Ocean Science Journal, Vol. 43 No. 2, 67-79(2008)

Article

Ocean Science Journal
http://osj.kr

Spring Dominant Copepods and Their Distribution Pattern in the Yellow Sea

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Received 18 October 2007; Revised 12 December 2007; Accepted 17 March 2008

Abstract – We investigated the relationship between mesoscale spatial distribution of environmental parameters (temperature, salinity, and sigma–*t*), chlorophyll–*a* concentration and mesozooplankton in the Yellow Sea during May 1996, 1997, and 1998, with special reference to Yellow Sea Bottom Cold Water (YSBCW). Adult calanoid copepods, *Calanus sinicus*, *Paracalanus parvus* s.l., *Acartia omorii*, and *Centropages abdominalis* were isolated by BVSTEP analysis based on the consistent explainable percentage (-32.3%) of the total mesozooplankton distributional pattern. The copepods, which accounted for 60 to 87% of the total abundances, occupied 73-78% of the copepod community. The YSBCW consistently remained in the northern part of the study area and influenced the spatial distribution of the calanoid copepods during the study periods. Abundances of *C. sinicus* and *P. parvus* s.l., which were high outside the YSBCW, were positively correlated with the whole water average temperature ($p<0.01$). In contrast, the abundances of *C. abdominalis* and *A. omorii*, which were relatively high in the YSBCW, were associated with the integrated chl–*a* concentration based on factor analysis. These results indicate that the YSBCW influenced the mesoscale spatial heterogeneity of average temperature and integrated chl–*a* concentration through the water column. This consequently affected the spatial distribution pattern of the dominant copepods in association with their respective preferences for environmental and biological parameters in the Yellow Sea during spring.

Key words – Yellow Sea Bottom Cold Water (YSBCW), copepods, chlorophyll–*a*, mesozooplankton, Yellow Sea

1. Introduction

Abundances and distributional pattern of marine zooplankton are strongly influenced by hydrographic conditions where they exist (Wang *et al*. 2003). Warm water mass branching from the Kuroshio Current is limited to south of 34°N (Zhang 1995) and defined the spatial patterns of warm water zooplankton in the Yellow Sea. The distribution of tropical zooplankton such as *Sagitta enflata*, *Labidocera acuta*, and *Euchaeta marina* is limited to areas south of 34°N, whereas temperate species such as *Euphausia pacifica* and *Acartia bifilosa* (*A. hongi*) distribute in the area north of 34°N in spring (Zhang 1995).

From spring to late fall, the Yellow Sea Bottom Cold Water (YSBCW) originating from the cold winter water, with lower temperature (<10°C) and relatively higher salinity (>32 psu) than ambient waters, persists in the central area of the Yellow Sea (Lie 1984; Seung 1992). During the summer from July to August, the YSBCW played an important sheltering role for the adult *C. sinicus* from surface waters above their thermal limits in the central part of the southern Yellow Sea (Wang *et al*. 2003; Pu *et al*. 2004). Besides, the YSBCW causes horizontal mesoscale heterogeneity of average temperatures in the Yellow Sea in spring (Lie 1984; Jang and Kim 1998). Mesozooplankton, which shows maximum abundance from May to June (Kang and Lee 1991; Choi and Park 1993; Wang *et al*. 2003), is numerically dominated by copepods such as *A. omorii*, *C. abdominalis*, *C. sinicus*, *Paracalanus* sp., and *Oithona atlantica* (Sim *et al*. 1988; Hwang and Choi 1993; Jang and Kim 1998). However, the effect of YSBCW on the distribution of spring copepods has not been studied in the Yellow Sea. Many studies on zooplankton have concentrated on the seasonal occurrences relative to hydrological conditions (Kim and Lee 1994; Park 1997; Zhang *et al*. 2005), or day-night differences of some copepods (Morioka *et al*. 1991),

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or taxonomic studies of some coastal mesozooplankton (Kang *et al*. 1990) in the Yellow Sea. Thus, this study was designed to identify existence of YSBCW and its effect on the distributional pattern of mesozooplankton by investigating environmental conditions (temperature, salinity, sigma-*t*, and chl-*a* concentration) within the range of 32-37°N and 123-126°E. Here, we present two types of spatial distributional patterns in the dominant copepods and discuss the related environmental and biological factors in the Yellow Sea in spring.

2. Materials and Methods

Sampling and laboratory analysis

Data were collected during 3 cruises conducted in the Yellow Sea in spring (May) in 1996, 1997 and 1998. All cruises were carried out as part of the ISEEYS program (Integrated survey on Environment and Ecosystem of the Yellow Sea) supported by the Ministry of Science and Technology, undertaken aboard the R.V. “Eardo”. Stations for analysis of the spatial distribution in mesozooplankton and its related environmental factors are plotted on Figure 1. Surveyed area during 3 cruises was not identical due to research vessel’s schedule associated with changeable weather conditions. Thus, the stations covered partly (1996) or mostly (1997 and 1998) the area which cold waters with characteristics of the Yellow Sea Bottom Cold Water (YSBCW) defined by Seung (1992) existed.

Vertical profiles of temperature and salinity were obtained using a SBE 911plus CTD and the data were binned into 1 m depth. Water samples for chlorophyll-*a* (chl-*a*) analysis were taken at depths of 0, 10, 20, 30, 50 and 70m using a 10-L Niskin sampler, and then filtered through 47-mm Whatman GF/F filters under vacuum pressure less than 125 mmHg. The filters, which were kept frozen in deep freezer, were extracted in 90% acetone overnight at a temperature of 4°C. Chl-*a* concentration was fluorometrically determined using a Turner-designs 10-AU based on Parsons *et al*. (1984). Mesozooplankton were sampled with a standard type net (330 μm in mesh size, 0.6m in diameter) by vertical hauls from 5m above the bottom to the surface at a speed of 0.5-1 m s^{-1} without distinction of day and night. The full-depth towing through whole water column was carried out to avoid the day-night difference of zooplankton abundance caused by diel vertical migration while the cruise survey was performed through the large study area for several days. The samples were immediately preserved with borax-neutralized formalin to a final concentration of 5% (v/v). The collected zooplankton was identified and enumerated under a stereomicroscope (model SZ-ILA-LSGA) in a laboratory.

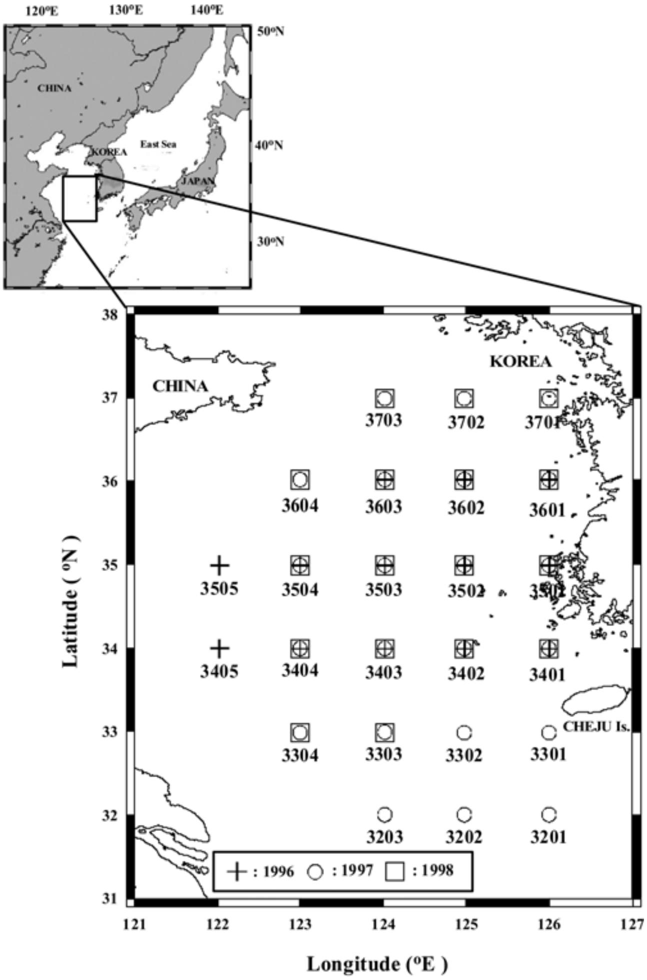

Fig. 1. Map showing the sampling stations in the research area; each symbol indicates the year investigated from 1996 to 1998. The numerals represent station numbers.

Data analysis

The representative species, which explain most of the entire distributional pattern in the mesozooplankton community, were chosen using the BVSTEP analysis program of PRIMER 5.2.8 computer package. The BVSTEP, based on the Spearman Rank correlation, finds the best additional variables which have effectively ‘explained’ all the biotic or abiotic structure by that combination of each variable when some threshold value of ρ reaches 0.95.

The relationship between the abundance of selected species and environmental parameters was analyzed by principal component analysis (PCA) based on correlation coefficients among parameters and by the linear regression analysis with the SPSS 10.0 statistical package. Temperature, salinity, sigma-*t* and chl-*a* concentration are considered as the possible controlling factors affecting the distributional pattern of the chosen species. Temperature, salinity and sigma-*t* are averaged through whole water column, and chl-*a* concentration was depth integrated, considering the sampled depth of mesozooplankton.

From spring to late fall, the cold water mass (YSBCW) originating from the cold winter water, with low temperature (<10°C) and relatively high salinity (>32psu), persists in the central area of the Yellow Sea (35-37°N and 123-126°E) and causes horizontal mesoscale heterogeneity of average temperatures in the Yellow Sea (Lie 1984; Jang and Kim 1998; Seung 1992). Thus, it is appropriate to consider the effect of YSBCW on the horizontal distribution of mesozooplankton on the basis of average temperature.

3. Results

Temperature and salinity (surface mixed and bottom layers)

The surface mixed layer is defined as a water column having temperature variation less than 1°C above thermocline depth, and the bottom layer was considered as the water column below the thermocline depth in this study. Salinity was also averaged based on the above definition of temperature.

The temperature in the surface mixed layer ranged between 11.61 and 16.33°C in 1996, 12.08 and 17.28°C in 1997, 12.14 and 15.55°C in 1998. Salinity in the surface mixed layer varied within the range of 31.59-33.67 psu in 1996, 31.18-33.65 psu in 1997, and 30.08-34.12 psu in 1998 (Fig. 2).

Temperature in the bottom layer ranged from 6.25-12.07°C in 1996, from 6.66-14.63°C in 1997, from 6.87-14.76°C in 1998. Salinity in the bottom layer varied within

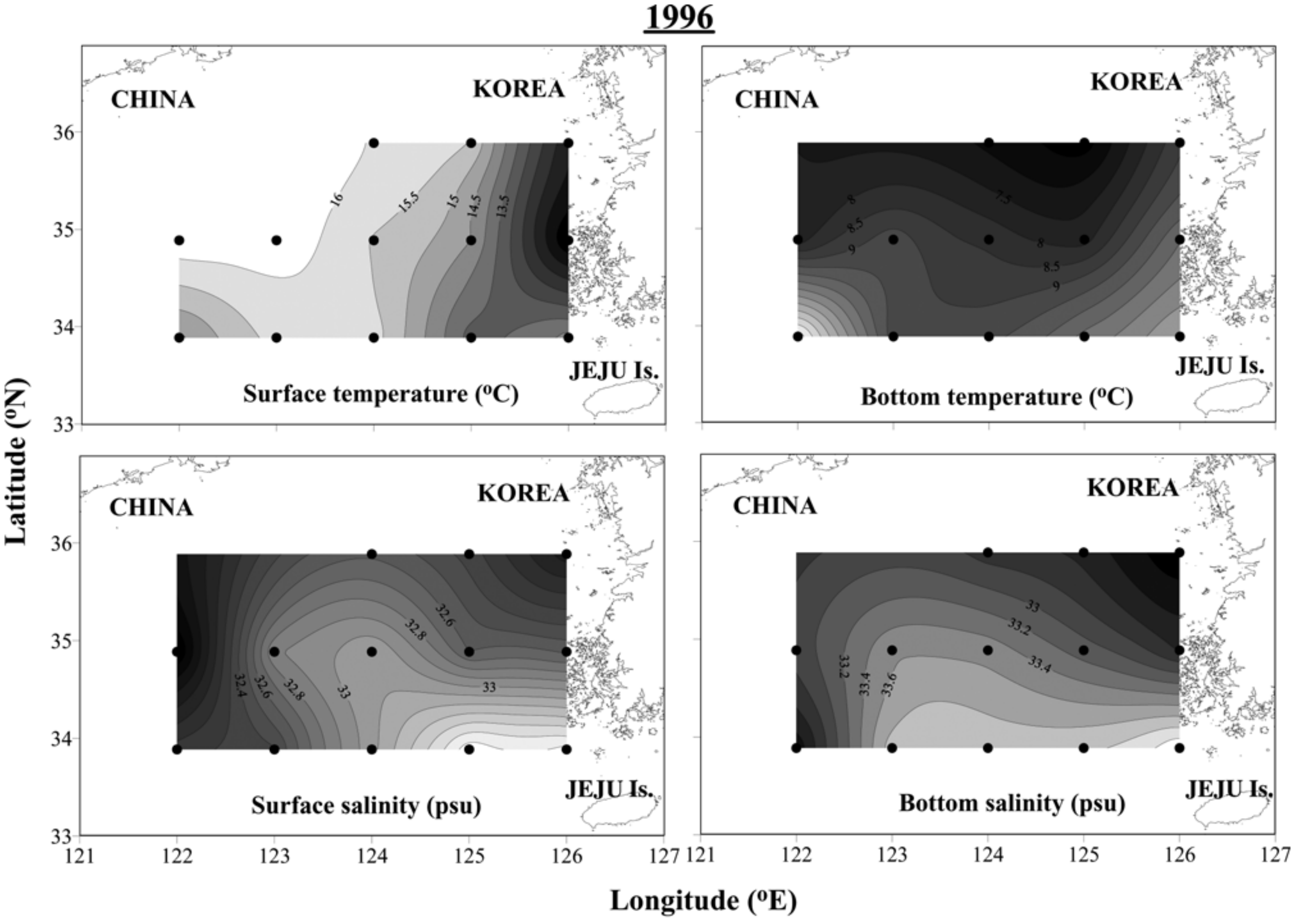

Fig. 2. Spatial distribution of average temperature and salinity in the surface mixed and bottom layers in the Yellow Sea in May 1996, 1997, and 1998.

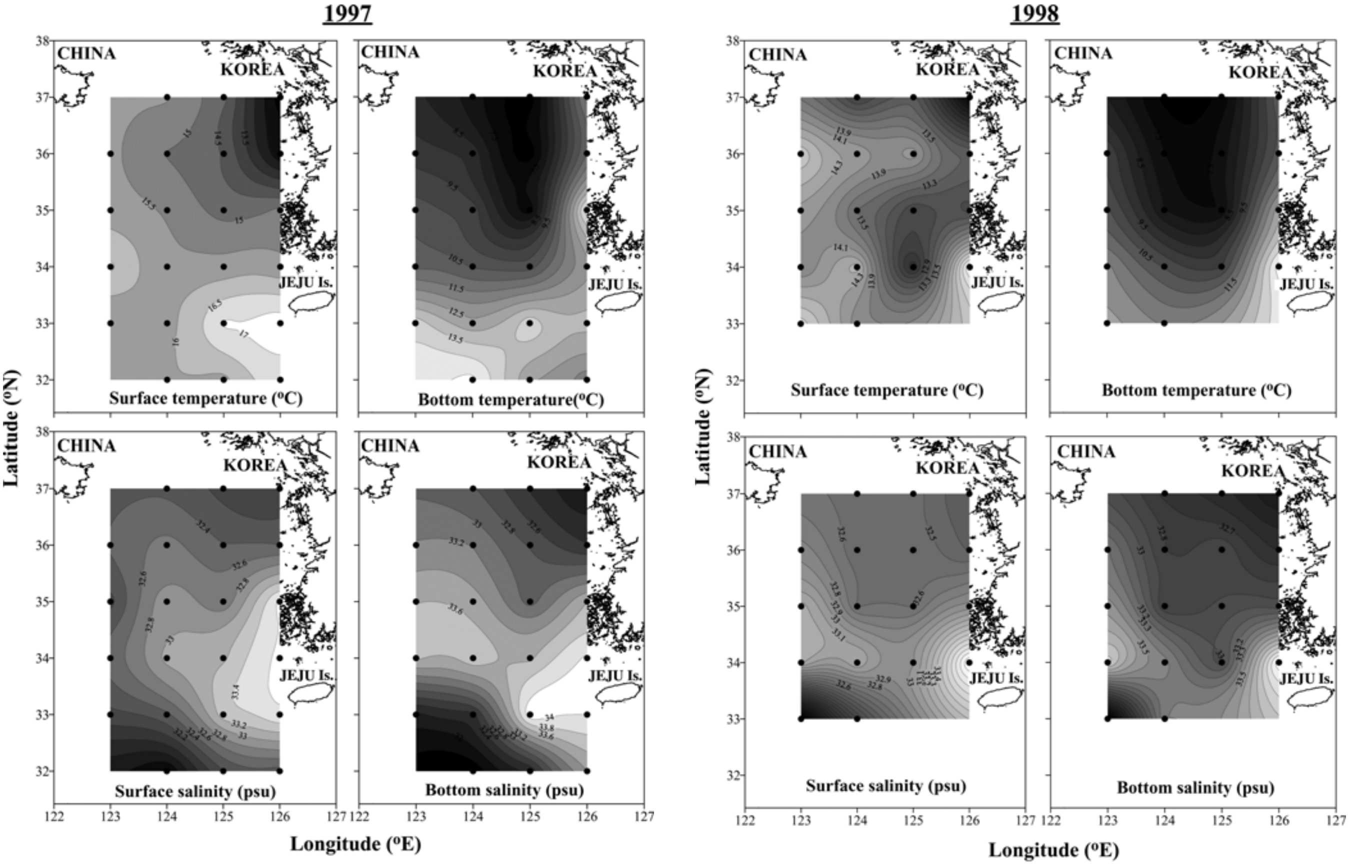

Fig. 2. (continued) Spatial distribution of average temperature and salinity in the surface mixed and bottom layers in the Yellow Sea in May 1996, 1997, and 1998.

the range of 32.25-34.37 psu in 1996, 31.66-34.15 psu in 1997, and 31.81-34.28 psu in 1998 (Fig. 2). The cold water mass (<10°C) existed in the bottom layer within the range of 34-36°N, 123-126°E in 1996, of 35-37°N, 123-125°E in 1997, of 34-37°N, 124-125°E in 1998 corresponding to the central area of the Yellow Sea, and it showed salinity higher than 32 psu during the study periods (Fig. 2).

Whole water averaged temperature and salinity

Spatial patterns in averaged temperature and salinity throughout the whole water column are shown in Fig. 3. The average temperature ranged from 8.1 to 14.4°C in 1996, and from 8.2 to 15.1°C in 1997 and 1998. The distributional pattern of average temperature was similar to that of bottom layer due to the relatively shallow thickness of surface mixed layer compared to the bottom layer. The thickness of surface mixed layer ranged from 5-15 m in 1996, 5-25 m in 1997, 8-35 m in 1998, corresponding to 8.7-18.3% of whole water depth in 1996, 13.2-29.8% in 1997, 12.2-43.2% in 1998. Accordingly, averaged temperature through whole water column was mostly dependent on the averaged temperature in the bottom layer during the study periods (Fig. 3). Average seawater temperatures of -10°C were found within the range of 35-37°N and 124-125°E, where the YSBCW distributed between 6.3 and 9.3°C in 1996, 6.6 and 9.2°C in 1997, and from 6.9 to 8.0°C in 1998, based on bottom temperature. Average temperatures higher than 10°C were distributed outside the range where the cold-waters distributed during the study periods (Fig. 3). The distinctive shape of the cold water mass (-10°C) associated with the YSBCW affected the mesoscale distribution of average temperature, leading to relatively low temperatures north of 34°N and higher temperatures south of 34°N. The spatial distributional pattern of present study could be characterized by existence of the YSBCW in the Yellow Sea in spring. In contrast, relatively high temperatures south of 34°N were attributable to the warm waters originating from the Kuroshio Current.

However, spatial distribution pattern of average salinity differed from that of the average temperature during the

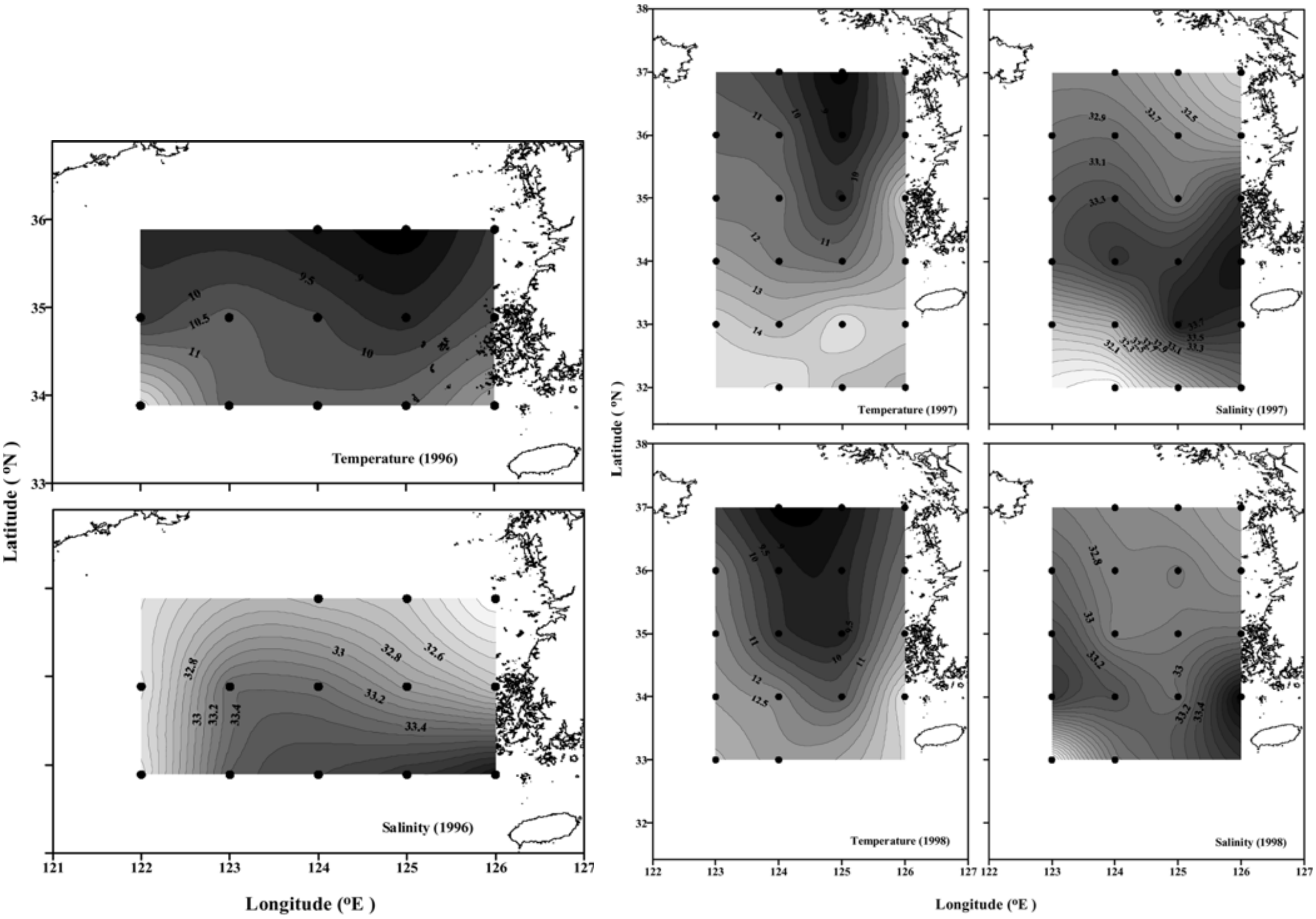

Fig. 3. Spatial distribution of average temperature (°C) and salinity (psu) through whole water column in the Yellow Sea in May 1996, 1997, and 1998.

study periods. More saline water was mainly distributed in the southern part of the study area by the intrusion of waters branching from the Kuroshio Current (Fig. 3). Average salinity gradually decreased from south to north along the coastal waters of China and Korea, while water mass higher than 32 psu was found in the area where the YSBCW existed. The average salinity through the water column ranged from 32.3 to 34.2 psu in 1996, 31.5 to 33.9 psu in 1997, and 31.3 to 34.2 psu in 1998 (Fig. 3).

Hydrography, chl-*a*, and copepods

Mesozooplankton were compared with average seawater temperature, salinity, and depth integrated chl-*a* concentration. From the mesozooplankton community, the copepods *Calanus sinicus*, *Paracalanus parvus* s.l., *Acartia omorii*, *Centropages abdominalis*, and the heterotrophic dinoflagellate *Noctiluca scintillans* were first isolated by BVSTEP analysis based on the consistent explainable percentage (-34.7%) of the total mesozooplankton distributional pattern (Table 1). The four copepods were widely distributed and represented 73-78% of the copepod abundance and 60-87% of total mesozooplankton abundance during the study periods. Even though the percentage of *N. scintillans* was high, with abundances between 3,398 and 5,304 inds. m^{-3}, the relationship of the species with the YSBCW was not considered because its occurrence was mainly limited to coastal waters in the northern part from 1996 to 1998.

The spatial distributions of the four copepods could be summarized into two types in relation to the whole water average temperature and integrated chl-*a* concentration (Figs. 4 and 5). From the viewpoint of average temperatures below 10°C, the YSBCW prevailed in the northern part within 124-125°E and 35-37°N during the study periods (Fig. 4). Abundances of *C. sinicus* and *P. parvus* s.l. were relatively low in the northern part affected by the YSBCW, but relatively high in the warm waters (>10°C) south of

Table 1. The smallest possible subsets of species, which explained most of the distributional pattern in the mesozooplankton community, were collected in May 1996, 1997, and 1998.

Species name	1996	1997	1998
Noctiluca scintillans	*(34.7%)	*(4.6%)	*(34.7%)
Calanus sinicus	*(17.1%)	*(9.2%)	*(17.1%)
Paracalanus parvus s.l.	*(10.5%)	*(11.5%)	*(10.5%)
Centropages abdominalis	*(7.9%)	*(10.3%)	*(7.9%)
Acartia omorii	*(9.7%)	*(32.3%)	*(9.7%)
Acartia bifilosa (=*A. hongi*)	*(0.9%)	*(8.9%)	*(0.9%)
Corycaeus affinis	*(2.0%)	*(4.9%)	*(2.0%)
Oithona atlantica	*(7.3%)	*(4.2%)	*(7.3%)
Euphausiids	-	*(<1%)	-
Mysids juvenile	-	-	*(<1%)
Amphipods	*(<1%)	-	*(<1%)
Appendicularians	*(<1%)	-	-
Chaetognaths	*(<1%)	*(<1%)	-
Siphonophores	-	*(<1%)	-
Ophiopluteus	-	-	*(<1%)
ρ	0.957	0.953	0.952
$\Delta\rho$	<0.001	<0.001	<0.001
Relative abundance (%)	93.1	88.9	94.1

*indicates species selected to explain the distributional pattern
Number in parentheses means relative abundance of the species

35°N from 1996 to 1998 (Fig. 4). In contrast, abundances of *C. abdominalis* and *A. omorii* were relatively high in the cold waters and low outside the cold waters during the study periods (Fig. 4).

The higher concentration of chl-*a* consistently occurred in the northern part associated with the YSBCW from 1996 to 1998 (Fig. 5). The averaged chl-*a* concentrations at stations north of 35°N were 50.8±14.6 mg m^{-2} in 1996, 38.6±30.2 mg m^{-2} in 1997, and 94.7±87.7 mg m^{-2} in 1998. And, they were 31.6±13.4 mg m^{-2} in 1996, 25.5±11.9 mg m^{-2} in 1997, and 52.0±5.4 mg m^{-2} in 1998 at stations south of 35°N. In 1998, remarkably high chl-*a* concentration was observed in the northern coastal stations (3601 and 3701) corresponding to the boundary between the YSBCW-related stratified waters and coastal waters, with an exceptionally high concentration of 315 mg m^{-2} and 198 mg m^{-2}, respectively. Generally, frontal area where different water masses meet shows high production of phytoplankton leading to high concentration of chl-*a*. The high abundances of *A. omorii* and *C. abdominalis*, which showed close relationship with the cold waters, occurred mostly in the northern part with high chl–*a* concentrations (Fig. 5).

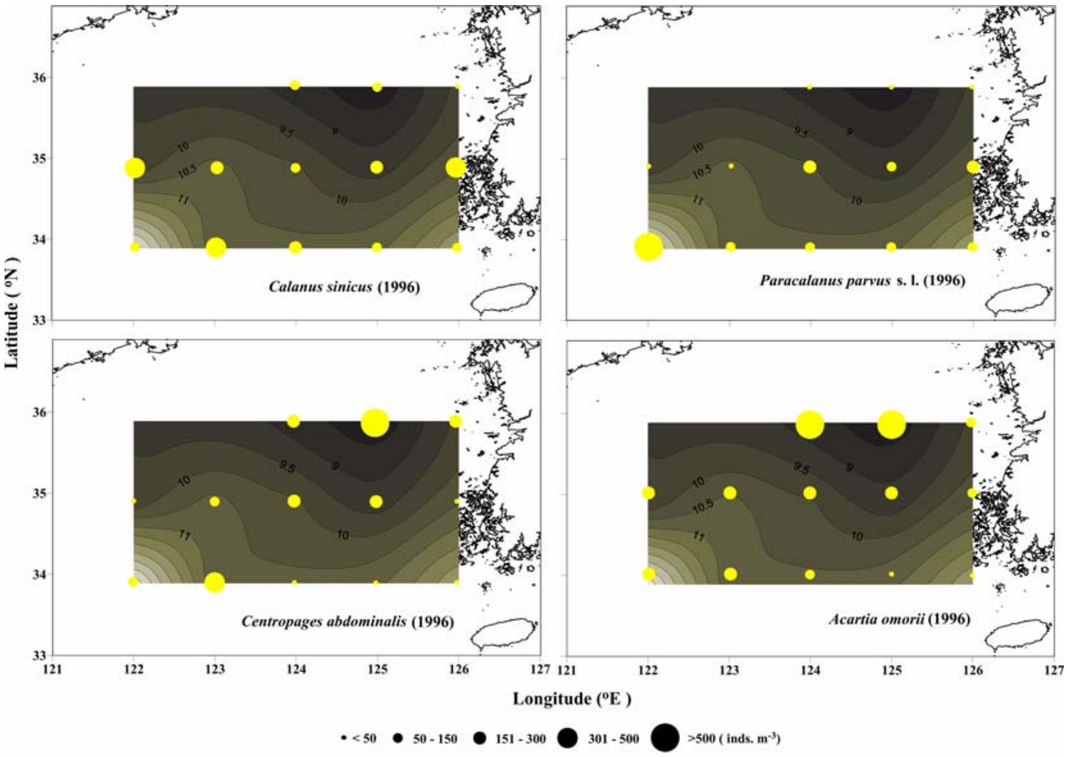

Fig. 4. Spatial distribution in the abundances of *Calanus sinicus, Paracalanus parvus* s.l., *Centropages abdominalis*, and *Acartia omorii* overlaid on the contour of average temperature (°C) in the Yellow Sea in May 1996, 1997, and 1998.

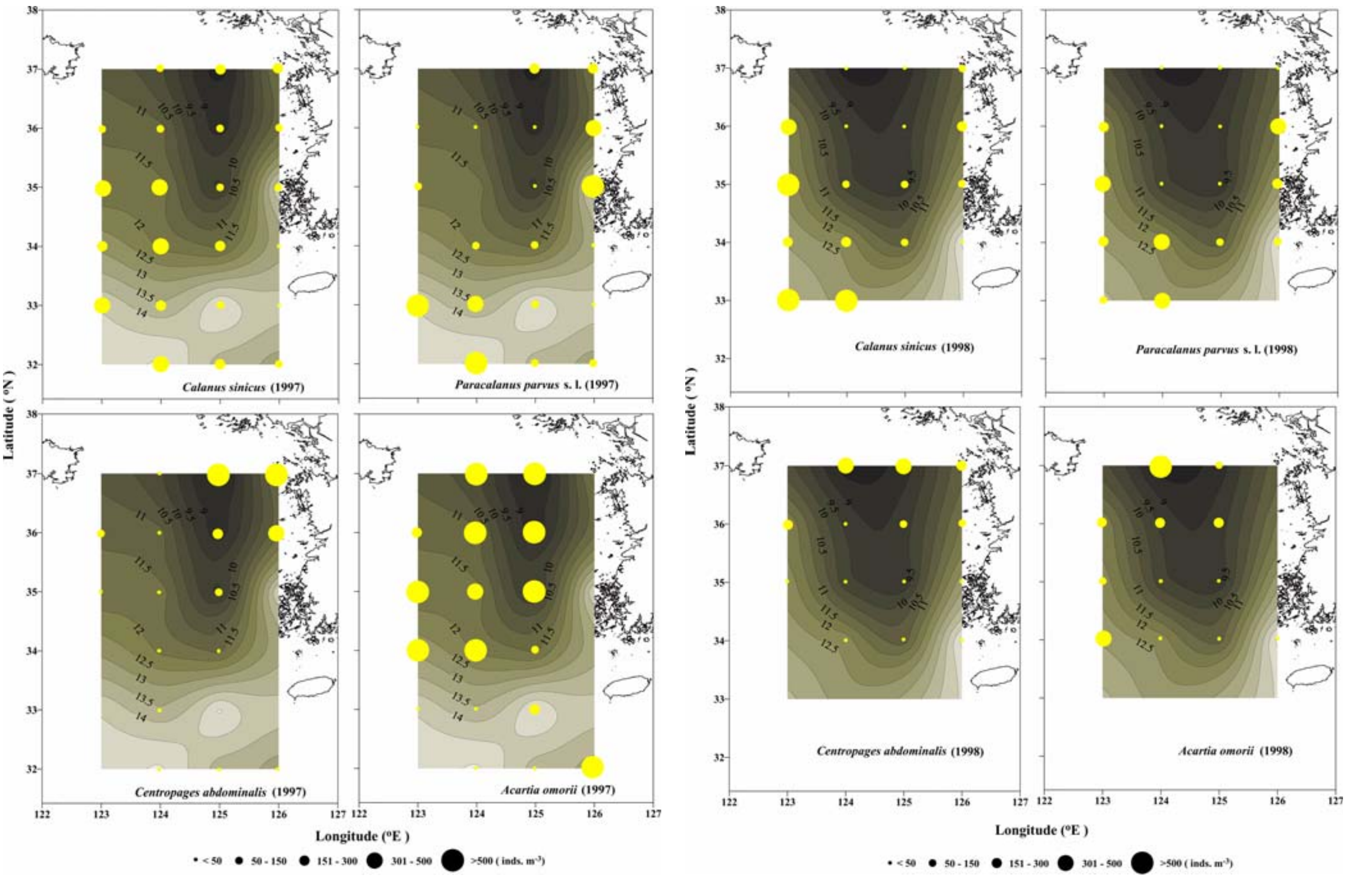

Fig. 4. (continued) Spatial distribution in the abundances of *Calanus sinicus, Paracalanus parvus* s.l., *Centropages abdominalis*, and *Acartia omorii* overlaid on the contour of average temperature (°C) in the Yellow Sea in May 1996, 1997, and 1998.

Copepods and environmental associations

Factor analysis was used to determine the biological and environmental parameters that showed a high degree of correlation with the spatial distributions of dominant copepods. Based on the correlations, two types of copepods were associated with average temperature and depth integrated chl-*a* concentration (Fig. 6).

In May 1996, the first principal component (Z_1) explained 40.7% of the variation in dominant copepods, which included *C. abdominalis* and *A. omorii*, and indicated high positive factor loading for average sigma-*t*, average salinity, and integrated chl-*a*, and negative factor loading for average temperature. In contrast, the second principal component (Z_2), which explained 29.1% of the variation in dominant copepods, showed positive factor loading for average sigma-*t* and *C. sinicus*. In the distribution of the factor loadings of Z_1 and Z_2 illustrated in a scatter diagram, dominant copepods could be classified into two association types: copepods whose abundance was associated with average temperature (type I), and species whose abundance was related to chl-*a* (type II; Fig. 6).

In May 1997, the first principal component (Z_1) explained 38.9% of the variation in dominant copepods, which included *C. abdominalis* and *A. omorii*, and indicated high positive factor loading for average sigma-*t*, average salinity, and integrated chl-*a* and negative factor loading for average temperature. In contrast, the second principal component (Z_2), which explained 22.6% of the variation in dominant copepods, showed low positive factor loading for integrated chl-*a*, *C. sinicus*, and *P. parvus* s.l. In the distribution of the factor loading of Z_1 and Z_2 illustrated in a scatter diagram, dominant copepods could be classified into two association types, which were similar to the types of May 1996 (Fig. 6).

In May 1998, the first principal component (Z_1) explained 33.9% of the variation in dominant copepods, which included *C. abdominalis* and *A. omorii*, and indicated high positive factor loading for average sigma-*t*, and average salinity, and a negative factor loading for average temperature.

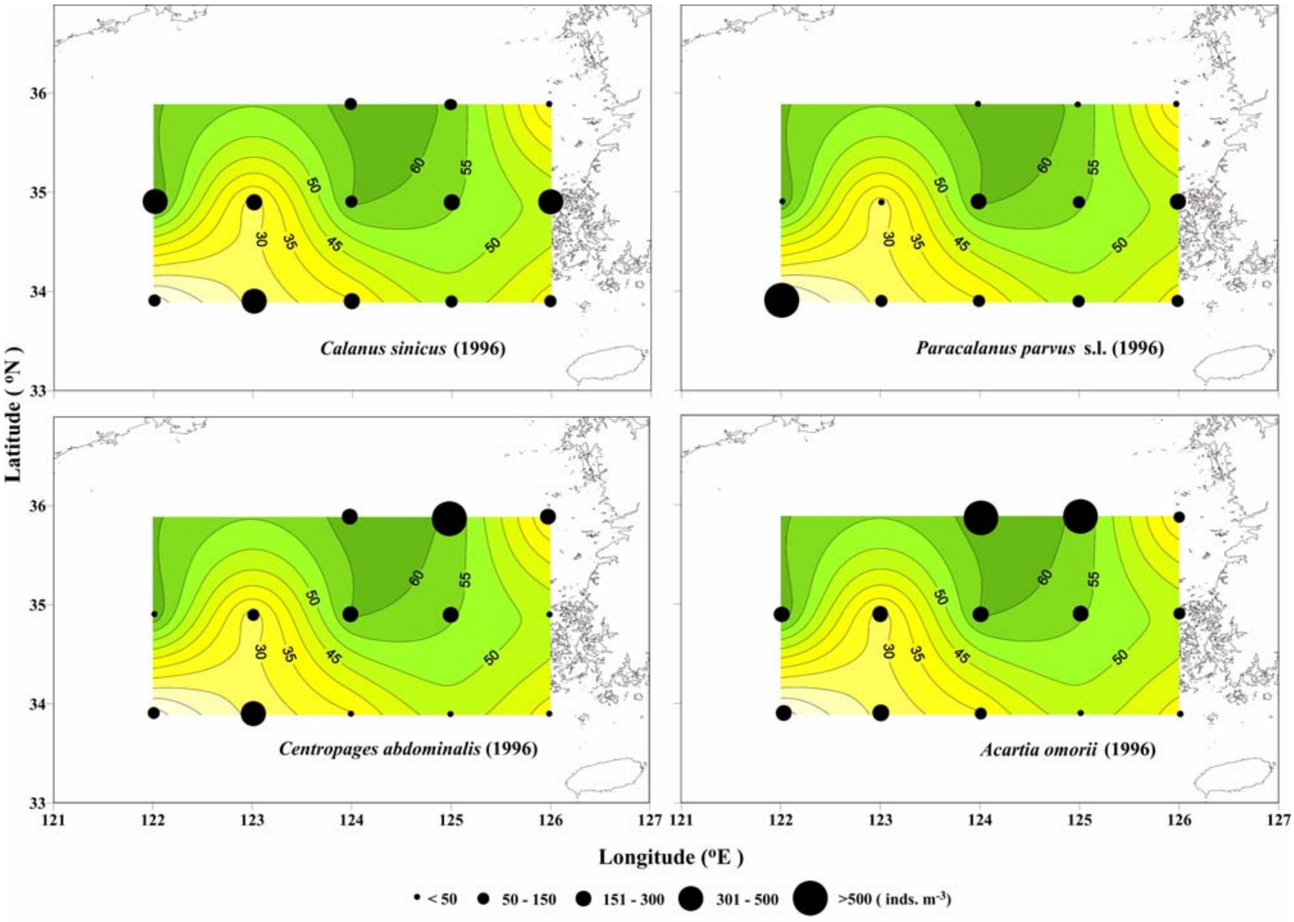

Fig. 5. Spatial distribution of *Calanus sinicus, Paracalanus parvus* s.l., *Centropages abdominalis*, and *Acartia omorii* overlaid on the contour of integrated chl-*a* (mg m^{-2}) in the Yellow Sea in May 1996, 1997, and 1998.

In contrast, the second principal component (Z_2), which explained 25.1% of the variation in dominant copepods, showed positive factor loading for average temperature, average salinity, *C. sinicus*, and *P. parvus* s.l.. The distribution of the factor loading for Z_1 and Z_2 illustrated in a scatter diagram coincided with those in 1996 and 1997 (Fig. 6).

4. Discussion

This is the first quantitative study on adult copepods in relation to the YSBCW located in the offshore waters of the Yellow Sea in spring. Previous studies of zooplankton dynamics in the Yellow Sea have mostly concentrated on the seasonal occurrence of mesozooplankton in coastal waters (Sim 1988; Kang and Lee 1991; Choi and Park 1993; Hwang and Choi 1993; Park 1997; Wang *et al*. 2003), diel vertical migration of *C. sinicus* in offshore waters (Morioka *et al*. 1991) and spatial heterogeneity of mesozooplankton in relation to warm current intrusion and across the frontal structure (Zhang 1995; Liu *et al*. 2003).

The YSBCW consistently persists in the central part of the Yellow Sea from early spring to autumn (Lie 1984). In summer, the YSBCW played a sheltering role for *C. sinicus* to avoid warm surface waters above their thermal range in the southern Yellow Sea. Accordingly, a high abundance of adult *C. sinicus* occurred in the area of YSCBW (<12°C) (Wang *et al*. 2003). Results of present study conducted in spring suggest that the YSBCW likely plays a seasonally different role in the spatial distribution of copepods. Spring-dominant copepods consistently showed two types of mesoscale distributional patterns; *C. sinicus* and *P. parvus* s.l. were positively correlated with average temperature, and *C. abdominalis* and *A. omorii* were associated with integrated chl-*a* concentration from 1996 to 1998 based on factor analysis. The distributional pattern of the copepods may have been affected by the existing YSBCW, which formed

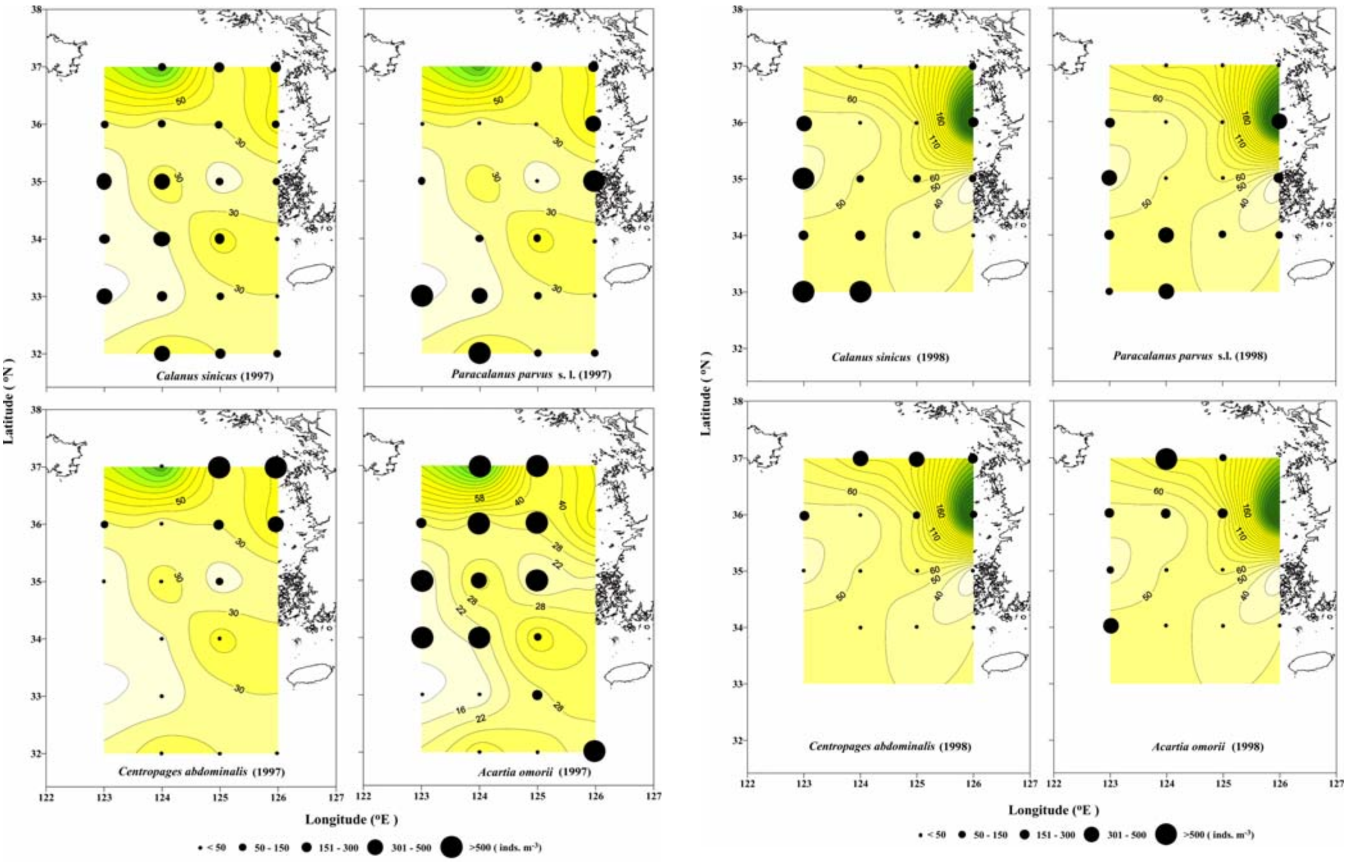

Fig. 5. (continued) Spatial distribution of *Calanus sinicus, Paracalanus parvus* s.l., *Centropages abdominalis*, and *Acartia omorii* overlaid on the contour of integrated chl-*a* (mg m^{-2}) in the Yellow Sea in May 1996, 1997, and 1998.

mesoscale spatial gradients of the average temperature and integrated chl-*a* concentration.

Copepod distributions are shaped not only by the physicochemical parameters but also by their reactions and adaptation to the ecosystem that they inhabit and in which they are evolving (Mauchline 1998). In temperate seas, temperature and food availability mainly govern the growth and productivity of marine copepods (Klein Breteler and Schogt 1994). Moreover, food saturation rates differ at various temperature levels (Hirst and Bunker 2003). Species-specific distributions that we observed in this study may have resulted from the responses of the copepods to the relative importance of temperature and food availability. Changes in resource availability due to the effects of temperature on food quantity or quality may also alter their responses *in situ* through the variation in developmental times and growth.

During the study periods, both surface and bottom temperature may have fallen into the favorable ranges for *C. abdominalis* and *A. omorii*, considering their occurrence in a wide range between 8.9 and 21.1°C, and between 4.0 and 25.0°C in the Yellow Sea and the Inland Sea of Japan, respectively (Park *et al*. 1990; Yoo *et al*. 1991; Liang and Uye 1996a; Liang *et al*. 1996; Table 2). Under these circumstances, food availability is suggested to be of greater importance to growth and development of the two copepods. Food type and amount have a significant impact on growth and development of *Centropages* species (Klein Breteler *et al*. 1982; Bonnet and Carlotti 2001). Both chl-*a* concentration and primary production of phytoplankton in the Yellow Sea are highest from May to June (Han and Choi 1991). Species composition of phytoplankton mostly consisted of net plankton such as diatoms (*Skeletonema costatum*, *Cylindrotheca closterium*, *Thalassiosira* spp.) and dinoflagellates during the study period (MOST 1998). Adult *C. abdominalis* followed the relationship of growth and chl-*a* concentrations, even though the genus *Centropages* is omnivorous (Slater and Hopcroft 2005). The development of *A. omorii* is also enhanced with increased food concentration at a fixed temperature (Klein Breteler and Schogt 1994). Species of *Acartia* genus lack most storage elements, so they are rapidly affected by changing food availability, resulting in a close association between food availability and production (Shin *et al.* 2003). The association of *C. abdominalis* and *A. omorii* with chl-*a* concentration supported that net plankton was available for optimum food size and quality, and that the field temperature was favorable for these copepods during the study periods.

Concurrently, the high abundances of the two copepods were observed in the cold waters (<10°C) of the central part of the Yellow Sea during the study periods. The highest abundance of *C. abdominalis* was observed at the northernmost station 3702 (8.1°C), while the lowest abundance occurred at stations with temperatures higher than 13°C during the study periods. This result is coincident with the distribution of *C. abdominalis* in the Inland Sea of Japan (Liang *et al.* 1996). *A. omorii* occurred abundantly between 8 and 12°C in offshore waters, whereas its lowest abundance was observed at stations between 12 and 15°C in well-mixed coastal waters and offshore waters south of 33°N, which are affected directly by warm waters branching from the Kuroshio Current. Distributional characteristics of the two species at three longitudinal transects from 124 to 126°E led them to be categorized as cold-water forms, which coincided with their seasonal peaks in the Inland Sea of Japan (Liang and Uye 1996a; Liang *et al.* 1996). Higher concentrations of chl-*a* were also observed at high latitudes in relation to the YSBCW and were coincident with the distribution of these two copepods, which was supported by the results of factor analysis (Fig. 6).

Factor analysis showed that abundances of *C. sinicus* and *P. parvus* s.l. were associated with the average temperature, and high abundances of these two copepods occurred outside the YSBCW. Abundances of *C. sinicus* were positively correlated with average temperatures between 8.1 and 15.1°C (r=0.41, p<0.01, n=43), whereas *in situ* abundances of this copepod were negatively correlated with temperatures ranging from 17.5 to 20.0°C (Ozaki *et al.* 2004; Fig. 7). *C. sinicus*, *P. parvus* s.l., and *A. omorii* are categorized as cold-water species whose upper lethal or sublethal temperatures are around 22-23°C (Uye and Liang 1998; Ozaki *et al.* 2004). These results indicate that *C. sinicus* likely prefers the thermal range between 8.1 and 17.5°C, rather than temperatures above 17.5°C. This pattern is opposite to abundances of *C. sinicus* occurring in the YSBCW (<10°C) of the southern Yellow Sea in summer (Wang *et al.*, 2003). This stemmed from the lethal summer surface temperature, which makes the copepod to move from the surface to deeper and cooler layers in the central part of the Yellow Sea. However, surface temperatures in the surface mixed layer in spring ranged from 10.5 to 17.3°C, which was in the range of optimal temperature for reproduction of *C. sinicus* according to Wang *et al.* (2003). Thus, abundances of *C. sinicus* were not likely high in the central part where the YSBCW was located in the study area. Temperature and food concentration are the major variables affecting the survival, development, metabolism,

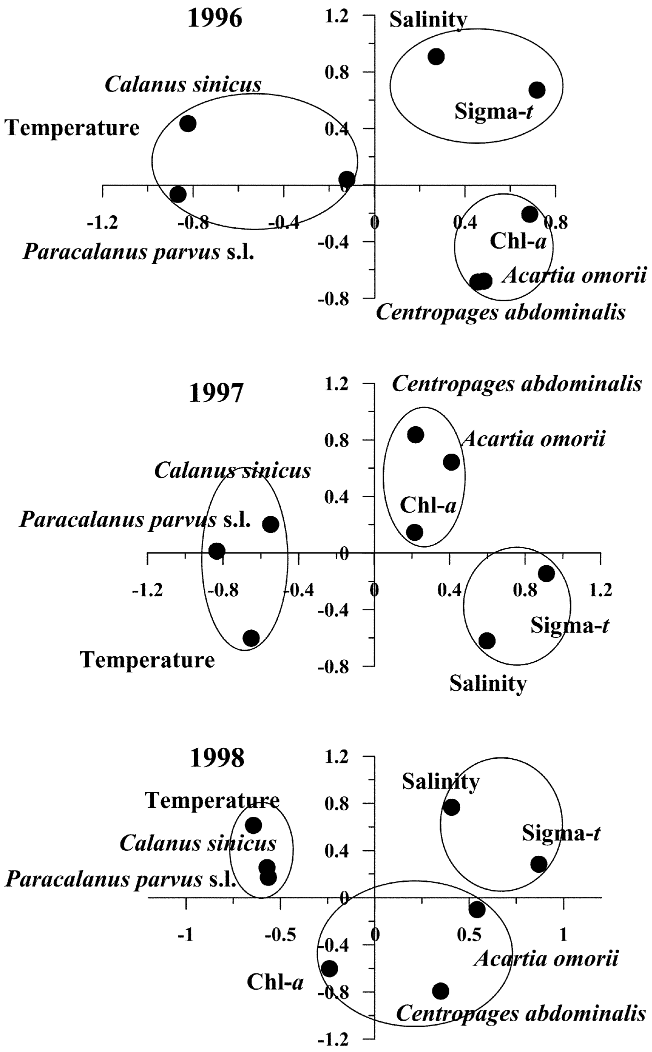

Fig. 6. Factor loading results for the first and second principal components based on the selected environmental factors and dominant copepods in the Yellow Sea from 1996 to 1998.

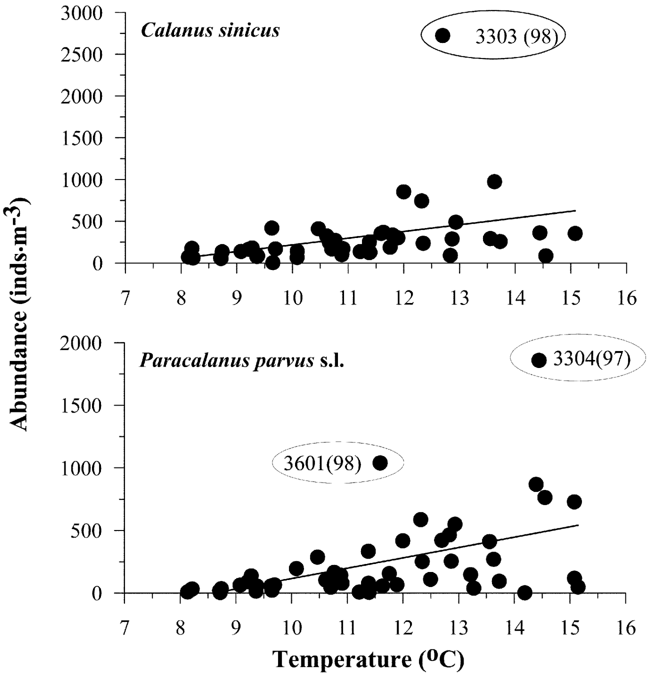

Fig. 7. The plots of abundances of *Calanus sinicus* and *Paracalanus parvus* s.l. versus average temperature during the study periods. The linear regression equations are y=80.2830X-585.9006 (r=0.407, p<0.01, n=45; *C. sinicus*) and y=82.6386X-710.4164 (r=0.495, p<0.001, n= 52; *P. parvus* s.l.). Parenthesis means the year.

and distribution of *C. sinicus* (Pu *et al.* 2004), rather than salinity (Wang *et al.* 2003). Under food-satiated conditions, the development of *C. sinicus* is dependent on temperature (Uye 1988). Our results showing a correlation between the abundance of *C. sinicus* and average temperature imply that the food concentration *in situ* was not limited to this species and suggest that the average temperature range was optimal to adult *C. sinicus*.

Abundances of *P. parvus* s.l. were also high in the relatively warm coastal waters and southern part of the Yellow Sea outside the YSBCW during the study periods. When all stations were included into the linear regression analysis, abundance of *P. parvus* s.l. was positively correlated with the average temperature from 8.1 to 15.1 °C (r=0.49, p<0.01, n=52), indicating that *P. parvus* s.l. preferred warm waters during the study periods (Fig. 7).

However, *P. parvus* s.l. has also been categorized as a cold-water species because it occurred throughout the year with the maximum abundance during winter-early spring in the Inland Sea of Japan (Liang and Uye 1996b; Uye and Liang 1998). Salinity is not a limiting factor for the growth of *P. parvus* s.l. under food-satiated conditions (Liang and Uye 1996b) or for the distribution of *C. sinicus* (Huang and Zheng 1986, cited in Wang *et al.* 2003).

In summary, the four dominant calanoid copepods (*C. abdominalis*, *A. omorii*, *C. sinicus*, and *P. parvus* s.l.) in the Yellow Sea were classified into two types based on the mesoscale distributional patterns during the study periods. The YSBCW affected the spatial patterns in accordance with the species-specific responses of the four copepods. High abundances of *C. abdominalis* and *A. omorii*, which prefer the cold waters of the YSBCW, occurred in the central part of the study area in association with high chl-*a* concentration. In contrast, abundances of *C. sinicus* and *P. parvus* s.l., which were positively correlated with average temperature (p<0.01) within the range between 8.1 and 15.1°C, were low in the central part of the Yellow Sea. The significant correlations between copepod abundances and environmental parameters indicate that the existence of the YSBCW affected the mesoscale spatial heterogeneity of the four dominant copepods during May 1996, 1997, and 1998.

Table 2. Temperature ranges in which the copepods occurred in field and laboratory observations.

Species name	Temperature (°C)	Study area	Sources
Calanus sinicus	5.0-23.0	Laboratory	Uye (1988)
	8.7-25.9	Inland Sea of Japan and adjacent Pacific waters	Huang *et al.*(1993)
	4.1-25.4	Kwangyang Bay	Soh and Suh (1993)
	9.0-29.1	The Yellow Sea	Wang *et al.* (2003)
Acartia omorii	10.0-15.0	Southern waters of Korea	Park *et al.* (1990)
	4.0-25.0	Korean Waters	Yoo *et al.* (1991)
	8.9-24.3	Inland Sea of Japan	Liang and Uye (1996a)
Paracalanus sp.	8.9-28.2	Inland Sea of Japan	Liang and Uye (1996b)
Centropages abdominalis	8.9-21.1	Inland Sea of Japan	Liang *et al.* (1996)

Acknowledgements

We express our gratitude to Dr. Ginger A. Rebstock for providing us with comments on this manuscript. The captain and crew of R/V Eardo did excellent jobs in support of ship activities during the study periods. This manuscript was supported by the projects "Development of standard plankton material and uncertainty of measurement suitable for KS A 17025" (PE97910) and "Development of Port Environmental Risk Assessment Technology" (PP 08420).

References

Bonnet, D. and F. Carlotti. 2001. Development and egg production in *Centropages typicus* (Copepoda: Calanoida) fed different food types: A laboratory study. *Mar. Ecol. Prog. Ser.*, **224**, 133-148.

Choi, K.H. and C. Park. 1993. Seasonal fluctuation of zooplankton community in Asan Bay, Korea. *Bull. Korean Fish. Soc.*, **26**, 424-437.

Han, B.S. and J.K. Choi. 1991. A study on the environmental conditions and phytoplankton ecology in the tidal front area of the Yellow Sea. *Yellow Sea Res.*, **4**, 39-55. (In Korean)

Hirst, A.G. and A.J. Bunker. 2003. Growth of marine planktonic copepods: Global rates and patterns in relation to chlorophyll-*a*, temperature, and body weight. *Limnol. Oceanogr.*, **48**, 1988-2010.

Huang, C., S. Uye, and T. Onbe. 1993. Geographic distribution, seasonal life cycle, biomass and production of a planktonic copepod *Calanus sinicus* in the Inland Sea of Japan and its neighboring Pacific Ocean. *J. Plankton Res.*, **15**, 1229-1246.

Huang, J. and Z. Zheng. 1986. The effects of salinity on the distribution of some copepods in the Jiulongjiang estuary. *Acta Oceanol. Sinica*, **8**, 83-91.

Hwang, H.J. and J.K. Choi. 1993. Seasonal characteristics of zooplankton community in the Mid-Eastern part of the Yellow Sea. *J. Oceanol. Soc. Korea*, **28**, 24-34. (In Korean)

Jang, M.C. and W.-S. Kim. 1998. Zooplankton distribution and environmental characteristics of the Yellow Sea in spring, 1996. *Ocean and Polar Res.*, **20**, 19-28.

Kang, Y.S. and S.S. Lee. 1991. Seasonal fluctuation of zooplankton biomass in the adjacent seas of Korea. *Bull. Nat. Fish. Res. and Dev.*, **45**, 13-21.

Kang, Y.S., S.H. Huh, and S.S. Lee. 1990. Taxonomy and distribution of Corycaeidae (Copepoda:Cyclopoida) in the Korean Waters in Summer. *J. Oceanol. Soc. Korea*, **25**, 49-61.

Kim, S.W. and J.H. Lee. 1994. Seasonal distribution of zooplankton communities in Inchon Dock, an artificially closed marine embayment facing the Yellow Sea, Western Korea. *J. Oceanol. Soc. Korea*, **29**, 376-382.

Klein Breteler, W.C.M., H.G. Fransz, and S.R. Gonzalez. 1982. Growth and development of four calanoid copepod species under experimental and natural condition. *Neth. J. Sea Res.*, **16**, 195-207.

Klein Breteler, W.C.M. and N. Schogt. 1994. Development of *Acartia clausi* (Copepoda, Calanoida) cultured at different conditions of temperature and food. *Hydrobiologia*, **292/293**, 469-479.

Liang, D. and S. Uye. 1996a. Population dynamics and production of the planktonic copepods in a eutrophic inlet of the Inland Sea of Japan. II. *Acartia omorii*. *Mar. Biol.*, **125**, 109-117.

Liang, D. and S. Uye. 1996b. Population dynamics and production of the planktonic copepods in a eutrophic inlet of the Inland Sea of Japan. II. *Paracalanus* sp. *Mar. Biol.*, **127**, 219-227.

Liang, D., S. Uye, and T. Onbe. 1996. Population dynamics and production of the planktonic copepods in a eutrophic inlet of the Inland Sea of Japan. I. *Centropages abdominalis*. *Mar. Biol.*, **124**, 527-536.

Lie, H.J. 1984. A note on water masses and general circulation in the Yellow Sea (Hwanghae). *J. Oceanol. Soc. Korea*, **19**, 187-194.

Liu, G.M., S. Sun, H. Wang, Y. Zhang, B. Yang, and P. Ji. 2003. Abundance of *Calanus sinicus* across the tidal front in the Yellow Sea, China. *Fish. Oceanogr.*, **12**, 291-298.

Mauchline, J., J.H.S. Blaxter, A.J. Southward, and P.A. Tyler. 1998. Advances in Marine Biology. Academic Press, San Diego. 710 p.

Morioka, Y., F. Shinohara, J. Nakashima, and T. Jrie. 1991. A diel vertical migration of the copepod *Calanus sinicus* in relation to well-developed thermocline in the Yellow Sea, October 1987. *Bull. Seikai Nat. Fish. Res. Inst.*, **69**, 79-86.

MOST (Ministry of Science and Technology). 1998. Integrated survey on environment and ecosystem of the Yellow Sea. KORDI, Korea, Technical report BSPN 97356-00-1099-3.

Ozaki, K., S.I. Uye, T. Kusumoto, and T. Hagino. 2004. Inter-annual variability of the ecosystem of the Kii Channel, the Inland Sea of Japan, as influenced by bottom intrusion of cold and nutrient-rich water from the Pacific Ocean, and a recent trend of warming and oligotrophication. *Fish. Oceanogr.*, **13**, 65-79.

Park, C. 1997. Seasonal distribution, egg production and feeding by the marine copepod *Calanus sinicus* in Asan Bay, Korea. *J. Oceanol. Soc. Korea*, **32**, 85-92.

Park, J.S., S.S. Lee, Y.S. Kang, B.D. Lee, and S.H. Huh. 1990. The distributions of copepods and chaetognaths in the southern waters of Korea and their relationship to the characteristics of water masses. *Bull. Korean Fish. Soc.*, **23**, 245-252.

Parsons, T.R., Y. Maita, and C.M. Lalli. 1984. A Manual of Chemical and Biological Methods for Seawater Analysis. Pergamon Press, New York. 173 p.

Pu, X.M., S. Sun, B. Yang, P. Ji, Y.S. Zhang, and F. Zhang. 2004. The combined effects of temperature and food supply on *Calanus sinicus* in the southern Yellow Sea in summer. *J. Plankton Res*., **26**, 1049-1057.

Seung, Y.H. 1992. Water masses and circulations around Korean Peninsula. *J. Oceanol. Soc. Korea*, **27**, 324-331.

Shin, K., M.C. Jang, P.K. Jang, S.J. Ju, T.K. Lee, and M. Chang. 2003. Influence of food quality on egg production and viability of the marine planktonic copepod *Acartia omorii*. *Prog. Oceanogr*., **57**, 265-277.

Sim, M.B., J.K. Choi, and D.Y. Kim. 1988. The distribution of zooplankton in the mid–eastern part of the Yellow Sea. *The Yellow Sea*, **1**, 1-10. (In Korean)

Slater, L.M. and R.R. Hopcroft. 2005. Development, growth and egg production of *Centropages abdominalis* in the eastern subarctic Pacific. *J. Plankton Res*., **27**, 71-78.

Soh, H.Y. and H.L. Suh. 1993. Seasonal fluctuation of the abundance of the planktonic copepods in Kwangyang Bay. *Korean J. Env. Biol*., **11**, 26-34.

Uye, S.I. 1988. Temperature–dependent development and growth of *Calanus sinicus* (Copepoda: Calanoida) in the laboratory. *Hydrobiologia*, **167/168**, 285-293.

Uye, S.I. and D. Liang. 1998. Copepods attain high abundance, biomass and production in the absence of large predators but suffer cannibalistic loss. *J. Mar. Syst*., **15**, 495-501.

Wang, R., T. Zuo, and K.E. Wang. 2003. The Yellow Sea Cold Bottom Water-an oversummering site for *Calanus sinicus* (Copepoda, Crustacea). *J. Plankton Res*., **25**, 169-183.

Yoo, K.I., H.K. Hue, and W.C. Lee. 1991. Taxonomical revision on the genus *Acartia* (Copepoda: Calanoida) in the Korean Waters. *Bull. Korean Fish. Soc*., **24**, 255-265.

Zhang, G.T., S. Sun, and F. Zhang. 2005. Seasonal variation of reproduction rates and body size of *Calanus sinicus* in the Southern Yellow Sea, China. *J. Plankton Res*., **27**, 135-143.

Zhang, H.Q. 1995. Relationship between zooplankton distribution and hydrographic characteristics of the southern Yellow Sea. *The Yellow Sea*, **1**, 50-67.