

Tintinnid diversity in the tropical West Pacific Ocean

LI Haibo^{1,2,4}, ZHANG Wuchang^{1,2,4}, ZHAO Yuan^{1,2,4*}, ZHAO Li^{1,2,4}, DONG Yi^{1,2,4},
WANG Chaofeng^{1,2,3,4}, LIANG Chen^{1,2,3,4}, XIAO Tian^{1,2,4}

¹ CAS Key Laboratory of Marine Ecology and Environmental Sciences, Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, China

² Laboratory for Marine Ecology and Environmental Science, Pilot National Laboratory for Marine Science and Technology (Qingdao), Qingdao 266237, China

³ University of Chinese Academy of Sciences, Beijing 100049, China

⁴ Center for Ocean Mega-Science, Chinese Academy of Sciences, Qingdao 266071, China

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Abstract

In order to investigate the tintinnid diversity, vertical distribution and latitudinal variation in the tropical West Pacific Ocean, water samples of different depths from surface to 200 m were collected along four transects. Totally 124 tintinnid species in 39 genera were detected. Most species preferred to live in the surface and subsurface waters. High tintinnid species richness, abundance and diversity index mainly occurred at depths slight shallower than the layer of deep chlorophyll maximum. Species richness, abundance and Shannon's diversity index were significant positive correlation with temperature and chlorophyll *a* *in vivo* fluorescence, but significant negative correlation with salinity and depth. The correlations between most dominant species and environmental factors were not significant. Tintinnid diversity was extremely high in this area, species richness ranged from 25 to 52 at each station, Shannon's diversity indexes were higher than 3 at most sampling positions from surface to 75 m. Proportions of redundant species were high, accounted for 87.90% of species pool and 60.38% of total abundance, indicating high capacity to response to changes in resource composition and predation pressures of tintinnid communities in the tropical West Pacific Ocean.

Key words: tintinnid, diversity, redundant species, tropical West Pacific Ocean

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1 Introduction

Tintinnids are planktonic ciliates with a size range of 20–200 μm (microzooplankton), belonging to subclass Choreotrichia, class Spirotrichea (Lynn, 2008). As important components of planktonic ciliates, tintinnids play a pivotal role in material circulation and energy flow in marine planktonic food web. Although tintinnid abundance is generally low in pelagic waters (Dolan et al., 2007; Gómsze, 2007), tintinnids are one of the best known groups of planktonic ciliates and have been recorded in oceans all around the world. Because of their lorica, tintinnids were considered as model organisms in the plankton study (Dolan et al., 2013). More than 900 tintinnid species have been recorded till now (Zhang et al., 2012). According to tintinnid genera occurrence in the global ocean, tintinnids were divided into cosmopolitan, neritic, warm water, boreal and austral biogeographical types on genera level (Pierce and Turner, 1993; Dolan et al., 2013).

Morphology and size of the lorica were conventionally used as taxonomic criteria despite of plasticity in lorica of some genera (Williams et al., 1994). Lorica oral diameter (LOD, diameter of the mouth end of the lorica) was related to size of their food items: largest prey is about 45% of the LOD and preferred prey (removed at maximum rates) is about 25% of the LOD (Dolan et

al., 2002).

The western boundary currents of the Northern Hemisphere include the Kuroshio Current and the Mindanao Current. Both of them are branches of the North Equatorial Current. The westward North Equatorial Current flowing along the 18°N (Hu et al., 2015). When reaching the Philippine coast, the North Equatorial Current bifurcates to feed the poleward Kuroshio Current (Stommel and Yoshida, 1972) and the equatorward Mindanao Current (Gordon et al., 2014).

Some researches about tintinnid have been done in the tropical West Pacific Ocean (Kim et al., 2012; Gómsze, 2007; Taniguchi, 1977). Tintinnid species richness was high in this area, and many species were selected as the indicator species of warm oceanic waters. Some species were restricted only in the Kuroshio zone (Kim et al., 2012). Compared with the East China Sea neritic zone, the tintinnid diversity was obviously higher in the warm ocean waters from the warm pool to East China Sea Kuroshio zone (Kim et al., 2012). The tintinnid abundance was low (mainly <20 ind./L) in the West Pacific Warm Pool and homogeneously distributed in the upper 100 m depth (Gómsze, 2007). Some species showed obvious vertical distribution, such as species in genera *Salpingella*, *Steenstrupiella* and *Protorhabdonella* (Gómsze, 2007).

Redundant species means species with low abundance and

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*Corresponding author, E-mail: yuanzhao@qdio.ac.cn

have similar ecological characteristics with abundant species. The occurrence of redundant species may increase the capacity of a community to respond to changes in resource composition and predation pressure (Naem, 1998; Dolan et al., 2016). As tintinnid species could be divided into different LOD size-classes, the most abundant species in each LOD size-class was abundant species, and the other species in the LOD size-class were considered as redundant species (Dolan et al., 2016). This means number of redundant species is the number of species in excess of the number of LOD size-class (Dolan et al., 2016).

The tintinnid latitudinal diversity gradient has been described based on the global species records in Pierce and Turner (1993). Tintinnid species richness was low near the poles, increasing toward the equator with a peak at about 10°–20° both north and south, and a slight inflection or decrease around the equator (Dolan et al., 2006).

The aims of this study were (1) to update the tintinnid species list in the tropical West Pacific Ocean, (2) to investigate the tintinnid diversity and its latitudinal variation in the tropical West Pacific Ocean, and (3) to find out the vertical distribution patterns of different tintinnid species.

2 Materials and methods

Thirty-three stations in four transects were sampled by the R/V *Kexue Yihao* in the West Pacific Ocean from November 26 to December 12, 2012 (Fig. 1). At every station, the vertical profiles of temperature, salinity and chlorophyll *a* *in vivo* fluorescence from the surface to 200 m were obtained using a conductivity-temperature-pressure (CTD) sensor (Sea-Bird 911, USA). Seawater samples (1 L) were collected by Niskin bottles attached to the rosette CTD system in different depths (5, 30, 50, 75, 100, 150 and 200 m) from surface to 200 m at most stations. At Sta. N18-7, the surface water samples were collected at 10 m instead of 5 m because there was oil on the surface, and no water was obtained at 150 m. At Stas N18-4, N23-1, N23-7 and N23-8, the water samples

at 200 m were lost. For tintinnid abundance determination, the seawater sample was fixed with 1% acid Lugol's iodine (Harris et al., 2000; Setälä and Kivi, 2003) in plastic bottle and kept in cool and dark places until analysis. In the laboratory, each seawater sample first was concentrated to about 100 mL by gently siphoning supernatant seawater out after settling for at least 48 h. The settling and siphoning process was repeated to concentrate each sample to a final 25 mL. The entire 25 mL concentrated sample was settled in an Utermöhl counting chamber for at least 24 h and then examined using an inverted microscope (Olympus IX 71, 100× or 400×). Each individual was photographed and measured, especially lorica length and lorica oral diameter (LOD). Tintinnid species were identified according to lorica morphology and size based on literatures (Kofoid and Campbell, 1929; Zhang et al., 2012). Tintinnid species were divided into different size-classes according to LOD. In each LOD size-class, all species except the most abundant species were considered as redundant species (Dolan et al., 2016).

The dominance index (Y) was calculated using the equation:

$$Y = \frac{N_i}{N} f_i, \quad (1)$$

where N_i was the total individual number of species i , N was total individual number of all species, f_i was the occurring frequency of species i among all stations. Species with $Y > 0.02$ was defined as dominant species (Xu and Chen, 1989).

The Shannon's diversity index (H_2') was calculated using the equation:

$$H_2' = - \sum_{i=1}^S \frac{N_i}{N} \log_2 \frac{N_i}{N}, \quad (2)$$

where S was the total number of tintinnid species found at all stations (Shannon, 1948).

Spearman rank-order correlation analysis (SPSS version 16) was used to detect significant relationships between variables.

3 Results

3.1 Hydrography

The vertical distribution of seawater temperature, salinity and chlorophyll *a* *in vivo* fluorescence (Chl *a*) of the four transects displayed significant stratification from surface to 200 m (Fig. 2). The temperature was in the range of 10.8–29.32°C, 18.15–29°C, 17.66–26.18°C and 12.43–29.84°C at Transects N8, N18, N23 and P, respectively (Fig. 2, Table 1). At each transect, the temperature decreased with the increase of depth. The average temperature was highest at Transect N18 ((26.10±2.67)°C), and lowest at Transect N23 ((22.79±2.54)°C). Although Transect N8 located in the lowest latitude area, the variation range of temperature was the biggest among the four transects and its average temperature was much lower than that of Transect N18. At Transect P, the temperature distribution was similar at the surface and subsurface waters. However, the temperature decreased from high latitude to low latitude stations at the depths deeper than 50 m (Fig. 2).

The salinity was in the range of 32.07–35.17, 31.4–35.19, 32.37–35.13 and 32.34–35.33 at Transects N8, N18, N23 and P, respectively. The lowest salinity occurred at the surface waters of each transect. The high salinity areas occurred at depth between 120 and 150 m, the maximum salinity occurred depth was deepest at Transect N18, shallowest at Transect N8. The average salin-

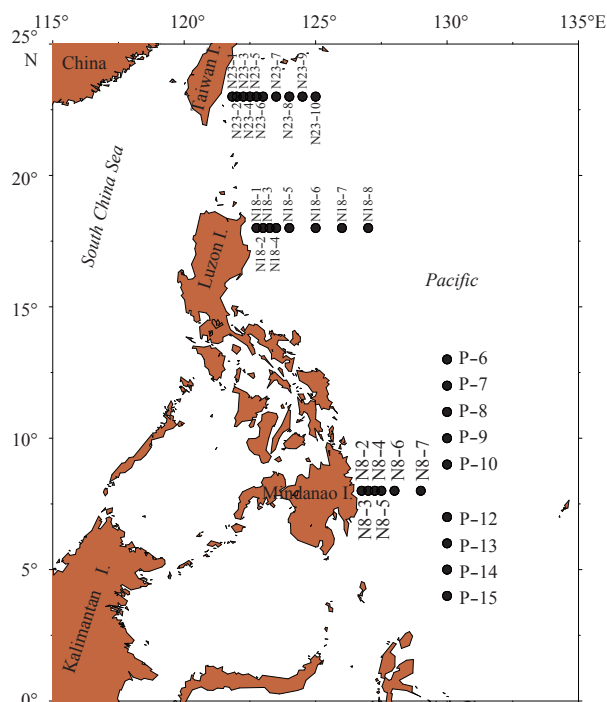


Fig. 1. Study area and location of sampling stations in the tropical West Pacific Ocean.

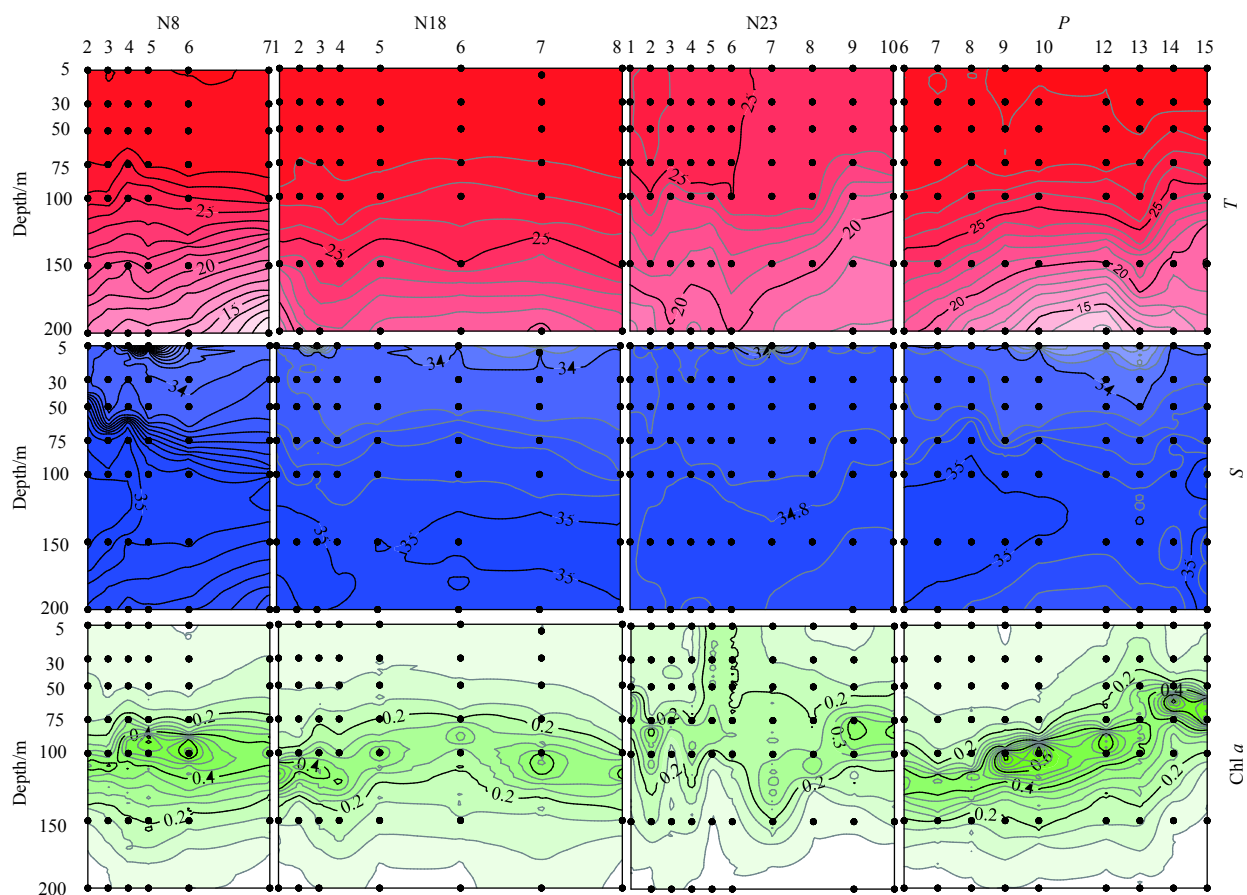


Fig. 2. Vertical distribution of temperature (T , °C), salinity (S) and Chl a ($\mu\text{g/L}$) *in vivo* fluorescence.

Table 1. Range and mean of temperature, salinity, chlorophyll a *in vivo* fluorescence (Chl a), species richness, abundance and Shannon's diversity index (H_2') along each transect

		Transect			
		N8	N18	N23	P
Temperature/°C	range	10.8–29.32	18.15–29	17.66–26.18	12.43–29.84
	mean	24.38±4.55	26.1±2.67	22.79±2.54	24.77±4.36
Salinity	range	32.07–35.17	31.4–35.19	32.37–35.13	32.34–35.33
	mean	34.64±0.42	34.63±0.41	34.66±0.18	34.66±0.41
Chl $a/\mu\text{g}\cdot\text{L}^{-1}$	range	0.04–0.70	0.04–0.58	0.03–0.46	0.04–0.86
	mean	0.18±0.14	0.15±0.11	0.15±0.09	0.19±0.17
Species richness	range	0–18	1–23	0–21	0–24
	mean	7.14±4.18	9.35±5.01	10.52±5.14	9.16±6.04
Abundance/ $\text{ind}\cdot\text{L}^{-1}$	range	0–33	1–52	0–90	0–66
	mean	10.33±7.33	15.94±11.75	19.12±14.52	18±15.42
H_2'	range	0–3.95	0–3.95	0–4.02	0–4.25
	mean	2.40±1.07	2.77±0.93	2.45±0.89	2.56±1.15

ity was similar among the four transects (Fig. 2, Table 1).

The Chl a was in the range of 0.04–0.70, 0.04–0.58, 0.03–0.46 and 0.04–0.86 $\mu\text{g/L}$ at Transects N8, N18, N23 and P, respectively (Fig. 2, Table 1). The Chl a distribution was much more confusion at Transect N23 than the other three transects. Along with the increase of depth, the Chl a increased at first and reached the peak, and then the Chl a decreased. The deep chlorophyll maximum (DCM) depths were different at the four transects. It occurred at about 100 m at Transect N8, 100–150 m at Transect N18, and 75–100 m at Transect N23, respectively. From high latitude to low latitude along with Transect P, the DCM depth varied

from deeper than 100 m at Sta. P-6 to shallower than 75 m at Sta. P-15. The average Chl a of Transect P was the highest ((0.19±0.17) $\mu\text{g/L}$) among the four transects.

3.2 *Tintinnid* species richness, abundance, Shannon's diversity index and dominant species

In total, 124 tintinnid species belonging to 39 genera were identified at the four transects (Table 2). Fourteen species only occurred once with low abundance. Most of the occurred species belong to warm water and cosmopolitan types. Only a few neritic species mainly in genus *Tintinnopsis* occurred occasionally with

Table 2. Tintinnid species list and their frequency of occurrence along each transect

Species	N8	N18	N23	P	Species	N8	N18	N23	P	Species	N8	N18	N23	P
<i>Acanthostomella conicoidea</i>	1	2	1	4	<i>E. fraknoi</i> ⁴⁾	2	3	18	8	<i>Rhabdonella</i> sp. ^{1), 4)}	7	8	13	7
<i>A. lata</i>	3	2	3	6	<i>E. haslae</i> ^{1), 4)}	10	16	9	16	<i>Rhabdonellopsis apophysata</i>	3	5	9	8
<i>A. minutissima</i> ^{1), 4)}	15	16	13	14	<i>E. lusus-undae</i>	17	6	15	20	<i>Salpingacantha exilis</i>	3	0	1	0
<i>Albatrossiella agassizi</i>	0	0	1	2	<i>E. macilentus</i> ³⁾	0	0	1	0	<i>S. perca</i>	3	4	0	0
<i>Amphorellopsis turbinea</i>	0	2	0	2	<i>E. pacificus</i> ²⁾	0	1	11	0	<i>S. simplex</i> ³⁾	0	0	0	1
<i>Amphorides amphora</i> ³⁾	0	0	1	0	<i>E. stramentus</i>	0	5	0	6	<i>S. unguiculata</i>	2	2	0	0
<i>A. minor</i> ⁴⁾	3	6	17	11	<i>E. tubulosus</i> ²⁾	0	0	1	1	<i>Salpingella acuminata</i> ^{1), 4)}	9	17	7	14
<i>A. quadrilineata</i>	2	7	13	11	<i>Favella azorica</i> ²⁾	1	1	0	0	<i>S. attenuata</i>	0	0	4	2
<i>Ascampbelliella armilla</i> ^{1), 4)}	9	32	34	32	<i>F. panamensis</i> ⁴⁾	0	0	4	0	<i>S. curta</i>	0	0	2	11
<i>A. retusa</i>	0	1	1	3	<i>Leprotintinnus simplex</i> ³⁾	0	0	1	0	<i>S. decurtata</i>	4	9	9	2
<i>Brandtiella palliata</i> ²⁾	9	4	1	5	<i>Metacylis conica</i> ²⁾	0	1	0	0	<i>S. faurei</i> ²⁾	1	2	3	1
<i>Canthariella brevis</i> ²⁾	7	13	14	15	<i>M. mereschkowskii</i> ²⁾	0	0	2	3	<i>S. laminata</i>	0	2	5	7
<i>C. pyramidata</i> ^{1), 4)}	8	5	5	9	<i>M. sanyahensis</i> ²⁾	3	5	1	5	<i>S. minutissima</i>	0	5	3	11
<i>C. septinaria</i>	1	3	3	1	<i>Ormosella apsteini</i>	2	2	1	0	<i>S. rotundata</i>	0	4	1	5
<i>Canthariella</i> spp.	6	8	7	9	<i>O. bresslaueri</i> ⁴⁾	2	2	6	3	<i>S. subconica</i>	1	3	3	4
<i>Climacocylis scalaria</i> ²⁾	0	4	0	3	<i>O. schweyeri</i> ²⁾	0	1	0	0	<i>Steenstrupiella gracilis</i> ⁴⁾	10	23	33	14
<i>C. scalaroides</i> ²⁾	0	1	8	7	<i>Parundella aculeata</i> ⁴⁾	2	8	10	3	<i>S. intumescens</i> ²⁾	8	4	3	11
<i>Codonaria oceanica</i>	2	2	0	2	<i>P. difficilis</i>	0	5	3	2	<i>S. robusta</i> ²⁾	2	6	10	13
<i>Codonella amphorella</i>	1	7	5	1	<i>P. inflata</i>	3	5	19	7	<i>S. steenstrupii</i>	10	13	8	19
<i>C. cuspidata</i> ²⁾	0	0	2	1	<i>P. spinosa</i> ³⁾	1	0	0	0	<i>Stenosemella ventricosa</i> ²⁾	0	0	1	0
<i>C. galea</i> ⁴⁾	0	0	5	0	<i>Petalotricha aperta</i> ²⁾	0	0	0	2	<i>Tintinnopsis beroidea</i> ²⁾	1	0	0	0
<i>C. perforata</i> ²⁾	0	0	6	0	<i>P. major</i>	3	0	0	0	<i>T. orientalis</i> ²⁾	0	4	0	2
<i>Codonellopsis meridionalis</i> ²⁾	0	0	0	3	<i>Poroecus apiculatus</i> ²⁾	0	1	0	0	<i>T. radix</i>	0	0	2	0
<i>C. morchella</i> ²⁾	1	0	5	1	<i>P. curtus</i>	2	3	1	4	<i>T. tenuis</i> ²⁾	1	0	0	3
<i>C. robusta</i>	0	0	1	1	<i>Proplectella claparedei</i>	3	6	8	4	<i>Tintinnopsis</i> sp. ²⁾	0	2	0	0
<i>Coxiella laciniosa</i> ²⁾	1	0	0	0	<i>P. fastigata</i>	0	0	3	0	<i>Undella clevei</i>	0	0	16	1
<i>C. pelagica</i> ²⁾	0	0	0	2	<i>P. globosa</i> ²⁾	0	0	2	1	<i>U. hadai</i> ²⁾	1	1	0	2
<i>Dadayiella cuspis</i>	0	8	9	2	<i>P. ovata</i> ^{1), 4)}	4	11	24	8	<i>U. hemispherica</i> ⁴⁾	0	0	2	2
<i>D. ganymedes</i> ^{1), 4)}	7	23	42	25	<i>P. parva</i> ²⁾	0	0	4	0	<i>U. ostfeldi</i> ⁴⁾	2	4	0	1
<i>D. pachytoecus</i>	1	6	4	5	<i>P. perpusilla</i> ^{1), 4)}	9	9	13	3	<i>U. turgida</i>	2	2	0	2
<i>Daturella</i> sp. ²⁾	0	0	0	2	<i>P. tenuis</i>	0	0	0	11	<i>Undella</i> sp. ²⁾	0	0	0	1
<i>Dictyocysta pacifica</i> ⁴⁾	1	0	9	2	<i>P. urna</i> ⁴⁾	4	8	2	7	<i>Wangiella dicollaria</i> ³⁾	0	0	1	0
<i>D. polygonata</i> ²⁾	4	10	5	6	<i>Protorhabdonella curta</i> ^{1), 4)}	7	17	11	19	<i>Xystonella clavata</i> ²⁾	0	0	1	0
<i>D. reticulata</i> ^{1), 4)}	2	10	20	4	<i>P. simplex</i> ^{1), 4)}	6	18	18	21	<i>X. longicauda</i> ²⁾	0	0	3	0
<i>D. spinosa</i>	0	0	2	2	<i>P. striatura</i>	8	1	12	12	<i>X. treforti</i>	3	3	14	4
<i>Epiplocyclus acuminata</i> ²⁾	5	7	8	3	<i>Rhabdonella amor</i> ^{1), 4)}	10	3	11	12	<i>Xystonellopsis brandti</i>	2	0	8	1
<i>E. constricta</i>	3	9	1	4	<i>R. conica</i> ²⁾	4	3	1	7	<i>X. cyclas</i>	4	3	1	2
<i>E. ralumensis</i> ²⁾	0	0	0	3	<i>R. cornucopia</i> ²⁾	0	2	18	4	<i>X. dahli</i>	0	1	4	0
<i>E. undella</i> ⁴⁾	7	4	0	2	<i>R. elegans</i> ²⁾	0	1	1	2	<i>X. favata</i>	0	5	7	4
<i>Epiplocyclus reticulata</i> ⁴⁾	0	2	14	0	<i>R. indica</i> ²⁾	0	6	14	0	<i>X. paradoxa</i>	0	1	2	0
<i>Epirhabdonella niei</i> ²⁾	5	5	1	1	<i>R. sanyahensis</i>	2	4	4	11					
<i>Eutintinnus apertus</i> ²⁾	12	19	17	13	<i>R. valdestrata</i> ²⁾	0	0	2	1					

Note: ¹⁾ Species occurred at each depth; ²⁾ species occurred at depths from surface to 100 m; ³⁾ species occurred at depths deeper than 100 m; ⁴⁾ species occurred at both surface and 200 m.

low abundance. A total of 68 species in 31 genera, 82 species in 31 genera, 95 species in 34 genera and 93 species in 34 genera tintin-

nids were identified at Transects N8, N18, N23 and P, respectively (Table 2). Tintinnid species richness at each sampling point

was in the range of 0–18, 1–23, 0–21 and 0–24 at Transects N8, N18, N23 and P, respectively. The highest tintinnid species richness occurred at 50 m of Sta. P-14. High species richness mainly occurred at 75 m or 50 m at Transects N8 and N18. Along with Transect P southward, high species richness depth varied from 100 m to 50 m slightly. At Transect N23, tintinnid species richness was low at the surface and bottom waters, and it was homo-

geneous between 30 m and 100 m (Fig. 3). On average, tintinnid species richness of Transects N8, N18 and N23 increased with the latitude northward, it was the highest at Transect N23 and the lowest at Transect N8 (Table 1). If put all species appeared at each depth of each station together, tintinnid species richness were higher than 30 at most stations (30 stations), ranging from 25 (Sta. N8-6) to 52 (Sta. N18-2).

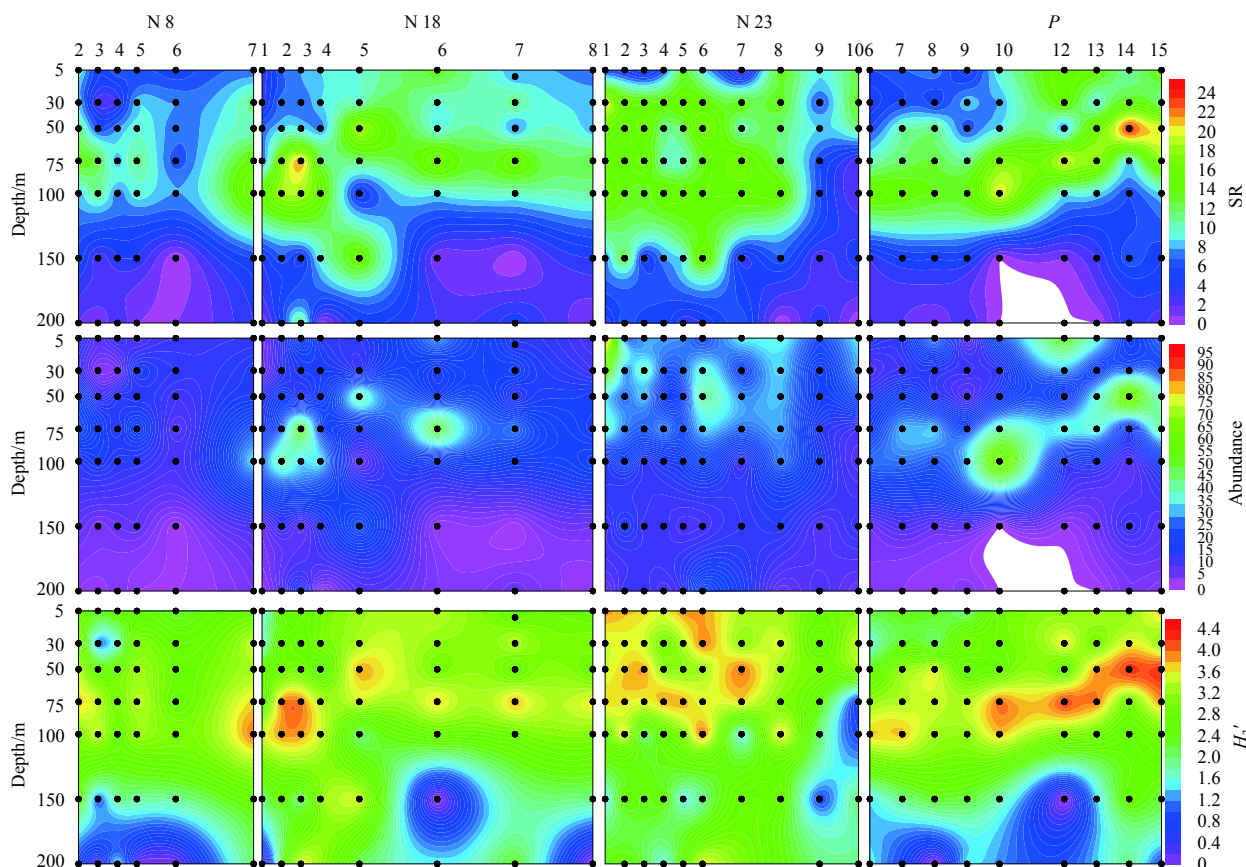


Fig. 3. Vertical distribution of tintinnid abundance (ind./L), species richness (SR) and Shannon's diversity index (H_2').

Tintinnid abundance ranged in 0–33, 1–52, 0–90 and 0–66 ind./L at Transects N8, N18, N23 and P, respectively (Table 1). The highest abundance (90 ind./L) occurred at surface of Sta. N23-1. Vertical distribution was similar with the distribution of species richness. At Transect N23, the abundance distribution was homogeneous from surface to 100 m (Fig. 3). Average abundance was the highest at Transect N23 (19.12 ± 14.52) ind./L and the lowest at Transect N8 (10.33 ± 7.33) ind./L (Table 1).

The Shannon's diversity index was considered as 0 at the sampling site where the tintinnid abundance was 0 ind./L. Shannon's diversity index was in the range of 0–3.95, 0–3.95, 0–4.02 and 0–4.25 ind./L at Transects N8, N18, N23 and P, respectively (Table 1). The distribution tendency of Shannon's diversity index was similar with that of tintinnid species richness, high levels mainly occurred at surface and subsurface waters (Fig. 3). The average of Shannon's diversity index was the highest at Transect N18 and the lowest at Transect N8 (Table 1).

There were 2, 2, 3 and 6 dominant species at Transects N8, N18, N23 and P, respectively. *Acanthostomella minutissima* and *Eutintinnus lusus-undae* were dominant species of Transect N8. *Ascampbelliella armilla* and *Steenstrupiella gracilis* were dominant species of Transect N18. *Ascampbelliella armilla*, *S. gracilis*

and *Dadayiella ganymedes* were dominant species of Transect N23. At Transect P, *A. armilla*, *D. ganymedes*, *E. lusus-undae*, *Protorhabdonella curta*, *P. simplex* and *S. steenstrupii* were dominant species. If put the four transects together, *A. armilla*, *D. ganymedes* and *S. gracilis* were dominant species.

3.3 Vertical distribution of different species

Among the 124 species, 25 species were detected at both surface and 200 m, only 13 species occurred at each depth. A total of 44 species occurred at depths from surface to 100 m, 6 species were only detected at depths deeper than 100 m occasionally (Table 2).

All the dominant species showed patchiness distribution. Their distribution patterns at different transects were different (Fig. 4). *Acanthostomella minutissima* was detected all depths at Transects N8 and N23, but disappeared at surface at Transects N18 and P. *Acanthostomella armilla* occurred all depth at Transects N18, N23 and P, but almost disappeared from 75 m to 200 m at Transect N8. *Dadayiella ganymedes* mainly distributed from surface to 150 m, and only occurred once at 200 m (Sta. N23-6). *Eutintinnus lusus-undae* was not detected at 200 m at the four transects, it disappeared at 5, 30 and 150 m at Transect N18. *Pro-*

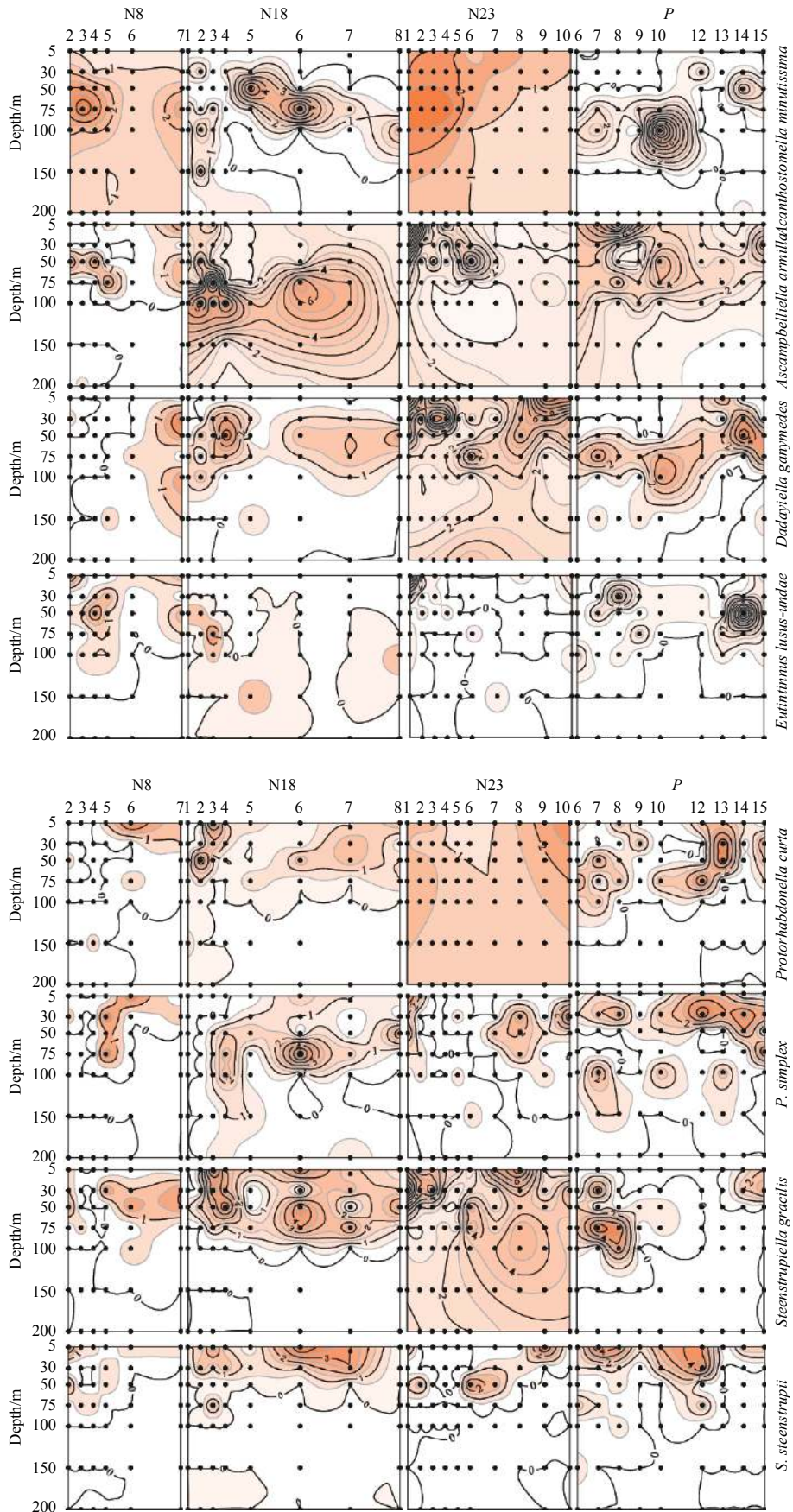


Fig. 4. Vertical distribution of dominant species abundance (ind./L) along each transect.

torhabdonella curta only occurred from surface to 150 m at Transects N8, N18 and P, but it appeared at 200 m at Sta. N23-9. *Protorhabdonella simplex* distributed from surface to 75 m at Transect N8, from surface to 150 m at Transect P, but occurred all depths at Transects N18 and N23. *Steenstrupiella gracilis* disappeared at 150 and 200 m at Transects N8, N18 and P, but occurred all depths at Transect N23. *Steenstrupiella steenstrupii* used to distribute at depth shallower than 75 m (Fig. 4).

3.4 Relationship between biological variables and environmental factors

Tintinnid species richness, abundance and Shannon's diversity index showed significant positive correlation with temperature and Chl *a*, but significant negative correlation with salinity and depth. However, there were no significant correlations between most dominant species and environmental factors (Table 3). From the scatter diagram, tintinnid species richness, abundance and Shannon's diversity index were high when temperatures were higher than 24°C. All the three biological variables increased with the increase of Chl *a*, but showed no significant variation with the change of salinity (Fig. 5). Tintinnid species richness increased from surface to 75 m, and then decreased until 200 m. The variation of tintinnid abundance and Shannon's diversity index along with the depth was similar. With the in-

crease of depth, tintinnid abundance and Shannon's diversity index showed a slight decrease from surface to 30 m, and then increased from 30 m to 75 m and get the peak at 75 m. From 75 m to 200 m, both of them decreased (Fig. 5).

Vertical variation tendencies of species richness at Transects N8, N18 and P were similar. From surface to 200 m, species richness increased at first, and then decreased. However, the peak occurred at 100 m at Transect N8, but 75 m at Transects N18 and P (Fig. 6). The variation of mean abundance were similar at Transects N8, N18 and P. Mean abundance decreased from surface to 30 m, then increased and get the peak at 75 m. It decreased from 75 m to 200 m (Fig. 6). At Transects N8 and P, Shannon's diversity index had a slight decrease from surface to 30 m and increased until reached the maximum at 75 m, it decreased from 75 m to 200 m. Different with Transect N8 and P, the Shannon's diversity index of Transect N18 had a slight increase at 30 m (Fig. 6).

Variations of species richness, mean abundance and mean Shannon's diversity index with depth at Transect N23 were different with those at Transects N8, N18 and P. Species richness decreased with the increase of depth but had a sharp increase at 75 m, and the maximum level occurred at 75 m. the mean abundance decreased from surface to 150 m and had a slight increase at 200 m. the Shannon's diversity index decreased from surface to 150 m and had a very slight increase at 30 m and 200 m (Fig. 6).

3.5 Lorica oral diameter size-class and redundant species

There were 68 species located in 14 lorica oral diameter (LOD) size-classes at Transect N8. 82, 95 and 93 species located in 15 LOD size-classes at Transects N18, N23 and P, respectively (Table 4). The 28–32 µm size-class contained the most species (15 species) and accounted for 22.01% and 18.29% of species pools at Transects N8 and N18, respectively. The 32–36 µm size-class contained the most species (16 and 17 species) and accounted for 16.84% and 16.28% of species pools at Transects N23 and P, respectively (Fig. 7). The most abundant LOD size-class located in 28–32 µm at the four transects, and counted for 23.96%, 23.34%, 30.44% and 21.25% of total species at Transects N8, N18, N23 and P, respectively (Fig. 7).

At each transect, most LOD size-classes were occupied by more than one species. Redundant species accounted for 79.41%, 81.71%, 84.21% and 83.87% of the species pools at Transects N8, N18, N23 and P, respectively. The abundance percentages of redundant species were 57.14%, 57.84%, 53.63% and 60.67% at Transects N8, N18, N23 and P, respectively. Put the four transects together, 109 species were redundant species, accounted for 87.90% of species pool and 60.38% of total abundance (Table 4). Along with Transect P southward, the percentage of redundant species increased from Sta. P-6 to Sta. P-9, it had a sharp decrease at Sta. P-10 and then increase until Sta. P-15 (Table 5).

4 Discussion

4.1 Tintinnid diversity in the tropical West Pacific Ocean

The tropical West Pacific region has been operating as a centre for the origin of marine biodiversity, and the richest diversity of many marine taxa was found in these waters (Tittensor et al., 2010, Allen, 2008; Briggs, 2005). Several studies about tintinnids at the similar areas have been done, and 43 tintinnid species were identified from samples analyzed in the equatorial Pacific along a transect between 160°E and 160°W (Gómez, 2007). A total of 88 tintinnid species were identified from samples sampled in the south of the Philippine Sea (Kim et al., 2012). In the present study, more species were identified compared with

Table 3. Spearman's rank correlation coefficient between biological variables and environmental factors

	<i>D</i>	<i>S</i>	<i>T</i>	Chl <i>a</i>
<i>Acanthostomella minutissima</i>	-0.09	0.01	0.16	0.34**
<i>Amphorides minor</i>	-0.32	-0.23	-0.15	0.04
<i>Ascampbelliella armilla</i>	-0.08	0.07	0.11	0.22*
<i>Canthariella brevis</i>	-0.25	-0.01	-0.16	-0.05
<i>Canthariella</i> spp.	0.15	0.31**	-0.23**	0.57**
<i>Dadayiella ganymedes</i>	-0.39**	-0.13	-0.11	-0.14
<i>Dictyocysta reticulata</i>	-0.45**	-0.27	-0.16	-0.07
<i>Eutintinnus apertus</i>	-0.25*	-0.15	0.05	-0.13
<i>E. fraknoi</i>	0.12	0.13	-0.13	0.30
<i>E. haslae</i>	-0.01	-0.01	0.25	0.19
<i>E. lusus-undae</i>	-0.25	-0.24	0.12	-0.14
<i>Parundella inflata</i>	-0.36*	-0.19	0.11	0.45**
<i>Proplectella ovata</i>	-0.03	0.13	0.06	-0.06
<i>P. perpusilla</i>	0.07	-0.05	0.17	0.11
<i>Protorhabdonella curta</i>	-0.13	-0.18	0.33*	0.10
<i>P. simplex</i>	-0.28*	-0.19	0.27*	0.11
<i>Rhabdonella</i> sp.	-0.17	-0.18	0.13	0.33*
<i>Salpingella acuminata</i>	-0.06	-0.15	0.10	0.11
<i>Steenstrupiella gracilis</i>	-0.11	0.06	-0.20	-0.01
<i>S. steenstrupii</i>	-0.25	-0.24	0.02	-0.10
Total abundance	-0.50**	-0.28**	0.43**	0.43**
Species richness	-0.44**	-0.25**	0.39**	0.47**
H_2'	-0.36**	-0.22**	0.33**	0.45**

Note: *T* represents temperature (°C), *S* salinity, Chl *a* chlorophyll *a* *in vivo* fluorescence (µg/L), *D* depth (m), and H_2' Shannon's diversity index. * Correlation is significant at the 0.05 level (2-tailed); ** correlation is significant at the 0.01 level (2-tailed).

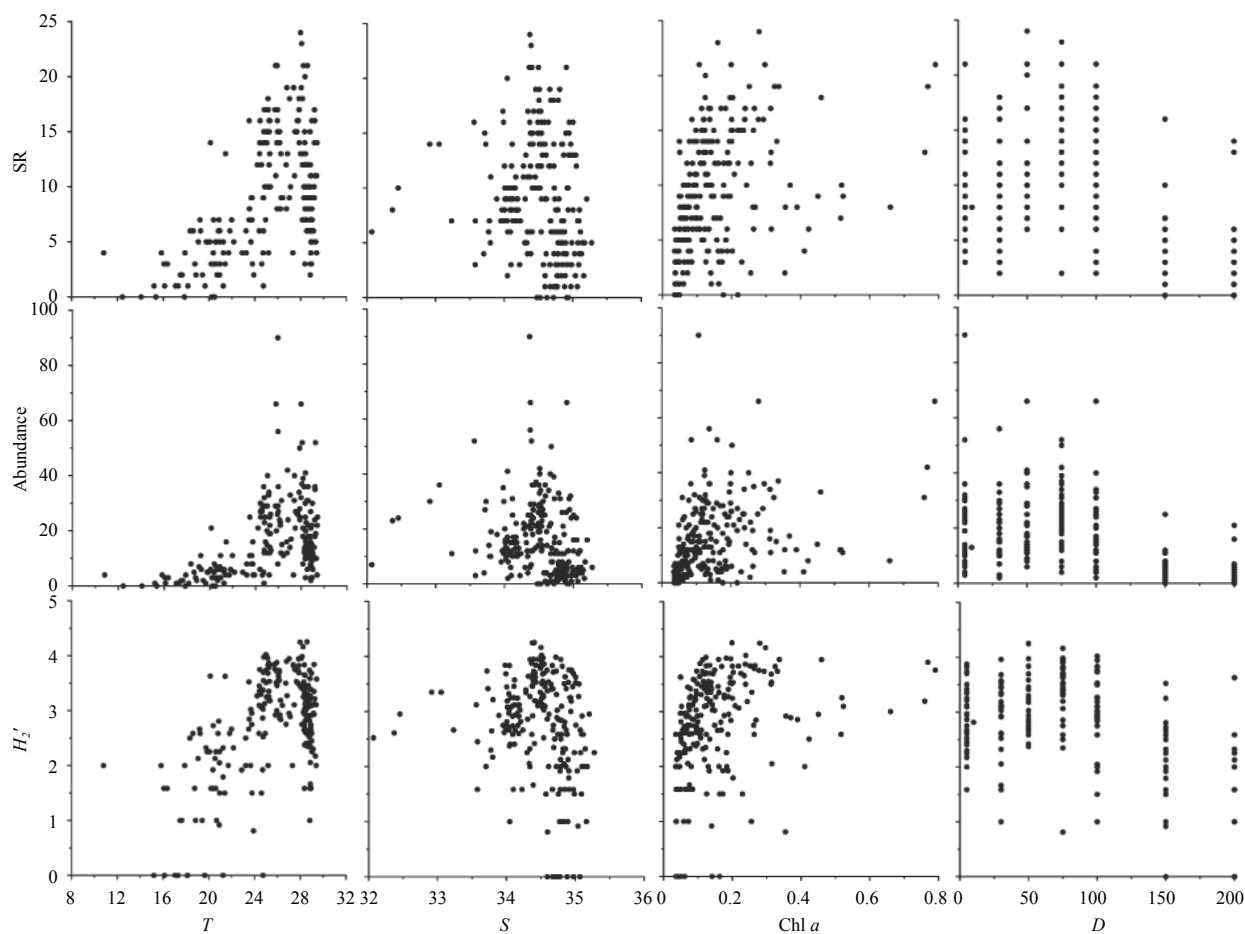


Fig. 5. Response of tintinnid species richness (SR), abundance (ind./L) and Shannon's diversity index (H_2') with the variation of temperature (T , °C), salinity (S), Chl a ($\mu\text{g/L}$) *in vivo* fluorescence and depth (D , m).

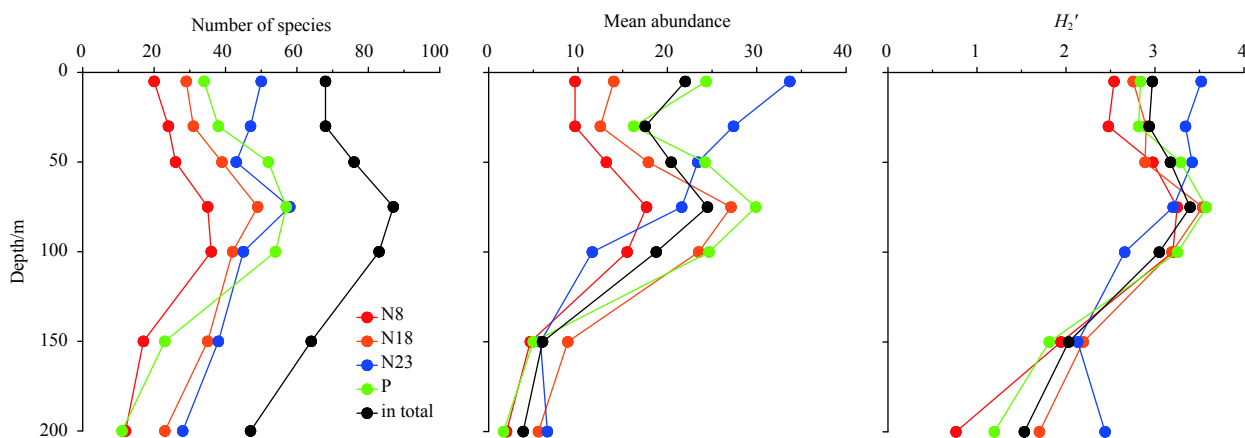


Fig. 6. Number of species, mean abundance (ind./L) and mean Shannon's diversity index (H_2') of tintinnid on four transects and in total.

Gómez (2007) and Kim et al. (2012). Totally 124 tintinnid species were detected and most of the species belonged to warm water and cosmopolitan types (Pierce and Turner, 1993; Dolan et al., 2013). Number of species was higher compared with previous reports from other areas. Totally 87 tintinnid species were reported at a transect from Italy through the Indian Ocean to New Zealand (Modigh et al., 2003); 70–80 species were identified from west to east Mediterranean Sea (Dolan, 2000; Dolan et al., 2002);

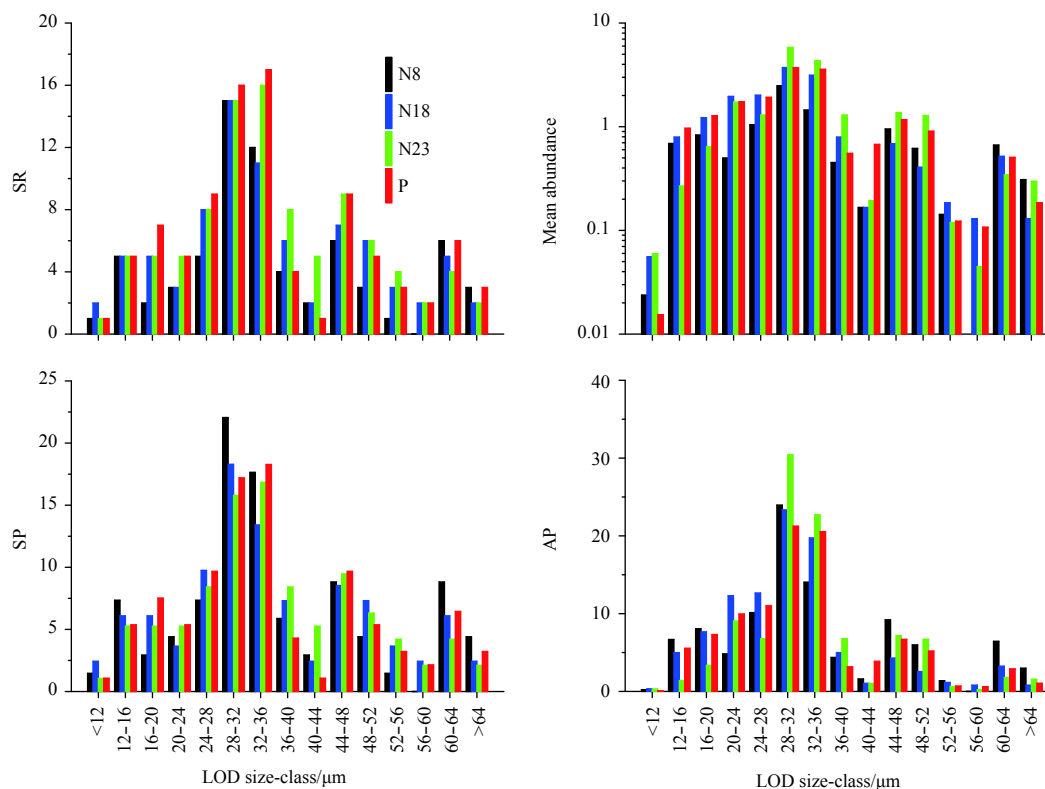
94 species in 36 tintinnid genera were identified through three cruises in the East China Sea (Li et al., 2016b); 149 species at a transect across the southeastern tropical Pacific were identified (Dolan et al., 2007), which was more than that in this study. However, tintinnid species richness ranging from 25 to 52 in this study, which was higher than that in the southeastern tropical Pacific ranging from 19 to 40 at each station (Dolan et al., 2007).

Tintinnid abundance ranged from 0 to 90 ind./L in the

Table 4. Variation of redundant species along the four transects

Transect	SR	LOD	TI	RS	PRS/%	TRI	PRI/%
N8	68	14	434	54	79.41	248	57.14
N18	82	15	861	67	81.71	498	57.4
N23	95	15	1 281	80	84.21	687	53.63
P	93	15	1 134	78	83.87	688	60.67
Total	124	15	3 710	109	87.90	2 240	60.38

Note: SR represents species richness, LOD lorica oral diameter size-classes, TI total number of tintinnid individuals, RS number of redundant species, PRS percentage of redundant species number, TRI total number of redundant species individuals, and PRI percentage of redundant species individuals.

**Fig. 7.** Variation of species richness (SR), mean abundance (ind./L), species richness percentage (SP/%) and abundance percentage (AP/%) in each LOD size-class along each transect.**Table 5.** Variation of redundant species along Transect P

Station	SR	LOD	TI	RS	PRS/%	TRI	PRI/%
P-15	45	12	151	33	73.33	74	49.01
P-14	44	12	143	32	72.73	84	58.74
P-13	46	14	144	32	69.57	70	48.61
P-12	40	13	145	27	67.5	70	48.28
P-10	34	12	155	22	64.71	77	49.68
P-09	36	10	83	26	72.22	39	46.99
P-08	36	11	117	25	69.44	51	43.59
P-07	33	11	111	22	66.67	71	63.96
P-06	35	13	85	22	62.86	36	42.35

present study, which was agreement with previous reports that tintinnid abundance was low at warm oceanic waters. Góme (2007) reported that tintinnid abundance was low than 40 ind./L in the equatorial Pacific. In the Indian Ocean, tintinnid abundance was in the range of 13.7–76 ind./L (Modigh et al., 2003). Taniguchi (1977) found average values of 10–20 ind./L along a latitudinal transect in the south Philippine Sea and showed a slight increase to 20–40 ind./L in the Celebes Sea. Shannon's diversity indexes were high than 3 at most sampling positions from

surface to 75 m in this study. This was consistent with the report of Kim et al. (2012), which showed that the diversities were high than 2.5 in the warm oceanic waters from the warm pool to the northward sites in the East China Sea Kuroshio zone. Tintinnid diversities in the range of 1.0–2.9 along a transect from Italy through the Indian Ocean to New Zealand (Modigh et al., 2003), indicated that tintinnid diversities were high in the tropical West Pacific Ocean.

The methods and sampling efforts may influence the estimation of species diversity (Góme, 2007). Generally, the net samples contained more species with low abundance compared with water samples. Using the method of hauling vertically from 200 m to the surface by a custom-made 20 μ m mesh plankton net in the equatorial Indian Ocean, Zhang et al. (2017) recorded higher total species (126 species belonging to 32 genera) and species richness (39–42) but lower abundance (0.19–2.98 ind./L) compared with those in the present study. Kim et al. (2012) collected samples from at least 50 m to the surface by vertical tows with a 20 μ m mesh plankton net; in the southeastern tropical Pacific, 10–60 L volumes samples were collected at each station (Dolan et al., 2007). The sampling efforts of those two researches were stronger than this study, however, tintinnid species rich-

ness were the highest in our study. Compared with Kim et al. (2012) and Gómeze (2007), more species were detected in the present study. In this study, species in genus *Proplectella* were ubiquitous and occurred at all depths. However, no species in genus *Proplectella* was detected by both Kim et al. (2012) and Gómeze (2007). Our study may give a more completely species list of the tropical West Pacific Ocean.

4.2 Vertical distribution of tintinnid

There were high salinity zones at depth between 120 and 150 m at each transect, the DCM depths mainly occurred a little shallower than the highest salinity depths. Tintinnid species richness, abundance and diversity indexes were low at and below the high salinity zones (Figs 2 and 3). The high salinity zones may prevent tintinnids and microphytoplankton moving downward.

In the present study, highest tintinnid species, abundance and diversity index mainly occurred at depths slightly shallower than the deep chlorophyll maximum (DCM) depths, and had similar distribution patterns with chlorophyll *a* *in vivo* fluorescence (Chl *a*). In the north Philippine Sea tintinnids were nearly restricted to the DCM depths (Gómeze, 2007). Tintinnid species richness, abundance and Shannon's diversity index showed significant positive correlation with Chl *a*. This characteristic indicated that the Chl *a* concentration limited the distribution of tintinnid in oligotrophic waters.

Tintinnids live mainly in surface waters and were divided into different vertical distribution patterns based on their priority depths (Kršinić, 1982). In this study, most species priority distributed at depths shallower than 100 m, 13 species were detected at all depths, 44 species were restricted at depths from surface to 100 m, and only 6 species were restricted at depths deeper than 100 m with extremely low abundance and occurrence frequencies (Table 2). The 6 species only detected at deeper waters in this study may also distribute at surface and subsurface water with extremely low abundance but the sampling efforts in this study were not strong enough to detect them.

Most species showed patchiness distribution and different distribution patterns at different transects (Fig. 4). This caused the variation of dominant species at different transects or even different stations. This can explain why the correlations between most dominant species and environmental factors were not significant. However, the top dominant species, including *Acanthostomella minutissima*, *Ascampbelliella armilla*, *Dadayiella ganymedes*, *Eutintinnus* spp., *Protorhabdonella* spp. and *Steenstrupiella* spp., were similar at different transects which indicated the complex and stabilization of tintinnid communities in the tropical West Pacific Ocean.

4.3 Lorica oral diameter size-class and latitudinal gradient of redundant species

Lorica oral diameter (LOD) is a conservative taxonomic characteristic of tintinnid (Laval-Peuto and Brownlee, 1986) and is related to the size of the food items ingested. The largest prey ingested is about 45% of the LOD and the size of the preferred prey (removed at maximum rates) is about 25% of the LOD (Dolan, 2002). Therefore the redundant species may locate in the same ecological niche and have similar ecological characteristics with the abundant species in each LOD size-class in an ecosystem. Theoretically, redundancy among species increases ecosystem stability (Naem, 1998).

The LOD size-class of 28–32 μm had almost the most species and accounted the most abundance at the four transects. In

the north Pacific and the Arctic, species in LOD of 22–26 μm accounted for 67.35% of the total abundance (Li et al., 2016a). This partly indicated that the size of the most abundant prey was bigger in tropical zone than in subarctic zone, which was inconsistent with our thoughts. Tintinnid species richness, LOD size-classes and redundant species show a latitudinal gradient. Along the transect from the high Arctic to the Sea of Japan, the number of redundant species increased from 0 to 14, and the percentage of redundant species increased from 0% to about 58% (Dolan et al., 2016). A total of 30 species with 14 LOD size-classes occurred in the boreal community in the north Pacific and the Arctic, means 16 redundant species and accounted for 53% of species pool in the boreal community (Li et al., 2016a). In the present study, totally 124 species located in 15 LOD size-classes, 109 species were redundant species, accounted for 87.9% of species pool and 60.38% of total abundance in the tropical West Pacific Ocean. The redundant species in the tropical West Pacific Ocean was extremely high and contributed high proportion to both species pool and abundance. The tintinnid communities in this area may be the most stable communities around the world and have high capacity to response to changes in resource composition and predation pressures.

Percentage of redundant species showed a decrease from Transects N23 and N18 to Transect N8. This tendency may indicated that the environmental factors of Transect N8 were not as stable as those of Transects N18 and N23, which can be partly reflected by the biggest temperature variation range.

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