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Vertical Migration of Sound Scatterers in the Southern Yellow Sea in Summer

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Abstract – Acoustic volume backscattering strength data were collected and Conductivity Temperature Depth (CTD) measurements were conducted in the southern Yellow Sea in summer 2005 and 2006. The high temporal and vertical resolution acoustic data measured with a 307 kHz Acoustic Doppler Current Profiler (ADCP) and a 250 kHz acoustic Doppler profile (ADP) had dominant diel variation, which resulted from vertical migration of sound scatterers. Some scatterers congregating in the bottom layer in the daytime migrated upward at dusk, and migrated downward into the bottom layer at dawn. The migration speeds were estimated. More than 33 days data show that the diel migration varies with time. The feature of migration measured with ADCP and ADP is consistent to some extent with what is described in the study on vertical migration of zooplankton in the southern Yellow Sea with conventional net samples.

Key words – vertical migration, sound scatterer, migration speed, diel variation, southern Yellow Sea

1. Introduction

The Acoustic Doppler Current Profiler (ADCP) is a commonly used tool to measure horizontal and vertical velocity components of ocean currents by measuring the Doppler shift of sound scatterer in water. The dominant sound scatterer in seawater at ADCP frequencies is zooplankton. Other scatterers can include suspended sediment, detritus and density gradients, though density gradients are relatively weak scatterers (RDI 1996). Thus, volume backscattering strength (Sv, dB) measured with ADCP and ADP has been used to monitor sediment (Sontek 1997; Yoshioka *et al.* 2005). The potential of ADCP as a means to measure zooplankton abundance and biomass has been realized (Flagg and Smith 1989; Heywood *et al.* 1991; Zhou *et al.* 1994; Ashjian *et al.* 2002). The influences of physical oceanography environments such as meander (Ashjian *et al.* 1994), eddy (Zimmerman and Biggs 1999), oceanic fronts (Wade and Heywood 2001), and transport of North Pacific Intermediate Water (Lü *et al.* 2004) on distribution of biology have been studied with shipboard ADCP.

In addition, Sv data collected with ADCP and ADP are dominated by daily variability, which has been interpreted as the diel vertical migration (moving upward at dusk and downward at dawn) of zooplankton, and the diel vertical migration is related to the daily light cycle (Plueddemann and Pinkel 1989; Fischer and Visbeck 1993; Kaneko *et al.* 1996; Ashjian *et al.* 1998; Zhu *et al.* 2000; Luo *et al.* 2000; Wade and Heywood 2001; Ashjian *et al.* 2002; Lenn *et al.* 2003; Lü *et al.* 2003; Lü *et al.* 2004). Biological synchro-samples provide a potent proof that the daily variability of intensity measured with ADCP is mainly caused by the diel vertical migration of zooplankton (Ashjian *et al.* 1998; Luo *et al.* 2000; Wade and Heywood, 2001; Ashjian *et al.* 2002). Seasonal variation of the diel migration (Fischer and Visbeck, 1993; Ashjian *et al.* 2002) has been studied with long time ADCP observations.

The Yellow Sea is a shallow marginal sea in the western Pacific Ocean. The average depth of the Yellow Sea is 44 m, and a shallow trough runs through it. In summer, solar forcing and wind mixing warm the upper part of the water column, leaving a dominant bottom pool of cold water called the Yellow Sea Cold Water (YSCW), which is an oversummering site for *calanus sinicus* (Wang *et al.* 2003). From spring to fall, *E. Pacifica* adults are abundant in

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the central area where the YSBCW prevailed (Yoon *et al.* 2006). The vertical distributions of temperature show that the water column is stratified into the upper and lower mixed layers, and the thermocline. The maximal thermocline intensity in summer is higher than 1.1 °C m^{-1} (Editorial Board for Marine Atlas 1990). The strong thermocline above the YSBCW forms a barrier to the diel vertical migration of zooplankton species (Wang and Zuo 2004).

This paper gives the results obtained from acoustic observation in the southern Yellow Sea in summer 2005 and 2006. The primary goal of this study is to detail vertical migration of sound scatterers at the observational site with fine temporal and vertical resolution.

2. Observations

Our observational site is in the southern Yellow Sea (Fig. 1), where floor depth is near 50 m and the semi-diurnal tide is dominant (Editorial Board for Marine Atlas 1990). CTD measurements and ADCP observations were carried out in the southern Yellow Sea on September 9 and 10 2005 on the *R.V.* Jinxing 2. CTD casts were made every one hour or two hours from 0700 on September 9 to 0800 on September 10, and temperature and salinity data of 21 CTD casts were collected with a FSI Micro-CTD. A 307 kHz RD Instruments Workhorse ADCP was suspended from *R.V.* Jinxing 2. The downward-looking ADCP was set 45 s sampling interval, 30 pings in each ensemble, and set 2 m bin size and 26 bins to measure the velocity throughout the water column and collect Echo Intensity (EI, count) data. The fist bin depth was 4.8 m. The ADCP acoustic record began at 0700 on September 9 and continued to 1000 on September 10. The sea surface was characterized as about sea state 1 during our observations.

A 250 kHz Sontek acoustic Doppler profile (ADP) was deployed on the seabed in the southern Yellow Sea in summer 2006 (Fig. 1). More than 33 days' data (from 0900 on July 20 to 0600 on August 23) were collected with the up-looking ADP. The ADP was set 600 s sampling interval, and set 2 m cell size and 30 cells. Temperature and salinity data were collected with a Seabird CTD on the *R.V.* Beidou on July 26.

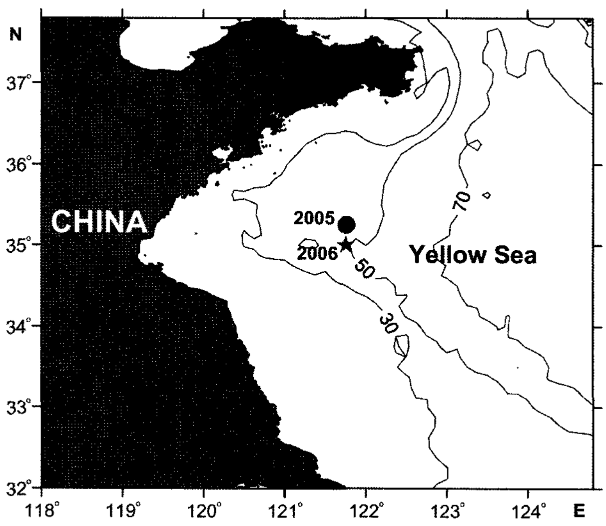

Fig. 1. Location of the observational sites.

3. Results of Observations in 2005

Temperature and salinity

Figure 2 shows the depth-time plots of temperature and salinity. The surface temperature was about 23 °C, and the temperature of the lower mixed layer was about 11-12 °C.

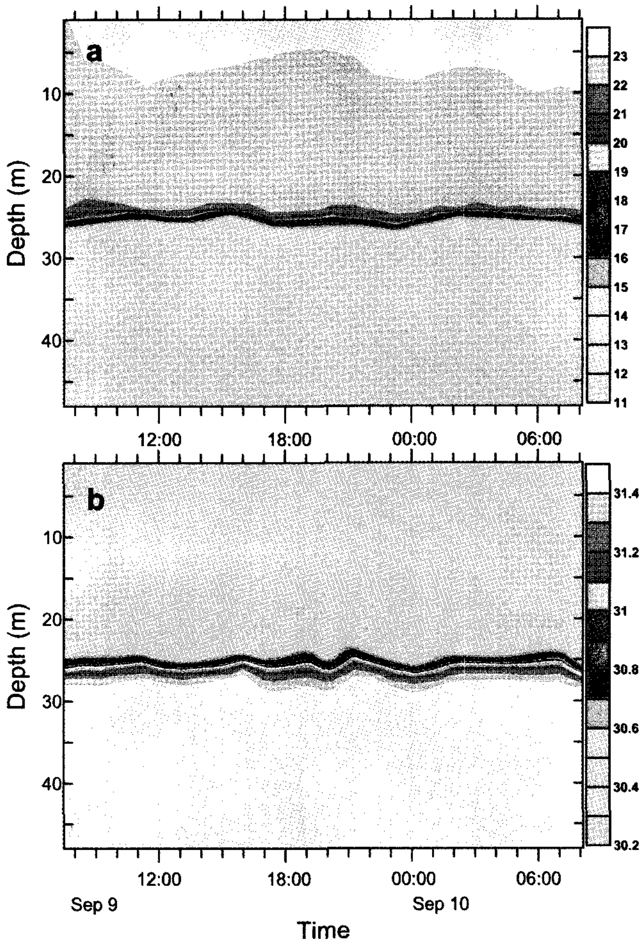

Fig. 2. Depth-time plots of temperature (°C) (a) and salinity (psu) (b).

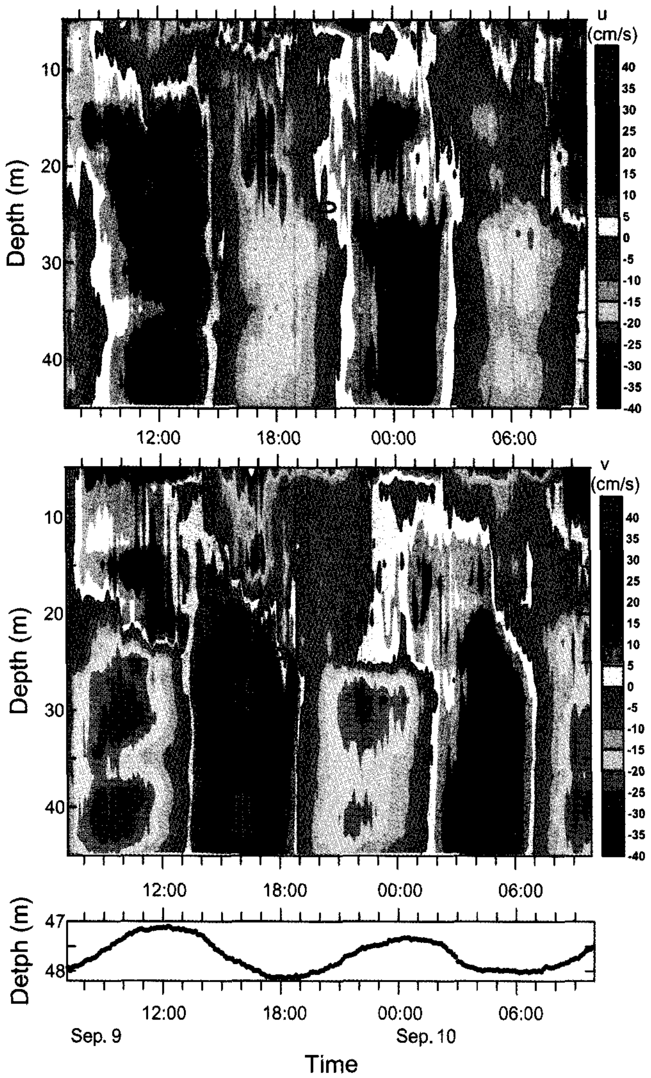

Fig. 3. The eastward velocity (u), northward velocity (v) and bottom depth measured with ADCP.

A very strong thermocline (thermocline intensity was higher than 2.0 °C m^{-1}) occurred at about 25 m depth, and its temperature decreased from 22 °C to 12 °C. The thermocline fluctuated with 1 m amplitude at tide frequency (Fig. 3). The salinity was about 30.2-20.4 psu in the upper mixed layer, and higher than 31.4 psu in the lower mixed layer. The halocline occurred at the same depth as the thermocline.

Current and volume backscattering strength

Figure 3 shows the eastward velocity, northward velocity and bottom depth measured with ADCP. The maximum current amplitude reached 40 cm s^{-1}. The eastward velocity was positive from 0900 to 1500 on Sep. 9 and from 2100 on Sep. 9 to 0003 on Sep. 10, and negative from 1500 to 2100 on Sep. 9 and from 0003 to 0009 on Sep. 10. The northward velocity also had semi-diurnal variation. However, the phase of the northward velocity in the lower mixed layer was later than in the upper mixed layer. The bottom depth was also characterized as semi-diurnal variation.

The averaged EI data of four beams were exported with RD instruments WinADCP software (version 1.13). Then, the 45-s-interval raw EI data were averaged over 450 seconds after removing invalid data based on standard percent good criteria. Rejection criteria include low correlation, large error velocity and fish detection (RDI 1996). In order to describe the distributional pattern of sound scatterers for ADCP measurements, EI data were converted to volume backscattering strength (Sv) in decibels using a formula (Deines 1999). The absorption coefficients versus depth and time were calculated using the equation of Francois and Garrison (1982).

The Sv was more than -80 dB above 12 m and below 42 m during observation (Fig. 4). In the daytime, the Sv was lower than -80 dB in the 13-42 m layer, and lower than -90 dB at about 30 m depth. In the nighttime, the strong Sv (higher than -80 dB) occurred in the whole 13-42 m layer, and then divided into two parts. One was under the thermocline, and the other was on the thermocline. From 0800 to 1600 on September 9, a relatively strong Sv occurred at the thermocline depth.

The Sv depends on the concentration of scatterers, and high concentration scatterers produce strong Sv. Due to compensating for the sound spreading and absorption, the locations of sound scatterers depicted with Sv are obvious. The distributional pattern of sound scatterers is characterized as dominant diel variability. Some scatterers congregated in 13-42 m layer in the nighttime and dispersed in the daytime. Scatterers congregating in the nighttime divided into two groups. One was on the thermocline, and the other was under the thermocline. The thermocline was the boundary. Scatterers congregating on the thermocline dispersed earlier than under the thermocline. Some scatterers congregated within the thermocline from 0800 to 1600 on September 9, and dispersed in the afternoon. There is no dominant diel variation in the bottom layer (below 42 m) for the reason that dominating scatterers in the bottom layer are bottom sediments stirred up by tidal current (Yoshioka *et al.* 2005).

Migration and migration speed

The significant day-night difference in Sv indicates a

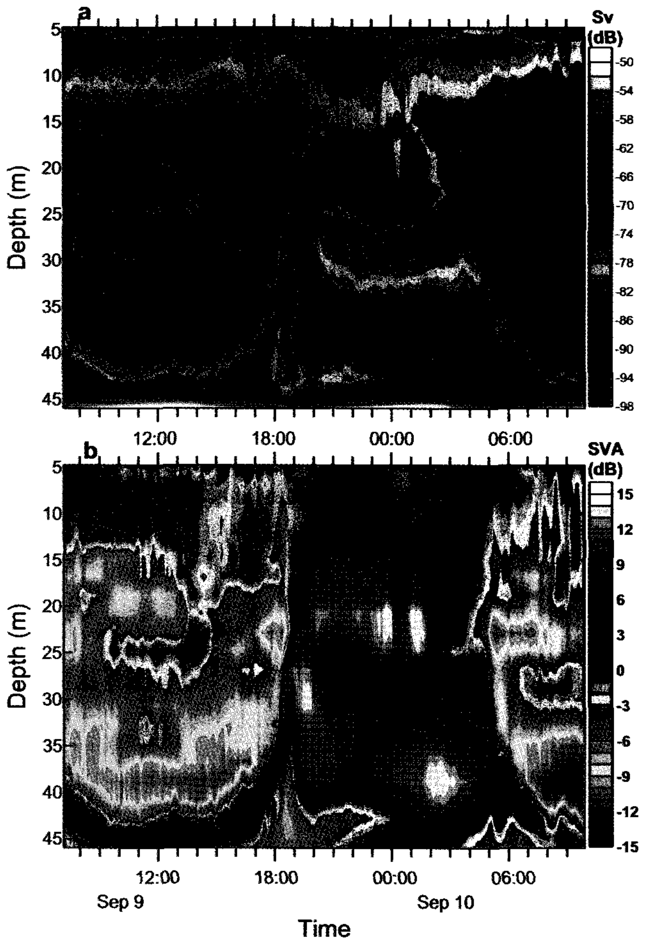

Fig. 4. Volume backscattering strength (Sv) versus depth and local time (a). Added arrows show migration of sound scatterers. Volume backscattering strength anomaly (SVA).

substantial redistribution of scatterers between day and night, which results from vertical migration of scatterers (indicated by arrows in Figure 4). There are some methods to estimate migration speed. Plueddemann and Pinkel (1989) estimate migration speed from the slope $\Delta z/\Delta t$ of the intensity anomaly ridges in the composite intensity anomaly field. Kaneko *et al.* (1996) estimate it (migration speed) from the slope of the isoline that shows the early morning and late afternoon rapid changes of Sv. Luo *et al.* (2000) estimate it from the derivative of D (t) with respect to time (t), and D (t) as the depth of the maximum Sv as a function of time. The definition of anomaly ridges (Plueddemann and Pinkel, 1989) is qualitative. The last two methods, which use Sv directly, are not valuable if conditions are that strong Sv occurs at a certain depth over the whole day.

In order to estimate migration speed, averaged Sv (Sv (z), variable z is depth) over 24 hours is calculated from 0700 on Sep. 9 to 0700 on Sep. 10. To emphasize the difference between Sv in daytime and Sv in nighttime, the Sv anomaly (SVA) is defined as:

$$SVA(z, t) = Sv(z, t) - Sv(z) \qquad (1)$$

Figure 4b shows SVA versus depth and local time. The 0-sioline (L0 (t)), which represents where and when the Sv equal the averaged Sv over 24 hours, is the boundary of Sv anomaly resulting from the redistribution of acoustic scatterers due to migration. The diel redistribution results in change of L0 with respect to time. Therefore, the diel migration speed is estimated from the rate of 0-isoline of SVA as the derivative of L0 (t) with respect to time (t).

Indicated by 0-isoline, some of scatterers in the bottom layer began migrating upward at 1500 Sep. 9. They moved upward from 40 m to 35 m (about 1650 to 1800 on Sep. 9) with a migration speed 0.12 cm s^{-1}, and the speed increased with time. Then, the scatterers moved upward with a speed 0.55 cm s^{-1} from 35 m to 26 m depth, where the thermocline occurred. Some scatterers moved through the thermocline and continued moving upward to 15 m depth with a speed 0.43 cm s^{-1}. While some of the upward-migrating scatterers traversed the thermocline to form one group in 15-25 m layer at dusk, the others turned back (moving downward) from the thermocline depth to form another group under the thermocline. The dominant downward migration (from 26 m to 35 m) occurred at about 0500 on Sep. 10 with a speed 0.60 cm s^{-1}. Scatterers kept moving downward from 35 m to 40 m with a speed 0.1 cm s^{-1}, and went into the bottom layer. Note that Scatterers congregating within the thermocline on September 9 began migrating upward at 1300.

4. Results of Observations in 2006

Temperature and salinity

The temperature profile was stratified into three layers: an upper mixed layer, a lower mixed layer, and a thermocline, which occurred between 10 and 20 m depth (Fig. 5). The thermocline intensity was 1.3 ℃ m^{-1}, and the thermocline thickness was 9 m. The salinity increased with depth, and the halocline occurred at the same depth as the thermocline.

Current and signal strength

Since current measured with ADP also had semi-diurnal

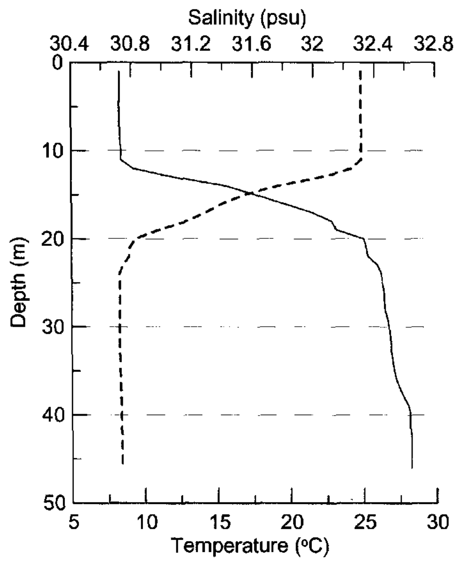

Fig. 5. Temperature and salinity profiles.

variation, the figure about it is not shown. The Signal Strength (SS) was exported with Sontek viewADP software (version 2.20). Then, the data were converted from counts to dB with the method described in the Sontek application notes (Sontek 1997). Figure 6 shows the depth-time plots of SS. Note here that one can compare depth-time pattern of SS measured with Sontek ADP with that of Sv measured with RDI ADCP, not their absolute value. The SS was higher in the surface due to acoustic surface reflection, and higher in the bottom layer due to stirring-up of bottom sediment (Yoshioka *et al.* 2005). Diel variation of SS (lower in the daytime and higher in the nighttime) was a consistent feature throughout 33 days. That indicates diel vertical migration of sound scatterers always occurred during observation. The pattern of SS diel variation varied with time. That indicates the coherence of the vertical migration varied with time. Especially, the two-group pattern of SS in the nighttime was dominant between Aug 9 and 18.

Daily average (a single day data from averaging synchronous data in different days) of SS from 1000 on Jul. 20 to 1000 on Aug. 22, and that from 1000 on Aug. 9 to 1000 on Aug. 18 were calculated (Fig. 7a and b). SS of 33-day-average and 9-day-average indicate that scatterers congregated in the nighttime and dispersed in the daytime. From Aug. 9 to 18, scatterers congregating in the nighttime formed two groups. The 15-m depth was their boundary. The group of scatterers congregating above the 15-m depth dispersed earlier than the other group. The two-group pattern is similar to what was observed in 2005 (Fig. 4).

The thermocline occurred between 10 and 20 m depth on Jul. 26 (Fig. 5). The status of the thermocline more than 10 days later was not known. Furthermore, two-group pattern of SS did not occur on Jul. 26 (Fig. 6). Therefore, one cannot confirm the relationship between the two group acoustic scatterers and the thermocline.

With the method described in section 3, the signal strength anomaly (SSA) is defined as the difference between the SS shown in Figure 7a and b and corresponding averages over 24 hours (Fig. 7c and d). The 0-sioline (L0 (t)) of SSA indicates the routine of migration. Scatterers in the bottom layer began migrating upward at about 1500. The

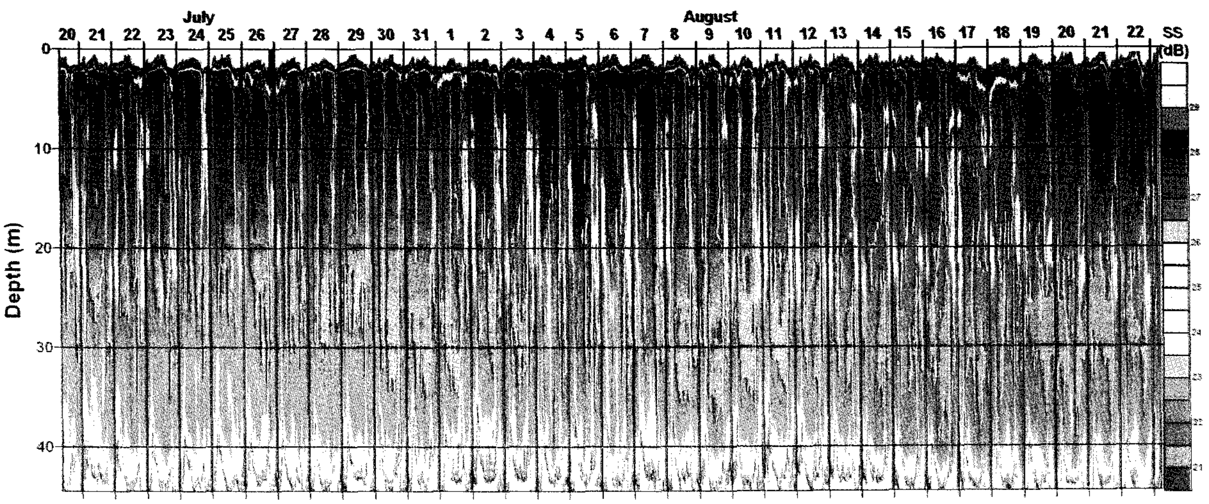

Fig. 6. Signal strength versus depth and local time. Data were averaged over 30 minutes. The arrow on July 26 indicates when the temperature and salinity data were collected.

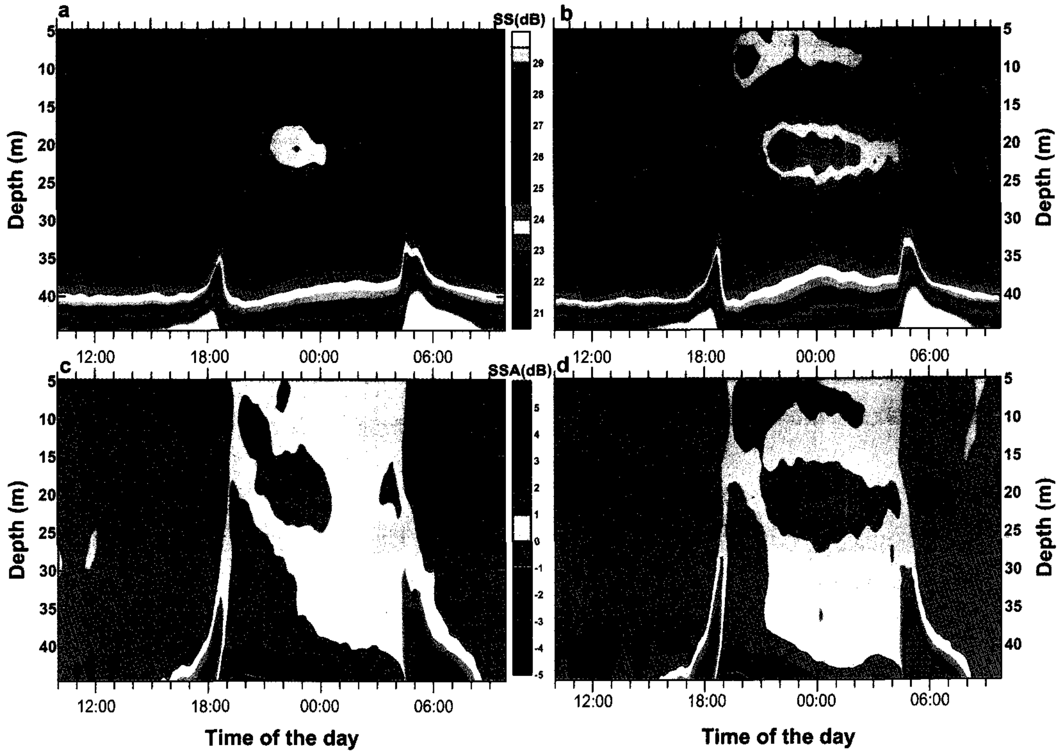

Fig. 7. Daily average of SS from 1000 on Jul. 20 to 1000 on Aug. 22 (a), and corresponding SSA (c). Daily average of SS from 1000 on Aug. 9 to 1000 on Aug. 18 (b), and corresponding SSA (d).

dominant upward migration (from 35 m to 20 m) occurred at about 1800, and the migration speed (estimated from L0) from 33-day-average and 9-day-average are 0.49 cm s^{-1} and 0.48 cm s^{-1}, respectively. The dominant downward migration (from 20 m to 38 m) occurred at about 0500 with speeds 0.30 cm s^{-1} and 0.52 cm s^{-1}, respectively.

Figure 8 compares the 0-isoline of SSA from 33-day-average and 9-day-average SS with that of SVA shown in Figure 4b. The lines indicate that the occurring time and the speed of the dominant upward and downward migrations in 2006 are close to that in 2005 except that the speed of dominant downward migration from 33-day-average in 2006 is slow.

5. Discussion and Summary

The distributional pattern of sound scatterers is characterized as dominant diel variation, and the tidal current cycle is semi-diurnal. It suggests that biological rather than physical processes are the source of the diel variation. The diel variation of Sv has been observed in deep sea (Plueddemann and Pinkel 1989; Fischer and Visbeck 1993; Kaneko *et al.* 1996; Luo *et al.* 2000; Wade and Heywood 2001; Ashjian *et al.* 2002; Lü *et al.* 2004) and shallow water (Ashjian *et al.* 1998; Zhu *et al.* 2000; Lü *et al.* 2003; Miller 2003; Lenn *et al.* 2003), and has been interpreted as the diel vertical migration of zooplankton.

No biological samples were taken during acoustic observation. However, some recent studies on zooplankton in the Yellow Sea can offer some information. Diurnal migration of zooplankton was investigated in the southern Yellow Sea (124°00'E, 34°15'N) in August 2001. Biological data were collected at standard depth by net (330 um mesh, 0.5 m^2 mouth area) with a 3-hour-interval. *Calanus sinicus*, one of the most dominant species, and *Euphausia pacifica* migrated upward to the lower boundary of the thermocline at dusk, and then moved downward (Zuo *et al.* 2004). That migration is indicated in the Sv and SS patterns (Fig. 4 a and Fig. 7b). Some zooplankton was distributed within the thermocline, such as *Paracalanus parvus*, *Oithona similis* and *Sagitta crassa*, and thermocline was suggested to be the most important influence on zooplankton vertical distribution in summer in the Yellow Sea (Zuo *et al.* 2004). That is consistent with what was shown in Figure 4

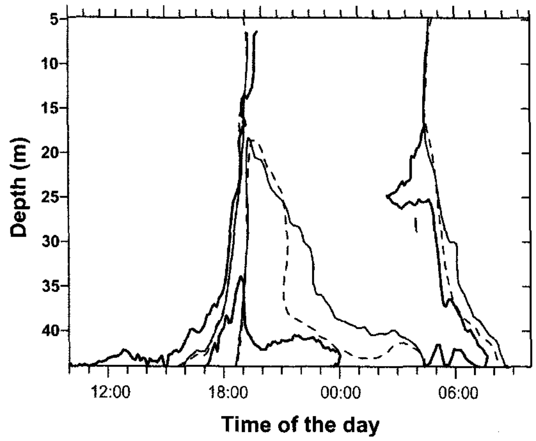

Fig. 8. 0-isolines of SSA from 33-day-average (thin line) and 9-day-average (dash line) SS and SVA (thick line). Replotted from Fig. 4 and Fig. 7.

(some scatterers concentrated within the thermocline). Hence, the migrating scatterers measured with the ADCP and ADP in our work are zooplanktons.

The migration speeds of zooplankton measured with acoustic method are between 1.0 and 4.0 cm s^{-1} in the eastern Northern Pacific (Plueddemann and Pinkel 1989), 4.0 cm s^{-1} (average) in the western equatorial Pacific (Kaneko *et al.* 1996), 2.0 cm s^{-1} (average) in the Arabian Sea (Luo *et al.* 2000) and about 1.0 cm s^{-1} in Beppu Bay (Zhu *et al.* 2000). The migration speeds in present study are smaller than those in previous studies.

Although acoustic measurement cannot distinguish the species of zooplankton, it offers a way of obtaining high temporal and spatial resolution biological data rapidly and non-intrusively. This non-intrusive technique circumvents the potential response of the zooplankton to the sampling instrument. In addition, acoustic observation can offer migration information of zooplankton in detail due to its fine temporal and spatial resolution. Finer results would be expected when acoustic measurements combine with conventional net collection.

The present study utilizes the acoustic data collected by a 307 kHz ADCP and a 250 kHz ADP to analyze vertical migration of sound scatterers in the southern Yellow Sea in summer. Acoustic data show dominant diel variation. This results from scatterers migrating upward at dusk and migrating downward into the bottom layer at dawn. The speed of dominant migration ranges from 0.30 to 0.60 cm s^{-1}. The two-group pattern in the nighttime occurs in ADCP and ADP data. ADP observation shows that the coherence of the vertical migration varies with time. The feature of migration depicted with acoustic data is consistent to some extent with what described in the net-based study on vertical migration of zooplankton in the southern Yellow Sea.

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