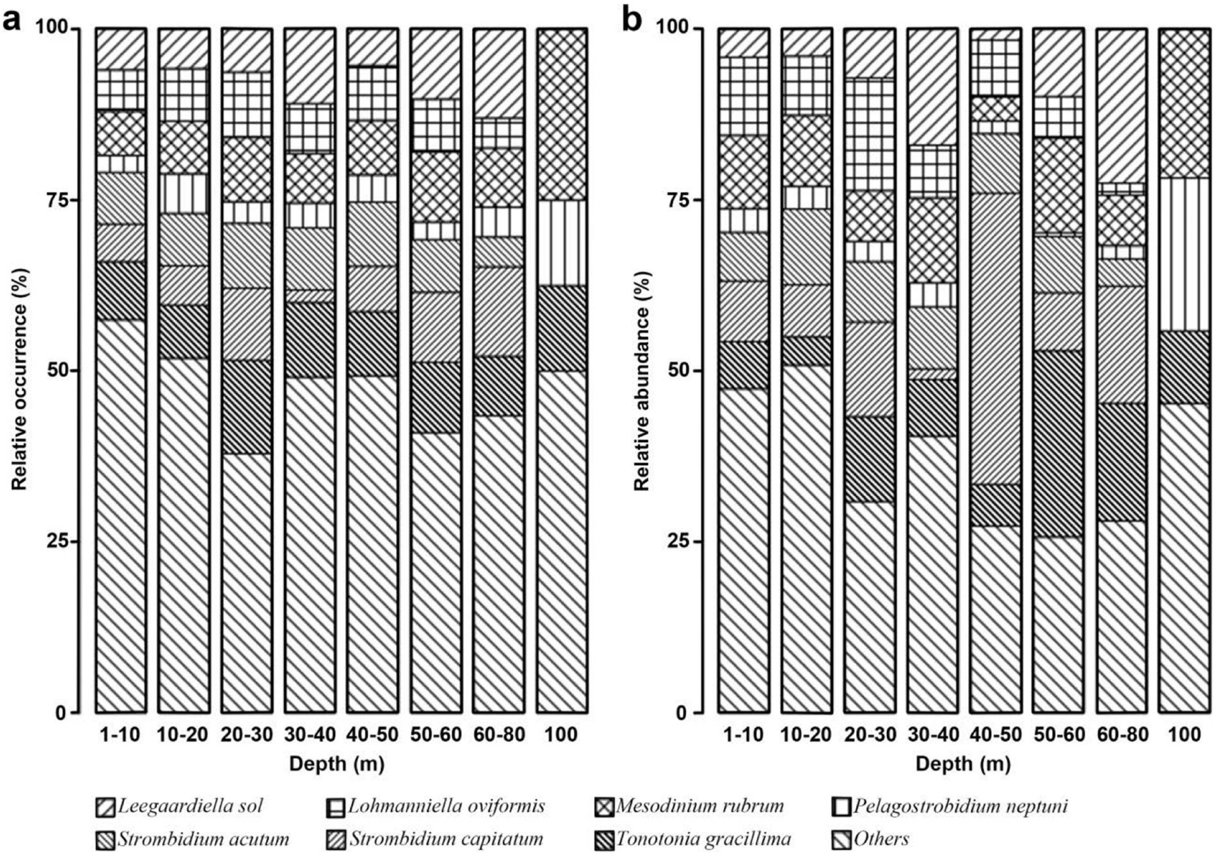

Fig. 6. Variations in relative species number (a) and relative abundance (b) from 1 m to 100 m during the study period.

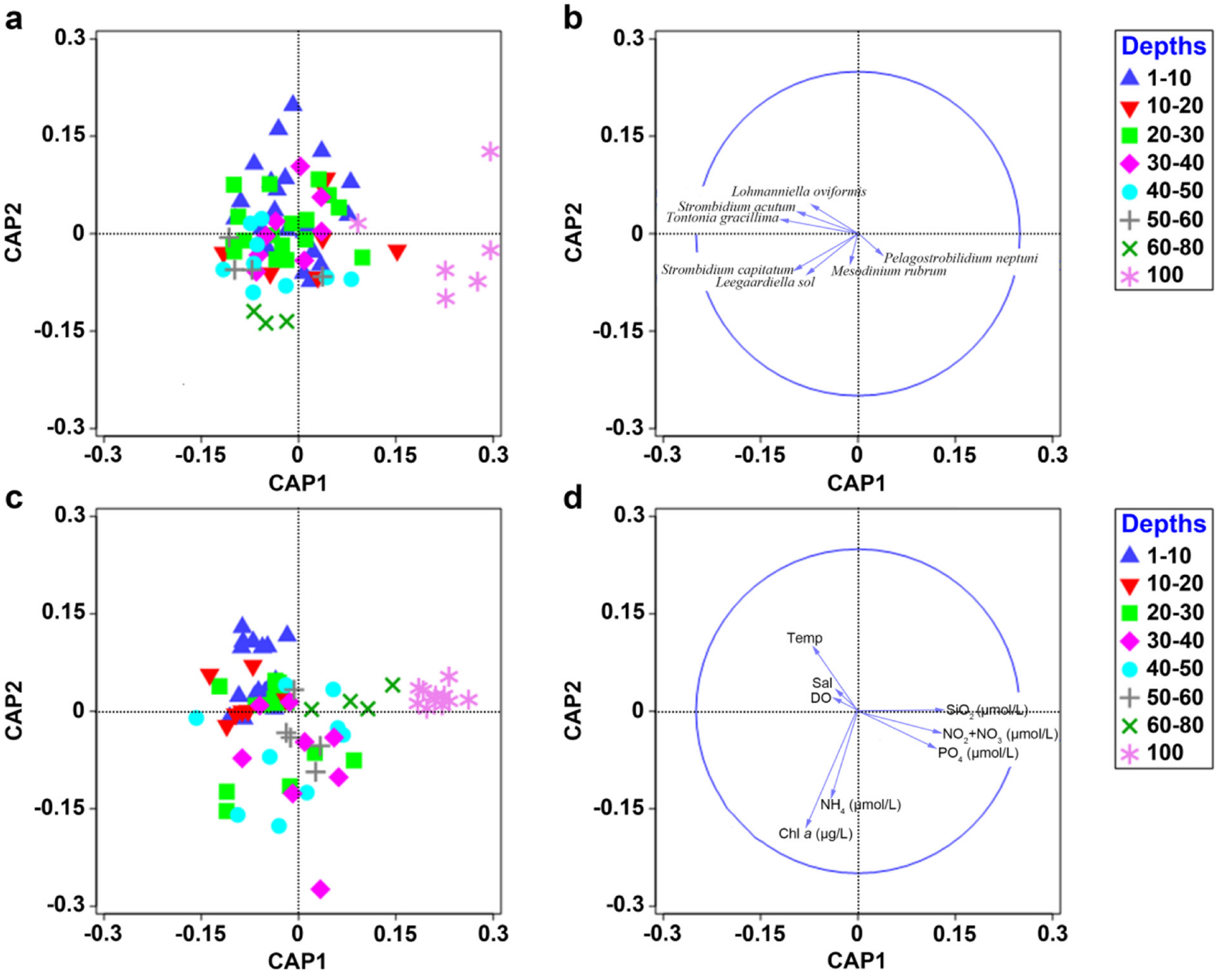

Fig. 7. Canonical analysis of principal coordinates for biotic data (a) with vectors (b), and for environmental variables (c) with vectors (d), showing the vertical patterns of biotic and abiotic matrices.

Table 1
RELATE analysis between the pelagic ciliate communities and environmental conditions, showing the top 9 best matches of abiotic variables to the changes in abiotic data.

Rank	Environmental variables	ρ value	*P* value
1	Temp, DO, PO_4, $NO_2 + NO_3$-N, NH_3-N	0.214	0.01
2	Temp, PO4, $NO_2 + NO_3$-N, NH_3-N	0.214	0.01
3	Temp, Sal, PO_4, $NO_2 + NO_3$-N, NH_3-N	0.213	0.01
4	Temp, Sal, DO, PO_4, NO_2 + NO3-N, NH_3-N	0.213	0.01
5	Temp, DO, PO_4, $NO_2 + NO_3$-N, NH_3-N, SiO_2	0.211	0.01
6	Temp, PO_4, $NO_2 + NO_3$-N, NH_3-N, SiO_2	0.211	0.01
7	Temp, Sal, PO_4, NH_3-N	0.210	0.01
8	DO, PO_4, NH_3-N	0.203	0.01
9	Sal, PO_4, NH_3	0.201	0.01

ρ value, Spearman correlation coefficient; *P* value, statistical significance level. PO_4, phosphate; $NO_2 + NO_3$, nitrate and nitrite; NH_4-N, ammonia; Temp, temperature; DO, dissolved oxygen; Sal, salinity.

and NH_4 (Table 1). Pearson correlation analysis demonstrated that the species number and total abundance of the ciliates were significantly and positively correlated with water temperature, NH_4, and Chl *a* (Table 2). Of the seven dominant species, three (*Mesodinium rubrum*, *Tontonia gracillima*, and *Pelagostrobilidium neptuni*) were generally significantly and positively related to water temperature, NH_4, and Chl *a* (Table 3).

4. Discussion

Since the 1990s, Arctic sea ice has decreased dramatically due to global climate changes (Serreze et al., 2007; Stroeve et al., 2007; Comiso et al., 2008; Perovich, 2011; Jiang et al., 2013). These changes affect the Arctic and global climate systems by altering heat exchange between the ocean and the atmosphere (Garrison and Buck, 1989; Budikova, 2009; Comeau et al., 2011; Overland, 2011). As reported previously, Pacific-origin Summer Water (PSW) reaches the Chukchi

Table 2
Pearson correlations between average values of the species number (*S*), abundance (*N*), richness (*D*), diversity (*H*′), evenness (*J*′) and average of environmental variables with spatial variations at 23 sampling stations in the Chukchi Sea and the northern Bering Sea of the western Arctic Ocean during the summer sea-ice reduction period.

Parameters	*S*	*N*	*D*	*J*′	*H*′
Temp	0.407[a]	0.417[a]	0.406[a]	0.196	0.360[a]
Sal	0.031	0.016	0.060	0.121	0.083
DO	0.051	0.034	0.073	0.176	0.112
PO_4	−0.380[a]	−0.390[a]	−0.346[a]	−0.411[a]	−0.396[a]
$NO_2 + NO_3$-N	−0.411[a]	−0.408[a]	−0.380[a]	−0.429[a]	−0.434[a]
NH_4-N	0.243[a]	0.295[a]	0.212	0.097	0.200
SiO_2	−0.299[a]	−0.296[a]	−0.265[a]	−0.379[a]	−0.337[a]
Chl *a*	0.475[a]	0.495[a]	0.456[a]	0.264[a]	0.442[a]

[a] Significant difference at the 0.05. See Table 1 for other abbreviations.

Table 3

Pearson correlations between average values of the dominant species abundances and average of environmental variables with spatial variations at 23 sampling stations in the Chukchi Sea and the northern Bering Sea of the western Arctic Ocean during the summer sea-ice reduction period.

Species	Temp	Sal	DO	PO_4	$NO_2 + NO_3$-N	NH_3-N	SiO_2	Chl *a*
Lohmanniella oviformis	0.113	0.143	0.148	−0.211	−0.210	−0.082	−0.069	0.216[a]
Mesodinium rubrum	0.474[a]	0.038	−0.013	−0.137	−0.170	0.396[a]	−0.057	0.507[a]
Pelagostrobilidium neptuni	0.185	0.001	0.005	−0.212	−0.251[a]	0.064	−0.110	0.165
Tontonia gracillima	0.283[a]	−0.068	−0.109	−0.106	−0.058	0.238[a]	0.041	0.206
Pelagostrobidium neptuni	0.395[a]	0.024	0.006	−0.240[a]	−0.235[a]	0.357[a]	−0.094	0.378[a]
Strombidium acutum	−0.006	0.106	0.138	−0.143	−0.172	0.078	−0.136	0.197
Tontonia gracillima	−0.099	−0.002	0.066	−0.293[a]	−0.308[a]	−0.064	−0.333[a]	0.275[a]

[a] Significant difference at the 0.05. See Table 1 for other abbreviations.

Sea, changes advective direction toward the northwest, along the northern slope of the Chukchi Sea, and is delivered to the Chukchi Borderland region, which consists of the Northwind Ridge and the Chukchi Plateau (Shimada et al., 2006; Carmack and Melling, 2011). Horizontal transportation and release of heat from PSW in that region are the primary reasons for the rapid and extensive sea-ice retreat and accompanying changes in the water column structure (Shimada et al., 2006). Therefore, pelagic ciliates living in this region are facing severe changes in environmental conditions in temporal and spatial terms (Jiang et al., 2014).

Previous investigations have demonstrated that ecological features of planktonic and periphytic ciliate communities can reflect water quality status (e.g., pollution or eutrophication) or changes in environmental conditions (Andersen, 1988; Xu et al., 2010, 2011; Jiang et al., 2011, 2013). In this study, the distributions of 44 ciliate species, and in particular those of the 7 dominant ciliates, indicated a clear vertical pattern among depths. Based on the results of multivariate and univariate analyses, pelagic ciliate communities showed significant variation in community pattern and biodiversity from 1 m to 100 m. Correlation analysis demonstrated that the spatial differences in these ecological features of pelagic ciliates at different depths were related significantly to changes in environmental variables along the depth gradient. Best matching analysis revealed that water temperature, DO, and nutrients (NH_4, PO_4, and $NO_2 + NO_3$), alone or in combination, were potential drivers that shape the vertical patterns of pelagic ciliates. Three dominant species (*Mesodinium rubrum*, *Tontonia gracillima*, and *Pelagostrobilidium neptuni*) were significantly and positively correlated with water temperature and the concentration of NH_4.

Community-based ecological parameters (e.g., species richness, abundance, and biodiversity indices) have been used commonly to summarize community features in field investigations and are amenable to simplified statistical analyses (e.g., Jiang et al., 2011; Xu et al., 2014). Thus, these parameters are considered to be helpful indicators in determining the water quality status of aquatic environments (e.g., Huston, 1979; Ismael and Dorgham, 2003; Jiang et al., 2011; Xu et al., 2014). Generally, higher values of these parameters indicate better water quality, with the possible exception that low levels of organic pollution are optimal (Huston, 1979; Ismael and Dorgham, 2003). In our study, species richness and abundance were significantly and positively related to water temperature and NH_4. Our findings suggest that these community-based features of pelagic ciliates, specifically those of the dominant ciliate species, can be used as a bioindicator of water quality status and its vertical distribution in Arctic ecosystems. However, further investigations must be conducted in a range of marine habitats and over extended time periods to verify this conclusion.

Our results are generally consistent with a previous report of the vertical distribution and structure of pelagic ciliate communities based on a dataset collected from a total of 32 stations at depths from the water surface to 150 m in a region of the western Arctic Ocean experiencing summer sea-ice reduction during the study period of August 1–September 10, 2012 (Jiang et al., 2015). In this study, on the other hand, we determined that the environmental variable ammonia, rather than the concentration of DO as reported by Jiang et al. (2015), was the main driver of the vertical distribution of ciliate abundance and richness from surface water to a depth of 100 m. This discrepancy might be due to differences in sampling water depths. For example, in the present study, species richness and abundance of ciliates dropped sharply, despite pronounced increases in the concentrations of PO_4, $Si(OH)_4$, and $NO_2 + NO_3$, in layers deeper than 90 m. This effect might be due to the low food supply (i.e., concentration of Chl *a*) available for the ciliates. Thus, we suggest that bioassessment of environmental status using pelagic ciliates is limited to water depths at which the food supply is sufficient for the survival of ciliates.

In this study, three species (group IV; Fig. 3a) occurred in samples collected from the depth of 40–50 m, where the NH_4 and Chl *a* concentrations peaked. Although they were not associated statistically with environmental variables, we nonetheless suggest that they are potentially useful indicators of water quality status at those depths.

In summary, the community structures of pelagic ciliates showed significant variation among eight water depths. The variations in the vertical distributions of ciliates were correlated significantly with changes in physico-chemical variables, especially ammonia, alone and in combination with water temperature, DO, and salinity. The distributions of the three dominant species had significant positive relations to water temperature and ammonia. Species richness and abundance were significantly and positively correlated with the concentrations of ammonia and Chl *a*. These results suggest that pelagic ciliates reflect vertical variations in the water quality status of Arctic ecosystems.

Acknowledgements

The authors thank the captain and crew of the *IBRV* ARAON who were most helpful in all shipboard operations. This research was supported by the K-AOOS Program (KOPRI; grant number PM18040) funded by the Ministry of Oceans and Fisheries, Korea.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2018.05.017.

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