Thesis for the Degree of Master of Science

Zooplankton community around Seogwipo in Jeju Island, Republic of Korea

by

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(대한민국 제주도 서귀포 주변의 동물 플랑크톤 군집)

Advisor: Professor Wongyu Park

by

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Abstract

Seasonal changes in the zooplankton community were studied at 30 stations around Seogwipo, Jeju Island, Republic of Korea. Zooplankton were vertically collected by a conical net in May 2020 (spring), August 2020 (summer), November 2020 (autumn), and February 2021 (winter). Water temperature and salinity were simultaneously measured at the zooplankton sampling sites by Sea-Bird 911plus CTD. The mean sea surface temperature was highest in summer (28ºC), intermediate in spring and autumn (17–20ºC), and lowest in winter (15ºC). The mean sea surface salinity was highest in autumn and winter (34 psu), intermediate in spring (33 psu), and lowest in summer (32 psu). The water mass around Seogwipo was divided by two water masses. Sea Area 1 was influenced by mixed waters originating from coastal areas, while Sea Area 2 was primarily affected by the Jeju Warm Current. A total of 256 species belonging to 10 phyla were identified. The mean density was highest in autumn (2,510 inds.m^{-3}) and lowest in winter (733 inds.m^{-3}). Copepods were the most dominant zooplankton community in all seasons. The species number in Sea Area 1 was lower than in Sea Area 2. The analysis revealed 91 warm-water species and 15 cold-water species. Notably, the warm-water species *Paracalanus parvus* s.l. and *Oncaea venusta*, as well as the cold-water species *Oithona atlantica* were frequently recorded across all areas and seasons. The cladoceran *Penilia avirostris* was observed only in summer, whereas the amphipod *Primno macropa* appeared exclusively in autumn. The density variations of dominant species between stations and seasons were correlated with environmental factors. This study elucidated that seasonal oceanographic patterns were key in regulating the zooplankton community.

Keywords: Zooplankton community, copepoda, Seogwipo, Jeju Island

대한민국 제주도 서귀포 주변의 동물 플랑크톤 군집

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요 약

대한민국 제주도 서귀포 주변의 30 개 지점에서 동물플랑크톤 군집의 계절적 변화를 연구했다. 동물플랑크톤은 2020 년 5 월(봄), 2020 년 8 월(여름), 2020 년 11 월(가을), 2021 년 2 월(겨울)에 원뿔형 네트를 이용해 수직 채집하였다. 수온과 염분은 동물플랑크톤 채집 지점에서 Sea-Bird 911plus CTD 를 사용하여 동시에 측정되었다. 평균 해수면 온도는 여름에 가장 높았고(28°C), 봄과 가을에 중간(17–20°C), 겨울에 가장 낮았다(15°C). 평균 해수면 염분은 가을과 겨울에 가장 높았고(34 psu), 봄에 중간(33 psu), 여름에 가장 낮았다(32 psu). 서귀포 주변의 수괴는 두 개의 수괴로 나뉘었다. 해역 1 은 연안에서 유래한 혼합수에 영향을 받았고, 해역 2 는 주로 Jeju Warm Current 의 영향을 받았다. 10 개 문(phyla)에 속하는 총 256 종이 확인되었다. 평균 밀도는 가을 (2,510 inds.m^{-3})로 가장 높았고 겨울 (733 inds.m^{-3})로 가장 낮았다. 동물플랑크톤 군집 중 요각류가 모든 계절에서 우점하였다. 해역 1 의 종 수는 해역 2 보다 적었다. 분석 결과 온수종은 91 종, 냉수종은 15 종이었다. 특히, 온수종인 *Paracalanus parvus* s.l.와 *Oncaea venusta*, 냉수종인 *Oithona atlantica* 는 모든 해역과 계절에서 출현하였다. 지각류 *Penilia avirostris* 는 여름에만 관찰되었고, 단각류 *Primno macropa* 는 가을에만 출현했다. 조사 정점과 계절 사이의 우점종의 밀도 변화는 환경 요인과 상관관계가 있었다. 이 연구는 계절에 따른 해양학적 패턴이 동물플랑크톤 군집을 조절하는 데 중요한 역할을 한다는 것을 보여주었다.

Keywords: 동물성 플랑크톤 군집, 요각류, 서귀포, 제주도

1. Introduction

Zooplankton are the key intermediary between primary production and higher trophic levels in marine food webs (Turner, 2004; Thorpe, 2024). These organisms are also utilized as sensitive indicators of marine environmental variations (Siokou-Frangou et al., 1998; Richardson, 2008). Environmental changes, whether seasonal or long-term, can affect zooplankton distribution and abundance, thereby influencing fluctuations in fisheries resource quantity (Thorpe, 2024). Therefore, knowledge of the zooplankton community is essential for understanding marine ecosystem dynamics and serves as baseline data for environmental protection and fisheries resources management.

Jeju Island is located southwest of the Korean Peninsula. The oceanography around the island is influenced by the Jeju Warm Current (JWC), the Tsushima Warm Current (TWC) as branches of the Kuroshio Warm Current (KWC), and the Changjiang Diluted Water (CDW) (Lee et al., 2019; Shin et al., 2022). The JWC and TWC are characterized by warm waters (>15°C) and high salinity (33–34 psu) (Chang et al., 2004; Lee et al., 2019; Shin et al., 2022). A thermohaline front in the southern part of the island separates coastal waters from the JWC, affecting water mass variations and zooplankton distribution (Lee et al., 2019). The CDW as a mixture of seawater and freshwater from the Yangtze River, lowers the Jeju's waters salinity in summer (<33 psu)

(Shin et al., 2022). The southern waters of Jeju also experience marine debris accumulation, including plastics (Song et al., 2021), which can negatively impact the function and health of zooplankton (Cole et al., 2013). Thus, zooplankton community patterns in Jeju’s southern waters are greatly influenced by oceanographic conditions, such as ocean currents, water masses, temperature, salinity, and anthropogenic impacts.

Zooplankton community rely on large-scale physical processes, such as the transport of water masses by ocean currents (Turner, 2004). Seasonal variations in water masses cause fluctuations in the abundance and distribution of both warm- and cold-water zooplankton species and act as a key factor in shaping zooplankton community patterns (Pepin et al., 2011; Shin et al., 2022). Changes in physical environmental factors, including temperature and salinity in marine ecosystems, can lead to rapid shifts in species richness and quantitative characteristics of zooplankton (Hwang et al., 2006). Rising sea surface temperatures have been shown to affect the zooplankton community structure and phenology (Richardson, 2008), as reported in Korean waters, including Jeju, over the past half-century (Han and Lee, 2020). Fluctuating salinity due to seasonal precipitation and evaporation also influences the zooplankton distribution, as each species has different tolerances to salinity changes (Richardson, 2008; Hall and Lewandowska, 2022).

We hypothesized that different marine environmental conditions affect the zooplankton community and its distribution patterns around Seogwipo in Jeju Island. The purpose of this study was to elucidate the seasonal characteristics of the zooplankton community around Seogwipo in Jeju Island, and the marine environment characteristics of these communities.

2. Materials and methods

2.1. Study area and sampling

Zooplankton were collected from 30 stations around Seogwipo, Jeju Island, Korea in May 2020 (spring), August 2020 (summer), November 2020 (autumn), and February 2021 (winter) (Figure 1). Zooplankton were sampled vertically by a conical net (45 cm diameter; 330 µm mesh size), equipped with a flowmeter at the net's mouth. The net was lowered to approximately 10 meters above the seabed. Samples were preserved with 4% formaldehyde solution. Temperature and salinity were simultaneously recorded during zooplankton sampling with a Sea-Bird 911plus CTD.

2.2. Sample analyses

Zooplankton samples were initially scanned by a stereo microscope before analysis. Approximately 300–500 zooplankton organisms per sample were aliquoted for analysis with a Motoda-type splitter (1/2–1/1024). Zooplankton were identified to the species level or the lowest possible taxonomic level and counted in a Bogorov counting tray under a dissecting microscope. The counted zooplankton were converted to individuals m^{-3} ($inds.m^{-3}$).

2.3. Data analyses

The horizontal profiles of sea surface temperature and sea surface salinity were visualized by Surfer v.10. Water masses were distinguished by cluster analysis with Euclidean distances on normalized temperature and salinity values. Seasonal variations in the zooplankton community were analyzed with Margalef's species richness index (d'), Shannon–Wiener diversity index (H'), and Pielou's evenness index (J'). Species density data was square-root transformed to balance the importance of common and rare taxa. Non-metric multidimensional scaling (nMDS) and cluster analysis were performed by the Bray-Curtis similarity index to examine seasonal similarities. An nMDS ordination with a stress value of <0.05 indicates excellent interpretability; <0.1 indicates good interpretability; <0.2 indicates acceptable interpretability; and >0.2 suggests challenges in data interpretation (Clarke, 1993). Cluster analysis using average linkage was carried out, and qualitative separation of groups was done by overall similarity (~30–63%). Similarity percentages (SIMPER) analysis with a cumulative contribution limit of 90% was applied to assess the percentage of species contributing most to differences observed between two water mass areas in each season. All these analyses were implemented by Plymouth Routines In Multivariate Ecological Research (PRIMER) v.6.1.6

(Clarke and Gorley, 2005). Environmental variables were further analyzed by redundancy analysis (RDA) in Origin Pro v.2024 to evaluate the relationship between the seasonal variations in the density of dominant zooplankton species and environmental variables, determining the relative influence of these factors.

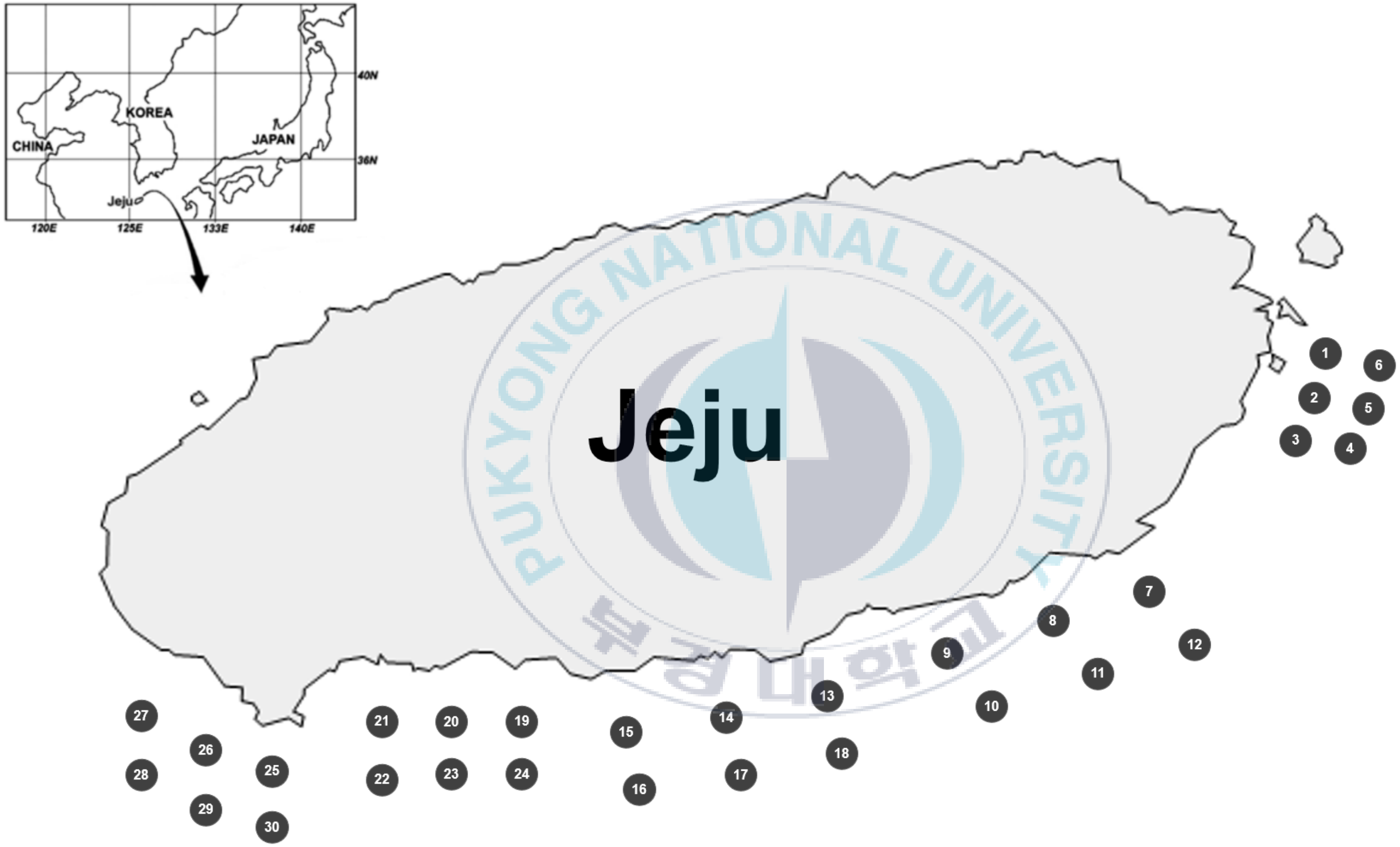

Figure 1. Sampling stations around Seogwipo, Jeju Island, Korea.

3. Results

3.1. Environmental characteristics

The horizontal profiles of sea surface temperature and salinity at all stations around Seogwipo in Jeju Island demonstrated seasonal variations. Water temperature was highest in summer, ranging from 23.3 to 29.7°C. In winter, water temperature was lowest and ranged from 10.8 to 16°C. Water temperatures ranged from 16.2 to 19.6°C in spring and from 19 to 21.3°C in autumn. The mean temperature for each season was 28±1.3°C in summer, 14.5±1.1°C in winter, 17.5±0.9°C in spring, and 20.4±0.5°C in autumn (Figure 2).

Sea surface salinity ranged from 32.4 to 34.4 psu in spring, 31.7 to 33.9 psu in summer, 31.7 to 34.7 psu in autumn, and 33.5 to 35.2 psu in winter. The mean salinity for each season was 33.5±0.6 psu in spring, 32.3±0.5 psu in summer, and 34.1±0.6 psu in both autumn and winter (Figure 3). Warm conditions with temperatures >15°C indicated the warm current influence. The low salinity in summer reflected the effect of CDW inflow.

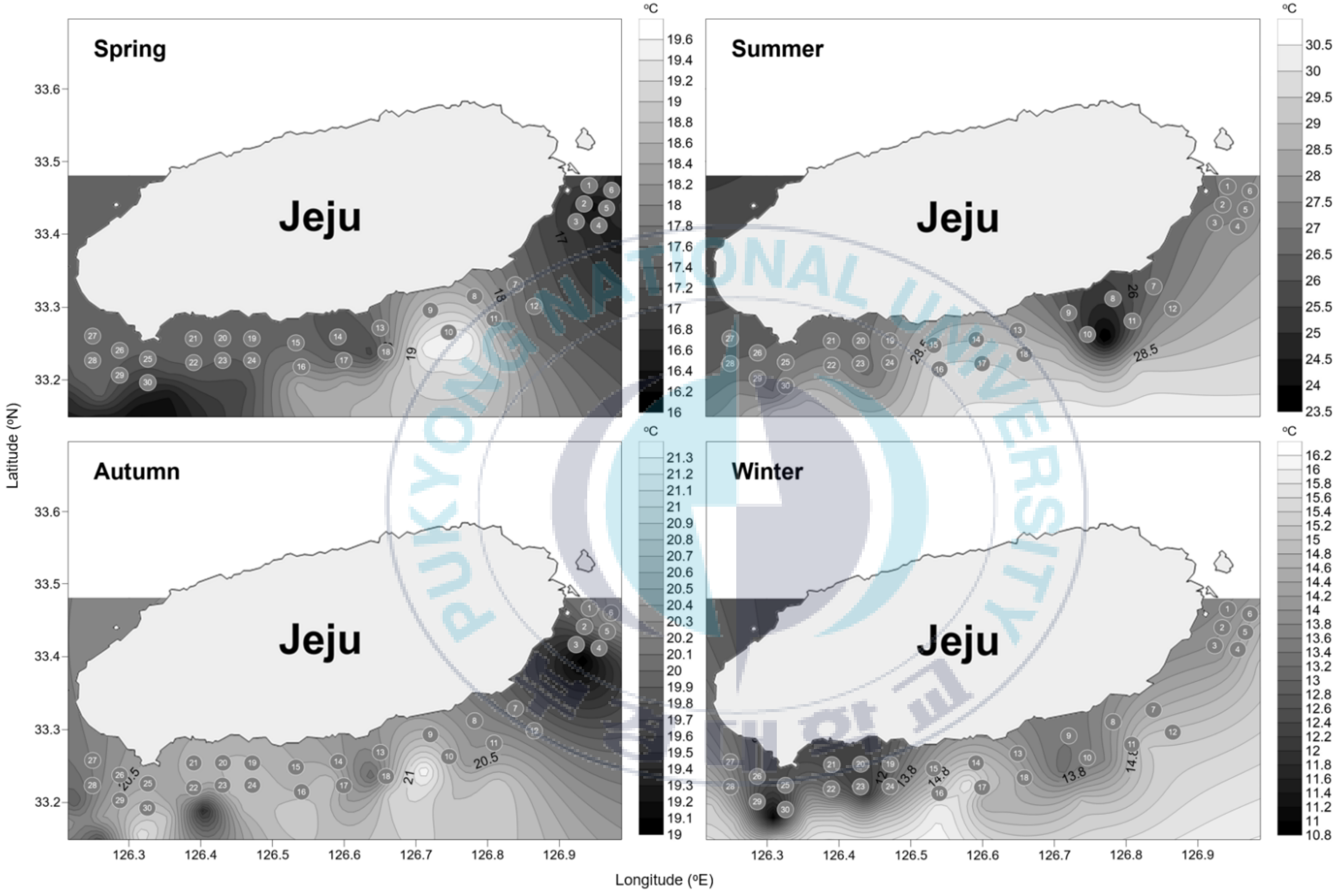

Figure 2. Seasonal horizontal distribution of temperature (°C) around Seogwipo, Jeju Island, Korea in May 2020 (spring), August 2020 (summer), November 2020 (autumn), and February 2021 (winter).

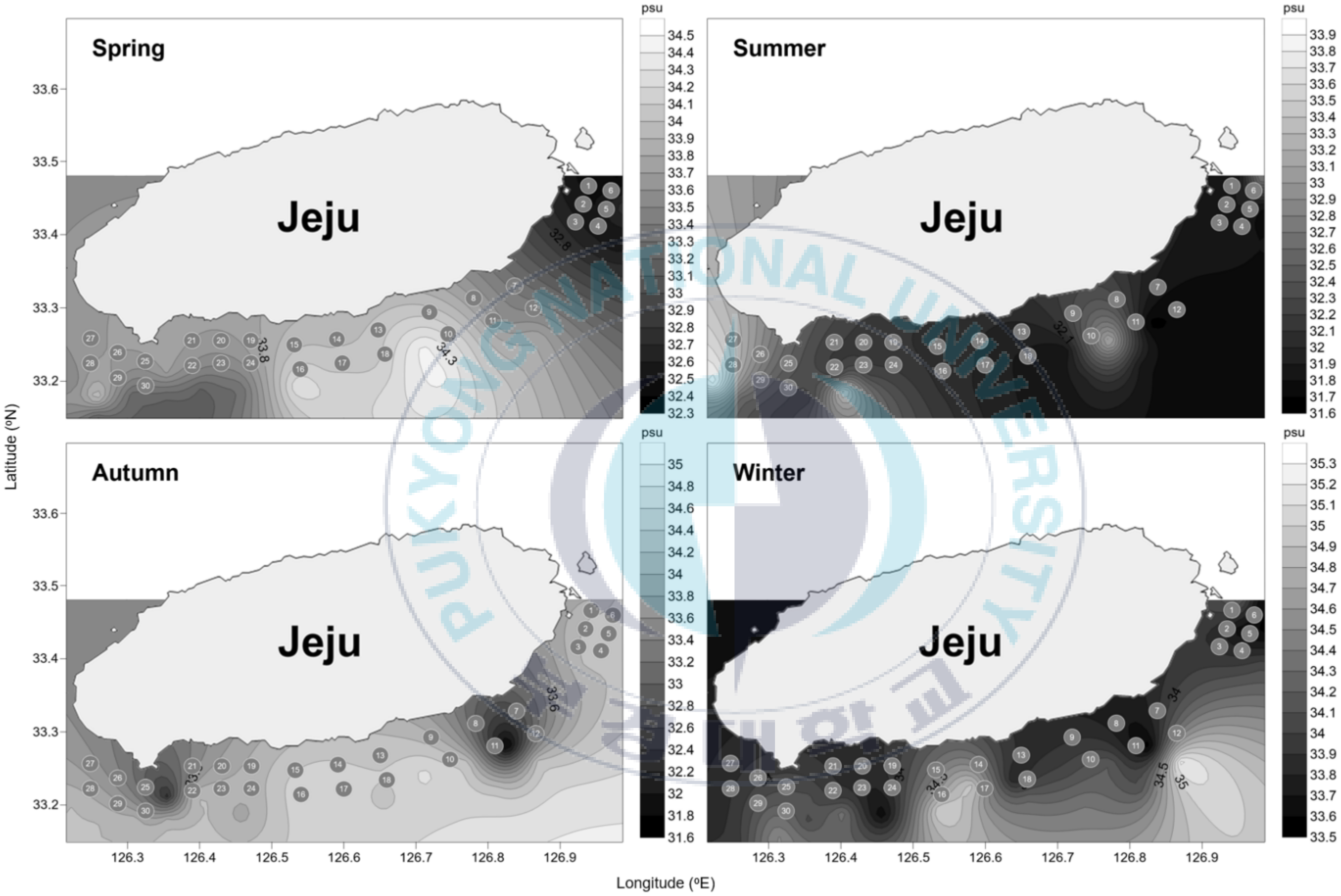

Figure 3. Seasonal horizontal distribution of salinity (psu) around Seogwipo, Jeju Island, Korea in May 2020 (spring), August 2020 (summer), November 2020 (autumn), and February 2021 (winter).

3.2. Water mass distribution

The clustering analysis divided the waters around Seogwipo in Jeju Island into two water mass areas. Sea Area 1 was characterized by mixed waters influenced by coastal areas (13–23°C), while Sea Area 2 was primarily influenced by JWC, with higher temperatures (15–28°C). In spring, seven stations located in the central part of the study area were classified as Sea Area 1, with the remaining stations in Sea Area 2. Only one station in summer and two stations in autumn and winter were classified as Sea Area 1, whereas the other stations were in Sea Area 2 (Figures 4 and 5).

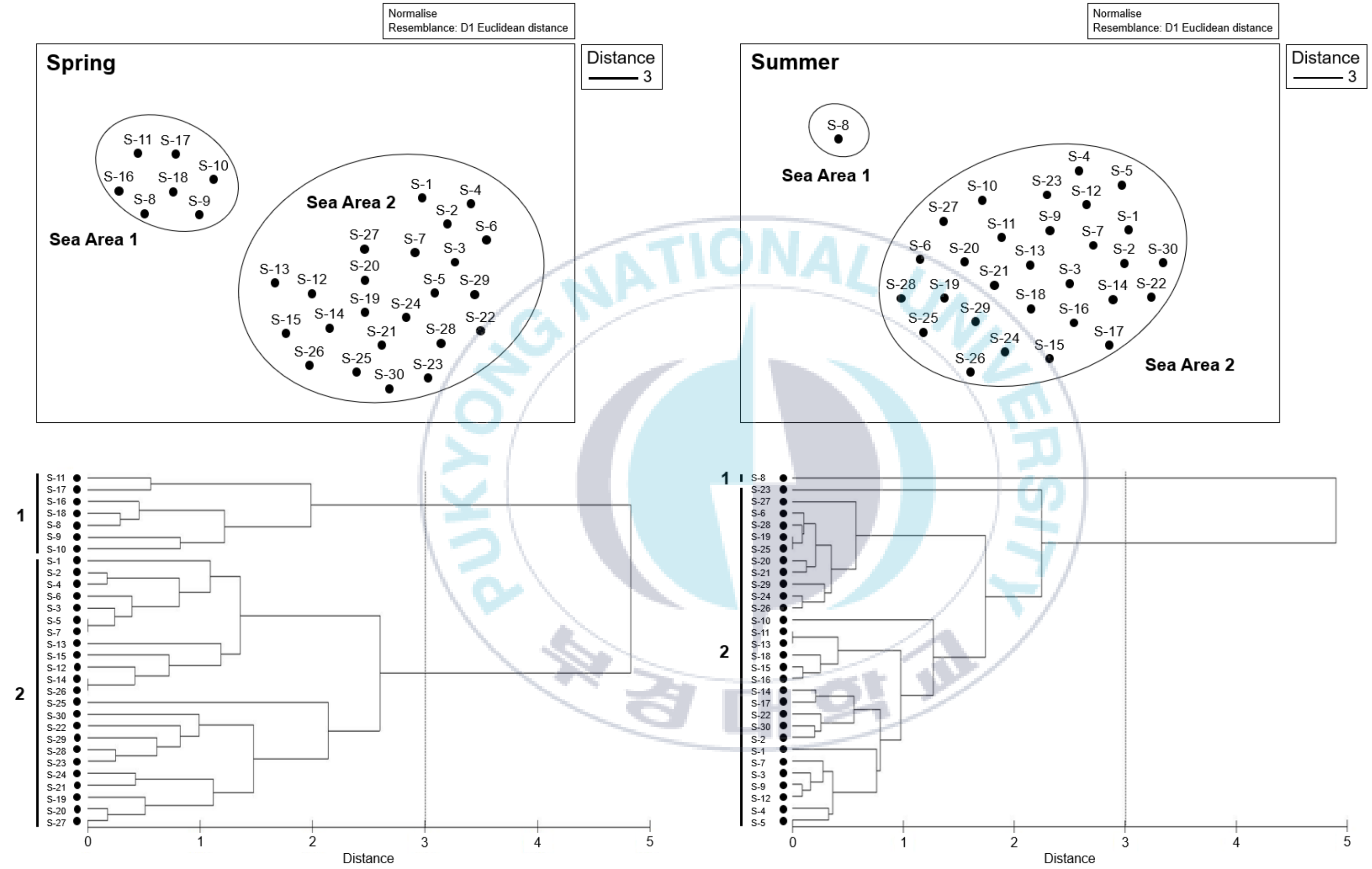

Figure 4. Cluster analysis in water mass distribution around Seogwipo, Jeju Island, Korea in May 2020 (spring), August 2020 (summer), November 2020 (autumn), and February 2021 (winter).

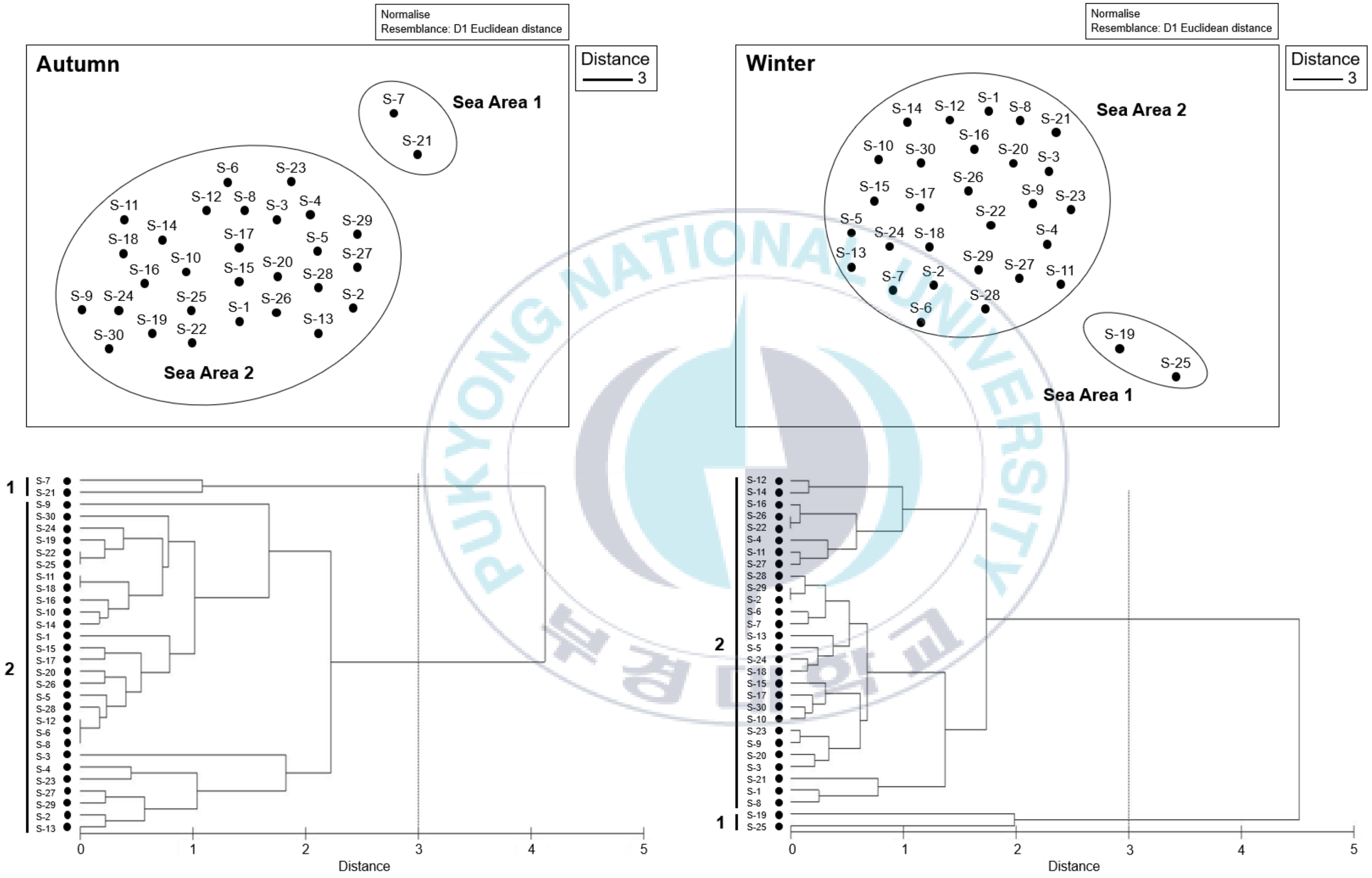

Figure 4. (Continued)

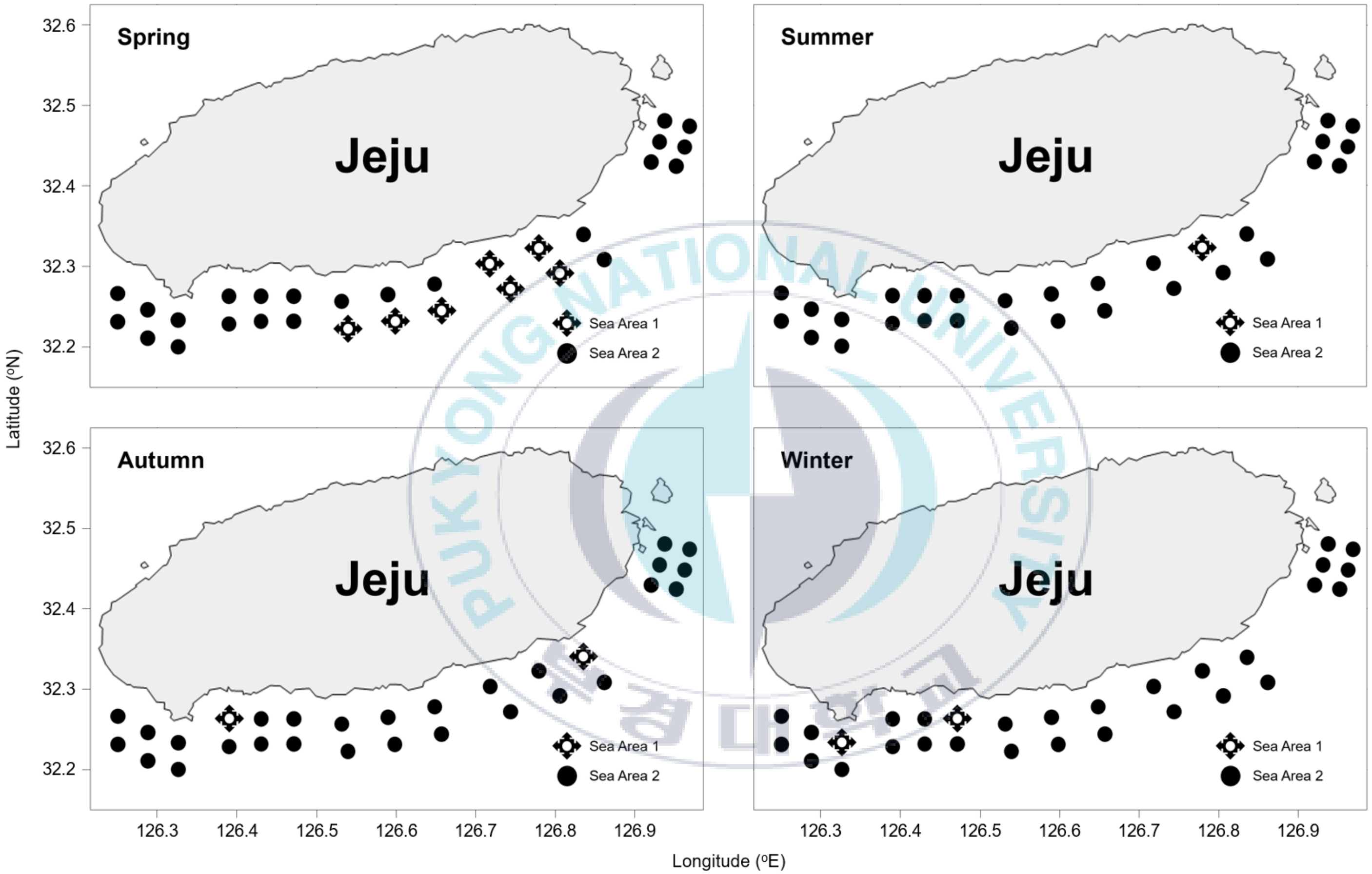

Figure 5. Water mass distribution around Seogwipo, Jeju Island, Korea in May 2020 (spring), August 2020 (summer), November 2020 (autumn), and February 2021 (winter).

3.3. Zooplankton community

A total of 256 zooplankton species from 10 phyla were identified. The species number varied with season. The species number was highest in winter (179 species), followed by autumn (160 species) and summer (135 species), and lowest in spring (75 species). The seasonal pattern of mean density was highest in autumn (2,510 inds.m^{-3}), followed by spring (1,334 inds.m^{-3}) and summer (1,148 inds.m^{-3}), and lowest in winter (733 inds.m^{-3}) (Figure 6).

All mean diversity indices showed the highest values in summer. Notably, the species richness index was highest in summer (9.5), followed by autumn (9.3) and winter (9), and lowest in spring (5.6). The diversity index was highest in summer (3.6), followed by autumn (3.4) and winter (3.2), and lowest in spring (2.7). The evenness index was higher in summer (0.9) than other seasons (0.8) (Table 1).

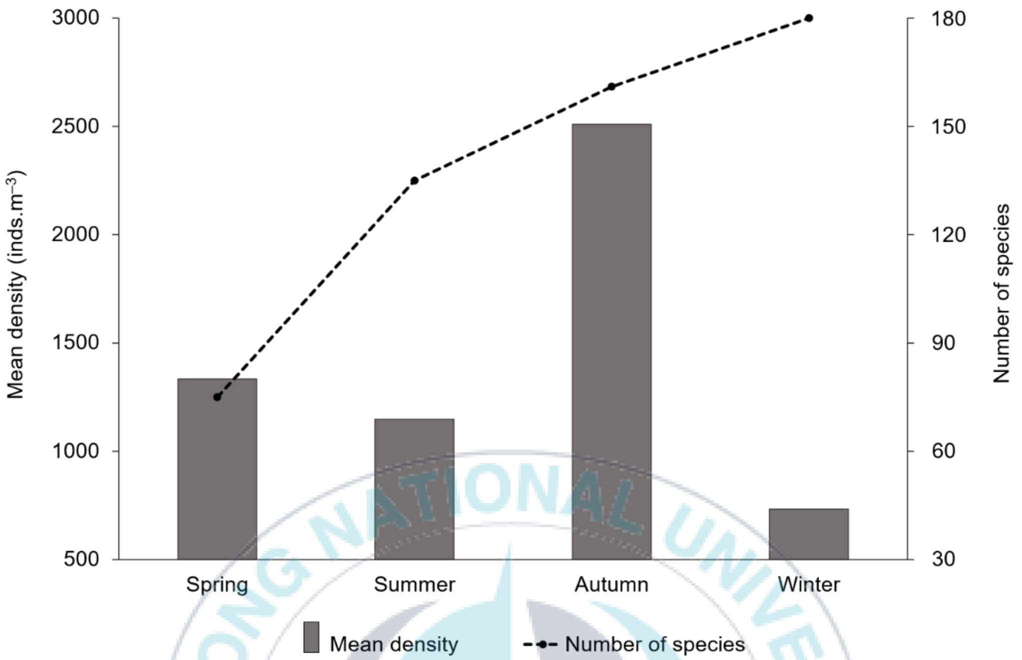

Figure 6. Mean zooplankton density (inds.m^{-3}) and species number around Seogwipo, Jeju Island, Korea in May 2020 (spring), August 2020 (summer), November 2020 (autumn), and February 2021 (winter).

Table 1. Diversity indices of the zooplankton community around Seogwipo, Jeju Island, Korea in May 2020 (spring), August 2020 (summer), November 2020 (autumn), and February 2021 (winter).

Season	Species richness index	Diversity index	Evenness index
Spring	5.6	2.7	0.8
Summer	9.5	3.6	0.9
Autumn	9.3	3.4	0.8
Winter	9.0	3.2	0.8

3.4. Spatial distribution of zooplankton density

The spatial distribution of zooplankton density varied by stations and seasons. In spring, the highest density occurred at station S-30 (8,151 inds.m^{-3}) and the lowest at station S-17 (8 inds.m^{-3}). In summer, the density was highest at station S-13 (2,539 inds.m^{-3}) and lowest at station S-6 (466 inds.m^{-3}). In autumn, the density was highest at station S-1 (6,043 inds.m^{-3}) and lowest at station S-22 (947 inds.m^{-3}). In winter, the density was highest at station S-4 (6,329 inds.m^{-3}) and lowest at station S-25 (25 inds.m^{-3}) (Figure 7).

In terms of water mass distribution, Sea Area 2 displayed higher densities than Sea Area 1 across all seasons. In spring, the density in Sea Area 1 was 15,409 inds.m^{-3}, and in Sea Area 2 was 24,610 inds.m^{-3}. In summer, the densities in Sea Areas 1 and 2 were 2,103 and 32,339 inds.m^{-3}, respectively. In autumn, the densities in Sea Areas 1 and 2 were 4,478 and 70,593 inds.m^{-3}, respectively. In winter, the density in Sea Area 1 was 2,414 inds.m^{-3}, and in Sea Area 2 was 19,584 inds.m^{-3} (Figure 8).

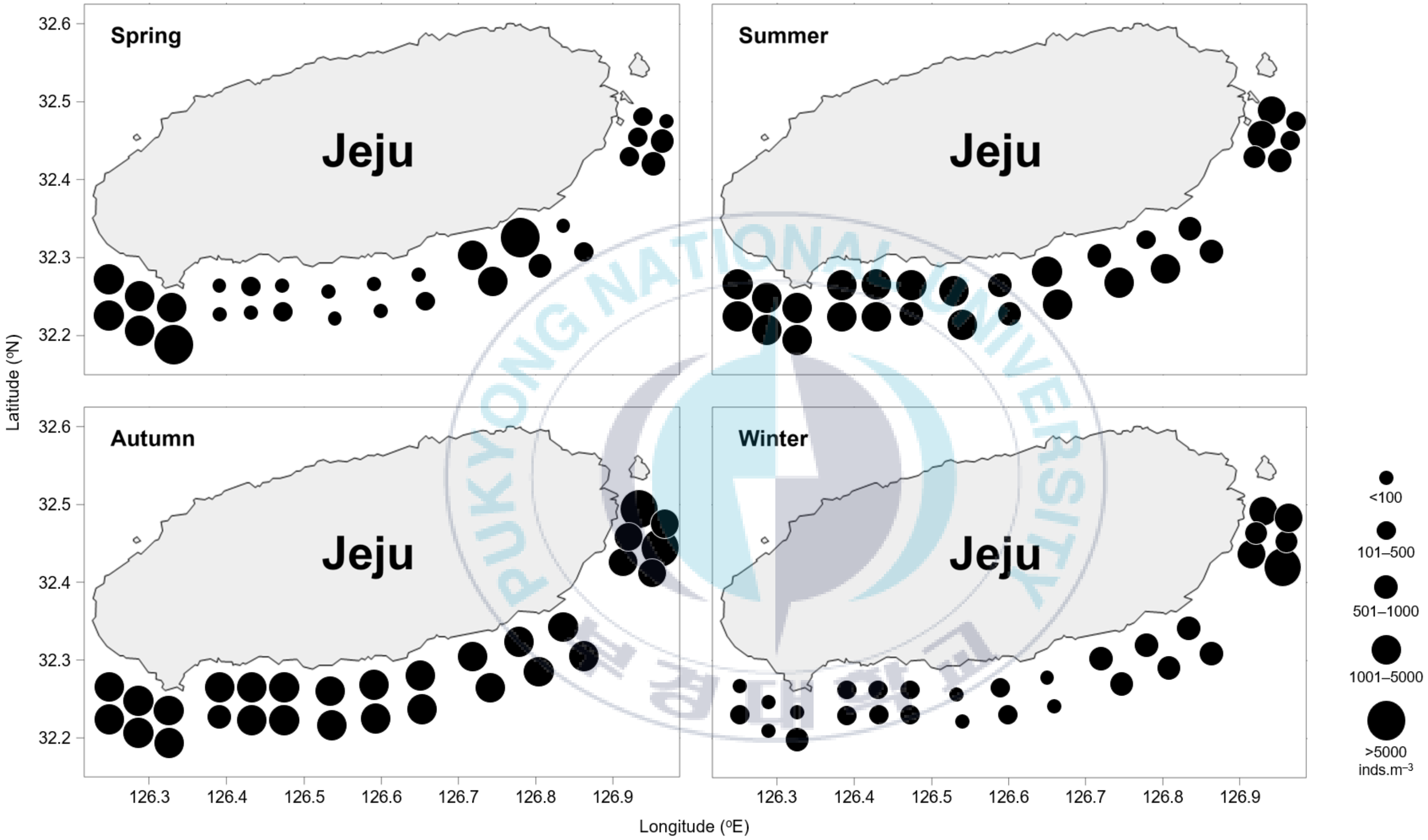

Figure 7. Spatial distribution of zooplankton density (inds.m^{-3}) around Seogwipo, Jeju Island, Korea in May 2020 (spring), August 2020 (summer), November 2020 (autumn), and February 2021 (winter).

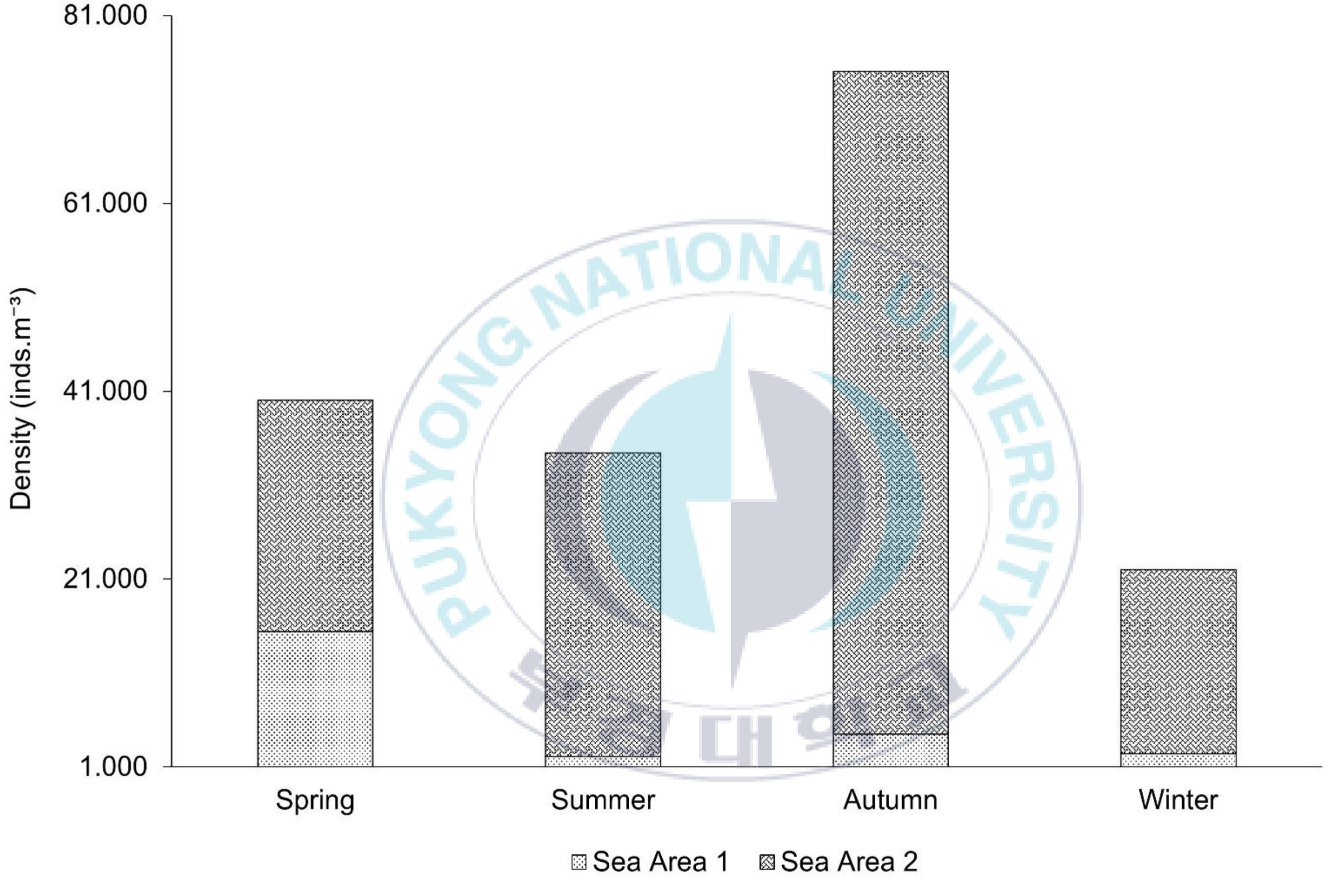

Figure 8. Zooplankton density (inds.m^{-3}) by water mass around Seogwipo, Jeju Island, Korea in May 2020 (spring), August 2020 (summer), November 2020 (autumn), and February 2021 (winter).

3.5. Changes in the occurrence of warm- and cold-water zooplankton species

In this study, 91 warm- and 15 cold-water zooplankton species were found and validated by previous studies (Appendices 1 and 2). The number of warm- and cold-water species in Sea Area 1 was lower than in Sea Area 2. For warm-water species, six species were identified in Sea Area 1 and 14 species in Sea Area 2 in spring. In summer, 13 and 41 species were observed in Sea Areas 1 and 2, respectively. In autumn, the numbers increased to 28 species in Sea Area 1 and 61 species in Sea Area 2, while in winter, 28 species were recorded in Sea Area 1 and 57 species in Sea Area 2. Among these species, *P. parvus* s.l. and *O. venusta* were consistently present across all water masses and seasons (Table 2).

For cold-water species, five species were identified in both Sea Areas 1 and 2 in spring. In summer, two and five species were observed in Sea Areas 1 and 2, respectively. In autumn, two species were recorded in Sea Area 1 and eight species in Sea Area 2, while in winter, four and 11 species were found in Sea Areas 1 and 2, respectively. The small copepod *O. atlantica* was the most frequently encountered, appearing across all water masses and seasons (Table 3).

Table 2. Distribution of warm-water zooplankton species identified in different water masses around Seogwipo, Jeju Island, Korea in May 2020 (spring), August 2020 (summer), November 2020 (autumn), and February 2021 (winter).

Warm-water species	Spring		Summer		Autumn		Winter	
	Sea Area 1	Sea Area 2	Sea Area 1	Sea Area 2	Sea Area 1	Sea Area 2	Sea Area 1	Sea Area 2
Copepoda								
Acartia danae				+				+
Acartia erythraea				+				
Acartia negligens					+	+		+
Acartia pacifica		+			+	+		+
Calocalanus gracilis						+		
Calocalanus pavo						+	+	+
Calocalanus pavoninus					+	+		
Candacia bipinnata						+		
Candacia catula						+		
Candacia curta					+	+		
Candacia pachydactyla						+		
Canthocalanus pauper						+		
Centropages furcatus						+		
Centropages gracilis						+		
Clausocalanus arcuicornis						+		
Clausocalanus farrani		+			+	+	+	+
Clausocalanus furcatus					+	+	+	+
Clausocalanus minor	+	+			+	+		+
Copilia mirabilis				+				
Corycaeus crassiusculus				+	+		+	
Corycaeus speciosus		+		+	+	+		+
Cosmocalanus darwinii			+	+		+		+
Ctenocalanus vanus	+	+	+	+		+		+
Ditrichocorycaeus dahli						+	+	+
Ditrichocorycaeus erythraeus						+	+	+
Eucalanus hyalinus								+
Euchaeta concinna		+		+	+	+	+	+
Euchaeta indica						+		+
Euchaeta longicornis								+
Euchaeta plana	+	+		+		+	+	+
Euchaeta rimana				+	+	+		+
Euterpina acutifrons							+	+
Farranula carinata				+		+		
Farranula concinna						+		
Farranula gibbula				+		+		
Goniopsyllus rostratus		+					+	+
Labidocera acuta				+				
Labidocera minuta						+		
Lucicutia clausi				+				

Table 2. (Continued)

Warm-water species	Spring		Summer		Autumn		Winter	
	Sea Area 1	Sea Area 2	Sea Area 1	Sea Area 2	Sea Area 1	Sea Area 2	Sea Area 1	Sea Area 2
Copepoda								
Lucicutia flavicornis							+	+
Macrosetella gracilis							+	+
Mecynocera clausi								+
Microsetella rosea							+	+
Nannocalanus minor		+					+	+
Neocalanus gracilis				+				
Oithona fallax				+	+	+	+	+
Oithona plumifera								+
Oithona setigera						+	+	+
Oithona tenuis			+	+	+	+		
Oncaea clevei					+	+		+
Oncaea mediterranea				+			+	+
Oncaea venusta	+	+	+	+	+	+	+	+
Onychocorycaeus agilis						+		+
Onychocorycaeus catus				+		+	+	+
Onychocorycaeus giesbechii								+
Onychocorycaeus pacificus			+	+	+	+		+
Paracalanus aculeatus				+	+	+	+	+
Paracalanus denudatus							+	+
Paracalanus parvus s.l.	+	+	+	+	+	+	+	+
Paraeuchaeta russelli		+		+		+		+
Pareucalanus attenuatus					+	+		+
Pleuromamma abdominalis						+		
Pleuromamma gracilis				+		+	+	+
Pontellina plumata				+				
Rhincalanus cornutus						+		+
Rhincalanus nasutus						+		+
Sapphirina darwinii						+		+
Sapphirina gemma				+				
Sapphirina opalina						+		
Scolecithricella longispinosa								+
Scolecithricella nicobarica				+	+	+	+	+
Scolecithrix danae				+	+	+		+
Subeucalanus crassus				+	+	+	+	+
Subeucalanus mucronatus				+		+	+	+
Subeucalanus subcrassus						+		+
Subeucalanus subtenuis					+	+		+
Temora discaudata			+	+				
Temora turbinata								+
Tigriopus japonicus							+	+
Triconia conifera			+	+		+		+
Undinula vulgaris			+	+	+	+		

Table 2. (Continued)

Warm-water species	Spring		Summer		Autumn		Winter	
	Sea Area 1	Sea Area 2	Sea Area 1	Sea Area 2	Sea Area 1	Sea Area 2	Sea Area 1	Sea Area 2
Non-Copepoda								
Penilia avirostris				+				
Pseudevadne tergestina				+				
Themisto japonica				+		+		
Themisto pacifica						+		
Aidanosagitta crassa			+	+				
Flaccisagitta enflata	+	+	+	+	+	+		+
Serratosagitta pacifica					+	+		
Zonosagitta nagae		+						+
Doliolum denticulatum			+	+	+	+		
Noctiluca scintillans			+	+	+	+	+	+

Table 3. Distribution of cold-water zooplankton species identified in different water masses around Seogwipo, Jeju Island, Korea in May 2020 (spring), August 2020 (summer), November 2020 (autumn), and February 2021 (winter).

Cold-water species	Spring		Summer		Autumn		Winter	
	Sea Area 1	Sea Area 2	Sea Area 1	Sea Area 2	Sea Area 1	Sea Area 2	Sea Area 1	Sea Area 2
Copepoda								
Acartia hudsonica						+		
Acartia omorii	+	+				+		+
Calanus sinicus	+	+				+	+	+
Candacia discaudata					+			
Ditrichocorycaeus affinis	+	+		+		+	+	+
Eucalanus bungii								+
Eucalanus californicus						+		+
Metridia pacifica				+				
Microsetella norvegica								+
Oithona atlantica	+	+	+	+	+	+	+	+
Oithona similis	+	+	+	+			+	+
Paraeuchaeta elongata								+
Pseudocalanus minutus				+				+
Scolecithricella minor						+		+
Non-Copepoda								
Primno macropa						+		

3.6. Multivariate analyses

The nMDS results presented good correspondence with the cluster analysis. The nMDS ordination plot and cluster analysis divided the stations into two groups. The nMDS stress coefficient was 0.09 (stress <0.1) in spring and winter, indicating that the similarity of the zooplankton community by water mass could be well interpreted. Meanwhile, stress values of 0.18 and 0.16 (stress <0.2) in summer and autumn suggested that the analysis results were interpretable. The multivariate analyses indicated that neighboring stations had relatively higher similarity than stations at farther distances (Figure 9).

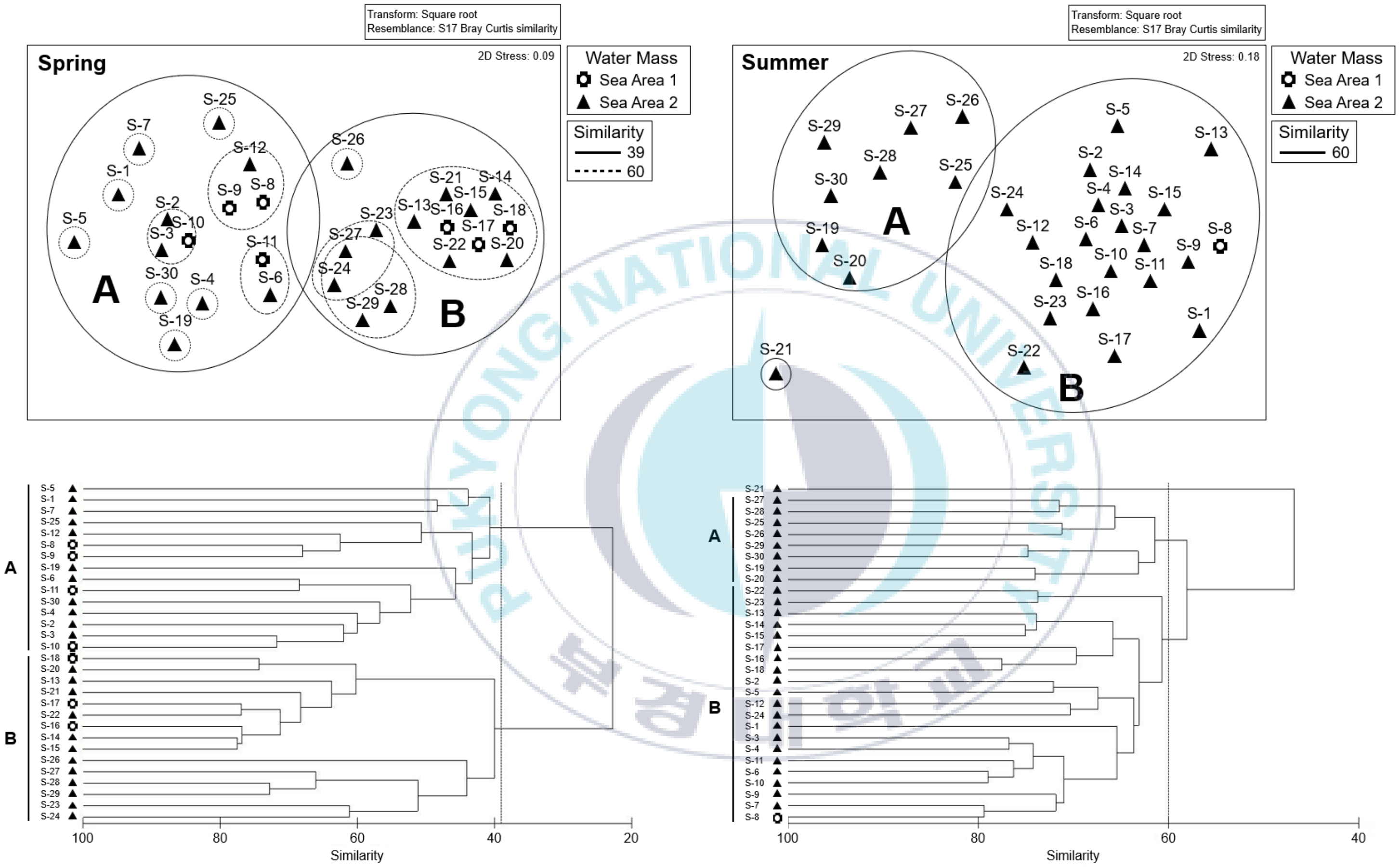

Figure 9. The nMDS ordination plot and cluster analysis by water mass around Seogwipo, Jeju Island, Korea in May 2020 (spring), August 2020 (summer), November 2020 (autumn), and February 2021 (winter).

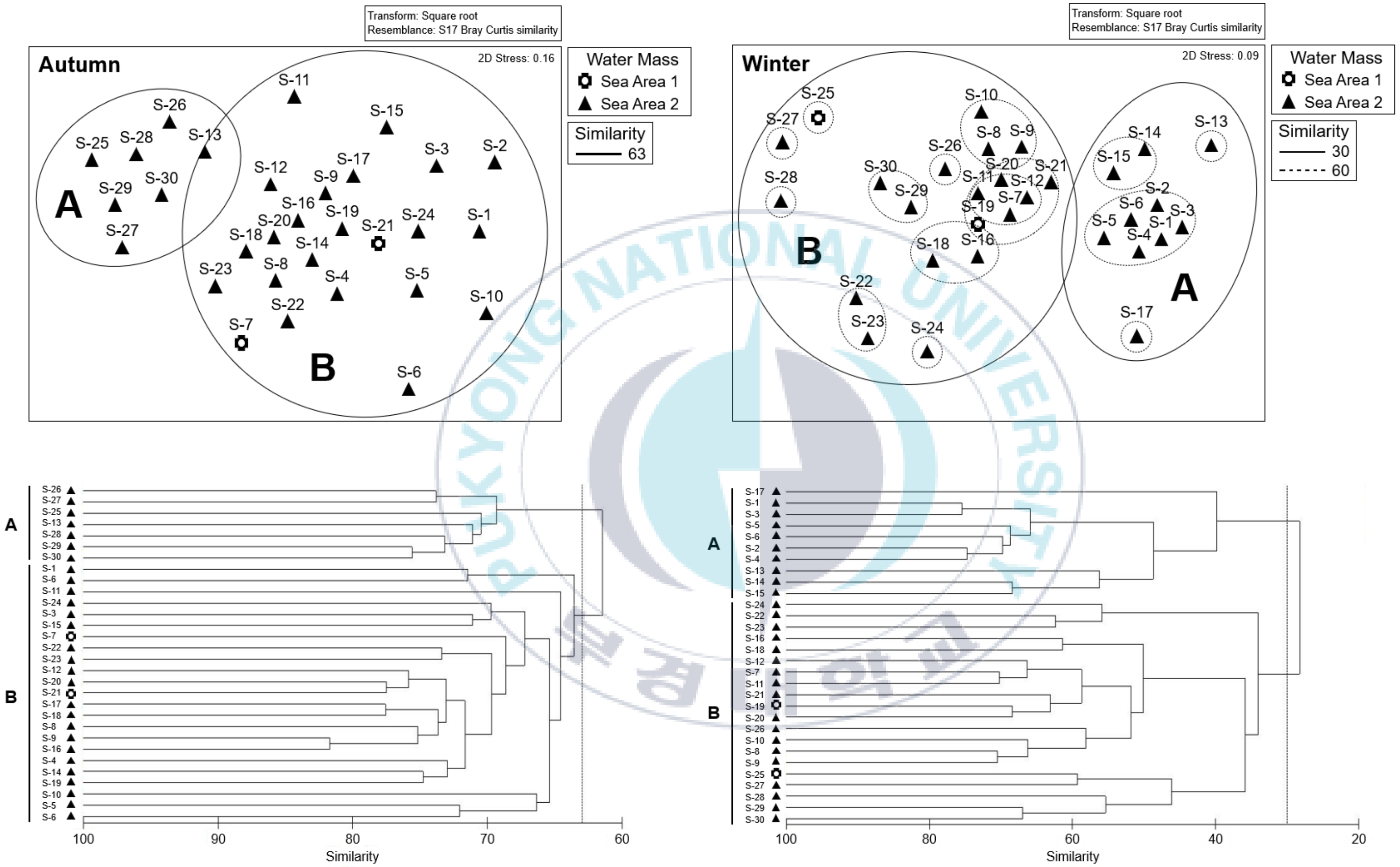

Figure 9. (Continued)

3.7. Seasonal changes in zooplankton composition

A total of 21 major zooplankton groups were found around Seogwipo in Jeju Island. Copepods were the dominant group in the zooplankton community, comprising 46.7% to 64.8% of the total zooplankton. Other groups varied from 20% and 0.6% (Figure 10).

The SIMPER analysis effectively revealed that five species predominantly contributed in two water mass areas during spring. Sea Area 1 was dominated by *P. parvus* s.l., *O. similis*, *D. affinis*, *O. venusta*, and *O. atlantica*, while Sea Area 2 by *P. parvus* s.l., *O. similis*, *D. affinis*, *O. atlantica*, and *C. sinicus*. The mean densities of all dominant species in Sea Area 1 ranged from 5 to 232 inds.m^{-3} (1.6% to 16.1%), whereas in Sea Area 2 from 5 to 109 inds.m^{-3} (2% to 22.1%) (Table 4).

In summer, Sea Area 1 was dominated by *P. parvus* s.l., *O. atlantica*, *O. similis*, *O. tenuis*, and *C. vanus*. Meanwhile, Sea Area 2 was dominated by *P. parvus* s.l., *O. venusta*, *O. atlantica*, *O. similis*, *O. tenuis*, and *U. vulgaris*. The dinoflagellate *N. scintillans* was also dominant in both water mass areas, whereas the chaetognath *F. enflata* was recorded in Sea Area 1. The mean densities of dominant species in Sea Area 1 ranged from 5 to 349 inds.m^{-3} (1.8% to 15.7%), while in Sea Area 2 from 7 to 302 inds.m^{-3} (1% to 13.8%) (Table 4).

In autumn, four species dominated each of the two water mass areas (*P. parvus* s.l., *O. fallax*, *O. venusta*, and *C. furcatus*). The mean densities of these dominant species ranged from 44 to 535 inds.m^{-3} (2.3% to 23.8%) in Sea Area 1 and from 52 to 563 inds.m^{-3} (2% to 24.6%) in Sea Area 2. In winter, Sea Area 1 was dominated by *P. parvus* s.l., *O. fallax*, *O. similis*, *O. venusta*, and *O. atlantica*, whereas Sea Area 2 by *P. parvus* s.l., *P. aculeatus*, *O. similis*, *O. atlantica*, *O. fallax*, *O. venusta*, and *C. furcatus*. Additionally, *N. scintillans* also abundantly occurred in both water mass areas. The mean densities of all dominant species ranged from 6 to 284 inds.m^{-3} (2.2% to 17.4%) in Sea Area 1 and from 9 to 251 inds.m^{-3} (1.8% to 27.4%) in Sea Area 2 (Table 4).

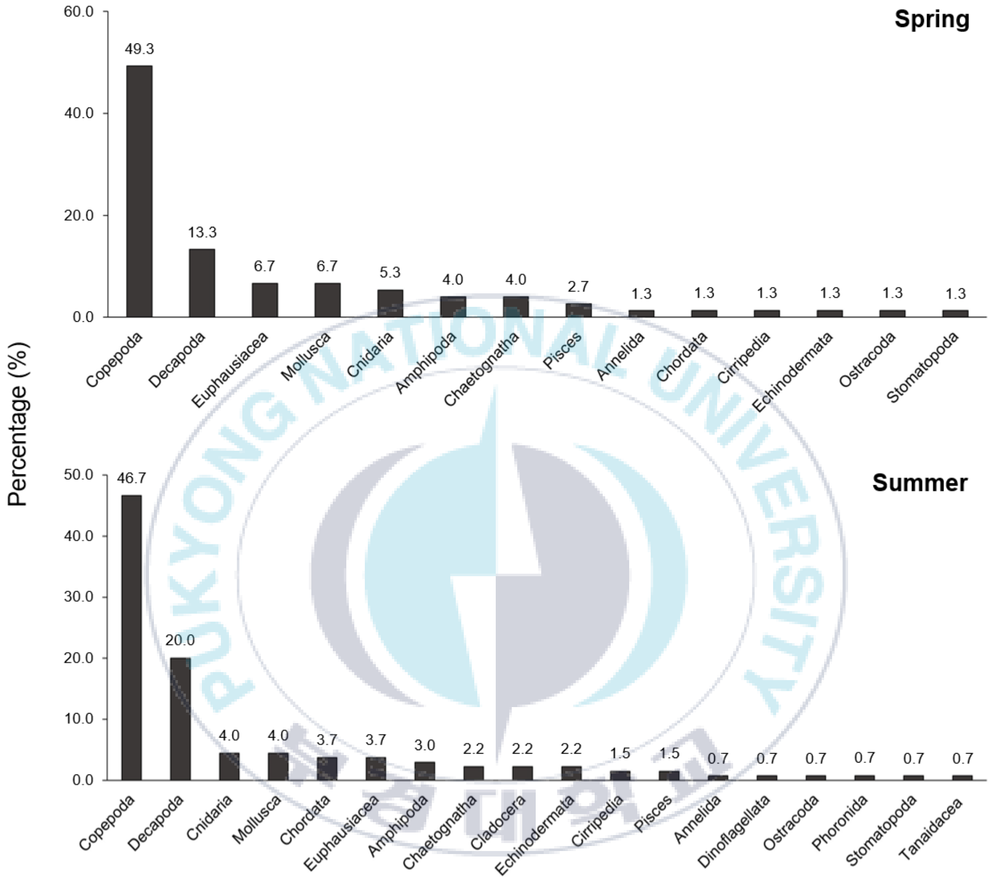

Figure 10. Seasonal changes in the relative proportion of zooplankton group (%) around Seogwipo, Jeju Island, Korea in May 2020 (spring), August 2020 (summer), November 2020 (autumn), and February 2021 (winter).

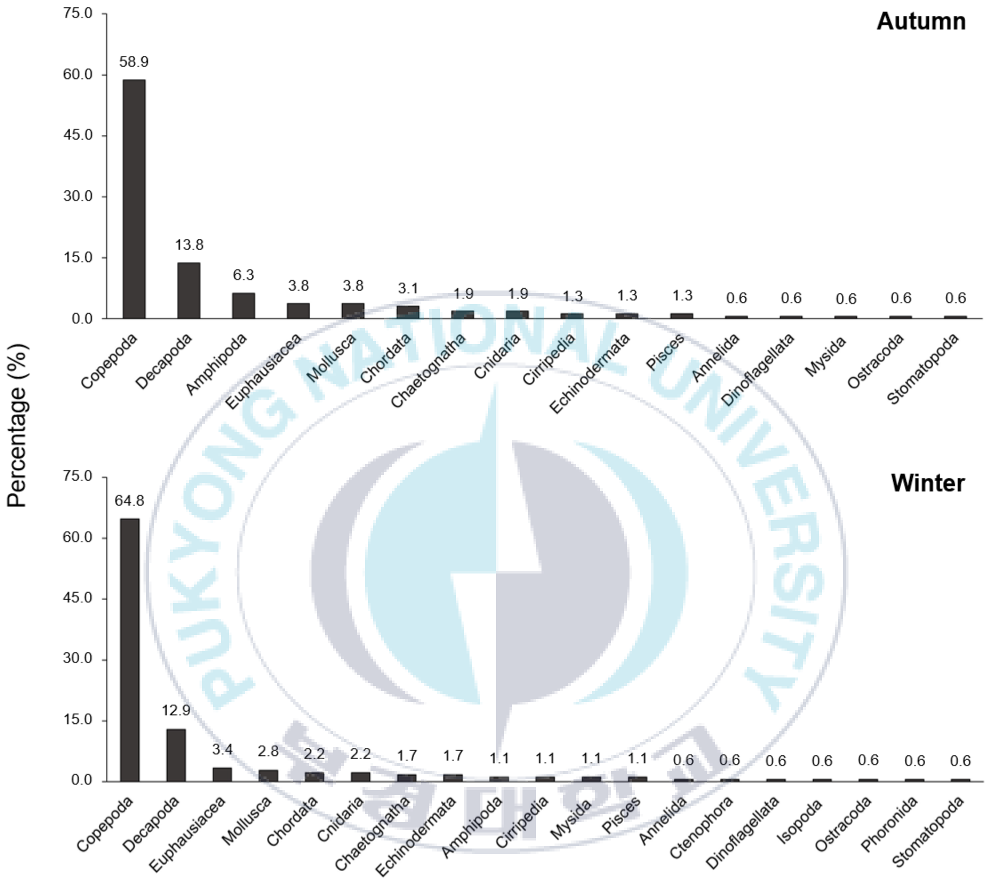

Figure 10. (Continued)

Table 4. Dominant zooplankton species by water mass around Seogwipo, Jeju Island, Korea in May 2020 (spring), August 2020 (summer), November 2020 (autumn), and February 2021 (winter).

Species by water mass	Mean density (inds.m^{-3})	Percentage of contribution (%)
Spring		
Sea Area 1		
Mean similarity: 37.4%		
Paracalanus parvus s.l.	232	16.1
Oithona similis	162	8.2
Ditrichocorycaeus affinis	19	6.5
Oncaea venusta	7	2.1
Oithona atlantica	5	1.6
Sea Area 2		
Mean similarity: 34.1%		
Paracalanus parvus s.l.	109	22.1
Oithona similis	95	10.2
Ditrichocorycaeus affinis	46	3.3
Oithona atlantica	8	2.0
Calanus sinicus	5	2.0
Summer		
Sea Area 1		
Mean similarity: 54.3%		
Noctiluca scintillans	349	15.7
Paracalanus parvus s.l.	124	6.8
Oithona atlantica	40	5.0
Oithona similis	31	5.0
Oithona tenuis	12	3.1
Flaccisagitta enflata	5	2.2
Ctenocalanus vanus	5	1.8
Sea Area 2		
Mean similarity: 61.2%		
Noctiluca scintillans	302	13.8
Paracalanus parvus s.l.	132	7.2
Oncaea venusta	46	5.6
Oithona atlantica	27	3.9
Oithona similis	24	2.7
Oithona tenuis	7	1.2
Undinula vulgaris	7	1.0

Table 4. (Continued)

Species by water mass	Mean density (inds.m^{-3})	Percentage of contribution (%)
Autumn		
Sea Area 1		
Mean similarity: 61.9%		
Paracalanus parvus s.l.	535	23.8
Oithona fallax	384	22.8
Oncaea venusta	125	2.6
Clausocalanus furcatus	44	2.3
Sea Area 2		
Mean similarity: 61.6%		
Paracalanus parvus s.l.	563	24.6
Oithona fallax	370	17.4
Oncaea venusta	127	4.4
Clausocalanus furcatus	52	2.0
Winter		
Sea Area 1		
Mean similarity: 43.2%		
Paracalanus parvus s.l.	284	17.4
Oithona fallax	37	5.9
Oithona similis	16	3.1
Oncaea venusta	7	2.7
Oithona atlantica	6	2.5
Noctiluca scintillans	6	2.2
Sea Area 2		
Mean similarity: 36.6%		
Paracalanus parvus s.l.	251	27.4
Paracalanus aculeatus	47	5.0
Oithona similis	41	4.8
Oithona atlantica	15	3.9
Oithona fallax	15	3.6
Noctiluca scintillans	11	2.2
Oncaea venusta	9	2.0
Clausocalanus furcatus	9	1.8

3.8. Seasonal occurrence of dominant zooplankton species

The dominant zooplankton species during this study represented small copepods (*P. parvus* s.l., *O. fallax*, *O. similis*, *D. affinis*, *O. atlantica*, *O. venusta*, *C. furcatus*, and *P. aculeatus*) along with the dinoflagellate *N. scintillans*. *P. parvus* s.l., *O. atlantica*, and *O. venusta* seasonally fluctuated with high mean density in autumn. The mean density of *O. fallax* also peaked in autumn but was absent in spring. *C. furcatus* did not occur in spring and summer, however, was found at its peak in autumn. *D. affinis* and *O. similis* were not recorded in autumn, but their highest mean densities were in spring. *P. aculeatus* was absent in spring but dominant in autumn and winter. *N. scintillans* did not appear in spring, however, dominated in summer (Figure 11).

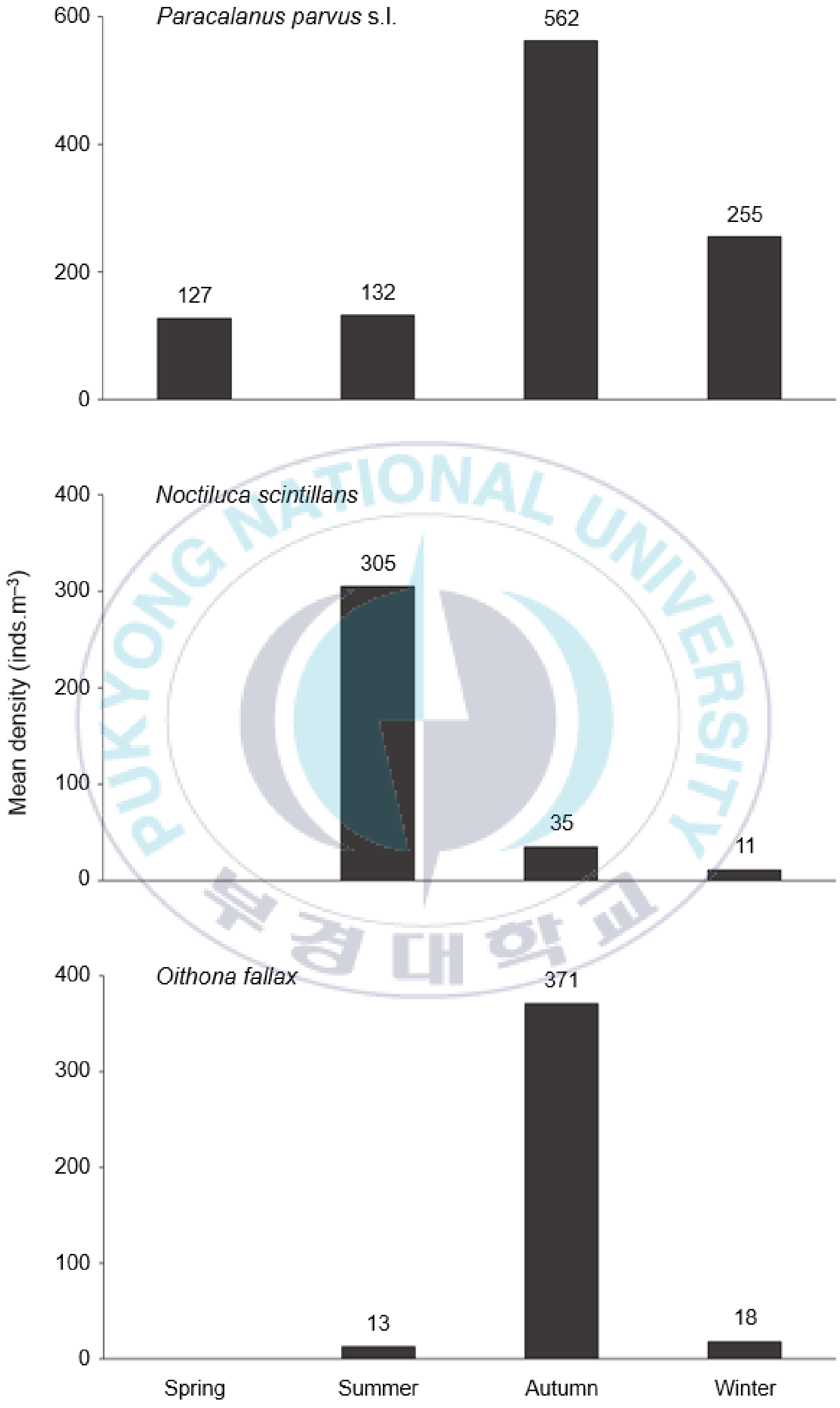

Figure 11. Seasonal variations in the occurrence of dominant zooplankton species around Seogwipo, Jeju Island, Korea in May 2020 (spring), August 2020 (summer), November 2020 (autumn), and February 2021 (winter).

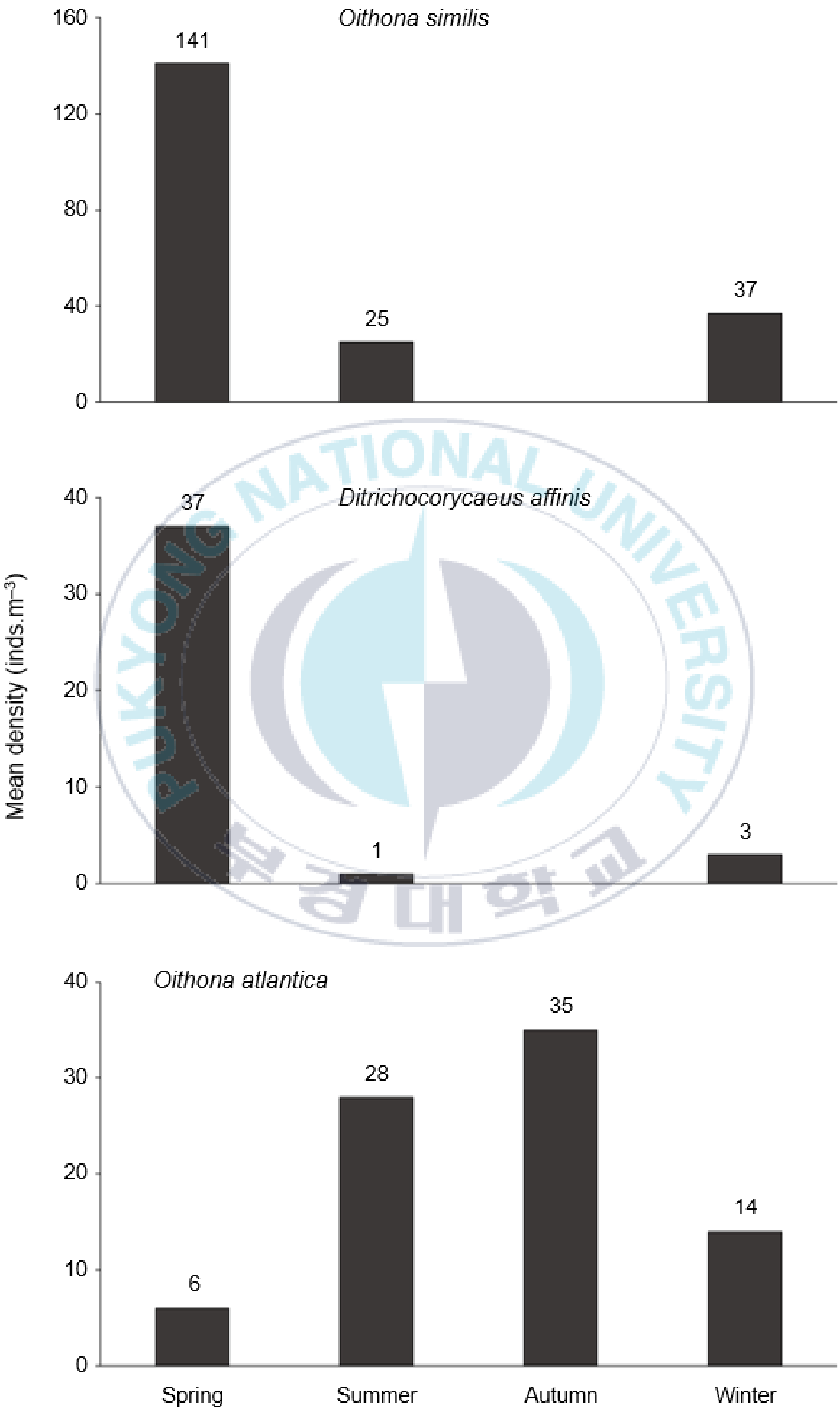

Figure 11. (Continued)

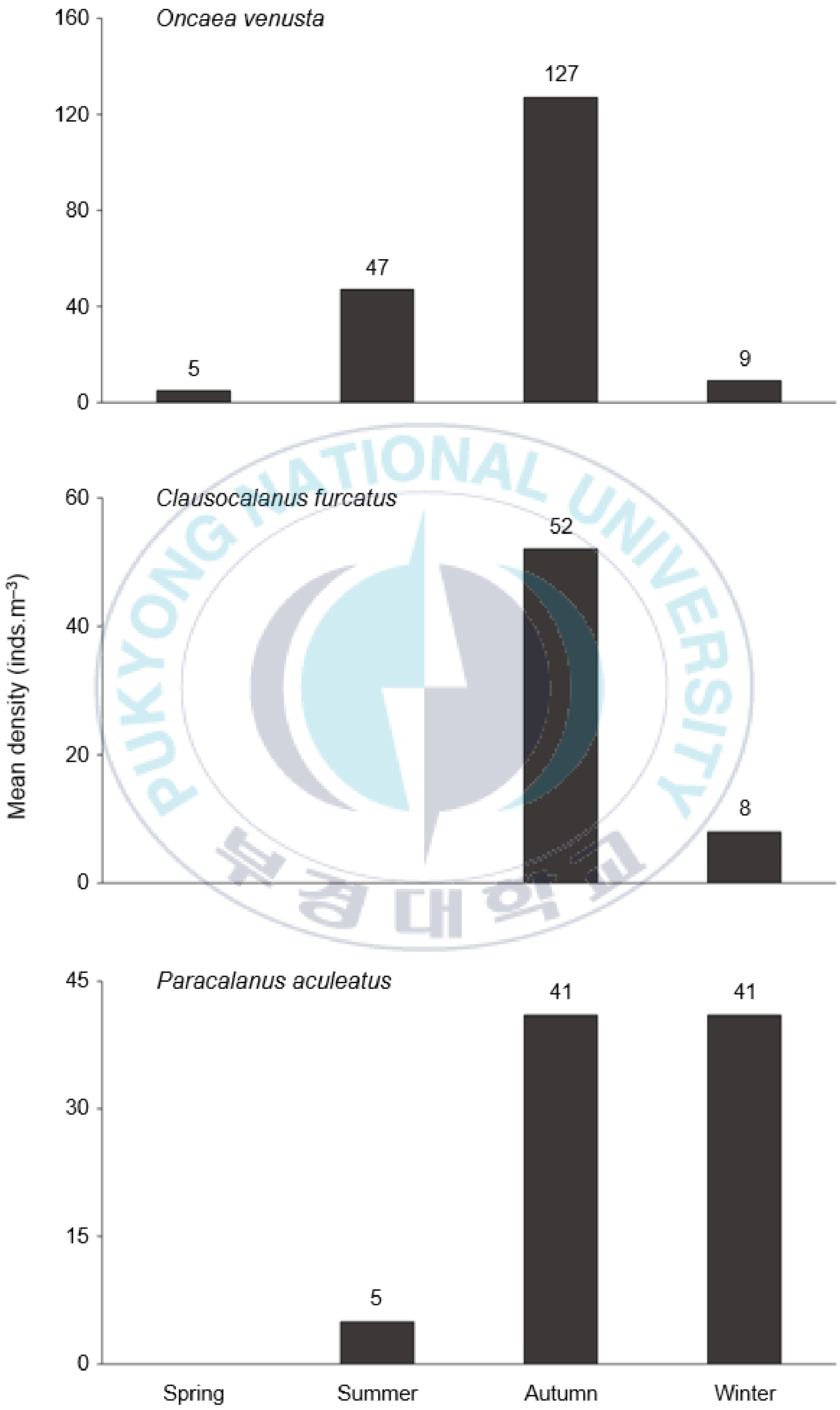

Figure 11. (Continued)

3.9. Relationship of environmental variables to zooplankton community

Redundancy analysis on the seasonal variations in densities of dominant zooplankton species revealed relationships with environmental variables. In spring, *O. similis* had a negative correlation with temperature and salinity. In summer, *O. atlantica* showed a negative correlation with salinity, whereas the opposite trend was demonstrated by *P. parvus* s.l. The dinoflagellate *N. scintillans* had a positive correlation with temperature, while *O. venusta*, *O. similis*, and *O. tenuis* showed opposite trends. In autumn, *O. fallax* was positively correlated with temperature, while *C. furcatus*, *O. venusta*, and *P. parvus* s.l. displayed negative correlations with salinity. In winter, *O. atlantica*, *O. similis*, *O. venusta*, and *P. aculeatus* had positive correlations with temperature, whereas *O. fallax* had an opposite trend. The opposite trend also with salinity was shown by *P. parvus* s.l. (Figure 12). Spring had the highest cumulative inertia value for the RDA components (16.4%), followed by summer (14.3%) and autumn (3.8%), and lowest in winter (2.9%) (Table 5).

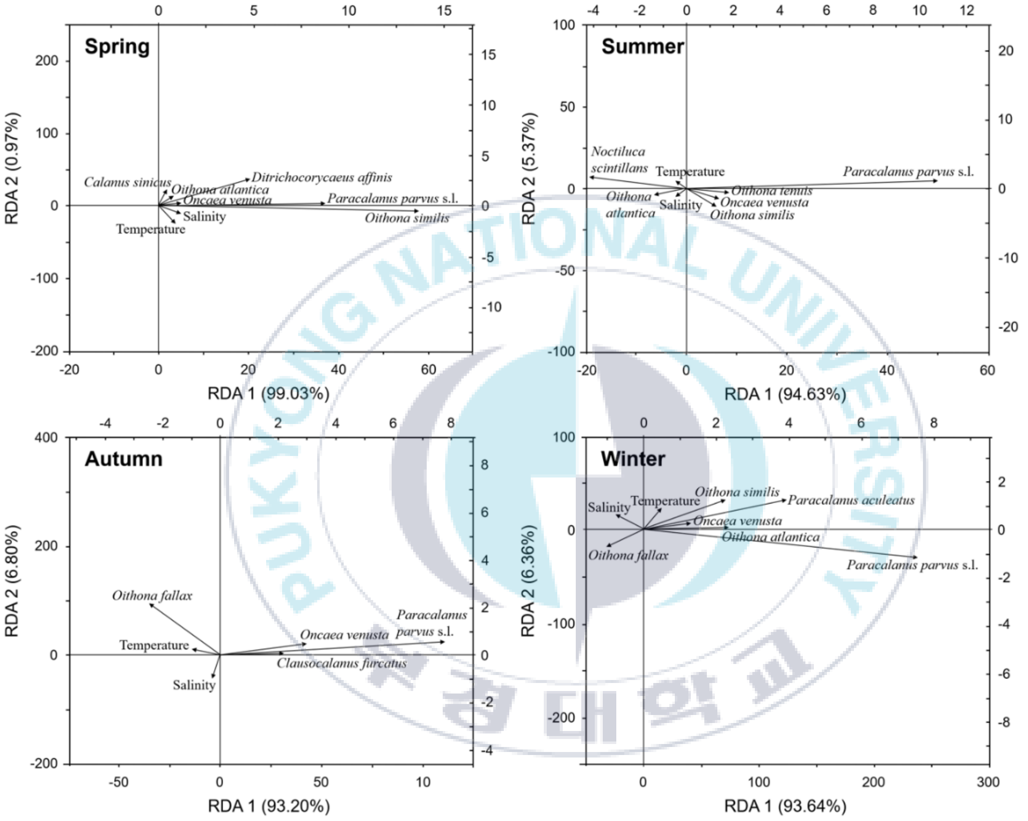

Figure 12. Biplot of redundancy analysis of the density of dominant zooplankton species according to temperature (°C) and salinity (psu) around Seogwipo, Jeju Island, Korea in May 2020 (spring), August 2020 (summer), November 2020 (autumn), and February 2021 (winter).

Table 5. Redundancy analysis of the density of dominant zooplankton species in relation to environmental variables around Seogwipo, Jeju Island, Korea in May 2020 (spring), August 2020 (summer), November 2020 (autumn), and February 2021 (winter).

Season	RDA	Eigenvalues	Inertia (%)	Cum. Inertia (%)
Spring	RDA 1	16,936	16.2	16.2
	RDA 2	166	0.2	16.4
Summer	RDA 1	5,400	13.5	13.5
	RDA 2	306	0.8	14.3
Autumn	RDA 1	5,523	3.5	3.5
	RDA 2	403	0.3	3.8
Winter	RDA 1	7,495	2.7	2.7
	RDA 2	509	0.2	2.9

4. Discussion

Zooplankton community is closely associated with water masses (Zuo et al., 2006; Pepin et al., 2011). This study indicated that the water mass around Seogwipo in Jeju Island could be divided into two water masses: (i) Sea Area 1 influenced by mixed waters from coastal areas; and (ii) Sea Area 2 predominantly affected by JWC. The presence of mixed water masses (Sea Area 1) between the dominant water masses (Sea Area 2) was also revealed, as illustrated by nMDS and cluster analysis. These multivariate approaches provided clear insights into the dynamics of the zooplankton community. These findings align with previous reports that mixed water masses often occur in transitional zones between distinct water masses (Zuo et al., 2006). The overlapping water masses detected by multivariate techniques may result from variations in environmental factors at each station, such as temperature, salinity, or depth, which also influence the zooplankton species distribution (Siokou-Frangou et al., 1998).

Marine zooplankton are ectothermic organisms with short generation times, implying that both seasonal and long-term environmental changes can affect their density (Richardson, 2008; Rombouts et al., 2009). The seasonal pattern of zooplankton density is characterized by a peak in spring and a low in winter (Shin et al., 2022). However, in this study, the highest density occurred in autumn. In water mass distribution, Sea Area 2 displayed higher diversity and density than Sea Area 1, likely due to the influence of the JWC.

Fluctuations in water temperature also affect the zooplankton density and species number (Bişinicu et al., 2023). Temperature changes lead to the simultaneous appearance of warm- and cold-water species, which subsequently increases species diversity (Batchelder et al., 2013). Rising sea surface temperatures drive shifts in zooplankton community toward warm-water species (Lewandowska et al., 2014). In warm conditions (>15°C), small copepods species dominated and adapted well (e.g., *P. parvus* s.l., *O. fallax*, *O. similis*, *D. affinis*, *O. atlantica*, *O. venusta*, *C. furcatus*, and *P. aculeatus*) (Morgan et al., 2003; Turner, 2004). Of the 91 warm-water species identified around Seogwipo, 53 were calanoid copepods. These groups are highly sensitive to water mass changes, with a stronger preference for warm temperatures and high salinities (Jang et al., 2012).

The small ocean calanoid *P. parvus* s.l. dominated in both water mass areas during spring, autumn, and winter, reflecting its adaptation to various environmental conditions. These findings validated previous records of the species' dominance in the neritic waters of the Korean Peninsula and the northern East China Sea, as well as its use as an indicator species for coastal waters expansion into open seas (Moon et al., 2010). The dinoflagellate *N. scintillans* was most abundant in summer, correlating with its adaptation to high temperature and lower salinity influenced by CDW (Tseng et al., 2011). Moreover, variations in dominant species density between stations and seasons correlated with environmental conditions, as confirmed by redundancy analysis.

5. Conclusion

The present study area was categorized into two water masses, revealing clear differences in zooplankton community patterns. The water mass with greater diversity, density, and distribution dominance was closely associated with JWC influence and was dominated by small ocean copepod species. All multivariate analyses applied produced coherent patterns in characterizing the zooplankton community and the influence of the water mass on its distribution.

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Appendix 1. Warm-water zooplankton species validated by previous studies around Seogwipo, Jeju Island, Korea in May 2020 (spring), August 2020 (summer), November 2020 (autumn), and February 2021 (winter).

Order	Family	Species	Authority by WoRMS (Walter and Boxshall, 2024)	References as warm-water species
Copepoda				
Calanoida	Acartiidae	*Acartia danae*	Giesbrecht, 1889	Shin et al., 2022
Calanoida	Acartiidae	*Acartia erythraea*	Giesbrecht, 1889	Yamazi, 1958
Calanoida	Acartiidae	*Acartia negligens*	Dana, 1849-1852	Shin et al., 2022
Calanoida	Acartiidae	*Acartia pacifica*	Steuer, 1915	Batten and Walne, 2011
Calanoida	Paracalanidae	*Calocalanus gracilis*	Tanaka, 1956	Hsieh et al., 2004
Calanoida	Paracalanidae	*Calocalanus pavo*	Dana, 1849-1852	Shin et al., 2022
Calanoida	Paracalanidae	*Calocalanus pavoninus*	Farran, 1936	Jang et al., 2012
Calanoida	Candaciidae	*Candacia bipinnata*	Giesbrecht, 1889	Shin et al., 2022
Calanoida	Candaciidae	*Candacia catula*	Giesbrecht, 1889	Kang and Hong, 1995
Calanoida	Candaciidae	*Candacia curta*	Dana, 1849-1852	Kang and Hong, 1995
Calanoida	Candaciidae	*Candacia pachydactyla*	Dana, 1849-1852	Yamazi, 1958
Calanoida	Calanidae	*Canthocalanus pauper*	Giesbrecht, 1888	Shin et al., 2022
Calanoida	Centropagidae	*Centropages furcatus*	Dana, 1849-1852	Shin et al., 2022
Calanoida	Centropagidae	*Centropages gracilis*	Dana, 1849-1852	Shin et al., 2022
Calanoida	Clausocalanidae	*Clausocalanus arcuicornis*	Dana, 1849-1852	Shin et al., 2022
Calanoida	Clausocalanidae	*Clausocalanus farrani*	Sewell, 1929	Shin et al., 2022
Calanoida	Clausocalanidae	*Clausocalanus furcatus*	Brady, 1883	Shin et al., 2022
Calanoida	Clausocalanidae	*Clausocalanus minor*	Sewell, 1929	Shin et al., 2022
Cyclopoida	Sapphirinidae	*Copilia mirabilis*	Dana, 1849-1852	Shin et al., 2022
Cyclopoida	Corycaeidae	*Corycaeus crassiusculus*	Dana, 1849-1852	Shin et al., 2022
Cyclopoida	Corycaeidae	*Corycaeus speciosus*	Dana, 1849-1852	Shin et al., 2022
Calanoida	Calanidae	*Cosmocalanus darwinii*	Lubbock, 1860	Shin et al., 2022
Calanoida	Clausocalanidae	*Ctenocalanus vanus*	Giesbrecht, 1888	Jang et al., 2012
Cyclopoida	Corycaeidae	*Ditrichocorycaeus dahli*	Tanaka, 1957	Shin et al., 2022
Cyclopoida	Corycaeidae	*Ditrichocorycaeus erythraeus*	Cleve, 1904	Hwang et al., 2006
Calanoida	Eucalanidae	*Eucalanus hyalinus*	Claus, 1866	Bradford-Grieve, 1994
Calanoida	Euchaetidae	*Euchaeta concinna*	Dana, 1849-1852	Shin et al., 2022
Calanoida	Euchaetidae	*Euchaeta indica*	Wolfenden, 1906	Shin et al., 2022
Calanoida	Euchaetidae	*Euchaeta longicornis*	Giesbrecht, 1888	Shin et al., 2022
Calanoida	Euchaetidae	*Euchaeta plana*	Mori, 1937	Shin et al., 2022
Calanoida	Euchaetidae	*Euchaeta rimana*	Bradford, 1974	Shin et al., 2022
Harpacticoida	Tachidiidae	*Euterpina acutifrons*	Dana, 1848	Hwang et al., 2006
Cyclopoida	Corycaeidae	*Farranula carinata*	Giesbrecht, 1891	Wi and Soh, 2013
Cyclopoida	Corycaeidae	*Farranula concinna*	Dana, 1849-1852	Hwang et al., 2006
Cyclopoida	Corycaeidae	*Farranula gibbula*	Giesbrecht, 1891	Shin et al., 2022
Harpacticoida	Peltidiidae	*Goniopsyllus rostratus*	Brady, 1883	Benedetti et al., 2016
Calanoida	Pontellidae	*Labidocera acuta*	Dana, 1849-1852	Shin et al., 2022
Calanoida	Pontellidae	*Labidocera minuta*	Giesbrecht, 1889	Jeong et al., 2009
Calanoida	Lucicutiidae	*Lucicutia clausi*	Giesbrecht, 1889	de Puelles, 2019
Calanoida	Lucicutiidae	*Lucicutia flavicornis*	Claus, 1863	Shin et al., 2022
Harpacticoida	Miraciidae	*Macrosetella gracilis*	Dana, 1848	Shin et al., 2022
Calanoida	Paracalanidae	*Mecynocera clausi*	Thompson, 1888	Shin et al., 2022
Harpacticoida	Ectinosomatidae	*Microsetella rosea*	Dana, 1847	Yamazi, 1958

Appendix 1. (Continued)

Order	Family	Species	Authority by WoRMS (Walter and Boxshall, 2024)	References as warm-water species
Copepoda				
Calanoida	Calanidae	*Nannocalanus minor*	Claus, 1863	Shin et al., 2022
Calanoida	Calanidae	*Neocalanus gracilis*	Dana, 1849-1852	Jang et al., 2012
Cyclopoida	Oithonidae	*Oithona fallax*	Farran, 1913	Jang et al., 2012
Cyclopoida	Oithonidae	*Oithona plumifera*	Baird, 1843	Shin et al., 2022
Cyclopoida	Oithonidae	*Oithona setigera*	Dana, 1853-1855	Shin et al., 2022
Cyclopoida	Oithonidae	*Oithona tenuis*	Rosendorn, 1917	Shin et al., 2022
Cyclopoida	Oncaeidae	*Oncaea clevei*	Früchtl, 1923	Shin et al., 2022
Cyclopoida	Oncaeidae	*Oncaea mediterranea*	Claus, 1863	Shin et al., 2022
Cyclopoida	Oncaeidae	*Oncaea venusta*	Philippi, 1843	Shin et al., 2022
Cyclopoida	Corycaeidae	*Onychocorycaeus agilis*	Dana, 1849-1852	Shin et al., 2022
Cyclopoida	Corycaeidae	*Onychocorycaeus catus*	Dahl, 1894	Shin et al., 2022
Cyclopoida	Corycaeidae	*Onychocorycaeus giesbechii*	Dahl, 1894	Shin et al., 2022
Cyclopoida	Corycaeidae	*Onychocorycaeus pacificus*	Dahl, 1894	Shin et al., 2022
Calanoida	Paracalanidae	*Paracalanus aculeatus*	Giesbrecht, 1888	Shin et al., 2022
Calanoida	Paracalanidae	*Paracalanus denudatus*	Sewell, 1929	Tanaka, 1960
Calanoida	Paracalanidae	*Paracalanus parvus* s.l.	Claus, 1863	Moon et al., 2010
Calanoida	Euchaetidae	*Paraeuchaeta russelli*	Farran, 1936	Shin et al., 2022
Calanoida	Eucalanidae	*Pareucalanus attenuatus*	Dana, 1849-1852	Shin et al., 2022
Calanoida	Metridinidae	*Pleuromamma abdominalis*	Lubbock, 1856	Shin et al., 2022
Calanoida	Metridinidae	*Pleuromamma gracilis*	Claus, 1863	Shin et al., 2022
Calanoida	Pontellidae	*Pontellina plumata*	Dana, 1849-1852	Jang et al., 2012
Calanoida	Rhincalanidae	*Rhincalanus cornutus*	Dana, 1849-1852	Shin et al., 2022
Calanoida	Rhincalanidae	*Rhincalanus nasutus*	Giesbrecht, 1888	Shin et al., 2022
Cyclopoida	Sapphirinidae	*Sapphirina darwinii*	Haeckel, 1864	Hwang et al., 2006
Cyclopoida	Sapphirinidae	*Sapphirina gemma*	Dana, 1849-1852	Yamazi, 1958
Cyclopoida	Sapphirinidae	*Sapphirina opalina*	Dana, 1853-1855	Yamazi, 1958
Calanoida	Scolecitrichidae	*Scolecithricella longispinosa*	Chen and Zhang, 1965	Shin et al., 2022
Calanoida	Scolecitrichidae	*Scolecithricella nicobarica*	Sewell, 1929	Shin et al., 2022
Calanoida	Scolecitrichidae	*Scolecithrix danae*	Lubbock, 1856	Shin et al., 2022
Calanoida	Eucalanidae	*Subeucalanus crassus*	Giesbrecht, 1888	Shin et al., 2022
Calanoida	Eucalanidae	*Subeucalanus mucronatus*	Giesbrecht, 1888	Shin et al., 2022
Calanoida	Eucalanidae	*Subeucalanus subcrassus*	Giesbrecht, 1888	Shin et al., 2022
Calanoida	Eucalanidae	*Subeucalanus subtenuis*	Giesbrecht, 1888	Shin et al., 2022
Calanoida	Temoridae	*Temora discaudata*	Giesbrecht, 1889	Shin et al., 2022
Calanoida	Temoridae	*Temora turbinata*	Dana, 1849-1852	Shin et al., 2022
Harpacticoida	Harpacticidae	*Tigriopus japonicus*	Mori, 1938	Han et al., 2018
Cyclopoida	Oncaeidae	*Triconia conifera*	Giesbrecht, 1891	Shin et al., 2022
Calanoida	Calanidae	*Undinula vulgaris*	Dana, 1849-1852	Shin et al., 2022
Non-Copepoda				
Ctenopoda	Sididae	*Penilia avirostris*	Dana, 1849	Rose et al., 2004
Onychopoda	Podonidae	*Pseudevadne tergestina*	Claus, 1877	Killi, 2020
Amphipoda	Hyperiidae	*Themisto japonica*	Bovallius, 1887	Havermans et al., 2019
Amphipoda	Hyperiidae	*Themisto pacifica*	Stebbing, 1888	Havermans et al., 2019
Aphragmophora	Sagittidae	*Aidanosagitta crassa*	Tokioka, 1938	Tokioka, 1974
Aphragmophora	Sagittidae	*Flaccisagitta enflata*	Grassi, 1881	Zhang and Xu, 2012
Aphragmophora	Sagittidae	*Serratosagitta pacifica*	Tokioka, 1940	Choo et al., 2022
Aphragmophora	Sagittidae	*Zonosagitta nagae*	Alvariño, 1967	Zhang and Xu, 2012
Doliolida	Doliolidae	*Doliolum denticulatum*	Quoy and Gaimard, 1834	Adam and Ishak, 2018
Noctilucales	Noctilucaceae	*Noctiluca scintillans*	Kofoid and Swezy, 1921	Ollevier et al., 2021

Appendix 2. Cold-water zooplankton species validated by previous studies around Seogwipo, Jeju Island, Korea in May 2020 (spring), August 2020 (summer), November 2020 (autumn), and February 2021 (winter).

Order	Family	Species	Authority by WoRMS (Walter and Boxshall, 2024)	References as cold-water species
Copepoda				
Calanoida	Acartiidae	*Acartia hudsonica*	Pinhey, 1926	Milligan et al., 2011
Calanoida	Acartiidae	*Acartia omorii*	Bradford, 1976	Shin et al., 2022
Calanoida	Calanidae	*Calanus sinicus*	Brodsky, 1965	Shin et al., 2022
Calanoida	Candaciidae	*Candacia discaudata*	Scott, 1909	Razouls et al., 2024
Cyclopoida	Corycaeidae	*Ditrichocorycaeus affinis*	McMurrich, 1916	Shin et al., 2022
Calanoida	Eucalanidae	*Eucalanus bungii*	Giesbrecht, 1893	Batten and Walne, 2011
Calanoida	Eucalanidae	*Eucalanus californicus*	Johnson, 1938	Shimode et al., 2012
Calanoida	Metridinidae	*Metridia pacifica*	Brodsky, 1950	Lee et al., 2019
Harpacticoida	Ectinosomatidae	*Microsetella norvegica*	Boeck, 1865	Svensen et al., 2018
Cyclopoida	Oithonidae	*Oithona atlantica*	Farran, 1908	Lee et al., 2019
Cyclopoida	Oithonidae	*Oithona similis*	Claus, 1866	Shin et al., 2022
Calanoida	Euchaetidae	*Paraeuchaeta elongata*	Esterly, 1913	Batten and Walne, 2011
Calanoida	Clausocalanidae	*Pseudocalanus minutus*	Krøyer, 1845	Persson et al., 2012
Calanoida	Scolecitrichidae	*Scolecithricella minor*	Brady, 1883	Morioka et al., 1997
Non-Copepoda				
Amphipoda	Phrosinidae	*Primno macropa*	Guérin-Méneville, 1836	Bowman, 1978

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