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The Yellow Sea Warm Current and the Yellow Sea Cold Bottom Water, Their Impact on the Distribution of Zooplankton in the Southern Yellow Sea

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The Yellow Sea Warm Current (YSWC) and the Yellow Sea Cold Bottom Water (YSCBW) are two protruding features, which have strong influence on the community structure and distribution of zooplankton in the Yellow Sea. Both of them are seasonal phenomena. In winter, strong north wind drives southward flow at the surface along both Chinese and Korean coasts, which is compensated by a northward flow along the Yellow Sea Trough. That is the YSWC. It advects warmer and saltier water from the East China Sea into the southern Yellow Sea and changes the zooplankton community structure greatly in winter. During a cruise after onset of the winter monsoon in November 2001 in the southern Yellow Sea, 71 zooplankton species were identified, among which 39 species were tropical, accounting for 54.9 %, much more than those found in summer. Many of them were typical for Kuroshio water, e.g. *Eucalanus subtenuis, Rhincalanus cornutus*, *Pareuchaeta russelli*, *Lucicutia flavicornis*, and *Euphausia diomedeae* etc. 26 species were warm-temperate accounting for 36.6% and 6 temperate 8.5%. The distribution pattern of the warm water species clearly showed the impact of the YSWC and demonstrated that the intrusion of warmer and saltier water happened beneath the surface northwards along the Yellow Sea Trough. The YSCBW is a bottom pool of the remnant Yellow Sea Winter Water resulting from summer stratification and occupy most of the deep area of the Yellow Sea. The temperature of YSCBW temperature remains ≤ 10°C in mid-summer. It is served as an oversummering site for many temperate species, like *Calanus sinicus* and *Euphaisia pacifica*. *Calanus sinicus* is a dominant copepod in the Yellow Sea and East China Sea and can be found throughout the year with the year maximum in May to June. In summer it disappears in the coastal area and in the upper layer of central area due to the high temperature and shrinks its distribution into YSCBW.

Key words: Zooplankton, Distribution, Yellow Sea, Warm Current, Cold Bottom Water

INTRODUCTION

The Yellow Sea is a marginal sea of the northwest Pacific, which is located between China and Korea north of the Yangtse River plume. In north it connected with the Bohai Sea, a shallow semi-enclosed bay, and in south connected with the East China Sea, which is divided from the Yellow Sea by the line from the Chongming Island (China) to the Cheju Island (Korea) generally. The Yellow Sea has an average depth of only 44 m but there is a deep trough (>70 m) extended from the southwest of Cheju Island towards north up to about 38°N. As a shallow shelf water the Yellow Sea is affected greatly by climatic and geographical conditions.

One of the characteristic features of the Yellow Sea is the warm water intrusion known as the Yellow Sea Warm Current (YSWC). During the winter monsoon period strong north wind drives southward flow at the surface along both Chinese and Korean coasts that is balanced by a northward flow along the Yellow Sea trough (Hsueh, 1988; Mask *et al.*, 1989; Teague and Jacobs, 2000; Jacobs *et al.*, 2000; Tang *et al.*, 2001). The YSWC advects warmer and saltier water into the Yellow Sea in winter and changes the zooplankton community structure greatly. Regarding the impact of YSWC on the zooplankton community structure and distribution, Cheng and Cheng (1962)

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reported that in winter some warm water species of planktonic foraminifera could distribute as far north as 35°N. Anon. (1977) reported that tropical species of Medusae, Copepoda, Amphipoda, Euphausiacea, Pteropoda and Chaetognatha could be found in the north west of Cheju Island. Zhang (1995) reported the occurrence of tropical species of zooplankton south of 32°N (in the area west of 124°E) and 34°N (in the area east of 124°E) based on the data collected during the China-Korea joint survey in 1992 in the southern Yellow Sea.

Another protruding feature in the Yellow Sea is the Yellow Sea Cold Bottom Water (YSCBW). It is in fact a bottom pool of the remnant of the Yellow Sea Winter Water (YSWW), which is formed in winter owing to the surface cooling and strong vertical mixing by the north monsoon. In summer it emerges as the remnant of the YSWW resulting from stratification (Ho, *et al.*, 1959; Kuan, 1963; Liu, *et al.*, 1992; Su and Weng, 1994). It begins to appear in May, develops into the most intensity in July and August and disappears (or in other words, becomes homogeneous vertically again) in winter and spring. Above the YSCBW there is a strong thermocline with maximum temperature gradient of about 6°C · m^{-1}, which forms a barrier to the vertical distribution and vertical migration of zooplankton. In summer this cold (<10°C) deep water, extending over 4 degrees longitude (121°15′E-125°05′E) and 5 degrees latitude (33°40′N-38°48′N) and accounting for 29% of the total volume of the Yellow Sea (Su and Weng, 1994), offers an oversummering site, or a harbor, to the temperate species that can not tolerate the high (>25°C) temperature in the upper layer and in the coastal area (Wang *et al.*, 2003).

Most of the previous zooplankton data were come from vertical or oblique hauls of the whole water column, so we have little knowledge about the vertical distribution and vertical migration of zooplankton species in relation to the YSWC and the YSCBW. In the past few years during the second phase of China-GLOBEC (Global Ocean Ecosystem Dynamics) program from 1999 to 2004 zooplankton samples were collected in the southern Yellow Sea from both the total water column and different layers. Based on those samples this work gives some preliminary results about the impact of the YSWC and the YSCBW on the zooplankton distribution.

METHOD AND MATERIAL

Zooplankton samples were collected during 5 cruises from 1999 to 2001 (Table 1). All cruises were conducted by the *R/V* Beidou. The research area, transects and stations are shown in Fig. 1. Two kinds of zooplankton samples were used in this study. A vertical tow from the sea bottom to the sea surface was made at each station with an 80 cm diameter conical net (mesh size 500 μm) (GB12763.6-91, 1991). Data from these samples were used to see the horizontal distribution of zooplankton species. Vertical tows at different layers with a closing net (the same type as above) were made at stations on the key transects to observe the vertical distribution of zooplankton species. The sampling layers were: 10-0 m, 25-10 m, 50-25 m, 100-50 m, and 200-100 m. Where the water depth was less than the lower limit of the above standard layers, the lowest tow would be made from the bottom to the upper limit of the proper layer. For instance, where the water depth was 78 m, the lowest tow was made from 78 m to 50 m. The upper and lower limit of the sampling layer might be adjusted slightly according to the position of thermocline. At a 24-hr time-series stations (Fig. 1-E, station 1-7, water depth 80 m) samples were collected from different layers (the same as above generally) every three hours (00:00, 03:00, 06:00, ..., 24:00) for a complete daily cycle in order to observe the diurnal vertical migration of zooplankton.

A flowmeter was mounted in the center of the net mouth to measure the volume of water filtered. Samples were preserved in 5% neutralized formalin seawater solution. Species of zooplankton were sorted and counted under a dissecting microscope. The abundance of each species was expressed as ind·m^{-2} for horizontal distribution analysis and ind·m^{-3} for vertical

Table 1. Cruises in which samples were collected and used for this study

year	date	region	R/V	Number of sampling stations
1999	Aug 28-30	Southern YS	*Beidou*	23
2000	Oct 21-22	Southern YS	*Beidou*	6
2001	Nov 15-29	Southern YS	*Beidou*	48
2001	Mar 28-30	Southern YS	*Beidou*	10
2001	Aug 11-14	Southern YS	*Beidou*	9

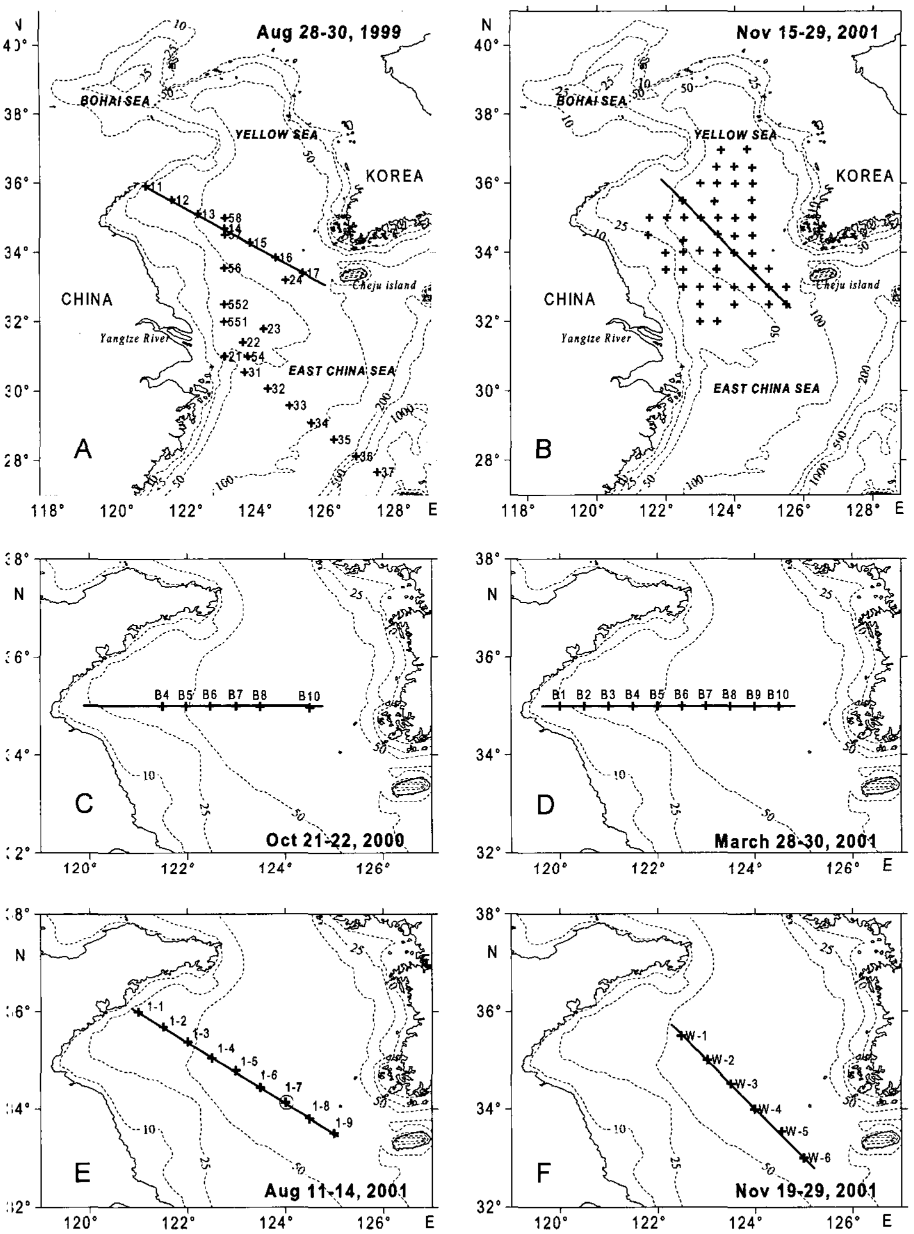

Fig. 1. Map of research area, transects and sampling stations.

distribution analysis.

CTD and chlorophyll *a* were measured at each station. Water samples for Chlorophyll *a* measurement were collected at 0 m, 5 m, 10 m, 20 m, 30 m, 50 m 100 m and 200 m depth and filtered onto GF/F filters, which were frozen and kept at −20°C until subsequent analysis. Chlorophyll *a* was measured by fluorescent method with a Turner Designs fluorometer.

RESULT

Impact of the YSWC

To see the warm water species distribution in related to the YSWC, plankton samples were collected in November 2001 in the southern Yellow Sea after onset of the winter monsoon. 71 zooplankton species were identified (Table 2), among which 39 species were tropical, accounting for 54.9%, much more than that found in summer. Many of them were typical for Kuroshio water, e.g. *Eucalanus subtenuis, Rhincalanus cornutus, Lucicutia flavicornis*, and *Euphausia diomedeae* etc. 26 species were warm-temperate accounting for 36.6% and 6 temperate 8.5%. However the zooplankton community was still dominated by temperate and warm-temperate species. *Calanus sinicus* was the overwhelming dominant one (dominance=0.4331). The second one was *Sagitta crassa*

Table 2. List of zooplankton species identified

Species	Ecological character	Distribution in China Seas	Stations of occurrence	Total specimens collected	Dominance
Phialidium chengshanensis	warm-temp	B,Y,E,S	1	10	0.0000
Liriope tetraphylla	warm-temp	Y,E,S	1	1	0.0000
Aglaura hemistoma	warm-temp	Y,E,S	2	20	0.0000
Physophora hydrostatica	warm-temp	Y,E,S	1	10	0.0000
Diphyes chamissonis	warm-temp	Y,E,S	3	30	0.0000
Muggiaea atlantica	temperate	B,Y,E,S	16	1184	0.0020
Chelophyes contorta	tropical	Y,E,S	1	10	0.0000
Pleurobrachia globosa	warm-temp	B,Y,E,S	1	10	0.0000
Penilia avirostris	warm-temp	B,Y,E,S	2	20	0.0000
Calanus sinicus	warm-temp	B,Y,E,S	48	85426	0.4331
Neocalanus tenuicornis	tropical	Y,E,S	1	4	0.0000
Canthocalanus pauper	tropical	Y,E,S	4	64	0.0000
Nannocalanus minor	tropical	Y,E,S	2	82	0.0000
Undinula vulgaris	tropical	Y,E,S	9	458	0.0004
Undinula darwinii	tropical	Y,E,S	1	10	0.0000
Eucalanus pseudattenuatus	tropical	Y,E,S	2	11	0.0000
Eucalanus crassus	tropical	Y,E,S	1	10	0.0000
Eucalanus subcrassus	tropical	Y,E,S	2	42	0.0000
Eucalanus subtenuis	tropical	Y,E,S	3	31	0.0000
Rhincalanus cornutus	tropical	Y,E,S	1	4	0.0000
Paracalanus parvus	warm-temp	B,Y,E,S	30	3716	0.0119
Paracalanus aculeatus	warm-temp	Y,E,S	11	187	0.0002
Paracalanus crassirostris	warm-temp	B,Y,E,S	3	206	0.0001
Acrocalanus gibber	tropical	Y,E,S	2	600	0.0001
Clausocalanus furcatus	tropical	Y,E,S	13	216	0.0003
Clausocalanus pergens	tropical	Y,E,S	2	80	0.0000
Chiridius poppei	tropical	Y,E,S	1	1	0.0000
Euchaeta marina	tropical	Y,E,S	5	964	0.0005
Euchaeta concinna	tropical	Y,E,S	14	1423	0.0021
Euchaeta plana	tropical	Y,E,S	19	6396	0.0129
Pareuchaeta russelli	tropical	Y,E,S	12	180	0.0002
Scolecithrix danae	tropical	Y,E,S	3	50	0.0000
Scolecithrix nicobarica	tropical	Y,E,S	9	1350	0.0013
Scolecithrix nicobarica	tropical	Y,E,S	1	10	0.0000
Scolecithricella longispinosa	tropical	Y,E,S	2	11	0.0000
Temora discaudata	tropical	Y,E,S	3	90	0.0000
Temora stylifera	tropical	Y,E,S	2	32	0.0000
Pleuromamma gracilis	tropical	Y,E,S	1	10	0.0000
Centropages dorsispinatus	warm-temp	Y,E,S	8	62	0.0001
Centropages furcatus	tropical	Y,E,S	4	17	0.0000
Centropages mcmurrichi	warm-temp	B,Y,E,S	1	1	0.0000
Lucicutia flavicornis	tropical	Y,E,S	1	10	0.0000
Candacia pachydactyla	tropical	Y,E,S	1	4	0.0000
Labidocera euchaeta	warm-temp	B,Y,E,S	7	1480	0.0011
Acartia bifilosa	temperate	B,Y,E	2	20	0.0000

Table 2. continued

Species	Ecological character	Distribution in China Seas	Stations of occurrence	Total specimens collected	Dominance
Acartia bifilosa	temperate	B,Y,E	2	20	0.0000
Acartia pacifica	warm-temp	B,Y,E,S	21	416	0.0010
Acartia negligens	tropical	Y,E,S	1	10	0.0000
Tortanus forcipatus	warm-temp	B,Y,E,S	1	1	0.0000
Oithona similis	warm-temp	B,Y,E,S	27	4494	0.0129
Oithona fallax	tropical	Y,E,S	1	10	0.0000
Oncaea venusta	tropical	Y,E,S	3	50	0.0000
Corycaeus speciosus	tropical	Y,E,S	3	22	0.0000
Corycaeus crassiusculus	tropical	Y,E,S	1	10	0.0000
Corycaeus affinis	warm-temp	B,Y,E,S	22	292	0.0007
Corycaeus catus	tropical	Y,E,S	4	84	0.0000
Themisto gracilipes	warm-temp	Y,E,S	39	4506	0.0187
Pseudeuphausia sinica	warm-temp	Y,E,S	10	74	0.0001
Euphausia diomedeae	tropical	Y,E,S	2	20	0.0000
Euphausia pacifica	warm-temp	B,Y,E,S	34	3323	0.0120
Acetes chinensis	warm-temp	B,Y,E,S	1	1	0.0000
Lucifer hanseni	warm-temp	Y,E,S	1	1	0.0000
Lucifer intermedius	warm-temp	B,Y,E,S	11	75	0.0001
Leptochela gracilis	temperate	B,Y,E	14	116	0.0002
Gastrosaccus pelagicus	temperate	B,Y,E	7	61	0.0001
Erythrops minuta	temperate	B,Y,E,S	2	11	0.0000
Acanthomysis longirostris	temperate	B,Y,E,S	8	62	0.0001
Creseis acicula	tropical	Y,E,S	1	9	0.0000
Sagitta enflata	tropical	Y,E,S	41	5429	0.0237
Sagitta crassa	warm-temp	B,Y,E,S	42	43578	0.1934
Sagitta nagae	tropical	Y,E,S	44	3552	0.0167
Oikopleura longicauda	warm-temp	Y,E,S	19	4027	0.0081
Doliolum denticulatum	tropical	B,Y,E,S	17	21630	0.0388

Notes: warm-temp=warm-temperate, B=Bohai Sea, Y=Yellow Sea, E=East China Sea, S=South China Sea.
Dominance=$(n_i/N)f_i$ in which n_i is the number of individuals of species i, N is the total individual number of all species, and f_i is the relative frequency of occurrence of species i.

dominance=0.1934). *Sagitta enflata* and *Doliolum denticulatum*, which have been referred as wide distributed warm water species, were relatively abundant with a dominance of 0.0388 and 0.0237 respectively. Most of the tropical species were very few. The species typical for Kuroshio water were very rare.

The horizontal distribution of *Euchaeta plana* and *Pareuchaeta russelli* and their vertical distribution on transact 1 (see Fig. 1-B) were given in Fig. 3 and 5. We selected these 2 species as example because they were typical for tropical species and also presented with a certain amount in samples. The horizontal distribution pattern of these 2 species (Fig. 3A and B) reflects clearly the pathway of the penetration of the warmer and saltier water – the YSWC. These tropical species originated from Kuroshio or Taiwan Warm Current penetrated into the Yellow Sea from the west of Cheju Island towards NNW and along the Yellow Sea Trough roughly. The north limit of their distribution was about 35°N–36°N. The horizontal distribution of temperature (not provided) did not show clearly the intrusion of the YSWC, however evidence could be found in the horizontal distribution of salinity (Fig. 2).

For most of the other tropical species, e.g. *Eucalanus subtenuis, Rhincalanus cornutus, Pareuchaeta russelli Lucicutia flavicornis* and *Euphausia diomedeae* etc, their horizontal distribution were not consecutive, because they were so rare. We plotted the positions where they were found with different symbols

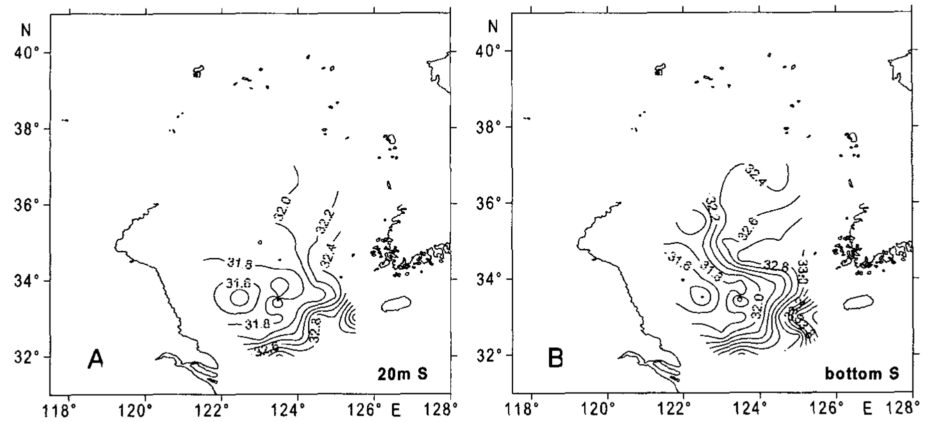

Fig. 2. Horizontal distribution of salinity at 20 m layer and bottom layer in November 2001.

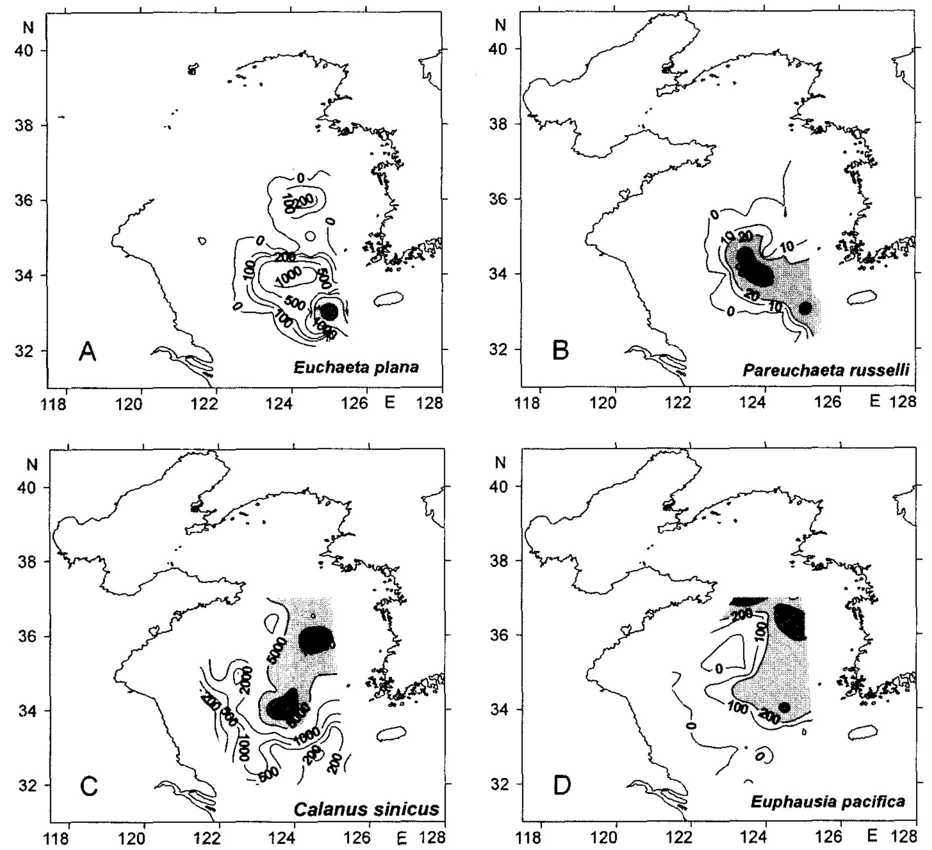

Fig. 3. Horizontal distribution (ind·m^{-2}) of *Euchaeta plana* (A), *Pareuchaeta russelli* (B), *Calanus sinicus* (C) and *Euphausia pacifica* (D) in November 2001.

in Fig. 6. The distribution pattern for all the other tropical species as a whole was the same as that of *Euchaeta plana* and *Pareuchaeta russelli.*

The vertical distribution of *Euchaeta plana* and *Pareuchaeta russelli* on transact 1 (Fig. 5-A and 5-B) shows that the penetration of these 2 tropical species happened not in the bottom layer but in the middle layer and shows also that the north limit of their distribution could reach as north as 35°N. The north limits of distribution were different in different species depending on their ecological properties. Among the 39 warm water species 36 species could extend northward to 33°N, 21 species to 34°N, 19 species to 35°N, 13 species to 36°N, only 3 species to 37°N. Stations close to Cheju Island have the highest diversity. And most of the warm water species found there were characteristic of Kuroshio water. The distribution area of most warm water species was roughly coincident with the area with salinity higher than 33 psu in 20 m layer. *Sagitta enflata* and *Doliolum denticulatum* have wider distribution.

Although large number of warm water species had been found in November after the onset of north monsoon, the zooplankton community was still dominated by temperate and temperate-warm species, e.g. *Calanus sinicus, Themisto gracilipes* and *Euphaisia pacifica*. *Calanus sinicus* is widely distributed in the margin seas of west North Pacific from Japan to Vietnam. This copepod can be found throughout the year in the Bohai Sea, the Yellow Sea and the East China Sea but shows a strong seasonal variation, with the year maximum in May to June. It dominates the meso-zooplankton in the Yellow Sea. In November its distribution pattern was opposite to those of the warm species (Fig. 3-C). The temperature of its high abundance area was <16°C. Even though November was not in its peak season, high abundance (>10,000 ind·m^{-2}) could be found in the deepest area. The same distribution pattern can also be found in *Euphaisia pacifica* (Fig. 3-D).

The vertical distribution of these temperate species on transact I (Fig. 1-B) shows also the different distribution pattern (Fig. 5C and 5-D) compared with the warm species. From Fig. 3-D it can be seen that the distribution center of *Euphaisia pacifica* was in the north part of our research area and transact 1 only passes through a small corner of its distribution area. However, from Fig. 5D it seems that *Euphaisia pacifica* prefer to staying in the cold (<11°C) bottom layer, where the residue of YSDCW can be found (Fig. 4-A).

Impact of the YSDCW

As mentioned above the YSDCW offers an oversummering site, or a harbor, to the temperate species that can not tolerate the high temperature (>25°C) in the upper layer and in the coastal area. *C. sinicus* is a typical temperate species with an upper thermal

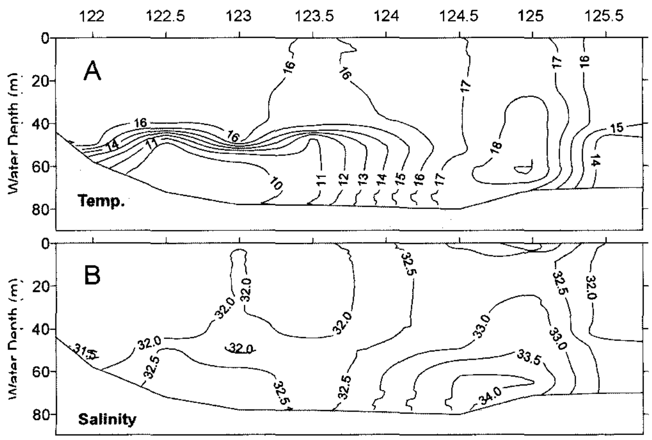

Fig. 4. Temperature (°C)(A) and salinity(psu)(B) profiles on transact 1 in November 2001. Numbers on X-axis represent the longitude of the stations.

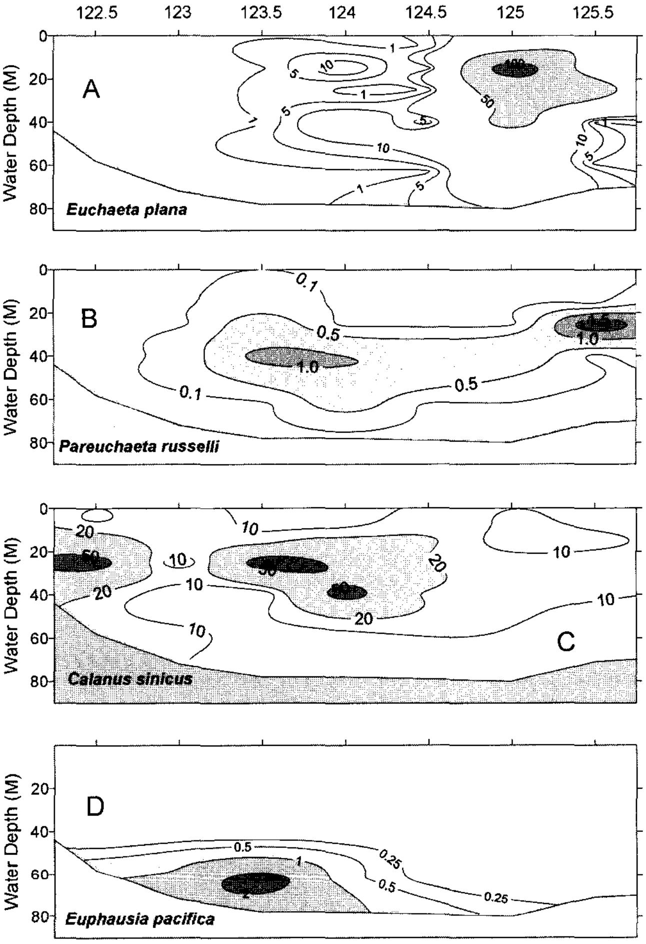

Fig. 5. Vertical distribution (ind·m^{-3}) of *Euchaeta plana* (A), *Pareuchaeta russelli* (B), *Calanus sinicus* (C) and *Euphausia pacifica*(D) on transact 1 in November 2001. Numbers on X-axis represent the longitude of the stations.

limit of ~23°C (Huang *et al.*, 1993). During the summer cruise of August 1999 the temperature of upper layer was higher than 25°C in most part of the Yellow Sea (Fig. 7-A). The population density of *C. sinicus* decreased to a very low level in coastal area but remained high abundance of adults and C5 in the central part of the southern Yellow Sea (Fig. 8), which was coincident with the territory of the YSCBW, where the bottom temperature was less than 12°C (Fig. 7-B).

The vertical distribution of adults and C5 of *C. sinicus* on transect 1(Fig. 1-A), which passes through the YSCBW from Jiaozhou Bay (China) to Cheju Island (Korea), clearly shows that this temperate species resided exclusively in the central deep cold (<12°C) layer occupied by the YSCBW (Fig. 9-A and Fig. 10-A, 10-B). A strong thermocline can be seen between 25 m to 30 m depth (Fig. 9-A) with a gradient of >2°C.m^{-1} at station 1-5. The surface water temperature there was as high as 27°C but the bottom

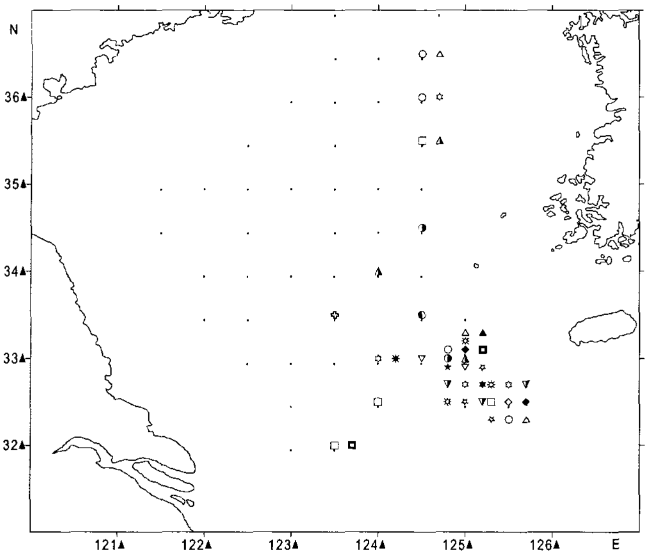

Fig. 6. Positions of the rare warm water species occurred in November 2001. ◇ *Acartia negligens*, ◆ *Acrocalanus gibbe*, □ *Canthocalanus pauper*, ▣ *Clausocalanus pergens*, ○ *Corycaeus catus*, △ *Corycaeus speciosus*, ▲ *Corycaeus crassiusculus*, ▽ *Euphausia diomedeae*, ☆ *Eucalanus subtenuis*, ★ *Eucalanus crassus*, ✩ *Eucalanus subcrassus*, ✸ *Lucicutia flavicornis*, ✙ *Neocalanus tenuicornis*, ▲ *Nannocalanus minor*, ▼ *Oncaea venusta*, ◑ *Undinula darwinii*, ◐ *Scolecithrix nicobarica*, ✲ *Scolecithrix danae* ✱ *Rhincalanus cornutus*.

temperature remained 9°C. All the adults and C5 resided exclusively in water below 25 m and 56.60% of them resided in the bottom layer below 50 m. The same distribution pattern can also be seen in *Euphausia pacifica* (Fig. 10-C). *Themisto gracilipes*, a temperate planktonic amphipod, seems to stay in the middle layer just below the thermocline (Fig. 10-D) and few individuals can reach to the upper layer in the front zone.

Fig. 12, 13 and 14 give the vertical abundance profiles of *Calanus sinicus*, *Euphausia pacifica* and *Themisto gracilipes* on the transects observed in different seasons (see Fig. 1, C-F) in the southern Yellow Sea. Those transects observed in different seasons were not the same, however, they all passed through the YSDCW. So from Fig. 12, 13 and 14 we can have some idea about the seasonality of the impact of the YSDCW on the vertical distribution of zooplankton. For *Calanus sinicus* (Fig. 12), during spring (March 2001) when the water became homogenous vertically (Fig. 11-B) and the YSDCW did not emerge, its high abundance area was restricted in the coastal area and in the upper layer. In summer (Aug. 2001) when the YSDCW was fully developed, its

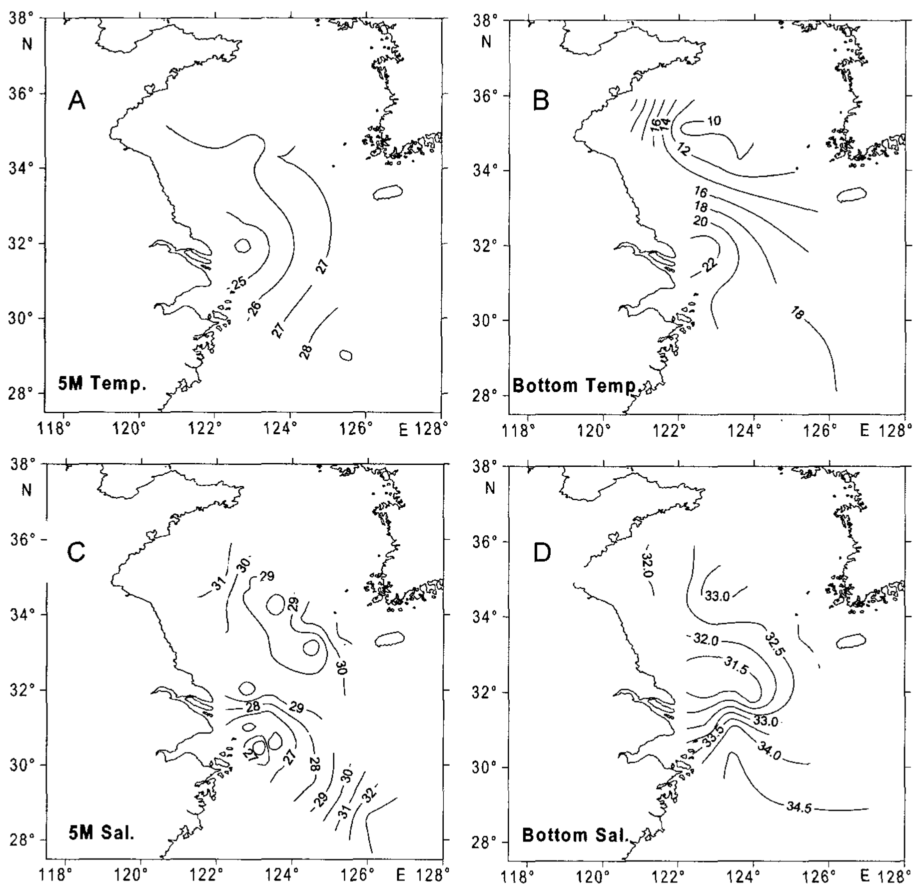

Fig. 7. Temperature (°C) and salinity (psu) distribution of 5 m layer(A, C) and those of bottom layer(B, D) in the research area, August 1999.

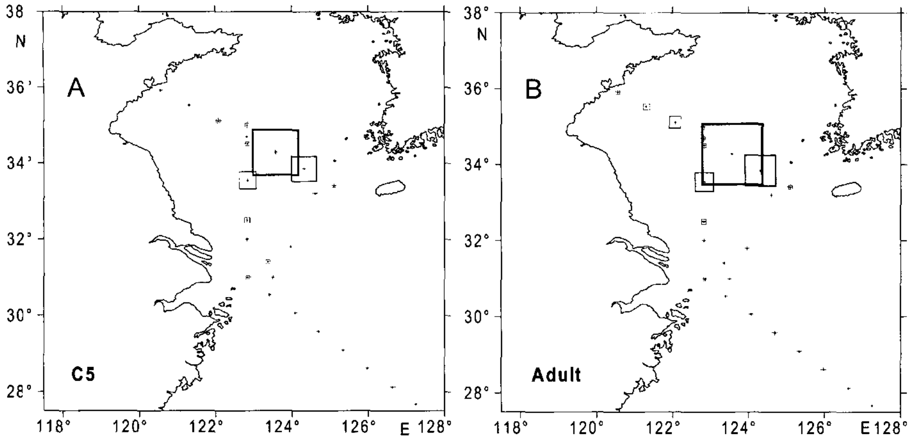

Fig. 8. Abundance of *Calanus sinicus* at sampling stations, August 1999. The areas of symbols are proportional to the abundance (ind·m^{-2}). The abundance value represented by the largest symbol in plot A equals to 7,716 ind·m^{-2} and that in plot B 8,514 ind·m^{-2}.

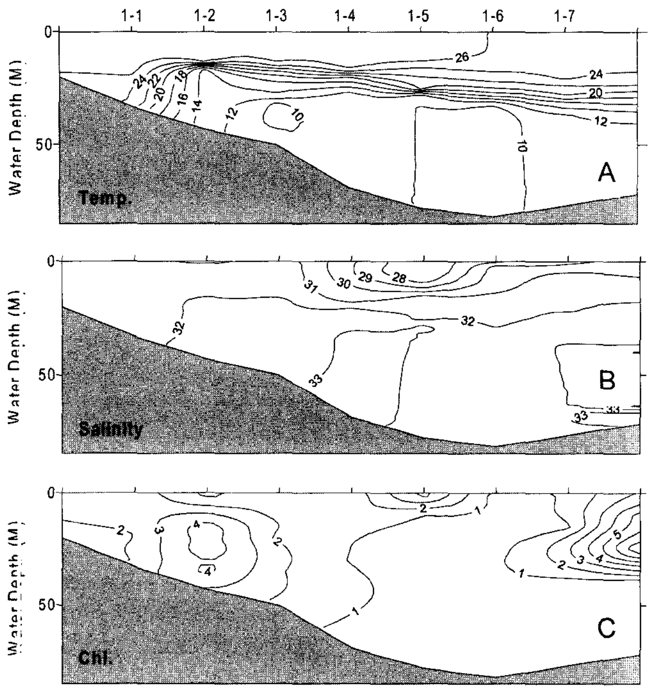

Fig. 9. Temperature (°C)(A), salinity(psu)(B) and chlorophyll *a* (μg/l) (C) profiles on transect 1, August 1999.

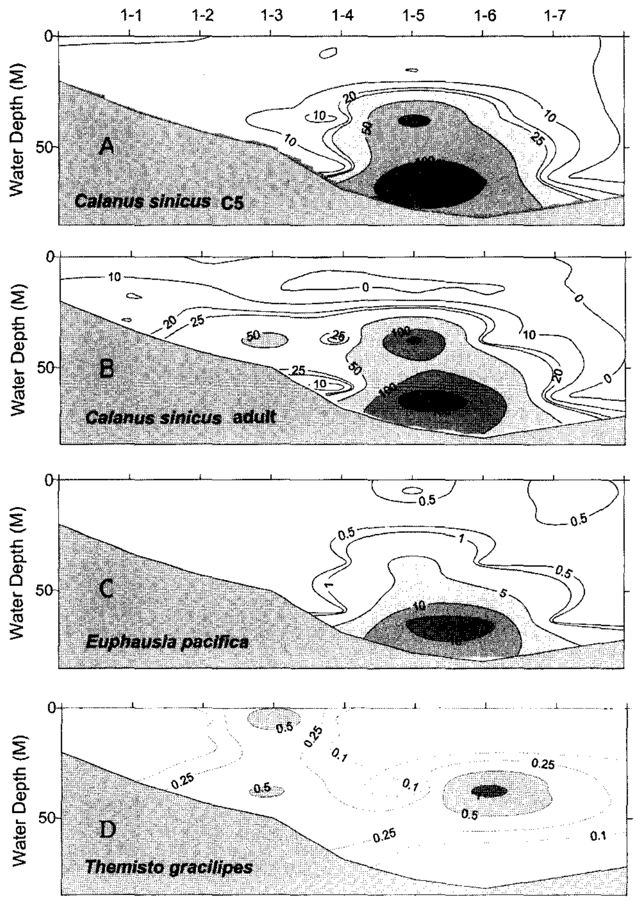

Fig. 10. Abundance (ind·m^{-3}) profiles of *Calanus sinicus* (A, B), *Euphausia pacifica* (C) and *Themisto gracilipes* (D) on transect 1, August 1999.

high abundance area moved to the deep layer. In October when the territory the YSDCW shrank to the central part of the Yellow Sea, this copepod was only found in the YSDCW with low abundance. In November the territory of the YSDCW shrank further and the lower limit of the mixing layer extended to about 50 m depth. Its distribution began to move to the middle and upper layer, where the temperature was about 16°C. For *Euphausia pacifica* there seems no difference in the distribution pattern of the abundance profiles in different seasons (Fig. 13). This euphausiid preferred to stay in deep layer no matter in summer or winter. The vertical distribution of *Themisto gracilipes* was somewhat different from that of *Calanus sinicus*. In March when the water was homogenous vertically it distributed mainly in upper layer. In mid-summer and autumn it stayed just below the thermocline. In November it distributed throughout the water column.

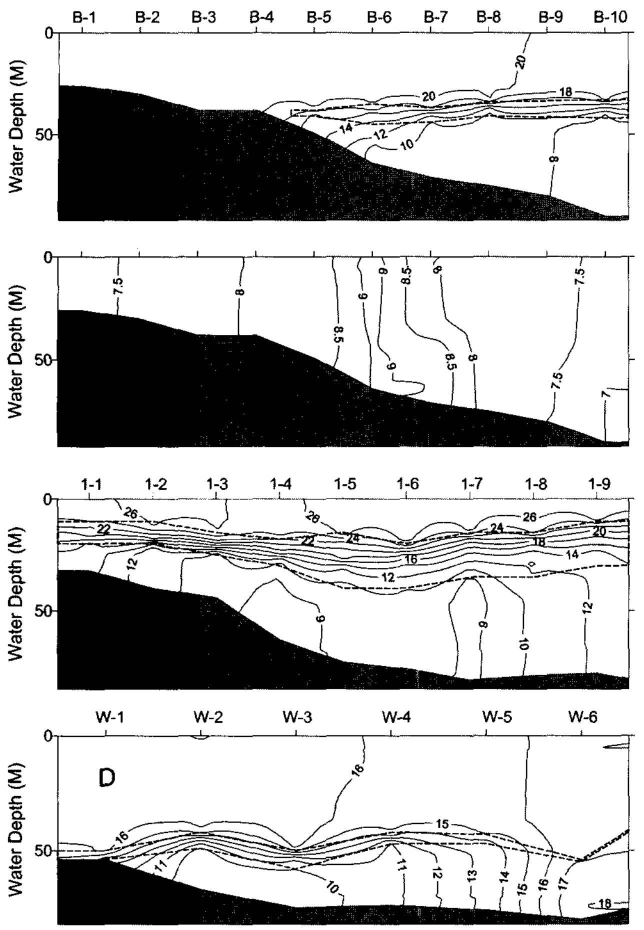

Fig. 11. Temperature (°C) profile on transects in 4 cruises (refer to Figure 1, C-D). The broken lines show the upper and lower limits of the thermocline (temperature gradient $\geq 0.2°C{\cdot}m^{-1}$.

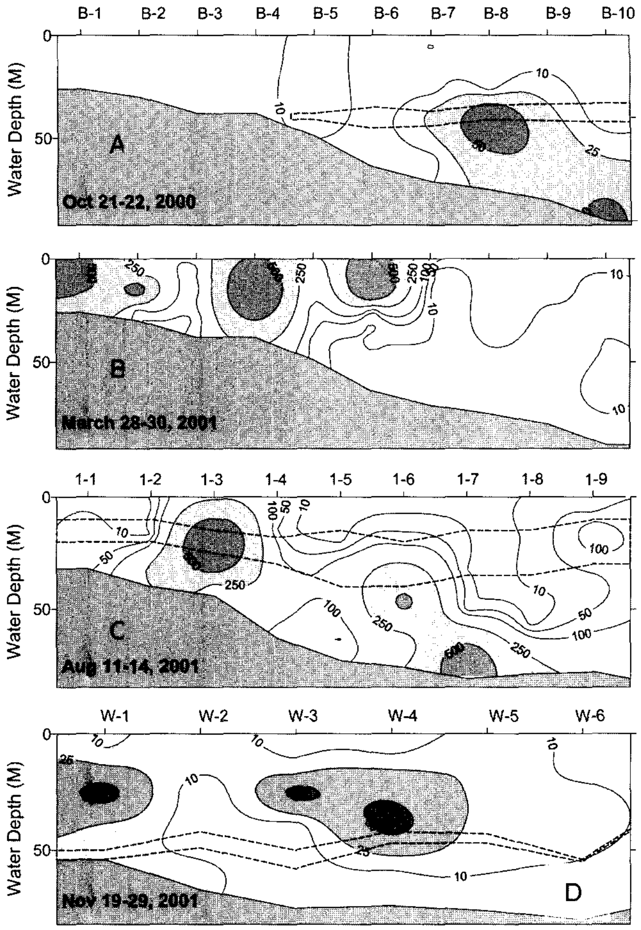

Fig. 12. Abundance (ind·m^{-3}) profiles of *Calanus sinicus* on the transect in the cruises of Oct. 2000(A), Mar. 2001(B), Aug. 2001(C) and Nov. 2001(D) (refer to Fig. 1, C-D). The broken lines show the upper and lower limits of the thermocline (temperature gradient $\geq 0.2°C{\cdot}m^{-1}$).

The relative abundance of *Calanus sinicus, Parcalanus parvus*, *Euphausia pacifica* and *Themisto gracilipes* in different layers at different times of the day at station 1-7 (located near the center of the YSDCW) in summer (Fig. 15) shows clearly the impact of the YSDCW on their diurnal vertical migration. *Calanus sinicus* tended to stay in the YSDCW close to the bottom all the day, moving upwards slightly in midnight. *Euphausia pacifica* performed generally the same pattern as *Calanus sinicus*. *Themisto gracilipes,* as mentioned above, tended to live in the middle layer just below the thermocline. It migrated slightly after dusk and returned to middle layer before dawn. As a whole, the distribution center of *Themisto gracilipes* was much higher than that of *Calanus sinicus* though they both stay below the thermocline. As comparison *Paracalanus parvus*, a small copepod, behaved differently. It stayed in the upper layer all the day moving downwards slightly in midday.

DISCCUSION

The YSWC and YSCBW are two protruding feature in the Yellow Sea. They have strong impact on the community structure, horizontal distribution, vertical distribution and vertical migration of zooplankton species in the Yellow Sea. The YSWC was identified as a sub-branch of the Tsushima Current–a branch of the Kuroshio Current (Uda, 1934) originally. However later works suggested that this current is not due to a branching of the Tsushima Current but rather a response to a pressure gradient set up by the north monsoon (Hsueh, 1988; Mask *et al.*, 1989; Teague and Jacobs, 2000; Jacobs *et al.*, 2000; Tang *et al.*, 2001). It is likely a year-round phenomenon but mainly occurs in winter. In fact it is a wind driven sporadic current events (Teague and Jacobs, 2000). Or, in other word, it is not a persistent

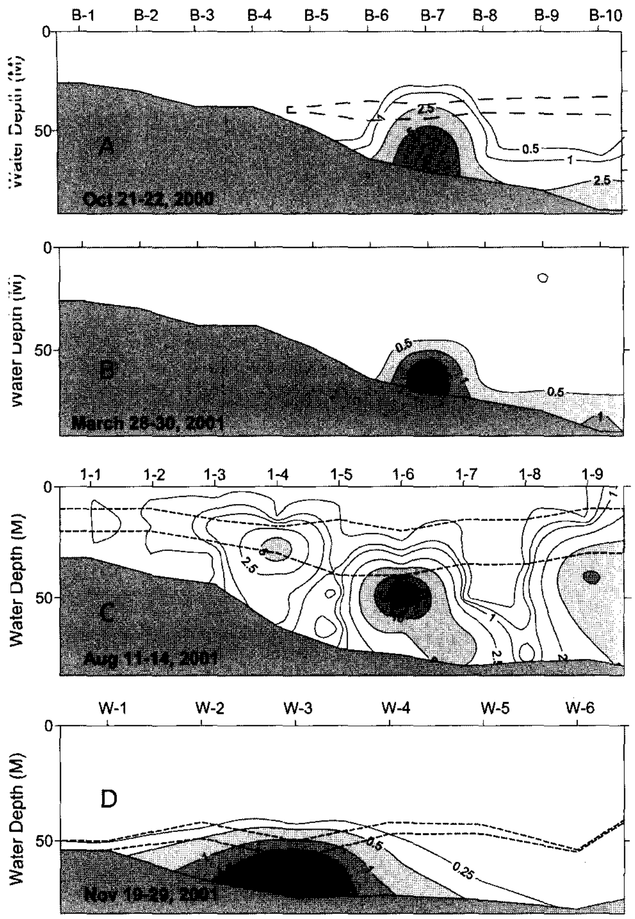

Fig. 13. Abundance (ind·m^{-3}) profiles of *Eupausia pacifica* on the transect in the cruises of Oct. 2000(A), Mar. 2001(B), Aug. 2001(C) and Nov. 2001(D) (refer to Fig. 1, C-D). The broken lines show the upper and lower limits of the thermocline (temperature gradient $\geq$ 0.2°C·m^{-1}).

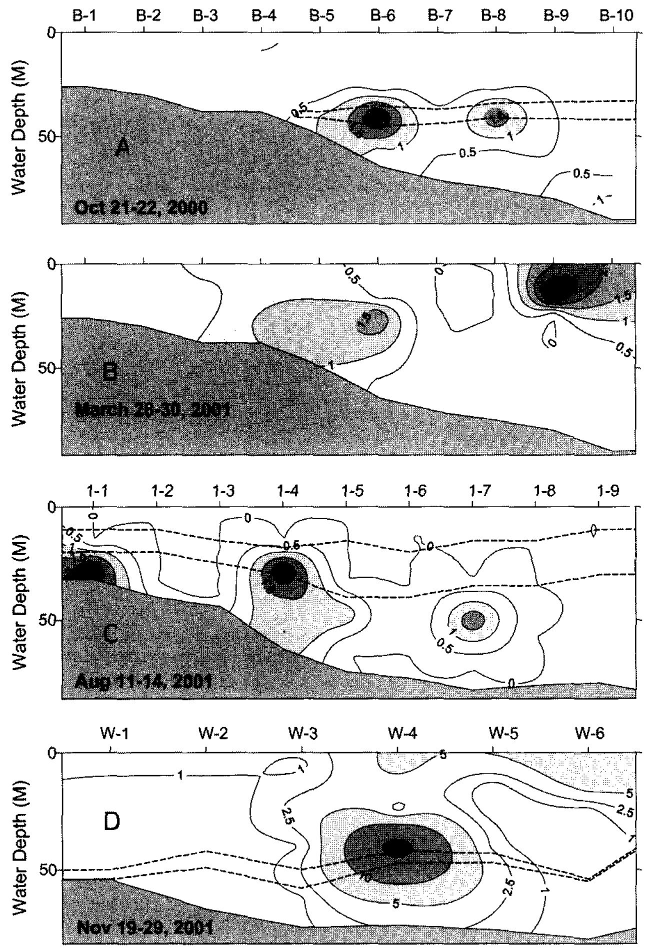

Fig. 14. Abundance (ind·m^{-3}) profiles of *Themisto gracilipes* on the transect in the cruises of Oct. 2000(A), Mar. 2001(B), Aug. 2001(C) and Nov. 2001(D) (refer to Fig. 1, C-D). The broken lines show the upper and lower limits of the thermocline (temperature gradient $\geq$ 0.2°C·m^{-1}).

mean current (Lie *et al.*, 2001). The north flow in summer was driven by different mechanism. The occurrence of large number of warm water species in winter demonstrates the existence of the intrusion of warmer and saltier water originated from the northern part of the East China Sea. The fact that less warm water species occurred in summer also indicated that the YSWC mainly occurs in winter. In summer warm water species can also be found in the Yellow Sea even more abundant but the diversity was much less than that found in winter. It is probably an expansion of their distribution area in response to the warm up of water temperature rather than the transportation by warm current.

The vertical profiles of warm water species (Fig. 5-A and 5-B) show that the penetration of YSWC in winter is not in the deep layer but happened mainly in middle layer. It is difficult to determine how far the YSWC could extend northward. Different author has different result by using different criterion. Judging from the horizontal distribution of most warm water species in this study the penetration might be as far north as 35-36°N.

As mentioned above the YSWC is caused by north wind burst and the wind pulses generally have duration of about 3 days to one week, so it is a sporadic event. Consequently the appearance of warm water species in the Yellow Sea, their distribution pattern, numerical abundance and north limit, would closely relate to the intensity of individual wind pulse and also to the phase of the wind pulse when the observation was made.

The YSBCW is a seasonal water mass that exists only in the warm half of the year (Su and Weng 1994). In summer its territory accounts for 29% of the total volume of the Yellow Sea with a temperature

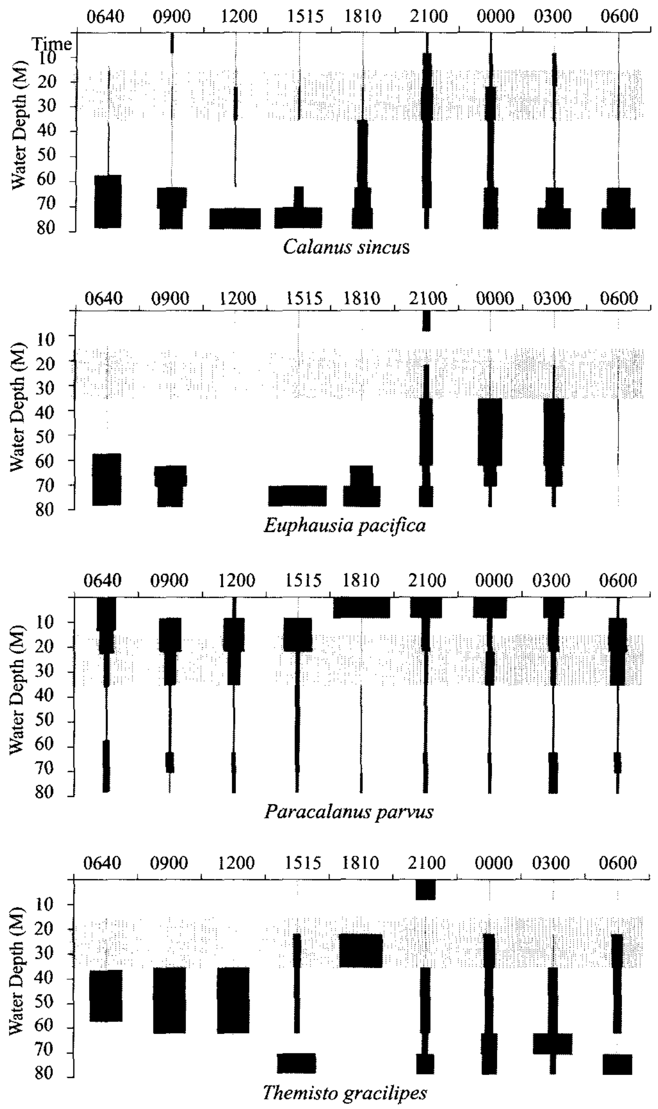

Fig. 15. Diurnal vertical migration of *Calanus sinicus, Euphausia pacifica, Themisto gracilipes* and *Paracalanus parvus* at St.1-7, August 2001. Shadowed areas show the position of the themocline.

of ≤ 10°C in most part. So it serves as a unique oversummering site for the temperate zooplankton species that can not tolerate the high temperature in the coastal area and in the upper layer of the central art of the Yellow Sea. *C. sinicus* has been referred to a warm-temperate and coastal species (Hulsemann, 1994), with a wide tolerant range of temperature and salinity (Huang and Zheng 1986; Huang, Uye and Onbe 1993). Huang *et al.* (1993) suggested an upper thermal limit of ~23°C based mainly on experimental studies. It is believed that for *C. sinicus* the tolerant range of temperature for survival of individuals would be 1-27°C (Wang *et al.*, 2003) and that for population reproduction 5-23°C. *C. sinicus* can be found throughout the year in the Yellow Sea with the peak season from April to July. In August and later on the numerical abundance decreased dramatically to a very low level due to the high temperature in most part of the Yellow Sea. It is obvious that the decrease of the numerical abundance in the Yellow Sea in August is caused by both the shrinkage of its distribution area and the low reproduction rate due to the low chlorophyll concentration (<0.1 $\mu g \cdot l^{-1}$) in the YSCBW and consequently low gut pigments contents (Li and Wang unpublished data) A resent observation by our colleague shows that the egg production rate of this species in the YSBCW was very low and its population consisted mainly of copepodite stage 5. It seems that the population in the YSCBW is likely in a semi-resting phase owing to the poor food supply and low temperature.

The strong thermocline above the YSBCW forms a barrier to the diurnal vertical migration of zooplankton species. The population of *Calanus sinicus* inhabited in the YSBCW could not migrate to the upper layer through the thermocline, however that inhabited in other places, where no thermocline appears, can migrate to the surface layer (Wang *et al.*, 1998). The strong thermocline might be another factor, which influenced the reproduction since it blocked the diurnal vertical migration of the adult females. Diurnal observations and experiments on board have indicated that *C. sinicus* spawned at night when they migrated to the surface layer (Zhang and Sun, personal communication). The strong thermocline also obstructs the downwards migration of the species living in the upper layer.

It is concluded that both the YSWC and the YSCBW have strong impact on the species composition, distribution and abundance of zooplankton in the southern Yellow Sea. The zooplankton data demonstrated that the YSWC is a seasonal, sporadic phenomenon close related to winter monsoon. And the YSCBW is an unique oversummering site, or harbour, for many temperate species.

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REFERENCES

Anon. 1977. Study on plankton in China Seas. In: Anon (ed), *Scientific Reports of "Comprehensive Oceanography Expedition in China Seas"*, Ocean Res. Off. Press, Tianjun, **8**: 1–159.

Cheng, T.Z. and Cheng, S.Y. 1962. On the ecology of the planktonic foraminifera of the Yellow Sea and the East China Sea. *Oceanol. et Limnol. Sin*, 4(1-2): 60–85. (in Chinese with English abstract)

GB12763.6–91, 1991. The specification for oceanographic surveyóMarine biology survey. Published by China State Bureau of Technical Supervision, 1–22. (in Chinese)

Ho, C., Wang, Y., Lei, Z. and Xu, S. 1959. A preliminary study of the formation of Yellow Sea Cold Water Mass and its properties. *Oceanol. Limnol. Sin.*, **2(1)**: 1–15 (in Chinese with English abstract).

Hsueh, Y. 1988. Recent current observations in the eastern Yellow Sea. *J. Geophys. Res.* (C Oceans), **93**(C6): 6875–6884.

Huang, C., Uye, S. and Onbe, T. 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**(11): 1229–1246.

Huang, J. and Zheng, Z. 1986. The effects of salinity on the distribution of some copepods in the Jiulongjiang estuary. *Acta Oceanol. Sin.* **8**: 83–91. (in Chinese with English abstract)

Hulsemann, K. 1994. *Calanus sinicus* Brodsky and *C. jashnovi*, nom. nov. (Copepoda: Calanoida) of the North-west Pacific Ocean: A comparison, with notes on the integumental pore pattern in *Calanus* s. str. *Invertebr. Taxon.*, **8**: 1461–1482.

Jacobs, G.A., Hur, H.B. and Riedlinger S.K. 2000. Yellow and East China Seas response to winds and currents. *J. Geophys Res.* (C Oceans), **105**(C9): 21,947–21,968.

Kwan, P.X. 1963. A preliminary study of the temperature variations and the characteristics of the circulation of the cold water mass of the Yellow Sea. *Oceanol. et Limnol. Sin.*, **5**(4): 255–284. (in Chinese with English abstract)

Lie, H.J., Cho, Ch. H., Lee, J.H. and Lee, S. 2001. Does the Yellow Sea Warm Current really exist as a persistent mean flow? *J. Geophys Res.* (C Oceans), **106**(C10): 22,199–22,210.

Liu, S., Shen, X., Wang, Y. and Han, Sh. 1992. Preliminary analysis of distribution and variation of perennial monthly mean water masses in the Bohai Sea, the Huanghai Sea and the East China Sea. *Acta Oceanol. Sin.*, **11**: 483–498 (in Chinese with English abstract).

Mask, A.C., O'Brien, J.J. and Preller, R. 1998. Wind-driven effects on the Yellow Sea Warm Current. *J. Geophys. Res.* (C Oceans), **103**(C13): 30,713–30,729.

Su, Y. and Weng, X. 1994. Water Masses in China Seas. In: Zhou, D., Liang, Y.B. and Zeng, C.K. (Editors). *Oceanology of China Seas*. Vol. 1[C], Dordrecht /Boston/London, Kluwer Academic Publishers, 3–26.

Tang, Y.X., Zhou, E.M. and Lie, H.J. 2001. On the origin and path of the Huanghai Warm Current during winter and early spring. *Acta Oceanol. Sin.*, **23**(1): 1–12. (in Chinese with English abstract)

Teague, W.J. and Jacobs, G.A. 2000. Current observations on the development of the Yellow Sea Warm Current. *J. Geophys. Res.* (C Oceans), **105**(C2): 3401–3411.

Uda, M. 1934. The results of simultaneous oceanographical investigations in the Japan Sea and its adjacent waters in May and June. *J. Imperial Fish. Exped. Stns*, **5**: 57–190.

Wang, R., Li, C., Wang, K. and Zhang, W. 1998. Feeding activities of zooplankton in the Bohai Sea. *Fish. Oceanogr.*, **7**(3/4): 265–271.

Wang, R, Zuo, T. and Wang, K. 2003. The Yellow Sea Cold Bottom Water – an oversummering site for *Calanus sinicus* (Copepoda, Crustacea). *J. Plankton Res.*, **25**(2): 169–183.

Zhang, H.Q. 1995. Relationship between zooplankton distribution and hydrographic characteristics of the sohern Yellow Sea. *J. Int. Soc. Yellow Sea Res.*, **1**: 50–67.

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