Vertical distribution of planktonic copepods in Tokyo Bay in summer

HIROSHI ITOH1,2,*, AIKO TACHIBANA3, HIDEAKI NOMURA4, YUJI TANAKA3, TOSHIO FUROTA1 & TAKASHI ISHIMARU3

1 Tokyo Bay Ecosystem Research Center, Toho University, 2–2–1 Miyama, Funabashi, Chiba 274–8510, Japan
2 Suido’sha Co. Ltd., 8–11–11 Hata, Tama-Ku, Kawasaki, Kanagawa 214–0038, Japan
3 Tokyo University of Marine Science and Technology, 4–5–7 Konan, Minato-ku, Tokyo 108–8477, Japan
4 Department of Marine Ecosystem Dynamics, Atmosphere and Ocean Research Institute, The University of Tokyo, 5–1–5 Kashiwanoha, Kashiwa, Chiba 277–8564, Japan

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Abstract: To investigate the vertical zonation in the copepod community in relation to stratified water-masses, multi-layer sampling at 1–2-m intervals using a submersible pump was conducted on 6 August 2009 in the inner part of Tokyo Bay, central Japan. Acartia sinjiensis showed a peak of the population density in the surface water, which was influenced by river discharge, and Paracalanus parvus s.l. had a peak contrastingly in the mid layer, which was intruded by coastal water from out of the bay through estuary circulation. Calanus sinicus occurred in the coastal water layer with other oceanic copepods. The most dominant species, Oithona davisae showed a remarkable peak in the pycnocline in the 3–6-m layer. Adults of Labidocera rotunda and Pseudodiaptomus marinus and immature copepods of Hemicylops japonicus accumulated just above the hypoxic bottom-water (DO < 1.0 mg L$^{-1}$). The shallower peak of the bimodally distributed Acartia omorii was very sharp and seemed to be formed by predation by the moon jellyfish Aurelia aurita s.l. on the copepods in the layers above and below the peak. The vertical zonation in the copepod community were reflected by the characteristic environmental conditions in Tokyo Bay in the summer, i.e. estuary circulation, hypoxia in the bottom layer and the distribution of jellyfish.

Key words: Aurelia, estuary circulation, hypoxia, Oithona davisae, pycnocline

Tokyo Bay is one of the most eutrophic embayments in Japan and its bottom water has become anoxic or hypoxic during seasons of strong water stratification (Fujiwara & Yamada 2002, Ishii & Ohata 2010). By the estuary circulation, the surface water that is influenced by river discharge flows in the surface layer while the coastal water flows into the mid or bottom layers in the stratified season and into the bottom layer in the mixing season (Fujiwara & Yamada 2002, Fujiwara 2007). The dominance by Oithona davisae Ferrari & Orsi in the copepod community in Tokyo Bay has been discussed in relation to anoxic or hypoxic bottom environments (Nomura & Murano 1992, Uye 1994) and the occurrence of species usually inhabiting waters outside of the bay (referred to as “oceanic species” sometimes) introduced by estuary circulation has been reported by many researchers (Nomura & Murano 1992, Nomura 1996, Itoh & Aoki 2010, Tachibana unpublished). Concerning the vertical distribution of copepods in Tokyo Bay, Anakubo & Murano (1991) reported seasonal changes at a station in the inner part of the bay over two year period. Naga-sawa & Marumo (1984) showed a vertical profile of O. davisae distribution over a longitudinal section of the bay. However, it has never been discussed what the exact relationship is between vertical zonation in the copepod community and stratified water masses, such as coastal water from out of the bay and hypoxic bottom water. Thus we conducted a preliminary survey by multi-layer sampling using a submersible pump.

The field survey was conducted on 6 August 2009 at a station (35°30’26”N, 139°50’22”E; depth, 22.5 m) off the mouth of the Tama-river (Fig. 1) by the T. V. “Hiyodori,” Tokyo University of Marine Science and Technology. Anchoring the boat, 2-m$^3$ of water was pumped up by a submersible pump (pumping speed: 0.5 m$^3$ min$^{-1}$) from each layer at 1-m intervals from the surface to 16-m depth and at 2-m intervals below 16-m depth (Fig. 2). Each plankton sample was filtered from 2-m$^3$ of water with a Norpac net (Motoda, 1957; mouth diameter, 45 cm; side length, 180 cm; mesh size, 100 $\mu$m) in a container on board. A total of 20 samples were collected during 10:00–11:40. The intake mouth (inner diameter, 63 mm) of the hose was set to the prescribed sampling depth by lowering it with a rope.

To avoid contamination with plankton in previous layers, the water in the hose was discarded for 15 seconds at each objec-

* Corresponding author. Hiroshi Itoh; E-mail, itoh@suido’sha.co.jp
Volume of water filtered was measured by a flow meter attached inside the center of the outlet hose. Water temperature, salinity, DO and fluorescence were monitored by a CTD (JFE Advantech Co., Ltd.) attached to the side of the intake mouth. The samples were immediately fixed and preserved in 5% formalin-seawater solution. In the laboratory, firstly *Aurelia aurita* (Linne) s.l. was sorted out and their wet weight measured. The enumeration of copepods was performed for subsamples divided into two size classes. A 1/4- or 1/8-aliquot of an original sample was made using a box-type splitter (Motoda 1959) and was sieved by 330-μm mesh net; all copepods that remained on the net were counted in their entirety. Small copepods that passed through the mesh were counted from a 1-mL aliquot extracted by a stempel pipette from the sieved water, measured in a 25–500 mL graduated cylinder; the abundance of small copepods was calculated from the numbers on the net and in the sieved water. Copepods were identified to the lowest possible taxonomic level and enumerated to number of individuals by separating adult and immature copepodids under a stereo-microscope and a compound microscope. The Shannon-Wiener index ($H'$) and Pielou’s index of evenness ($J'$) were calculated on the basis of adult copepods as indices of species diversity. For a comparison of vertical distribution, the depth ($D_{50\%}$) above and below which 50% of the population resided was calculated for each species or stage (Pennak 1943).

In the surface layer (0–3-m depth), salinity was low (26.07–27.07) and high values of water temperature (25.9–27.0°C) were observed (Fig. 3). A pycnocline was formed at 3–6-m depth, being recognized by drastic changes of water temperature (25.9–21.6°C) and salinity (27.07–30.77). Below the pycnocline, stratifications of temperature and salinity were weak and little variation was found below 19-m depth with respect to water temperature and below 13-m depth with respect to salinity. DO showed a bimodal distribution with peaks at the surface ($\approx 8$ mg L$^{-1}$) and the 13–15-m depth ($\gtrapprox 4$ mg L$^{-1}$) layers. The mid-depth peak is probably due to the intrusion of coastal water from out of the bay by estuary circulation. This is also indicated by temperatures and salinities that were slightly higher than those just above and below the peak layer, respectively. The bottom water at 19-m depth and below was nearly anoxic ($<1.0$ mg L$^{-1}$). The concentration of chlorophyll-$a$ showed a maximum value (11.7 μg L$^{-1}$) in the surface layer and decreased with depth sharply till the lower limit of the pycnocline, then gradually decreasing to the minimum ($<1$ μg L$^{-1}$) in the 13–17-m depth layer, and again increasing gradually to-
wards the bottom. A predator, *A. aurita* s.l. occurred at 6–7-m depth and 10–11-m depth.

The total abundance of copepods showed a remarkable peak (988×10^3 indiv. m^-3) at 4-m depth and small peaks at 9-m (103×10^3 indiv. m^-3) and 18-m (40×10^3 indiv. m^-3) depth (Fig. 4). The vertical distribution of adult copepods was similar to that of the total abundance in having remarkable peaks at 4-m and 9-m depth. *Oithona davisae* comprised over 75% and over 90% of total copepods in the layers excluding the 13–18-m depth layer, where *Acartia omorii* Bradford and *Pseudodiaptomus*...
**mus marinus** Sato were relatively abundant. The number of species of adult copepods was larger (>12 species) in the 13–16-m depth layer than in other layers (<10 species). The species diversity indices were high in the 13–18-m depth layer with the maximum values at 15-m depth for $J'$ and at 16-m depth for $H'$.

For the seven dominant species and *Calanus sinicus* Brodsky, a typical visitor from out of the bay, vertical distribution is

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**Fig. 4.** Vertical distribution of abundance (open circles including immature copepodids), numerical composition of dominant species, number of species and species diversity index for adult copepods at the study site. A dominant species was defined as a species occupying more than 10% of the total abundance of adult copepods in each sample.

**Fig. 5.** Vertical distribution of eight main species at the study site. Closed circle, adult; open circle, immature copepodid. Arrows indicate $D_{40}$: A, adult; C, immature copepodid.
shown according to the order of $D_{50\%}$ in Fig. 5. The population of *Acartia sinjensis* Mori was concentrated at 1-m depth and did not occur below the pycnocline. Adults of *O. davisae* formed a remarkable peak ($385 \times 10^3$ indiv. m$^{-3}$) at 4-m depth in the pycnocline and a weak peak ($84 \times 10^3$ indiv. m$^{-3}$) at 9-m depth. Immature copepods of *O. davisae* also formed a peak at 4-m depth but their $D_{50\%}$ was slightly shallower than that of the adult stage. *Acartia omorii* showed a bimodal vertical distribution with a sharp peak ($156 \times 10^3$ indiv. m$^{-3}$) at 8-m depth and a secondary peak ($63 \times 10^3$ indiv. m$^{-3}$) at 12–14-m depth. *Paracalanus parvus* (Claus) s.l. formed a remarkable peak (maximum: 92 indiv. m$^{-3}$) at 13–16-m depth. Adults of *C. sinesis* occurred between 6–18-m depth and immature copepods in the 10–16-m depth layer, in low densities ($\leq 6$ indiv. m$^{-3}$). Adults of *Labidocera rotunda* Mori and *Pseudodiaptomus marinus* showed a peak at 18-m depth, while the populations of their immature copepods were located shallower than the adults, with a peak at 1-m depth for the former species and at 13-m depth for the latter. A commensal copepod, *Hemicyclops japonicus* Itoh & Nishida showed a peak ($630 \times 10^3$ indiv. m$^{-3}$) at 18-m depth as in *L. rotunda* and *P. marinus* adults. The planktonic phase copepodid I comprised the great majority of the specimens with a small number of the benthic copepodids II–V (Itoh & Nishida 1995), which seem to have emerged from the anoxic bottom.

The present study indicated that the top 3-m layer was influenced by river discharge and the 13–15-m layer was influenced by coastal waters from out of the bay. A higher abundance of *A. sinjensis* was found in the former layer and of *P. parvus* s.l. and *C. sinesis* in the latter layer. The brackish-water species, *A. sinjensis* (Ueda 1991) inhabits predominantly the estuary of the Tama-river (Tadasugi & Itoh 1999), while *P. parvus* s.l. is the dominant species in the coastal waters of southern Honshu, central Japan and co-occurs with *C. sinesis* (Kidachi & Itoh 1979). The occurrence of these species is attributed to the two different water masses (i.e. brackish and coastal waters, respectively). It is also revealed that the coastal water intruding into the mid-layer contributed to the high species diversity of copepods in the bay, by the occurrence of oceanic copepods such as *Oncaeae media* Giesbrecht, *O. scottodicaloi* Heron & Bradford-Grieve, *O. venusta* Philippi, *O. zernovi* Shmeleva, *Triconia minuta* (Giesbrecht) and *T. umerus* (Böttger-Schnack & Boxshall), all of which were most abundant in the mid-layer.

Species with a peak in the transitional layer, between different water masses were also found. *Oithona davisai* showed a peak in the pycnocline, and adults of *L. rotunda* and *P. marinus* and immature copepods of *H. japonicus* showed a peak just above the hypoxic bottom water (DO $< 1.0$ mg L$^{-1}$). Similar modal distribution of copepods in pycnoclines and oxyclines have been reported from oceanic and coastal waters around the world. Modal distribution of *Acartia longiremis* (Liljeborg), *Centropages hamatus* (Liljeborg) and *Paracalanus parvus* (Claus) above the pycnocline during summer was reported from a shallow land-locked fjord in Norway (Magnenes et al. 1989). Herman (1984) reported that the oxygen minimum layers can present a barrier to the downward migration of some copepods. As examples for brackish waters, Harada et al. (1985) reported a peak of abundance of *A. sinjensis* (as *A. plumosa*) and *O. davisae* (as *O. arvensis* Nishida & Ferrari) in the pycnocline from Lake Naka-Umi and that of *Pseudodiaptomus inopinus* Burckhardt and *Sinocalanus tenellus* (Kikuchi) in the pycnocline just above the hypoxic bottom layer from Lake Shinji-Ko. As the factor leading to extreme reduction of copepod abundance, DO $< 1.0$ mg L$^{-1}$ was reported from Chesapeake Bay (Roman et al. 1993) as well as in the present study.

*Oithona davisae* and *A. omorii* showed a bimodal vertical distribution with a peak in the 8–9-m depth layer where DO was low (2–3 mg L$^{-1}$). This peak is probably attributable to predation by *A. aurita* s.l., which is an important predator on these copepods (Ishii & Tanaka 2001), because it was absent in the 8–9-m depth layer but abundant just shallower and just deeper than this layer.

The present study showed that estuary circulation, hypoxia in the bottom layer and predation by *A. aurita* s.l. are important factors affecting the vertical distributions of copepods in Tokyo Bay during the stratified season. The present results on vertical distribution of some copepods (e.g. *O. davisae*, *P. parvus* s.l. and *P. marinus*) are similar to those obtained in near shore waters of Tokyo Bay during the period from 1980–1982 (Anakubo & Murano 1991). This suggests that the present results represent general phenomena at this site. However, further surveys by multi-layer sampling in other seasons and regions are necessary, because the relationship between these environmental factors and the vertical distribution of plankton is critical information for better understanding the long-term fluctuations of the plankton community in the bay.

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